Development of a Modular Reconfigurable Machine for Reconfigurable Manufacturing Systems

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Declarations

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I, Jared Padayachee, declare that

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Abstract

The Reconfigurable Manufacturing Systems (RMSs) paradigm has been formulated to encapsulate methodologies that enable manufacturing systems to effectively cope with changes in markets and products. RMSs are systems which are envisioned to be capable of a rapid change in manufacturing layouts, process configurations, machines and control components to provide a quick response to changes in the master production schedule. This research was initiated due to the necessity for new forms of production machinery to be design for RMSs, which can aid manufacturers in the adjustment of system capacity and functionality at lower costs.

This thesis presents the development of Modular Reconfigurable Machines (MRMs), as a novel machining solution within the scope of RMSs. MRMs are characterized by modular mechanical structures that enable the flexibility of the machine to be adjusted in response to changes in products. The concept of adjustable flexibility implies that the flexibility of the machines may be balanced to exactly match the requirements of the system when changes in production plans occur. Product changes are managed by a variation of machining processes and Degrees of Freedom (DOF) on a platform. The modular nature of these machines permits this to be done easily and cost effectively. MRMs therefore possess an advantage over traditional machining systems, where an adjustment of system functionality would require the procurement of new machinery. Manufacturers will also have the option to purchase machines with flexibility that may be increased as needed, instead of investing in highly flexible and expensive CNC systems, with features that are often excessive and unused.

Main points of this research included the development of mechanical modules for assembly into complete machines. The number and types modules used in an assembly could be changed to provide the kinematic and process optimization of the mechanical hardware according to production requirements. In conjunction to the mechanical development, a suitable Mechatronic control system will be presented. The focus of control development was the facilitation of seamless system integration between modular mechanical hardware and the controller at both hardware and software levels. The control system is modular and distributed and characterised by a “plug-in” approach to control scalability. This is complimented by a software architecture that has been developed with a focus on hardware abstraction for the management of a reconfigurable mechanical and electronic architecture.

A static and dynamic analysis of the MRM system is performed for a selected mechanical configuration. The performance of the mechanical and control system is also evaluated for static and dynamic positioning accuracy for different modes of motion control. The implications for MRMs are then analysed, which include system functionality and capacity scaling, manufacturing expansion flexibility and system life spans. The research was concluded with an analysis of the challenges and problems that must be addressed before MRMs become industrially acceptable machines.

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List of Acronyms and Abbreviations

AC	Alternating Current
Acc	Accuracy, Acceleration
ADC	Analogue to Digital Converter
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
BLU	Basic Length Unit
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAN	Controller Area Network
CAPP	Computer Aided Part Programming (Also Computer Aided Process Planning)
COTS	Commercial Off-The-Shelf
CNC	Computer Numerically Controlled
CR	Control Resolution
DC	Direct Current
Dec	Deceleration
DMS	Dedicated Manufacturing System
DMT	Dedicated Machine Tool
DOF	Degrees of Freedom
DSP	Digital Signal Processor
EDM	Electric Discharge Machining
FIFO	First-In-First-Out
FMS	Flexible Manufacturing System
HTM	Homogenous Transformation Matrix
I2C	Inter Integrated Circuit (Read as: „I" squared „C")
ICR	Input Capture Register
IDE	Integrated Development Environment
I/O	Input/ Output
ITM	Improved Tustin Method
MIPS	Million Instructions Per Second
MRM	Modular Reconfigurable Machine
NC	Numerical Control
NCK	Numerical Control Kernel
NURBS	Non-Uniform Rotational Basis Spline
OAC	Open Architecture Control

List of Acronyms and Abbreviations

OCR	Output Compare Register
OS	Operating System
PC	Personal Computer
PID	Proportional-Integral-Derivative
PREMADE	PRogram for REconfigurable MAchine DEsign
PROFIBUS	PRocess FIeld BUS
PWM	Pulse Width Modulation
Ref	Reference
Rep	Repeatability
RMS	Reconfigurable Manufacturing System
RMT	Reconfigurable Machine Tool
SERCOS	SErial Real-time COmmunication System
SMMEs	SMall and Medium Enterprises
TCP/IP	Transmission Control Protocol/ Internet Protocol
TIPO	Time for InterPOlation (Interpolation Cycle Time)
TWI	Two Wire Interface
USART	Universal Synchronous and Asynchronous serial Receiver and Transmitter
USB	Universal Serial Bus

Nomenclature

A	area, approach allowance
A_c	clamped area
A_t	tensile stress area
a_x	acceleration
b	mechanical damping coefficient
C_p	cutting coefficient
c	damping coefficient
D_o	original diameter, outer diameter
d	diameter, nominal diameter of a bolt, depth of cut
d_c	diameter of collar or bearing
d_m	mean/nominal diameter of a power screw
E	modulus of elasticity, position error
E_C	concatenation error
E_m	mechanical position error
E_O	edge offset error
E_p	position control error, tracking error
$E_{i+1\leftarrow i}$	error matrix
EH	chord height error
ER	radial error
e	error
F	force
F_e	external bolt force
F_c	normal clamping force between interfaces
F_i	initial bolt tension
F_o	magnitude of a harmonic force
f	coefficient of friction, frequency
f_c	collar coefficient of friction
f_r	linear feed rate
${}^{i+1}f_{i+1}$	link-wise force
g	gravity, grip length
I	moment of inertia
J	moment of inertia of a rotating shaft
K	cutting coefficient, electromotive constant
K_d	derivative gain
K_i	integrator gain
K_p	proportional gain
K_{pp}	proportional position control gain
K_t	cutting coefficient
k	stiffness, interpolation number
k_b,	bolt stiffness
k_c	interface stiffness
k_i	bolt tightening constant
L	length, thread lead, motor inductance
ΔL	increment in length
M	magnitude of acceleration
M_M	maximum position
M_m	minimum position
M_n	module homogenous transformation matrix
M_t	drill turning moment
${}^{i+1}_{i}M_n$	module homogenous transformation matrix
m	mass, cutting coefficient
N	rotational speed, number of configurations, number of iterations, reduction ratio

Nomenclature

n	number of enhancement modules, number of measurements
${}^{i+1}n_{i+1}$	link-wise torque
P	thread pitch, load
P_A	angular pitch of a screw
P_T	translational pitch of a screw
${}^{i+1}_{i}P$	position matrix
p	number of encoder pulses
R	radius, electrical resistance
Ref	reference value
Res_x	residual length
R_{MR}	material removal rate
${}^{i+1}_{i}R$	rotation matrix
r	number of enhancement modules selected at a time, frequency ratio
S	tool feed per revolution, sum of axial increments
$\vec{\$}$	a screw
$\vec{S}$	unit vector
S_p	proof strength
S_{shear}	shear strength
s	standard deviation
T	time constant, iteration time
T_m	machining time
T_{step}	step time
${}^{work}_{tool}T$	machine homogenous transformation matrix
t	time, thread height, thickness
u	output of position controller
V	linear speed
V_{nom}	nominal voltage
V_{ref}	reference voltage
W	load on power screw
$\dot{W}$	power
X	amplitude of harmonic response
ΔX	axial increment on X-axis
ΔX_o	axial increment on axis after Acc/Dec control
x	distance on X-axis, cutting coefficient
x_e	end position
x_s	start position
$\bar{x}$	mean/ average value
ΔY	axial increment on Y-axis
y	distance on Y-axis, cutting coefficient
${}^{i}\hat{Z}_i$	joint axis unit vector
z	distance on Z-axis
α	X-Y-Z Euler Angle, angular increment for ITM interpolator
α_n	thread angle
β	X-Y-Z Euler Angle
γ	X-Y-Z Euler Angle
δ	deflection
ε	skewness error
θ	drill point angle, angular position
δ	damping factor
τ_i	actuation force or torque

Nomenclature

φ	phase angle
ω	angular frequency
ω_d	damped frequency
ω_n	natural frequency

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1. Introduction

1.1 Manufacturing Challenges

The rationale for this research originates in the need to address manufacturing challenges that have emerged as a result of global economic competition in recent years. The ability of a manufacturer to monopolise a market is dependant on product innovation and the ability to respond rapidly and efficiently to market demands. Computer Aided Design (CAD) packages are an indispensable tool for product innovation. The advancements in CAD packages have considerably reduced product development times in the past decade [1]. The heightened rate of product development has resulted in products being introduced into markets in shorter periods of time. A consequence of this trend is the shortening production life of consumer goods. The challenge arising from a frequently changing product portfolio is the cost effective initialisation of new manufacturing configurations.

Frequent changes in market characteristics are induced by advancements in technology and erratic consumer trends. The necessity to favourably influence consumer behaviour has forced manufacturers to seek and exploit niches in global markets. The concept of product design by the customer has emerged as an inevitable consequence of increasing consumer awareness [2]. The manufacturing of products to customer specifications possesses the ability to fragment global markets and create niches for further exploitation. The challenge arising in product customisation is the need for increased process variation, dynamic production scheduling and the fabrication of these items at mass production rates.

The challenges arising from global economic competition may be translated into requirements for the design of future manufacturing systems. Lang et al [3] have identified four requirements for a manufacturing enterprise to effectively achieve the objectives of profitability and increased market share in a competitive environment. In brief, these requirements are:

(i) *Short manufacturing lead time*: Short lead time requires the quick initialization of manufacturing systems. Early product introduction increases the likelihood for obtaining and retaining a larger market share.

(ii) *Increased product variety and product customization*: Increased product variety and product customization increases the appeal of goods to consumers with varied preferences.

(iii) *Mass production rates for low product volumes:* The fragmentation of markets by product customization results in the demand for specific variants in small quantities. Improved production rates increase the likelihood of monopolizing resultant niche markets that may be shared by global competitors.

(iv) *High quality products at lower prices*: Globalization has resulted in a multiplicity of manufacturers offering consumers similar, high quality goods. The negative effects of market saturation may be avoided by an enterprise that is capable of producing personalized products at competitive prices.

The cost effective initialization of manufacturing systems that meet the outlined requirements has required the reengineering of manufacturing paradigms. Dedicated Manufacturing Systems (DMSs) and Flexible Manufacturing Systems (FMSs) have been identified as incapable of meeting the challenges of modern manufacturing [1].

The inadequacy in these systems has been primarily attributed to the structure of these systems and the types of production machinery employed in each. The reconfigurable manufacturing paradigm has been proposed by Koren et al [1], to encapsulate new methodologies for the design of manufacturing systems and equipment that will provide solutions to the challenges arising. Systems that will be developed according to this paradigm are called Reconfigurable Manufacturing Systems (RMSs).

RMSs are systems that are intended to provide a rapid response to dynamic changes in production requirements, through the reconfiguration of hardware and software resources. Mehrabi et al [4] have endeavoured to identify enabling technologies that must be developed for RMSs. These technologies include open architecture software systems, reconfigurable production equipment, scalable control systems and simulation and sensor systems for fault diagnosis. This research focused on the development of suitable production equipment for reconfigurable manufacturing environments.

1.2 Motivation for the Study

The conceptualization of the reconfigurable manufacturing paradigm has prompted the reengineering of production machinery. The inadequacies of DMSs and FMSs in meeting the demands of modern manufacturing have been traced, in part, to the production machines employed in each system. DMSs and FMSs employ machines that possess fixed mechanical architectures and exhibit closed proprietary control systems that are generally expensive or impossible to upgrade. RMSs require production machines with extensible and customizable mechanical hardware. The extensibility of a machines mechanical hardware is necessary to allow an expansion of the production envelope trough the process of reconfiguration. The customization of the mechanical hardware further implies that the machine, although flexible, will not possess excessive functionality. The notion of customized flexibility is essential in reducing the capital investment in manufacturing infrastructure.

RMS machines require scalable and open control systems. The scalability of a machines control system is necessary to facilitate the reconfiguration of the mechanical hardware. Existing Dedicated Machine Tools (DMTs) and Computer Numerically Controlled (CNC) machines posses unalterable monolithic control systems that generally do not provide the facility for the integration of additional actuation and control features on a platform. The implementation of user specific actuators, sensors and control algorithms, on commercially available processing platforms, possesses the potential to optimize the performance of a manufacturing system. Performance benefits include a reduction in machine cycle times, reductions in tool breakage, a reduction in rework and improvements in product quality. The creation of manufacturer specific features on a machine is currently only available on custom built hardware. The implementation of custom built hardware in a manufacturing system is uneconomical and not feasible if systems are to be initialized rapidly. The reengineering of commercially available machines is necessary to facilitate the implementation of user specific features within bounds that are acceptable to machine building companies.

Production scalability is a desired characteristic for RMSs. The scalability of production streams through the redistribution of hardware resources is an attractive, cost effective solution to scalability in systems producing a variety of products.

The concept of scalability through hardware redistribution involves the movement of resources between different production streams, as the capacity requirement of each stream varies. Hardware sharing between streams will ensure more complete use of system resources, and a potential reduction in capital investment. The ability of machines to facilitate production scalability has thus far been limited or impossible.

Regarding DMTs, production scalability is achieved through the purchasing of additional machines and the duplication of production lines. In a system employing DMTs, the redistribution of machining resources between distinctly different production streams is generally impossible. CNC machines, on the contrary, possess the ability to aid in the scalability of production streams. CNC machines are flexible in a manner that parts produced by one stream are capable of being produced by the machines employed in a second production stream. The limitation with a CNC machine being redistributed as a machining resource to another production stream is that the parts being created in that stream fall must fall within its production envelope. RMSs require machines with extensible production envelopes to enable advanced scalability with existing hardware resources.

1.3 Project Objectives

The objectives of this research were to:

- Research and establish a list of the essential characteristics that RMSs must display
- Research and establish criteria and design principles for reconfigurable machines
- Research, design and construct a mechanically reconfigurable machine for RMSs
- Research, design and implement a suitable control system. This must include the development of the electronic hardware, the programming of machine control algorithms and the creation of a Graphical User Interface (GUI) for human interaction
- Analyse the performance of the prototype machine and evaluate its applicability to RMSs

1.4 Scientific Contribution of the Dissertation

This research presents the development of a Modular Reconfigurable Machine (MRM) for RMSs. MRMs are machines that have been designed to be functionally modular in their mechanical and control architectures. A prototype has been designed for material removal operations. The novel modular design of the mechanical architecture permits the reconfiguration of the machines kinematic chain and processing functions in accordance to changing production requirements. The mechanical reconfiguration of the platform was achieved by the addition and removal of modular units of hardware from its structure. According to the literature survey, reconfigurable machines of this nature have not been previously developed by industrial machine builders or academia. The MRM possessed a modular, scalable Mechatronic control system which lays in direct contrast to traditional monolithic numerical control systems. The control system is lean, and low cost, being created with the intention of illustrating a unique style of control implementation for modular, numerically controlled machines. Although open architecture control has been highlighted as an essential feature for reconfigurable machines, the creation of a fully comprehensive open architecture controller was beyond the scope of this research.

The scientific contribution of this research is the enhancement of manufacturing system functionality through the reconfigurability offered by MRMs. The modular nature of MRMs further aids in the scalability of system production capacity through the synergistic redistribution of hardware. Machine modules may be considered as a resource, instead of entire machines and these modules that may be distributed between production streams as necessary. The movement of modules between streams provides a unique and elegant solution to system scalability (i.e. system production capacity scaling).

The MRM presented in this dissertation has been developed to perform material removal processes. It should be noted that the design methods presented in subsequent chapters may be extrapolated to create reconfigurable machines for other types of processing operations. Such machines may include Numerically Controlled (NC) robots, chip mounters and assembly machines with modular end effectors or other modular components.

1.5 Research Publications

- J. Padayachee, G. Bright; *Modular Reconfigurable Machines for Reconfigurable Manufacturing Systems*; 24th ISPE International Conference on CAD/CAM, Robotics and Factories of the Future; 29-31 July 2008; Koriyama; Japan
- J. Padayachee, I. Masekamela, G. Bright, C. Kumile, N.S. Tlale; *Modular Reconfigurable Machines Incorporating Open Architecture Control*; 15th International Conference on Mechatronics and Machine Vision in Practice (M2VIP'08); 2-4 December 2008; Auckland; New Zealand
- J. Padayachee, G. Bright; *Modular Reconfigurable Machining Systems for Reconfigurable Manufacturing Environments*; 2nd Robotics and Mechatronics Symposium (RobMech 2008); 10-11 November 2008; Bloemfontein; South Africa; Pages 6 – 11
- J. Padayachee, G. Bright, I Masekamela; *Modular Reconfigurable Machine Tools: Design, Control and Evaluation*, South African Journal of Industrial Engineering; Volume 20, Number 2; November 2009 ; Pages 127-143
- J. Padayachee, G. Bright; *Design of Reconfigurable Machine Tools for Reconfigurable Manufacturing;* 3rd Mechatronics and Robotics Symposium; (RobMech 2009); 9 November 2009; Pretoria; South Africa
- J. Padayachee, G. Bright; *The Development of a Mechatronic Control System for Modular Reconfigurable Machine Tools*; Australasian Conference on Robotics and Automation (ACRA 2009); 2-4 December 2009; Sydney; Australia
- J. Padayachee, S. Davrajh, J. Collins, G. Bright; *The Development of Reconfigurable Manufacturing Equipment for Product Mass Customization*; International Conference on Competitive Manufacturing (COMA '10); 3-5 February 2010; Stellenbosch; South Africa; Pages 291-296
- J. Padayachee, G. Bright; *The Design of a Reconfigurable Control System for NC Machines with Augmented Flexibility*; 25th ISPE International Conference on CAD/CAM, Robotics and Factories of the Future; 14-16 July 2010; Pretoria; South Africa

1.6 Outline of Dissertation

Chapter One: Introduces the reader to the background of the project, the motivation for the research and the resultant scientific contributions. The objectives of the project are also presented.

Chapter Two: Analyses the inadequacies of existing manufacturing paradigms. The concept of reconfigurable manufacturing is presented and an analysis of the benefits of RMSs is conducted. Enabling technologies for RMSs are identified including the characteristics they must display.

Chapter Three: Analyses the merits and inadequacies of existing types of production machinery. Other developments are presented on the design of reconfigurable machines and useful advancements are identified.

Chapter Four: Presents the concept of MRMs, the criteria they must display and the principles used in their design. Engineering specifications for the development of a prototype library of modules are presented in this chapter.

Chapter Five: Presents the mechanical design and modelling of MRMs. Mechanical assemblies for different MRM configurations are presented. The static and dynamic analysis of a selected assembly is also included.

Chapter Six: Presents the electronic hardware system that was developed for the actuation and control of the MRM assemblies.

Chapter Seven: Presents the software system that was developed for execution of user programs on MRM platforms.

Chapter Eight: Addresses the assembly and calibration of MRM systems. Results are presented for the performance of the tool positioning systems in MRMs under different modes of motion control.

Chapter Nine: Summarizes the performance of the system. The implications of MRMs for reconfigurable manufacturing are presented and problems in MRMs are also identified.

Chapter Ten: Concludes this dissertation with a discussion of the advantages and disadvantages of MRMs, including problems that will require future research.

1.7 Chapter Summary

This chapter introduced the reader to the challenges in modern manufacturing that have provided the motivation for this research. The scientific contributions of the research were discussed and the objectives of the project were outlined. References have also been provided to conference papers and journal publications that have emerged from the work presented in this dissertation.

2. Reconfigurable Manufacturing Systems

2.1 A Review of Dedicated Manufacturing Systems

Dedicated Manufacturing Systems are historically the first manufacturing system paradigm, introduced at the beginning of the 1900's [5]. These systems are designed for the production of a single item or a bounded group of products. The dedicated nature of these systems implies a lower capital investment in system initialization, as compared to more flexible systems. These systems employ transfer line technology, dedicated machinery and fixed automation for optimized, robustly system performance. DMSs are capable of producing a high volume of units rapidly and cost effectively while maintaining high standards of quality [6]. However, achieving significant product variety is impossible due to the inflexible nature of the Dedicated Machine Tools employed in DMSs.

The lack of system scalability is a problem in DMSs. The capacity of a dedicated system may be scaled up by duplicating production lines when the demand for products exceeds the current capacity of a system. This is a very costly approach to system scalability and is not feasible as the minimum step size in system capacity is limited to the capacity of the line being duplicated [6]. Although DMSs are designed for high production capacities, these systems do not always operate at maximum capacity. When the demand for products is low DMSs possess excessive functionality and such systems are only economical when market demand for a specific product is high.

2.2 A Review of Flexible Manufacturing Systems

The Flexible Manufacturing paradigm was introduced in the 1970's to overcome the problem of inflexibility in manufacturing systems of the time [7]. Flexibility is viewed as the ability of a system to change and assume different positions or states in response to changing requirements rapidly and with minimal penalty in effort, cost or performance [8]. FMSs are systems with fixed hardware and fixed, but programmable software to manage changes in products and production schedules [9]. Such systems are designed for general flexibility, with CNC machines, robots and flexible material handling systems as their main elements [5].

At the machine level, CNC machines provide the framework for flexibility in FMSs. These machines are created with generic processing capabilities that enable the system to respond to reasonable changes in products and product families without an additional capital investment in new machinery. A generic number of axes and a generic spindle imply that CNC machines are not kinematically or dynamically optimized to any specific operation. The result is that CNC machines often possess unused functionality.

A survey on FMSs was conducted by Mehrabi et al [7] in the year 2002. The objective of the survey was to perform an assessment of the satisfaction of manufacturers and other related agencies with the performance of FMSs and associated technologies such as CNC machines. Industry respondents included machine tool builders, automotive, aerospace, robotics and mining companies in the United States.

The results revealed that two-thirds of the organizations that participated in the survey were dissatisfied with the performance of FMSs. The problems with FMSs according to the survey were:

- High system initialization costs
- Fifty percent of correspondents reported that their systems possessed excessive functionality
- The CNC machines in many cases possessed excessive features that were never used
- Fifty percent of correspondents reported excess tool magazine capacity
- Correspondents reported problems in operator training, system reliability and maintenance, software and communication, and the cost involved in increasing system capacity

Further research by Lin et al [10] has revealed that FMSs as a whole have low throughputs of customized parts and display significantly longer payback periods than DMSs. Based on the survey conducted by Mehrabi et al [7], manufacturing enterprises, government and trade organizations, research institutions and manufacturing system builders agreed that the reconfigurable manufacturing paradigm was the next logical advancement in the evolution of global manufacturing.

2.3 The Reconfigurable Manufacturing Paradigm

The reconfigurable manufacturing paradigm was conceptualized through an international collaboration between researchers in the United States and Europe. Participating universities included the University of Michigan, University of Stuttgart, Politechnico di Milano and Katholieke Universiteit Leuven [1]. The definition of a Reconfigurable Manufacturing System is as follows:

> *" A Reconfigurable Manufacturing System (RMS) is a system that combines the advantages of DMSs and FMSs by designing it at the outset for rapid change in structure, as well as in its machines and controls, in order to quickly adjust production capacity and functionality in response to market or product changes."*

RMSs are envisioned to possess intermediate functionality and production capacity between DMSs and FMSs; this will enable a RMS to display the best features of these two historic paradigms (see Figure 2.1). The intermediate positioning of RMS aims at a compromise between large production volumes and high product variety to achieve a reasonable output of an assortment of products.

The main objective of the RMS paradigm is to increase manufacturing system responsiveness to market and product changes. RMSs must therefore provide the functionality and capacity that is required, when it is necessary. A RMS may therefore display performance characteristics more likened to the extremities of either DMSs or FMSs, depending on system requirements at different times. The responsiveness of the system is achieved by the design of its elements for structural and software transformability. Production streams and processes are envisioned to be transformed by the reconfiguration of machines and the rearrangement of flow paths between machines.

At a machine level, rapid transformations are envisioned to be achieved by the changing of machine hardware components and the installation and reconfiguring of software.

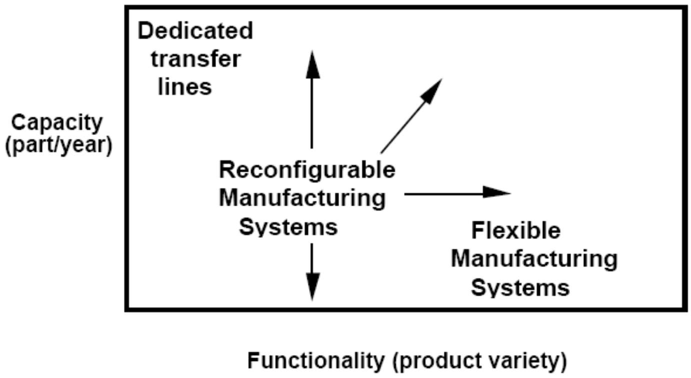


Figure 2.1: Characteristics of Manufacturing Systems in Capacity- Functionality Coordinates [9]

RMSs extend further to incorporate features of lean manufacturing. Lean manufacturing is defined as an adaptation of mass production in which workers and work cells are made more flexible and efficient by adopting methods that reduce waste [11]. Lean manufacturing aims at a reduction of waste in production on a number of levels:

- *Market*: At the market level lean manufacturing aims to eliminate features in products that are unnecessary or unwanted by customers.
- *Enterprise*: At the enterprise level lean manufacturing aims to reduce waste due to over production and the holding of excessive inventory.
- *System*: At the system level lean manufacturing reduces waste due to production flaws and the waste of raw materials and consumables due to inefficient processes.

In general the objective of lean manufacturing is the reduction of any identifiable form of waste, thereby optimizing the efficiency of production and maximizing profits [11]. Figure 2.2 summarizes the economic goals of the dedicated, flexible and lean manufacturing paradigms. RMSs aim to achieve these goals in addition to enhancing system responsiveness to market demands, thereby granting manufacturers a competitive advantage.

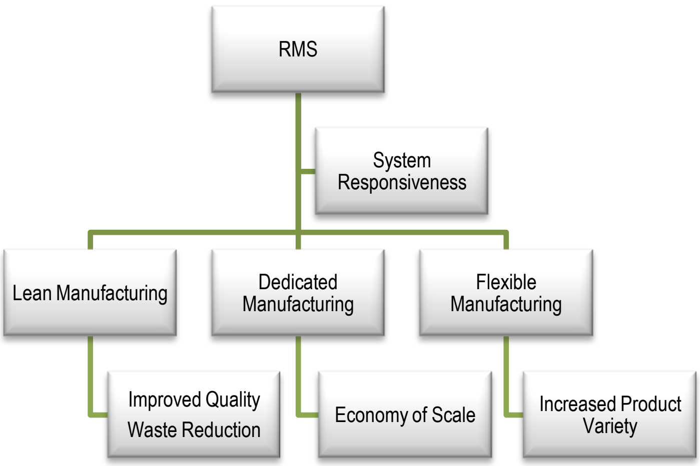


Figure 2.2: The Economic Goals of Various Manufacturing Paradigms

2.4 Customized Flexibility in RMSs

RMSs are intended to be low cost systems that incorporate the high output of DMSs while combining the flexibility of FMSs. The low cost and high output of these systems are intended to be achieved by basing manufacturing system configurations on specific product families. Once the fabrication of a product family is complete, the system reconfigures to produce a different group of products. Galan et al [12] have established product families as the starting point in the configuring of a RMS and have endeavoured to provide a systematic approach for the subsequent formation of optimized part families. The efficiency of a configuration is dependent on the commonality of product/part features, the similarity in manufacturing processes and the market demand of each product.

The level of flexibility in a RMS must be tailored through reconfiguration, to the manufacturing requirements of each product family. Extensive studies on the various types of flexibility in a manufacturing system are presented by Sethi and Sethi [13] and Browne et al [14]. Flexibility may be broadly categorized into three groups: system hardware and software flexibility, system management and control flexibility and system expansion flexibility. The reduction in cost of system infrastructure is primarily concerned with the limitation of hardware and software flexibility. Hardware and software expenses form a substantial component of the capital investment in the initialization of a system. Unused (excessive) features are representative of capital that yields a zero return to an investor.

Through each reconfiguration cycle the following types of flexibility must be customized to ensure that the system does not possess unnecessary functionality [13, 14]:

- *Machine Flexibility*: The number of processing operations and axes displayed by a machine.
- *Material Handling Flexibility*: The total number of paths between machines.
- *Volume Flexibility:* The ability to vary production volumes.
- *Process Flexibility:* The set of part types that can be produced by current process configurations.

The limitation of these four types of flexibility is also intended as a means of customizing and optimizing each reconfigured state, enabling greater production volumes than FMSs. The ability of the system to then assume new machine characteristics as well as new material handling, volume and process flexibility characteristics through reconfiguration, is dependent on the expansion flexibility of the system.

2.5 Scalable Production Capacity in RMSs

Cost effective and rapid capacity scaling is essential in providing a profitable response to increases in product demand. Figure 2.3 illustrates the cost versus capacity characteristics of DMSs and FMSs and the idealized trend that RMSs are expected to exhibit. The DMS trend indicates a large minimum step size in capacity scaling, and the cost of increasing the production rate is high. An additional investment in capacity for DMS is only profitable for a long term, sustained increase in product demand.

The FMS characteristic indicates a smaller minimum step in capacity scaling, however the overall cost of increasing a FMSs capacity is higher. The higher cost is due to the large price difference between CNC machines and the DMTs employed in DMSs. The cost of flexible material handling systems is also higher than that of the fixed transfer lines employed in DMSs. The capacity gain in a FMS is also low compared to capital invested. This trend is due to low production volumes capable by CNC machines and as mentioned, these machines exhibit a longer pay-back period than DMTs.

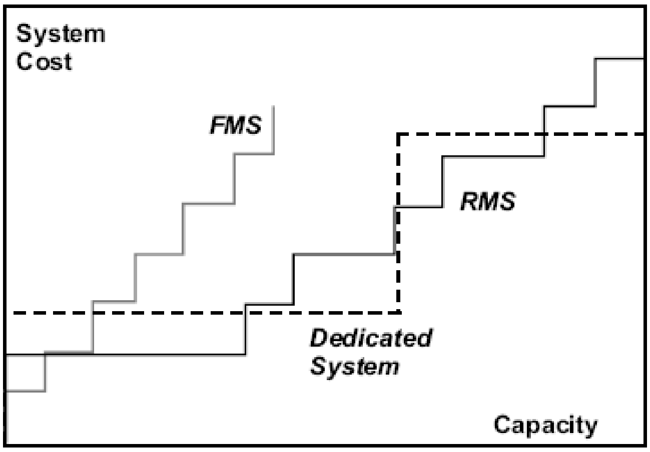


Figure 2.3: Manufacturing System Cost versus Capacity [1]

The RMS cost versus capacity characteristic is prescribed to exhibit features of both DMSs and FMSs. RMSs are predicted to display a small minimum step size in capacity scaling. A smaller step size implies a greater responsiveness to moderate increases in product demand, and the risk involved with capital investments are lower. The gain in capacity for an individual step is envisioned to be high to provide a more profitable response to increased market demand. The frequency of capital investment in infrastructure is also expected to be low as machines for RMS are to be designed for easy modification and reuse.

2.6 Reconfigurability and Expansion Flexibility in RMSs

Expansion flexibility is the ease with which a system's capacity or functionality may be augmented through physical changes in the system [13, 14]. Rapidly adjustable capacity and functionality are the desired features for RMSs as this will enable these systems to cope with changes in markets and products, quickly and efficiently. It should be noted that under the context of RMSs, the understanding of expansion flexibility is consistent with that of reconfigurability [15]. The expansion flexibility of an RMS is prescribed to be maintained by the design of its hardware and control systems for easy rearrangement and rapid changes in their internal structures. If RMS machines, material handling systems, assembly robots and quality control systems are not designed for easy reconfigurability, the reconfiguration process will be lengthy and impractical [1]. Presently design methods and reconfiguration methodologies are under development, and enabling technologies for RMSs are not commercially available.

2.7 Manufacturing System Life Cycle

The lifespan of a manufacturing operation is determined by the expansion flexibility of the systems employed in view of product or market changes, before the system as a whole becomes unresponsive, redundant and outdated. The lifecycle of a system is the cycle of system expansion/reconfiguration as production requirements evolve over a period of time. The period for which a manufacturing configuration is suitable, is generally inconsistent and is strongly related to changes in market demand and progression in consumer goods technologies.

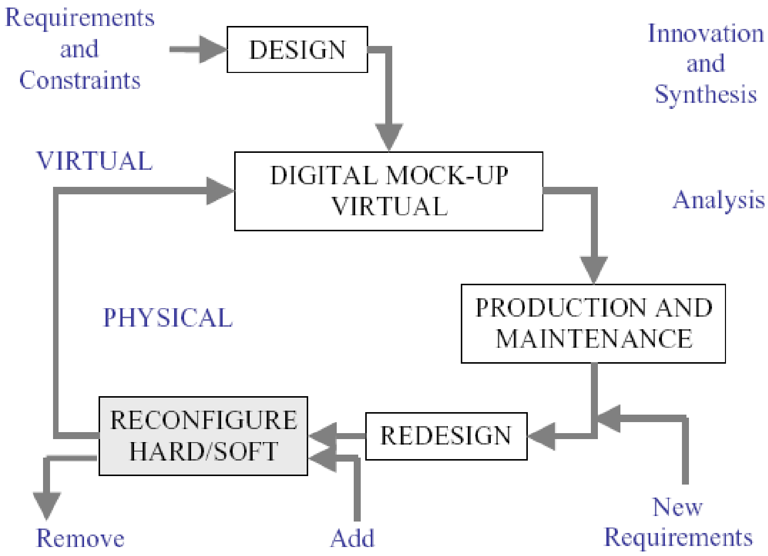


Figure 2.4: Manufacturing Systems Lifecycle, Initial Design, Redesign and Reconfiguration [15]

ElMaraghy [15] modelled the lifecycle of a manufacturing system as outlined in Figure 2.4. This model illustrates the initial design of a manufacturing system based on production requirements and constraints at the time of initialization. The initial system design is analysed, simulated, implemented and maintained until new manufacturing requirements emerge. The system is then redesigned and reconfigured cyclically as necessary. The process of reconfiguration is intended to extend the lifespan and utility of a manufacturing system. The lifespan of a RMS is envisioned to be significantly longer than a DMS, and the cost of extending its lifespan much lower than FMSs. This is to be achieved by the design of RMSs and their enabling technologies for expansion flexibility.

2.8 Essential Characteristics of RMSs

RMSs are systems where machine components, mechanisms, machines, cells, conveyors and other material handling systems can be added or removed in different configurations as required [7]. To display such reconfigurability RMSs must possess the following characteristics: modularity, convertibility, integrability, customization and diagnosability. Koren et al [1] and Mehrabi [9] discuss these terms as they relate to RMSs as follows:

Modularity: Requires the design of system components; mechanical and electronic control hardware as well as software to be modular or support modularity.

Convertibility: Requires the design of the system for a rapid conversion to produce the new products. Design for rapid conversion aims at reducing system down time and ramp-up time. Conversion entails the retooling of machines, the reorientation of machine axes, the integration of additional mechanical and control hardware into platforms and the loading of programs to produce the next family of parts.

Customization: Requires systems to be the initialized with only the necessary functionality and capacity needed for production. Customization requires that the machines used in production be kinematically and functionally matched to their applications.

Integrability: Requires the design of system components to be easily integrated into the system as required. Design for integrability facilitates the upgrading of system components as new technology emerges. The process of integration is greatly facilitated by the use of standardized components, interfaces and communication protocols in hardware and software systems.

Diagnosability: Requires system and machine design that incorporates diagnostics that will facilitate the quick identification of sources of problems within the system. Tools for the diagnosis of quality and reliability problems become indispensable if system ramp-up time is to be minimized.

The characteristics of modularity, convertibility, customization, integrability, and diagnosability are qualities that enable reconfigurability/expansion flexibility in machines, work cells and systems at large. These characteristics are recommended to be applied at all levels of a RMS (system, process, machine, software and control) to ensure a fully reconfigurable system.

2.9 Enabling Technologies for RMSs

RMSs require the development of enabling technologies that will bring to realization the idealized aims and predicted advantages of the paradigm. The goals of previous manufacturing paradigms have dictated the features of the technologies associated with those systems and cannot be implemented in RMSs without further improvement. Technologies that require development for RMSs are reconfigurable: machining systems, fixturing systems, assembly systems, quality control system and material handling.

This research is concerned with the development of a reconfigurable machining system and advancements in the field of reconfigurable machine tools are discussed in detail in Chapter 3. A brief summary of global research efforts on other technologies for RMSs are summarized in Table 2.1. This list is by no means exhaustive and intended only to highlight some important areas of research in RMS.

Table 2.1: Global Research in Enabling Technologies for RMS

Field of Research	Publication	Authors
Reconfigurable Quality Control	Design Requirements of Quality Control Systems for Reconfigurable Cellular Manufacturing Environments	S. Davrajh, G. Bright [16]
	Integration of Reconfigurable Inspection with Stream of Variations Methodology	J. Barhak, D. Djurdjanovic, P. Spicer, R. Katz [17]
	Reconfigurable Inspection Machine for Machining Production Lines	R.Katz, M.G. Zutek, Y. Koren [18]
Reconfigurable Material Handling	Reconfigurable Materials Handling Control Architecture for Mass Customization Manufacturing	A.J. Walker, L.J. Butler, N. Hassan, G. Bright [19]
Reconfigurable Assembly	A Reconfigurable Assembly Cell for Mechanical Products	F. Giusti, M. Santochi, A. Arioti [20]
	Modular Reconfigurable Flexible Final Assembly Systems	J. Heilala, P. Voho [21]
	Reconfigurable Dual Robot Assembly System, Design , Developments and Future Directions	S.J. Hseih [22]
Reconfigurable Robotics	Theory and Application of Reconfigurable Robotic Systems	I. M Chen [23]
	Design Fundamentals of Reconfigurable Robotic Gripper Systems	R Kolluru, K.P. Valavanis, S.A. Smith, N. Tsourveloudis [24]
Reconfigurable Manufacturing Cells	Rapid Response Manufacturing Through Reconfigurable Robotic Work Cells	I.M. Chen [25]
	Reconfiguration of Manufacturing Cell Control Systems and Reuse of their Components	R.P. Monfared, R.H. Weston [26]
Software and Control of RMSs	Process Control and Configuration of a Reconfigurable Production System using a Multi-Agent Software System	J.J. van Rensburg, H. Vermaak [17]
	Control Architecture for Reconfigurable Manufacturing Systems	L. Ferrarini, C. Veber, A. Luder, J. Peschke, A. Kalogeras, J. Gialelis, J. Rode, D. Wunsch, V. Chapurlat [28]

2.10 Chapter Summary

This chapter summarized the merits and problems of existing manufacturing paradigms. The concept of reconfigurable manufacturing was introduced and a definition of RMSs was provided. Matters pertaining to system flexibility, capacity, expansion flexibility and system life cycles were discussed in the context of RMSs. Enabling technologies for RMSs were identified and essential characteristics for the design of reconfigurable manufacturing equipment were presented.

3. Automated Production Machines

3.1. Dedicated Machine Tools

The design of a production machine is dependent on the flexibility and performance required from it. There are two customary design schemes for production machines. The first scheme initiates machine design based on the knowledge of the part, or product that is to be produced on that machine. The second scheme initiates machine design based on generic processing operations without prior knowledge of the manufacturing functions it will ultimately perform.

Dedicated Machine Tools (DMTs) are those machines that have been designed based on prior knowledge of a part or product. These machines are characteristic of DMSs, being created for the purpose of producing a known part rapidly and efficiently [1]. The design scheme for DMTs restricts the kinematic flexibility, spindle size, range of tooling and fixturing of the machine to the exact capability required to produce a given part. DMTs also possess fixed automation that is restricted in functionality to the control of specific operations. DMTs are often created in-house by manufacturers. Commercial alternatives for the purchase of DMTs are generally restricted, due to the specific nature of the equipment. The creation of DMTs is also widely initiated through the consultation of manufacturers with machine building companies.

The restrictive nature of DMT design results in machines that are optimized for a specific process. The advantages of an optimized, lean design are: the production of high quality goods, high production volumes, less raw material wastage and rework, rapid system ramp-up and relatively low cost of machines. Manufacturing enterprises such as The Boeing Company in Washington, USA favour the implementation of DMTs over more flexible machine tools due to the robust performance and cost savings derived from a dedicated design [29].

A DMT is the optimal machine, purely in consideration of robust performance with regard to manufacturing a specific part. Nonetheless the disadvantages of DMTs become evident in consideration of dynamic manufacturing environments. The greatest inhibiting factor for the implementation of DMTs in RMSs is the inability of these machines to effectively cope with changes in products. DMTs cannot be cost effectively converted when parts or products change and are therefore only economical for the long term production of specific items [30]. DMTs may be implemented in RMSs, but in limited numbers for the manufacturing of standardized components that are not expected to change through multiple product iterations.

3.2. Computer Numerically Controlled Machines

The concept of Numerical Control (NC) originated after World War II, when in 1947 the United States Air Force developed a method for moving two axes by using punch cards including coordinate data to manufacture aircraft parts [31]. In 1952, a three axis milling machine, the world"s first official NC production machine was developed at the servo laboratory, at Massachusetts Institute of Technology. Early NC machines were hardwired and performed functions according to the configuration of connected elements by electrical wiring. The advent of digital computing led to the integration of microprocessor technology in NC machines since the 1980"s and these machines are now known as Computer Numerically Controlled (CNC) machines.

In present times CNC technology has been applied to the development of a variety of machines. CNC machines are generally multi-purpose machines, being design to perform wide range operations. These machine tools can be classified as "cutting machines" and "non-cutting machines" [31]. Cutting machines perform material removal and common processing operations are: milling, drilling, turning, engraving, flame cutting and Electric Discharge Machining (EDM). Non-cutting machine tools include CNC presses and bending machines. The scope of CNC technology extends to robotic systems, welding and painting machines, semi-conductor handlers and chip mounting machines. Figure 3.1 illustrates three types of machines based on CNC technology.

a. **b.** **c.**

Figure 3.1: Production Machines Based on CNC Technology [32, 33, 34]

a. The Haas vertical CNC mill – Material removal with a cutting tool [32]
b. A wire EDM – Material cutting via electric discharge [33]
c. Robotic CNCs – Non cutting CNCs [34]

CNCs are characteristic of FMSs, enabling these systems to produce a variety of products [1]. The automotive, maritime, aerospace and tool manufacturing industries are among the many industries that implement CNCs. These machines are also commonplace in engineering workshops and Small and Medium Enterprises (SMMEs) that service the specific needs of larger industries such as power generation and chemical processing plants.

With regard to material removal, CNCs possess a generic number of axes and a generic spindle. The flexible mechanical architecture of CNCs ensures a broad machining envelope, facilitating the „absorption‟ of changes in parts or products. The generic nature of these machines additionally limits the possibility of redundancy and allows the integration of CNCs into multiple manufacturing configurations. Further advantages of this technology include: reduced operator involvement and the machining of complex contours.

The comprehensive flexibility of CNCs results in these machines being generally expensive with low production rates achieved on a platform. The flexibility of the machines in most manufacturing implementations may be excessive and although being designed for general flexibility these machines may nonetheless lack the functionality needed for a specific operation. The fixed mechanical architecture of both CNCs and DMTs neither permit any mechanical alterations to the machine, nor facilitates the integration of new hardware and additional sensors onto the platform.

CNC machines are primarily programmed in G-Code (ISO 6983), with advancements such as Computer Aided Part Programming (CAPP) and Computer Aided Manufacturing (CAM) software emerging in recent years for easier program generation. The software architectures of the machines are fixed, but the machine is end user programmable [35]. The proprietary nature of such control systems does not afford the end user access to the controller and upgrades or enhancements to the system are either impossible or very costly [4].

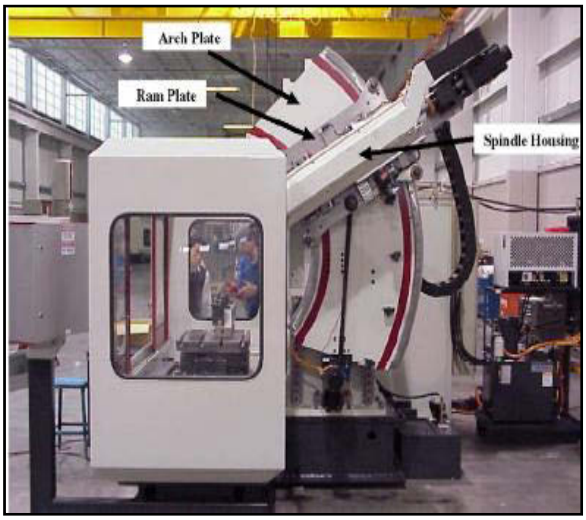
The inability to access the lower levels of the controller hinders the application of more efficient algorithms, the integration of new sensors and restricts the machine in being interfaced with a higher control system. Researchers in both academia and industry have concluded that traditional, closed CNC machine tools do not provide the functionality, flexibility or cost effectiveness necessary to match the demands of modern manufacturing [8].

3.3. Reconfigurable Machine Tools: The Arch Type RMT

The development of reconfigurable machinery has been motivated by the inadequacies in DMTs and CNCs, these are: poor expansion flexibility, rigid mechanical and control architectures and excessive or limited functionality. The philosophy of reconfigurable machine design has yet to converge on a single set of principles. Internationally, perspectives on the design of reconfigurable machines follow three strains of thought:

(i) Reconfigurable Machines are to be designed with intermediate flexibility between CNCs and DMTs: the part family approach to machine design.
(ii) The flexibility of reconfigurable machines must exceed that of CNC machines: the design for a wider range of generic operations.
(iii) It is not meaningful to distinguish reconfigurable machines from CNC machines: implement CNC machines in RMSs.

a.



b.

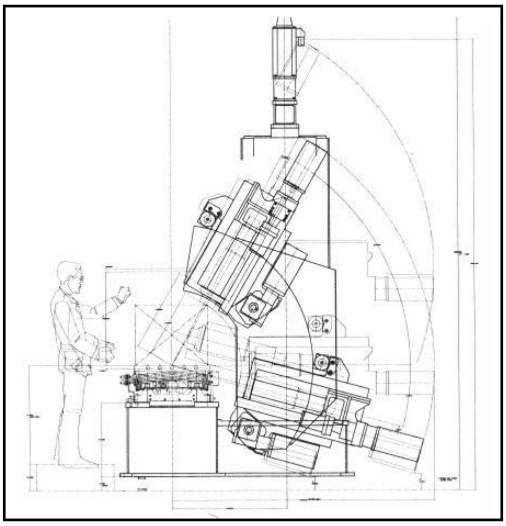


Figure 3.2: The Arch Type Reconfigurable Machine Tool [36]

a. The Arch Type RMT
b. Reconfigurable position of the Z-axis. The angle of inclination can be changed from -15^{o} to 60^{o}

The philosophy of Reconfigurable Machine design for intermediate flexibility between CNCs and DMTs was first proposed by researchers at the University of Michigan. This philosophy was applied to the creation of the worlds first Reconfigurable Machine Tool (RMT), the Arch Type RMT (see Figure 3.2.a).The objective of creating the Arch Type RMT was to illustrate the principle of constructing machine tools around part families. The machine was not restricted to a single part as in the case of a DMT, nor did the machine possess general-purpose flexibility as in CNC machines.

The flexibility of the machine was restricted by designing it around a family of V6 and V8 engine blocks [37]. The machine could perform milling operations on discreet inclined planes. Figure 3.2.b illustrates the reconfiguration of the machine by reorienting the machine spindle in 15^o steps through a range from 15^o degrees below the line of the work table to 60^o above the line of the work table. The discreet reorientation of the machine spindle reduced the number of active DOF during machine operation, simplifying the machine control system. Benefits demonstrated by this method of machine design are:

- lean design by a part family approach to flexibility,
- the realisation of design simplicity by use of non-orthogonal machine axes,
- a lean mechanical and control design by discreet reorientation of machine axes,
- the potential for high production volumes by mechanically optimised machine configurations.

The literature survey has indicated that the Arch Type RMT has been the only significant attempt at the development of a serial reconfigurable machine tool to date.

3.4 Reconfigurable Machine Tools: Design Methods

3.4.1 Virtual Modularity in RMT Design

Shinno and Ito [38, 39, 40] developed a methodology whereby the structural configuration of machine tools may be generated from simple geometric objects. This introduced the notion of structurally generating machinery from elementary modular subsystems. The structural synthesis of machines from simple virtual modules has been conducted by Chen and Yan [41]. Researchers at the University of Michigan further extrapolated this methodology for the fabrication of a virtual library of precompiled mechanical modules from which multiple types of machine tools could be assembled [42,43]. The structural synthesis of machines from a precompiled library of modules has been identified as an important advancement in facilitating the rapid design of machines.

The concept of modular design of machine tools has been discussed in academia since the 1980‟s. It has thus far been successfully used for the virtual synthesis of machine tools. The methodology has however, not been practically adopted for the creation of machines that are physically modular.

3.4.2 Kinematic Optimization of RMTs

Landers et al [30] and Moon and Kota [42, 44] have developed a mathematical framework for the synthesis of a kinematically viable machine tool from a library of mechanical building blocks. The methodology is intended to yield optimized and kinematically exact solutions in reference to the part being produced.

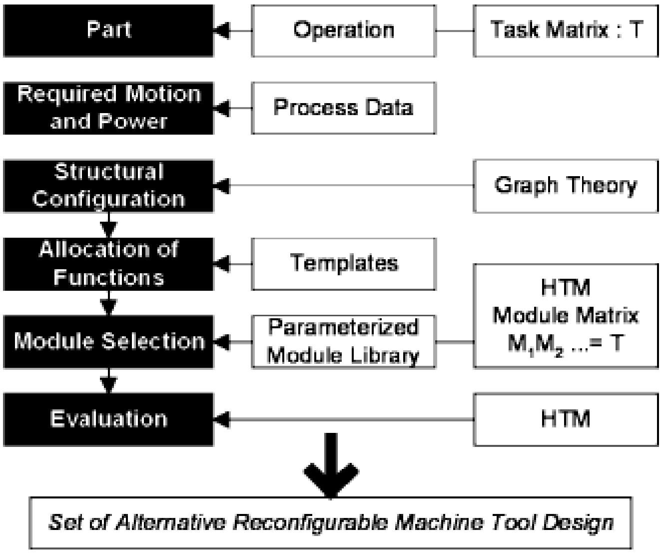


Figure 3.3: RMT Kinematic Design Methodology [30]

The sequence of steps in this methodology is illustrated in Figure 3.3. The first step in the methodology is the use of a screw theory based mathematical representation to obtain a task matrix from process plans and CAD drawings. The motion of any rigid body may be represented by a screw, which is comprised of a rotation about an axis and a translation about that axis. In this method discreet tool trajectories are represented by a screw. The general format of a screw is given by equation 3.1:

$$\vec{\$} = [M_M\ M_m\ M_c](P_A + \varepsilon P_T)\{\vec{S} + \varepsilon \vec{S}_o\} \tag{3.1}$$

M_M, M_m and M_c represent the maximum, minimum and current positions of the tool in the trajectory. The term $(P_A + \varepsilon P_T)$ represents the pitch of the motion and lastly the term $\{\vec{S} + \varepsilon \vec{S}_o\}$ represents the direction of motion. The complete set of screws, used to describe the desired operation is then condensed into a Homogenous Transformation Matrix (HTM). Elements of the task transformation matrix are represented by templates in a Function Structure Graph as illustrated in Figure 3.4. The graph gives the overall topology of the required machine tool, and suitable library modules are assigned to appropriate place holders or templates on the graph.

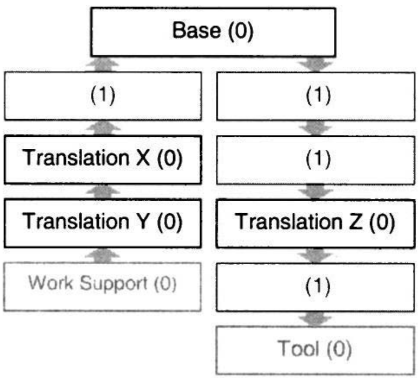


Figure 3.4: An Example of a Function Structure Graph [42]

It is recommended for RMT design that mechanical modules are combined into a library and parameterised according to individual HTMs [44]. The individual HTMs of the modules assigned to the Function Structure Graph are then concatenated according to equation 3.2 to yield a feasible machine transformation matrix:

$$^{work}_{tool}T = M_1 M_2 M_3 \dots M_n \qquad (3.2)$$

If the resultant machine transformation matrix is in the image of the task transformation matrix then the current selection of modules is kinematically viable. This method is capable of yielding multiple, kinematically viable module sets for the construction of a machine tool. A library of modules may include a range of kinematically equivalent units; in this instance the optimal machine configuration is obtained by examining different module combinations while considering factors such as: mechanical stiffness, actuator speeds and torque.

3.4.3 Software Aids in Virtual RMT Synthesis

The rapid development of machine tools is necessary for shortening the production lead time on newly developed products. Software systems intended to shorten the machine design process have been developed at the University of Michigan (USA) and Fraunhofer Institute for Machine Tools and Forming Technology (Germany). The software package developed by the Fraunhofer Institute is called VRAx, which was created to give German machine tool companies a competitive advantage over their Japanese, South Korean and Chinese counterparts [45]. The VRAx system was not created with the intention of developing RMTs; however it does feature related design techniques. The software possessed the ability to create and store common machine components in a database. These components can be accessed at a later stage and used to create multiple types of machinery rapidly in a virtual environment. The concept employed in this software is a direct parallel to that of virtual modular machine design.

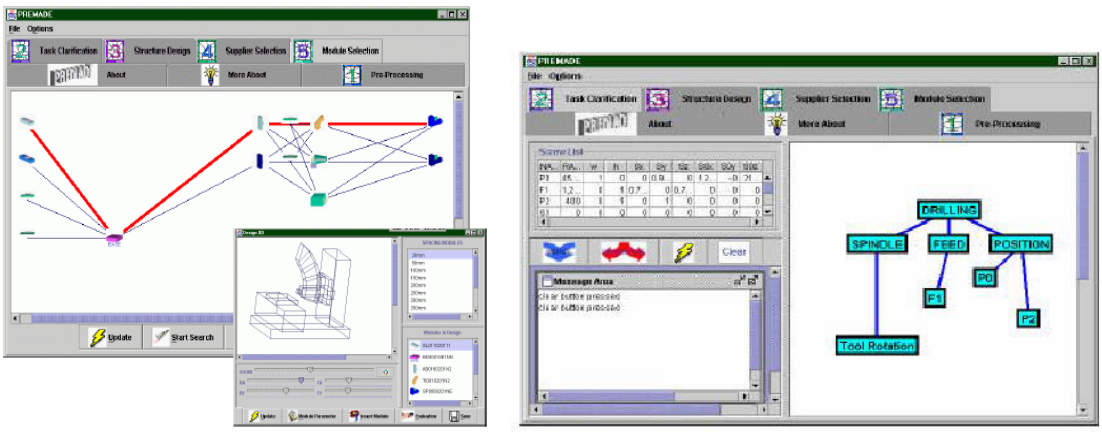


Figure 3.5: Screen shots of PREMADE (PRogram for REconfigurable MAchine DEsign) [37]

The University of Michigan developed a software package called PREMADE (PRogram for REconfigurable MAchine DEsign). The PREMADE package was designed specifically for the development of RMTs and contained a library of virtual mechanical modules for the rapid design of machines [37]. The software package incorporated the mathematical methodology developed by Moon and Kota [42, 44] and was capable of generating feasible machine designs based on the input of relevant part data.

Figure 3.5 illustrates a screen shot of the software. It should be noted that neither the VRAx system nor PREMADE have been made commercially available.

3.5 Open Architecture Control

Mehrabi et al [4] have emphasized the importance of Open Architecture Control (OAC) in machine control systems for RMSs. OAC aims at the easy implementation and integration of user-specific controls by means of open interfaces and configuration methods in a vendor neutral, standardized environment [46]. OACs are designed for PC-based control hardware. The advent of faster processors for Personal Computers (PCs) and a reduction in their prices have increased the use of PC-based controllers for machining systems. PC-based controllers are flexible, open and can be easily integrated into multiple manufacturing configurations [47].

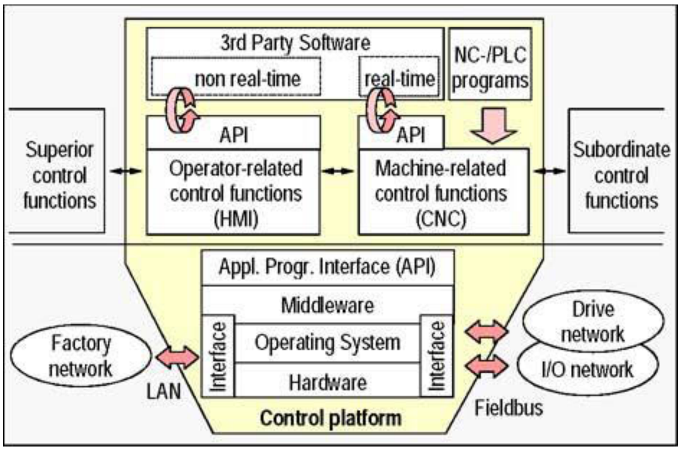


Figure 3.6: Components of Open Control Systems [46]

Figure 3.6 illustrates essential components that an OAC must possess and the interaction between these components. OACs provide lower level access to control components and facilitate the integration of third party software by means of standardized internal and external interfaces. Standardized external interfaces are divided into programming interfaces and communication interfaces. For machine tools G-Code (ISO 6983) forms the programming interface, creating an internationally standardized method of machine programming.

Standardized communication interfaces with superior control systems entail provision for Ethernet and TCP/IP for machine integration into a factory wide control network. Communication networks such as CAN, PROFIBUS and SERCOS are used to communicate with subordinate peripheral devices such as Digital Signal Processor (DSP) boards and microcontrollers that are used for low-level processing and I/O operations. The use of standardized communication methods overcomes the problems associated with proprietary communication methods and physical connectors when hardware upgrades or repairs become necessary.

The creation of an internal interface for an OAC is concerned with the provision of an Application Programming Interface (API) for operator and machine related control functions. An API would serve to completely shield the application software from the hardware platform, thus facilitating the easy installation, and modification of third party application software. Further advantages include software portability, scalability and interoperability [48].

Since the 1990‟s, organizations like Open Systems Architecture for Controls within Automation systems (OSACA), Open Modular Architectures Controllers (OMAC) and academic institutions like University of Michigan, University of British Columbia have drawn standards and developed open architecture controllers for machine tools [49]. Most controllers of this nature are implemented on PC‟s supporting a real-time Operating System (OS). Although several controllers have been successfully implemented, much work is still needed in improving the openness and real-time performance.

3.6 Chapter Summary

This chapter presented a review of DMTs and CNC machines. The advantages and disadvantages of these established types of machine tools were discussed and their inadequacies formed the motivation for the development of reconfigurable machines. The Arch Type RMT was presented, including other international research developments in the field of RMS machinery. OAC systems were recommended for inclusion in reconfigurable machines and the benefits of such systems were discussed.

4. Modular Reconfigurable Machines

4.1 Design Approach

This research proposes the development of Modular Reconfigurable Machines (MRMs) as a new solution in the design of automated production machines for RMSs. The design of a MRM prototype required the application of the Mechatronic engineering approach. Mechatronics may be defined as the synergistic integration of mechanical engineering, with electronics and computer control in the design and manufacturing of industrial products or processes [50]. This is one of many definitions of Mechatronic engineering that aim to describe the synergistic interaction of several elements in multidisciplinary engineering. The core disciplines of Mechatronic engineering are illustrated in Figure 4.1. A typical Mechatronic system consists of mechanical hardware, actuators, sensors, controllers, signal conditioning, digital hardware, interface devices and power sources [51]. MRMs, like other automated production machines, are Mechatronic systems as they consist of all of the typifying elements.

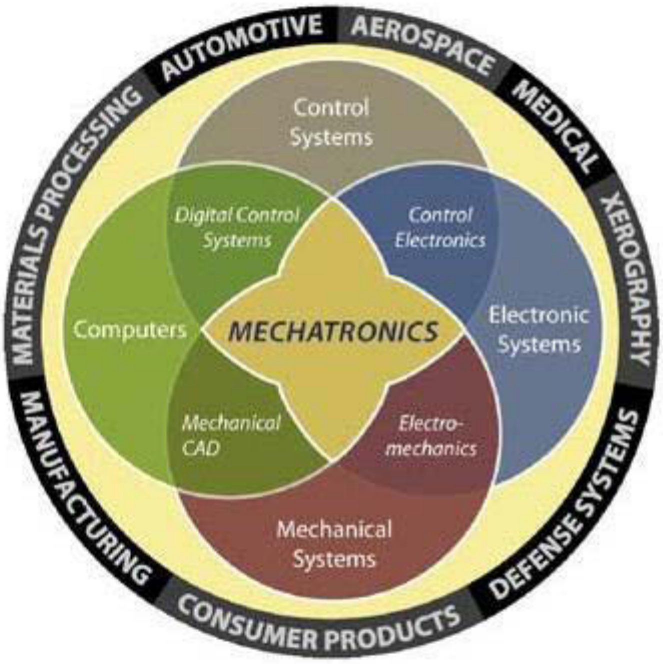


Figure 4.1: Graphical Representation of Mechatronic Engineering [52]

Mechatronic Engineering as a design approach promotes the study of the relationships between mechanical, control, electrical and digital subsystems at the earliest stages of the design process. The cross disciplinary examination of interacting systems is essential for development of lean, robust and cost effective designs. The Mechatronic approach involves a concurrent engineering stance to the development of various subsystems as opposed to the traditional sequential method of first developing the mechanical system, then the electrical system and finally the digital system [51]. In this design approach the concurrent engineering principles are applied as early as the conceptual design phase, in order to optimise the final product. Figure 4.2 illustrates the stages involved in the design of a typical Mechatronic system.

Figure 4.2: Sequence of Operations - Mechatronic Design Process (Adapted from [53], [54])

4.2 Design Concept

4.2.1 Design Perspective

The design of reconfigurable machinery has yet to converge on a single set of principles. The primary division in design philosophies is based on views of machine flexibility. The matter arising is if a reconfigurable machine should assume an intermediate level of flexibility between DMTs and CNC machines, or should it be designed to exceed the flexibility of typical CNCs. The Arch Type RMT is the only prototype machine that has been developed for RMSs to date. This machine was developed with intermediate flexibility between DMTs and CNCs, having been designed around a family of V6 and V8 engine blocks.

In a dynamic manufacturing environment problems may be encountered with designs that are either highly customized or excessively generic. With regard to machine design around a part family, the manufacturer bears the risk of machinery becoming redundant if drastic changes in products are expected. In the case of the Arch Type RMT, designs on automotive engines are not expected to change drastically over a short period of time, and the design of the machine around a part family was acceptable. In many other industries such as industries based on trend driven consumer products, product lifecycles are short and improvements in technology are rapid. Machines employed in the manufacturing of consumer goods with short production lives must be adaptable to dynamic changes in product portfolios and cannot be strictly designed around a part family. Conversely machines may be designed to possess comprehensive inbuilt flexibility, potentially exceeding that of current CNC machines; however such machines would be expensive, complex and will inevitably possess unused features in different manufacturing implementations. To avoid the problems associated with rigidly customized or excessively generic designs, the concept of Modular Reconfigurable Machines (MRMs) has been developed.

MRMs are oriented towards customized flexibility as in the case of the Arch Type RMT; nonetheless the flexibility of the machine may be extended through the process of reconfiguration. It is envisioned that through design for reconfigurability the machining envelope of a MRM could ultimately exceed that of similar CNC machines, although at each configured state the machine will possess only the functionality required for the operation at hand. The concept of customized, yet extensible flexibility in MRMs is realized by a modular design approach. MRMs are machines that are defined to be fully modular in their mechanical and control architectures. Although the idea of modular machines has been pre-existent, no fully modular machine has been developed by industry or academia.

4.2.2 Adopted Principles for MRM Design

The principle of machine design from a library of precompiled modules is indispensable in the synthesis of MRMs. This concept is essential for the rapid development of production machinery to capitalize on market opportunities. The concept of developing machines from a library of modules has been previously exploited in virtual machine tool design environments such as PREMADE and VRAx, as discussed in Section 3.4. The idea has nonetheless, never been extrapolated for the fabrication of a physical library of machine modules. Neither have machine tool builders developed individual automated modules for the synthesis of complete machining systems, with the possibility of after market reconfiguration. The main differences between the MRM library of modules and those developed elsewhere [37] are:

- the library exists at a physical level,
- modules within the library are intended for the complete synthesis of modular machine structures,
- modules are intended to be assembled and disassembled in a “building block” fashion,
- modules are intended to be mechanically autonomous and
- modules are intended to enable the after market reconfiguration of machinery.

The complete library of mechanical modules may be considered as the general solution to machining systems for reconfigurable manufacturing. Through the modular, interchangeable capability of the modules, customized solutions may be extracted from the general solution and the property of customized flexibility is present in this approach. The mathematical methodology for module selection developed by Moon and Kota, as discussed in [42, 44] may be implemented to extract the desired machining solution from the generic solution i.e. the identification of the necessary modules for the synthesis of a machine that is exactly matched to the application.

4.2.3 Conceptualization of MRMs: Virtual Mock-Up

The concept of MRMs was first tested in the virtual environment provided by the Autodesk Inventor 11 software package. Within this environment a conceptual library of mechanical modules was created for the synthesis of machinery (see Figure 4.3). The conceptual library was first created to clarify the concept of modular machine design and explore decisions on module connectivity and module functions. Modules within the library were categorized according to three classes: Process, Motion and Accessory Modules.

Process Modules

Process modules are those modules within the library that provide a single manufacturing process.

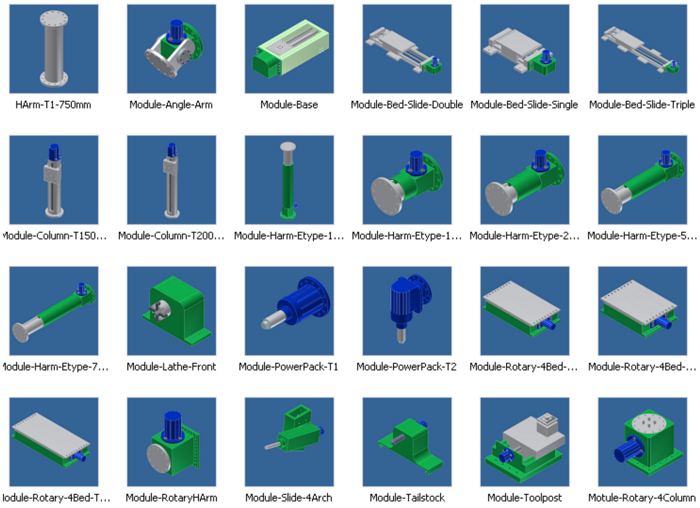


Figure 4.3: A Conceptual Library of MRM modules [55]

The focus of MRM development in this research has been on material removal processes, and modules in the **conceptual library** were created for milling, drilling and boring processes. Process modules are envisioned to be the end effectors of a platform and a reconfiguration of the processing functionality is to be achieved by the interchange of MRM cutting heads. Figure 4.4 illustrates the concept where by a 3-axis milling machine is reconfigured into a 3-axis line boring machine by the substitution of a single module. Reconfigurability of this nature has not been illustrated by previous RMT designs.

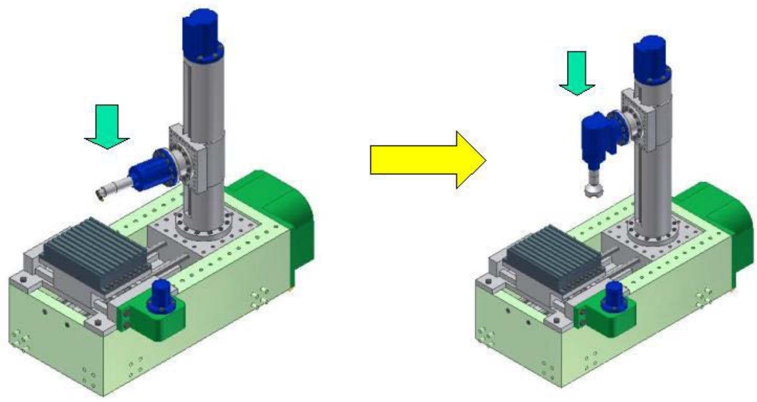


Figure 4.4: The Reconfiguration of a 3-Axis Boring Machine to a 3-Axis Milling Machine [55]

Motion Modules

Motion modules are units that contribute to the axes of a machine and are responsible for the DOF available to the cutting tool. One motion module corresponds to one axis of a machine. In total six types of motion modules were conceptualised enabling translations along the three axes of a conventional Cartesian system (X, Y, Z) and rotations about those axes (A, B, C). Although six types of motion modules are intended to be made available only the necessary combination for a specified operation will be integrated into the machining platform.

Figure 4.5 illustrates the kinematic reconfiguration of a 3-axis milling machine into a 4-axis milling machine through the integration of an additional motion module.

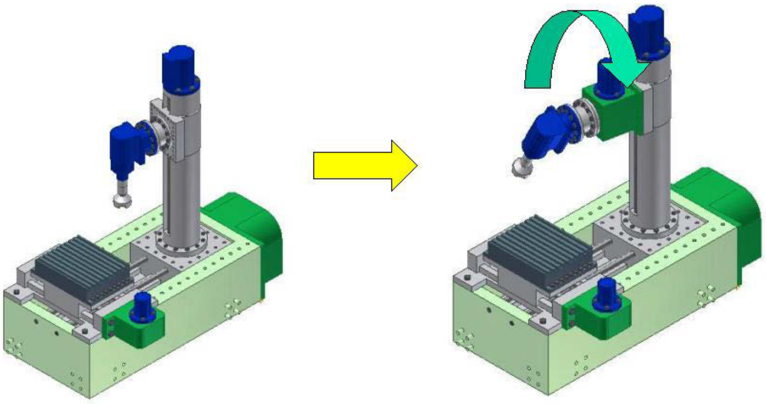


Figure 4.5: The Reconfiguration of a 3-Axis Milling Machine to a 4-Axis Milling Machine [55]

Accessory Modules

Accessory modules are units of hardware that are not directly responsible for the material removal process; however these units enable a machine to perform the required operation more efficiently. Such modules include cutting fluid supply and work-clamping modules, steady rests, flow rests etc. In certain instances a machine may not be able to perform an operation without a critical accessory module, e.g. a work table module.

4.2.4 Digital Electronic Control

The concept of a mechanically modular machine required a similar approach to the conceptualization of a suitable electronic control system. Mechanical modules are to possess dedicated electronic control modules that map to the mechanical hardware on a 1:1 basis. The creation of a monolithic control system for MRMs would not suffice due to the scalable nature of the mechanical hardware. The electronic control system is therefore specified to be modular and scalable to exactly match the physical characteristics of a MRM platform.

Figure 4.6: Reconfigurable Software and Modular Electronic Control Systems for MRMs

MRMs are also specified to possess OAC systems, implemented on PC-based hardware. OAC is essential for software scalability in correlation to changes in the mechanical and electrical architectures of the machine tool. It is recommended that the MRM host control software be created in C++ to promote a modular programming approach. The architectural style of C++ presents an advantage in the object oriented nature of the programming language. The ability of an object to hide its representation from other client software makes it possible to change the software implementation without affecting the client. This is an essential feature for MRM software, as the system is expected to reconfigure with every reconfiguration of the physical hardware.

As the architecture of the machine changes software modules are envisioned to be added or removed from the host control system. Ideally, software modules are envisioned to be integrated as „Plug-Ins", with a single Plug-In corresponding to a single mechanical module. It should be noted that the creation of a fully functional OAC system with modular software is a momentous task and was beyond the scope of this research.

4.3 Design Specifications

A prototype library of MRM modules was to be designed for assembly into machines which display reconfigurability in their processing functions and degrees of freedom. Table 4.1 summarizes the engineering specifications that were prescribed for the development of the library of modules. The specifications also extend to the resultant machines that are assembled from the modules. The allocation of engineering specifications to different entities of the machine tool was strongly influenced by restrictions in development costs for the prototype system. Many of the performance specifications were therefore intentionally set lower than the specifications of industrially available machines.

Table 4.1: Design Specifications for a Prototype Library of MRM Modules

General	
Processing functions	Drilling and Turning
Machinable Materials	Wax and Plastic
Drilling - degrees of freedom	3-6
Turning - degrees of freedom	2-3
Motion Modules (Modular Axes)	
Linear Axes	
Maximum speed of at least	100 mm/min
Worst Accuracy	1 mm
Worst Repeatability	± 0.5 mm
Rotary Axes	
Maximum speed of at least	1 rev/min
Worst Accuracy	1.5°
Worst Repeatability	± 1°
Process Modules (Modular Cutting Heads)	
Drilling capacity	1 mm – 10 mm
Turning capacity	100 mm billet
Drilling Assemblies	
Work table size	100 mm by 100 mm
Maximum part size	100 mm x 100 mm x 100 mm
Turning Assemblies	
Maximum part length of at least	400 mm
Maximum swing over bed of at least	300 mm
Electrical Specifications	
Operating voltage	220 volt, AC
Digital electronics power supply	12 volt, DC
Software Specifications	
Software programming languages	C/C++
Machine operating system	Linux
Machine programming language	Simplified G-Code

4.4 Chapter Summary

This chapter presented the Mechatronic design approach for the development of reconfigurable machine tools. The chapter proceeded with a discussion on design perspectives for reconfigurable machines and the principles adopted for MRM design. A library of modules and machines were presented in a virtual mock-up, to illustrate the concept and features of MRMs. Engineering design specifications were presented for the development of a prototype library of modules and the machines that will emerge from their assembly.

5. Mechanical Design and Modelling

5.1 Mechanical Modules

The development of a MRM system began with the creation of a library of mechanical modules for assembly into complete machine tools. These modules, as discussed in Chapter 4, were intended to possess the ability to be assembled in different configurations to give rise to machines with varying architectural and functional features. During the process of developing a library of modules for MRMs, the possibility of using Commercial Off-The-Shelf (COTS) hardware was considered. Companies in South Africa and abroad offer automated solutions such as linear axes, rotary axes and other types of actuation mechanisms for the development of Mechatronic systems. Researchers such as Mpofu et al [56] have undertaken the task of examining the potential use of COTS hardware for the development of production machinery. Some of the outcomes of their research were:

- no company, local or international, was found to offer a complete set of modules for the development of reconfigurable machines,
- COTS modules did not possess standardized interfaces and the integration of modules from multiple manufacturers would require the use of numerous adaptor plates,
- COTS modules displayed non-standardized motors, supply voltage requirements and proprietary control protocols.

The use of commercially available axes units of hardware was minimal in this design due to the non-standardized nature of those systems. Commercially available units of hardware, which are of a more elementary nature such as spindles, tool holders and chucks were used in the creation of certain modules.

5.2 Mechanical Integrity and Design Objectives

The construction of a machine from modules presents an inherent design compromise in the mechanical integrity of a machining structure to enable advanced reconfigurability. The dimensional accuracy and strength of a modular structure is expected to be diminished in comparison to a similar integral cast structure. Modular machine tools were therefore expected from the outset to display reduced performance with regard to conventional CNC machines with integrated cast iron structures.

During the design process for MRM modules, the following factors were identified as essential to the construction of a viable machine tool: adequate strength and rigidity, adequate vibration damping, sufficient power/torque/speed and accurate control of motion. Due to budget constraints in the development of a prototype platform, the negative effect of modularization on these factors could not be diminished to the fullest extent by optimum material and component selection or by the implementation of ideal manufacturing processes. The primary objective of the design has been to explore the functional flexibility achievable in machine tools by a mechanically modular architecture. In view of mechanical integrity, the platform presented in subsequent sections has been designed to machine plastics, wax and other soft materials only.

5.3 Generic Architecture of MRM Modules

MRM modules were designed to be physically autonomous units. Module autonomy implies that all components of the drive and sensory infrastructure are to be contained within the body of the module. The functional modularity of an MRM platform has been divided such that one module contributes to one degree of functionality to a platform. A single module performing a dedicated function limited the number of electro-mechanical actuators within a module to one. Electro-mechanical actuation within modules was provided by either permanent magnet DC motors or AC induction motors, depending on the modules function. MRM modules therefore operated with 12 V DC power, except certain cutting heads that required 220 V AC power for an induction motor.

MRM modules contained in-built power transmission mechanisms such as belt drive systems, gear boxes and power screws for speed reduction and torque amplification. It was compulsory that these mechanisms be contained within the framework of an individual module to simplify the assembly and reconfiguration of modular machines. The provision of standardized mechanical interfaces on the body of the module permitted the interconnectivity of modules and the transmission of torque and forces from module to module.

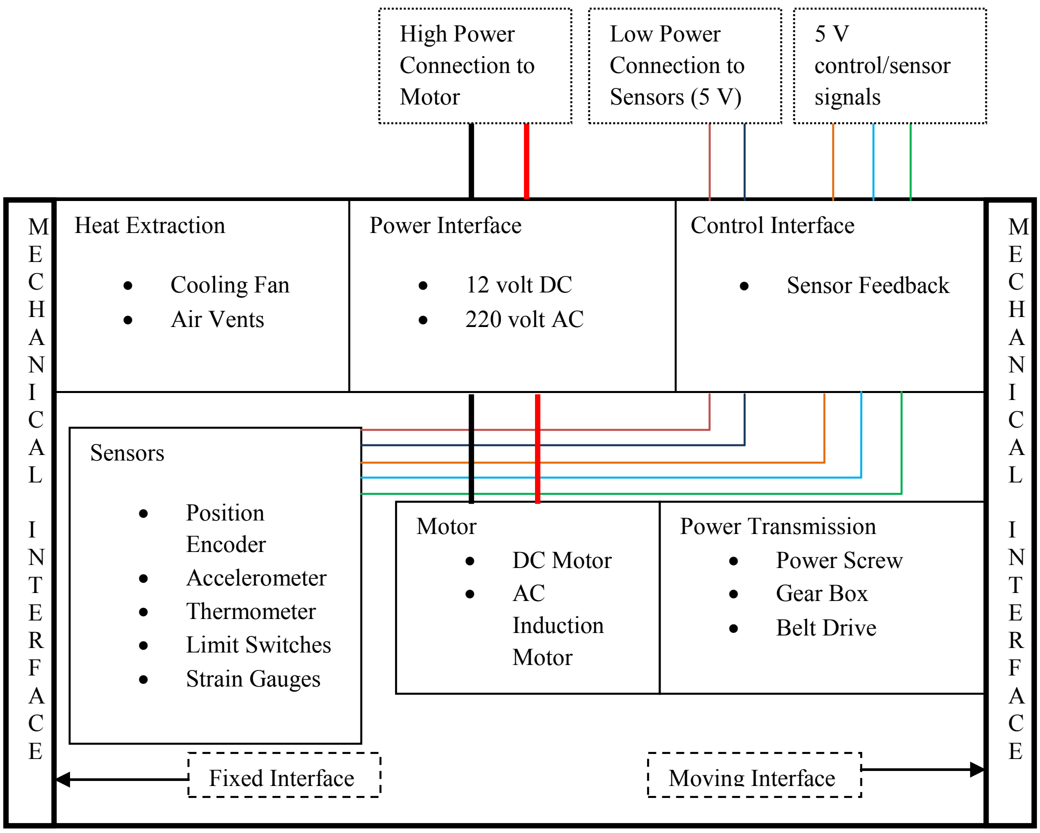


Figure 5.1: General Architecture of an MRM Module

Electric power was supplied to the modules via standardized electric connections, which enabled modules to be quickly plugged into the power grid. MRM motion modules (modular axes) contained linear encoders for position feedback and limit switches to prevent collisions between internal mechanical components.

Process modules contained accelerometers for vibration sensory feedback. Feedback from sensors was achieved by the provision of a standardized control interface/connection on the modules. Although prototype modules contained a limited variety of sensors, future industrial implementations may include thermal sensors for the activation of heat extraction and strain gauges for the early detection of mechanical failure. Due to the prototypical nature of the existing platform motors were generally low powered and module heating was negligible. For industrial grade modules it is recommended that heat extraction be incorporated into the architecture.

MRM modules did not contain any embedded digital hardware. The choice not to embed digital hardware within a module was based on ease of accessibility to control circuitry for upgrades and repairs. Furthermore heat, dirt and noise generated within the module would have detrimentally affected the performance and lifespan of an internal digital system. The interfacing of modules with externally located control circuitry was achieved through the standardized control interface. Figure 5.1 illustrates the general architecture of an MRM module. Details of the internal elements and their implementation in specific modules are discussed in proceeding sections.

5.4 Mechanical Interfacing

5.4.1 Bolted Interfaces

MRM modules are connected together by means of a series of standardized mechanical interfaces. These interfaces enable torque and force propagation throughout the machine structure. For a robust solution these interfaces are required to be mechanically simple, easy to align and possess sufficient strength to support tensile and shear forces during machining. MRM modules were manually integrated into platforms, and bolted interface plates were selected as the method of interfacing.

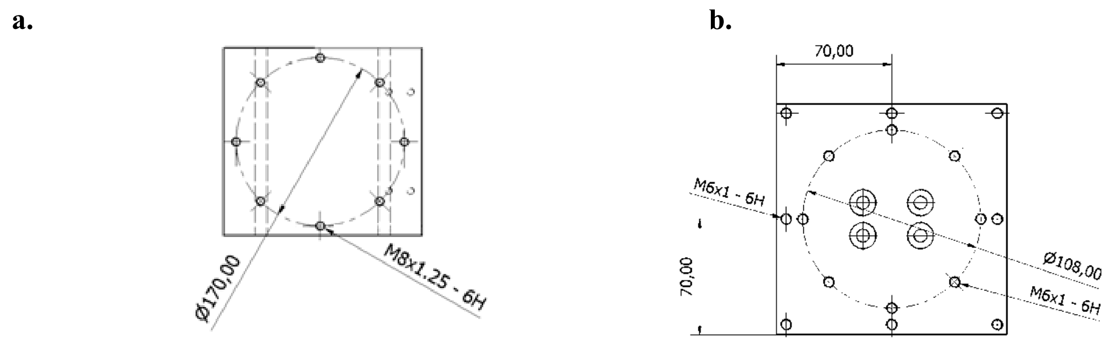


Figure 5.2: Examples of MRM Module Interfaces

a. Single interface found on the base module
b. Double interface found on the column module

The application of standardized interfaces at multiple levels of the machines architecture was essential to ensure the interchangeability of modules. The library of modules employed a series of different interfaces, as the torques experienced at different levels of the machine may vary drastically. Torque is increasingly amplified at modules further away from the cutting tool, with the largest torques and forces being experienced by the base module.

An example of an MRM module interface is illustrated in Figure 5.2.a. This example consists of a single pattern of isometric threaded holes that will enable a bolted connection with an adjacent module. The interface of Figure 5.2.b contains two symmetrical patterns, which extended the range of modules that could be connected to this interface. A maximum of two connection patterns were used per interface. The full series of interfaces that were used in the design are contained in Appendix A.

5.4.2 Interface Failure

Interface integrity is of primary concern in the design of modular machines. The creation of a machine structure from modular elements as opposed to an integral cast structure presents a design trade off in the mechanical performance. The mechanical integrity of the machine is dependent on the performance of the interfaces. Bolted interfaces present three modes of failure that must be avoided during the operation of a machine, these are: joint separation, failure by thread stripping and failure by shear.

Joint Separation and Thread Stripping

Joint separation is the separation of two bolted interface plates under the action of an external tension force F_e. Joint separation itself is not a form of fracture; however it does affect the accuracy and repeatability of the machine. During joint separation, the normal clamping force F_c, which two interfaces exert on each other, is zero. The minimum external tension force per bolt F_e that will lead to separation is given by equation 5.1. Equations 5.2-4 give the bolt stiffness k_b, interface plate stiffness k_c (bolt threaded into interface plate) and clamped area A_c, required to calculate this force. E is the modulus of elasticity of the material, A_t is the tensile stressed area and L is the length of either the bolt or the interface.

$$F_e = \frac{k_b + k_c}{k_c} F_i \tag{5.1}$$

$$k_b = \frac{A_t E}{L_{bolt}} \tag{5.2}$$

$$k_c = \frac{A_c E}{L_{int}} \tag{5.3}$$

$$A_c = d^2 + 0.68dg + 0.065g^2 \tag{5.4}$$

The initial bolt tension F_i is usually based on the constant k_i being specified in a range of 0.75 to 1.0. When a stronger bolt is threaded into a weaker material k_i must be reduced accordingly. Equation 5.5 relates the initial bolt tension to proof strength S_p for a preselected value of k_i.

$$F_i = k_i A_t S_p \tag{5.5}$$

Thread Stripping

Thread stripping, unlike joint separation is a catastrophic mode of failure. In this design the interface material was usually weaker than the bolt material, due to aluminium modules being fastened extensively with steel bolts.

The tensile force required to shear the thread on a interface is given by equation 5.6, where t is the height of the thread on the interface plate, d is the nominal diameter of the thread and S_{shear} is the shear strength of the interface material.

$$F_e = \pi d(0.75t)S_{shear} \tag{5.6}$$

Failure by Shear

Interface failure by shear occurs as a result of excessive direct shear and torsional forces on a bolted structure. Due to geometric positioning, the effective shear force among bolts in the same interface is usually unequal. For a MRM the shear force on a bolt in a particular interface is dependent on:

- The number of modules on a platform
- The type of processing function
- The profile of the cutting tool and the direction tool feed

The number of possible loading configurations that could lead to interface failure by shear is numerous. Interface failure occurs when the shear stress exceeds the ultimate shear strength on a single bolt.   The force at shear failure of an individual bolt is given by equation 5.7:

$$F = AS_{shear} \tag{5.7}$$

Interface Loading

Five interfaces were used in the library of modules. The minimum external force for joint separation, thread stripping and shear failure for each of these interfaces is presented in Table 5.1 (see Appendix A for calculations).

Table 5.1: Minimum Loads for Interface Failure

Interface Type	Recommended Assembly Torque (Nm)	Total Joint Separation Force (N)	Total Thread Stripping Force (N)	Maximum Shear Force per Bolt (N)
One	39.76	285352	293144	38000
Two A & B	16.38	153024	183217	21375
Three	16.38	153024	183217	21375
Four	62.64	156868	320536	40448
Five	31.62	104672	256429	25886

5.5 MRM Motion Modules (Modular Axes)

5.5.1 Modular Degrees of Freedom

Machining DOF was modularized according to the adopted design approach. The design of the modular kinematic chain was achieved by the following steps:

(i) determine the maximum number of DOF per operation,
(ii) allocate modular DOF to cutting tool,
(iii) allocate modular DOF to the work table/ work clamping system,
(iv) relate allocated DOF to an absolute coordinate system on the work table/ work clamping system.

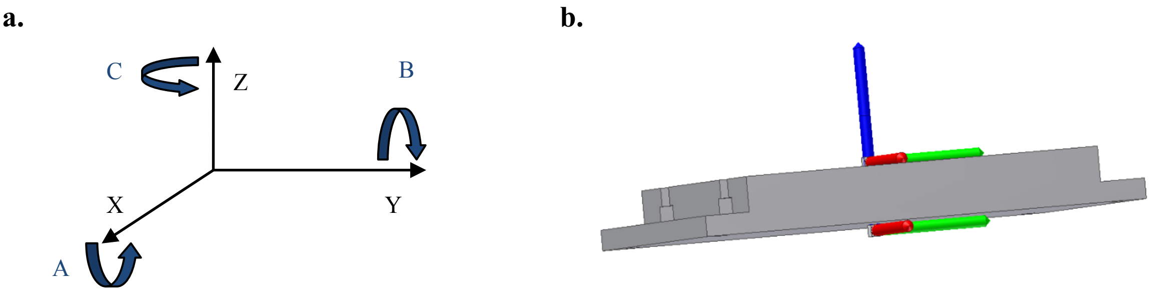


Figure 5.3: Cartesian Reference Coordinate Systems

a. Right hand coordinate system
b. Fixture of an absolute coordinate system to the work table (Red: X-axis, Green: Y-axis, Blue: Z-axis)

The prototype library of MRM modules was created with sufficient hardware to enable drilling and turning operations, with the possibility of enabling more processes with the creation of more modules. During the creation of the MRM module library it was established that a maximum of three DOF would be utilized in the turning configuration while a maximum of six DOF would be utilized in the drilling configuration. A conventional right hand Cartesian coordinate system as depicted in Figure 5.3.a was used to classify the axes that were to be created for the module library. The coordinate system is fixed to an absolute point of reference on the desired machine tool during the conceptualization phase. An absolute point of reference would be on a work holding/clamping element such as the work table depicted in Figure 5.3.b. Imposing an absolute coordinate system is necessary for classifying axes, procedural machine programming and position control.

In material removal operations it is preferable that less DOF be allocated to the machine spindle, in favour of greater stability during operation [57]. In turning operations the work piece rotates in the chuck of the cutting head, while the cutting tool traverses across the material. Based on design for machining stability all DOF were allocated to the tool post in the turning configuration. In drilling operations the tool rotates in the spindle of the cutting head, and the forces during drilling are expected to be much lower than in turning. The drilling configuration therefore possessed an equal distribution of DOF between the work table and the cutting head. Table 5.2 summarizes the allocation of modular DOF in the kinematic architecture of the desired drilling and turning configurations.

Table 5.2: Allocation of DOF for Drilling and Turning Configurations

Degree of Freedom	Drilling	Turning
Linear X-Axis	Cutting Head	Tool Post
Linear Y-Axis	Work Table	Tool Post
Linear Z-Axis	Cutting Head	-
Rotary A-Axis	Cutting Head	-
Rotary B-Axis	Work Table	-
Rotary C-Axis	Work Table	Tool Post

5.5.2 Generalized Kinematic Modelling

Each mechanical module possessed two active standardized mechanical interfaces (a module may possess more than two interfaces, however only two are used in any configuration). The first stage in the kinematic modelling of a MRM is the placement of localized coordinate systems at the centre of both interfaces of a module as depicted in Figure 5.4. This permits each module to be kinematically described by a Homogenous Transformation Matrix (HTM) M_n that relates the two coordinate systems placed on either interface.

Figure 5.4: Placement of Localized Reference Frames on a Module

The Denavit –Hartenberg (D-H) method [58] of fixing a reference frame to links in a kinematic chain is applicable, however this method is not always convenient. The D-H method is best suited for application to serial robots and may result in unnecessarily complex transformation matrices when applied to different kinematic arrangements.

As an alternative to the D-H method, the following sets of guidelines were developed to fix local reference frames to modules:

(i) The placement of the local coordinate system on an interface must be such that it will coincide with the coordinate system of an adjacent interface once assembled.

(ii) The axis of actuation must be labelled according to the motion the modules provides with regard to the global reference frame. For example if a module has been identified as the global X-axis, then the two local X-axes must be parallel to the global X-axis.

(iii) No rotations of local reference frames are permitted between the two interfaces of a module unless the module is a rotary axis.

(iv) Frame 1 is always assigned to the tool holder or tool post. The kinematic chain terminates with link „n" being assigned to the material clamp/ work table.

The HTM for any module is obtained from equation 5.8. The rotation component of the transformation matrix is constructed according to the X-Y-Z Euler angle convention [58], where angles γ, β and α represent the respective rotations of the reference frame „i" about the X, Y and Z axes of the reference frame „i+1", in the given order. The position component of the HTM represent the X, Y, Z offsets of the reference frame i with regard to frame i+1.

$$ {}^{i+1}_{i}M_n = \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma & x \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma & y \\ -s\beta & c\beta s\gamma & c\beta c\gamma & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5.8) $$

Module transformation matrices are concatenated in order of assembly from the cutting tool to the work holder, yielding a final matrix that describes the position of the tool holding module relative to the global reference on the work holding module. The forward kinematic model for any MRM is given by equation 5.9:

$$^{Work}_{Tool}T = M_n M_{n-1} M_{n-2} \dots M_1 \qquad (5.9)$$

5.5.3 Axis Drive Systems

Drive System Alternatives

Machine axes on automated production machines are conventionally powered by:

- hydraulic drive systems,
- electric servo motors,
- pneumatic drive systems.

When selecting an appropriate actuator for MRM motion modules factors such as cost, positioning accuracy, speed, ease of control, actuator heating, required maintenance and ease of implementation were considered. Table 5.3 presents a selection matrix that weighs the relative importance of each factor; and evaluates the performance of each alternative against these factors to yield the optimal choice.

Table 5.3: Actuator Selection Matrix (R= Rating (10), S = Weighted Score (100))

Factor	Weighting	Hydraulic		Electric Servo		Pneumatic	
		R	S	R	S	R	S
Cost	9	7	63	7	63	5	45
Positioning Accuracy	10	7	70	9	90	4	40
Speed	7	5	35	9	63	9	63
Ease of Control	7	5	35	8	56	5	35
Actuator Heating	7	7	49	5	35	7	49
Required Maintenance	7	5	35	8	56	7	49
Ease of Implementation	7	6	42	9	63	6	42
Weighted Total		329		426		323	

According to the selection matrix, an electric servo drive system has been identified as the optimal choice. This was implemented accordingly.

Drive System Implementation

MRM motion modules each contained a 12 volt, 100 watt permanent magnet DC motor for actuation. A HEDS-5540 incremental (optical) encoder was attached to the output shaft of each motor for speed and position measurement; this formed the servo drive system illustrated in Figure 5.5. The choice of servo drive system was based primarily on cost and for industrial implementations DC servomotors with fully integrated absolute encoders are recommended. The encoders used in this system were capable of resolutions of up to 1024 pulses per revolution with a two channel quadrature output; alternatively one channel of the encoder could be used providing a resolution of 512 pulses per revolution. Further details on the HEDS-5540 can be found in Section 6.6.

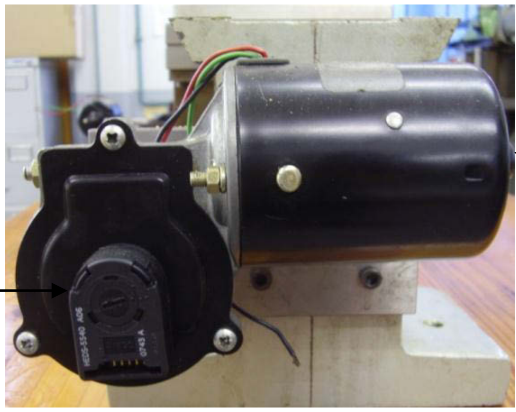


Figure 5.5: Servo Drive System Consisting of a 12 volt DC Motor and an Incremental Encoder

Figures 5.6 and 5.7 illustrate the performance characteristics of the motor with regard to torque, speed and current. When unloaded the maximum shaft speed of the motor is in the proximity of 60 rev/min. During normal operation the motor was capable of a torque of 12 Nm at 20 rev/min. The motor stalls on a resisting torque of 20 Nm while drawing a current of 18 amps.

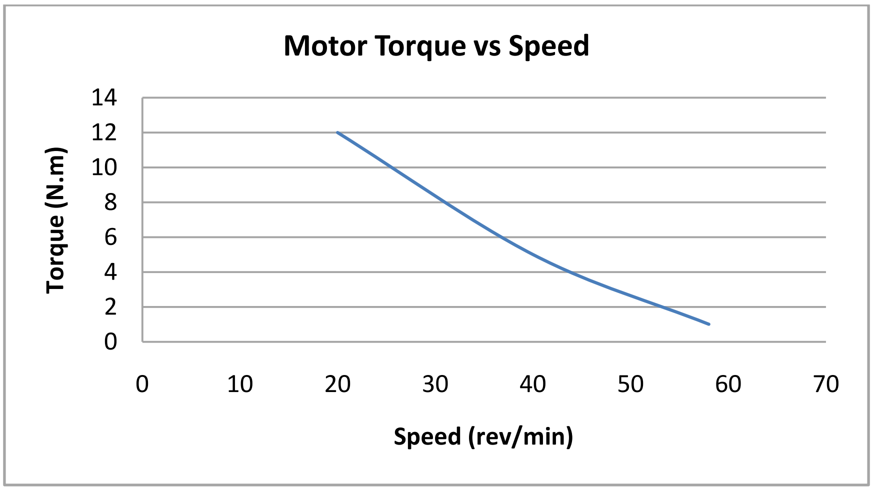


Figure 5.6: Torque vs Speed Characteristic of Axis Drive Motor

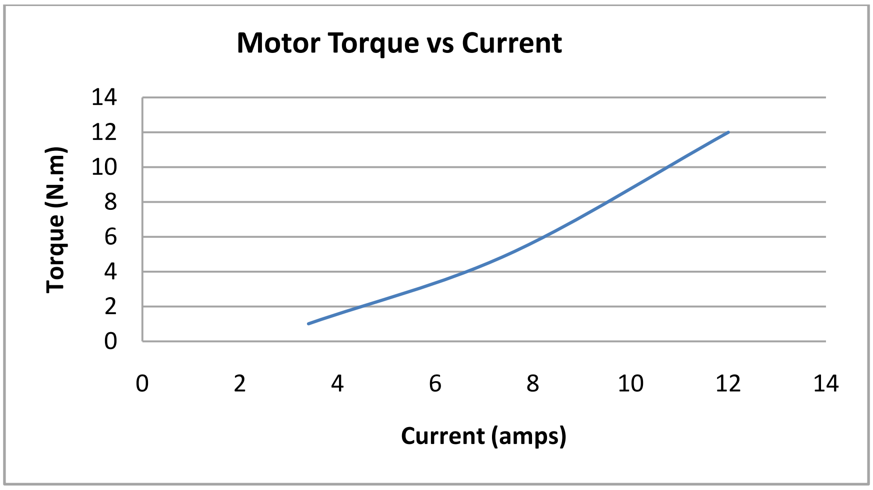


Figure 5.7: Torque vs Current Characteristic of Axis Drive Motor

5.5.4 Linear Axes

Actuation of Linear Axes

Linear axes in conventional machine tools are driven by power screw mechanisms coupled to servo motors [57]. The Acme lead screw or re-circulating ball screws are ideal for machine tool slide applications. These screws provide good positioning accuracy, low friction and require less drive power than other screw profiles. During the development of a library of modules an ISO Metric screw profile was selected for linear modules. Although this thread profile is less optimal than Acme or re-circulating ball screws, the cost was significantly lower. Figure 5.8 illustrates the thread profile of a conventional ISO Metric screw.

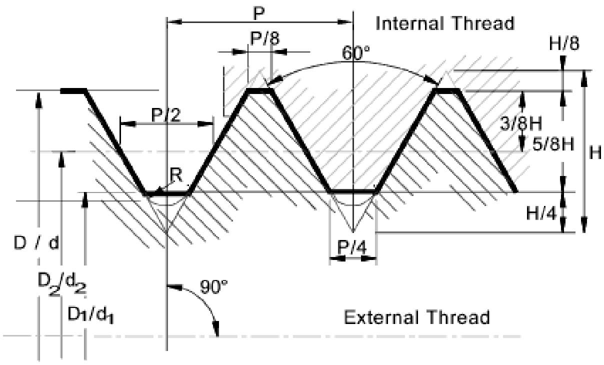


Figure 5.8: ISO Metric Screw Profile [59]

The total torque required to drive a power screw in a direction opposing an applied load W ("raising the load") is calculated by equation 5.10; where d_m is the mean diameter of the screw. For a single start ISO Metric thread, the lead L is equal to the pitch P; and the angle α_n is equal to 30°. The coefficient of friction between the screw and the corresponding nut is f. The torque required to overcome collar/bearing friction is calculated by the second expression in equation 5.10, where d_c is the collar diameter and f_c is the coefficient of friction of the collar. The total torque required to drive a power screw in the same direction as the applied load ("lowering the load") is calculated by equation 5.11. The linear speed V, power $\dot{W}$ and efficiency of a power screw are calculated by equations 5.12, 5.13 and 5.14 respectively. N is the rotational speed of the screw in rev/min.

$$T = \frac{W d_m}{2} \frac{f \pi d_m + L \cos \alpha_n}{\pi d_m \cos \alpha_n - f L} + \frac{W f_c d_c}{2} \quad (5.10)$$

$$T = \frac{W d_m}{2} \frac{f \pi d_m - L \cos \alpha_n}{\pi d_m \cos \alpha_n + f L} + \frac{W f_c d_c}{2} \quad (5.11)$$

$$V = NL \quad (5.12)$$

$$\dot{W} = \frac{\pi N}{30} T \quad (5.13)$$

$$Efficiency = \frac{WL}{2\pi T} \quad (5.14)$$

Base Module (X - Axis)

The MRM base module is a central module to all MRM configurations. This module forms the foundational structure of the machine, upon which other modules are added. The body of the module is cast iron, which provided the strength and mass necessary to support the rest of the machine structure while providing vibration damping.

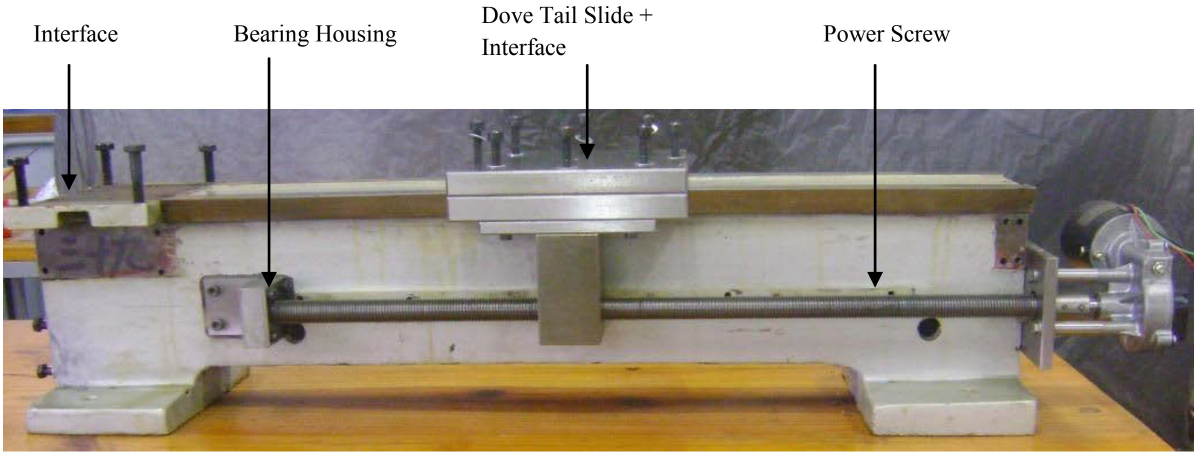


Figure 5.9: MRM Base Module (X-axis)

The drive mechanism consisted of a steel „dove tail" slide mechanism driven by an ISO Metric M20x2.5 power screw. Steel was selected as the slide material, as it would provide the necessary strength and durability against wear. The power screw is of high tensile steel and it turns in a nut that was manufactured out of brass. The screw is supported by a deep groove ball bearing on one end and is coupled to the motor on the opposite end. Figure 5.10 illustrates the drive mechanism of the module and Table 5.4 summarizes the module"s specifications. The module code for all MRM modules is as follows "MRM-Type-Range-Moving Interface-Static Interface". Calculations for the loading specifications may be found in Appendix C.3 and C.4. The maximum normal (vertical) load on the slide has been specified as not applicable as the prior failure of other MRM modules in all configurations is expected prior to the failure of the slide under a normal load. Engineering drawings for the base module are located in Appendix G; these drawings are a **sample** of the drawings that were generated during this research, the CAD drawings of other modules are located on the supplementary DVD.

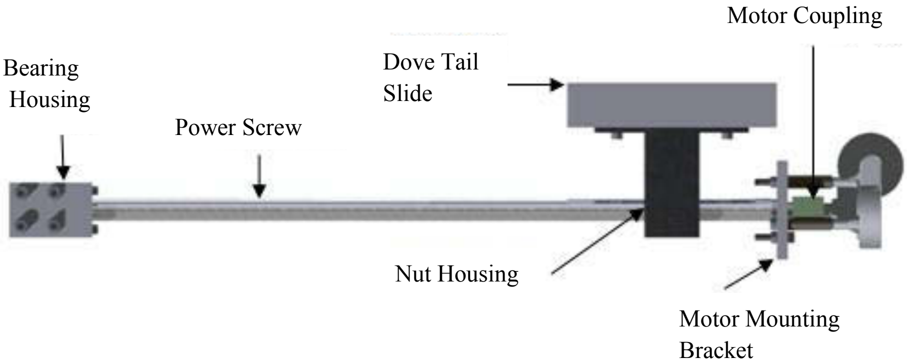


Figure 5.10: Drive Mechanism of the Base Module

The MRM base module is designated as the X-axis in both drilling and turning configurations. The HTMs for this module in the drilling and turning configurations are given by equations 5.15 and 5.16 respectively; the limits are with reference to local frame „i+1". Refer to Appendix B.1 for calculations and illustrative diagrams.

$$ {}^{i+1}_{i}M_{Base-Drilling} = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & 2.5 \\ 0 & 0 & 1 & 215 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (257.5 \leq x \leq 757.5) \qquad (5.15) $$

$$ {}^{i+1}_{i}M_{Base-Turning} = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & 2.5 \\ 0 & 0 & 1 & 19 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (192.5 \leq x \leq 692.5.5) \qquad (5.16) $$

Table 5.4: Specifications of the Base Module

Module Data	MRM Base Module
Module Code (B = Base)	MRM-B01-500-T1-T4/5
Module Control Resolution (refer to section 8.8)	$4.883\text{x}10^{-3}$ mm
Module Range	500 mm
Moving Interface	Type one
Static Interface(s)	Type four and five
Max Speed	145 mm/min
Max Actuation Load	930 N
Max Normal Load on Moving Interface	N/A

Work Table Slide Module (Y-Axis)

The "work table slide" module supports the worktable in the drilling configuration. This module is also of a foundational nature upon which further enhancement modules may be added. The module was created with a steel framework to provide adequate strength in the module. This system was intended to provide sufficient support during drilling operations, for other machining operations such as milling, a heavier cast iron structure with a dove tail slide is recommended.

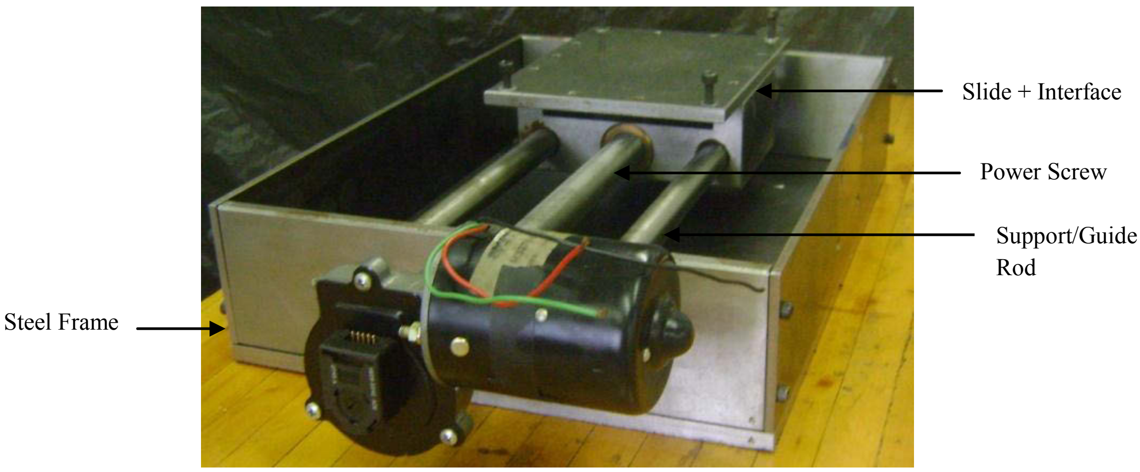


Figure 5.11: MRM Work Table Slide Module (Y-axis)

The drive mechanism of this module consisted of a steel slide driven by an ISO Metric M24x3 power screw. The screw was of high tensile steel and possesses a large diameter for added rigidity. The power screw is supported by two deep groove ball bearings at either end, and runs in a brass nut that is housed in the slide. Two 20 mm silver steel (BS-1407) rods from the support and guide mechanism for the slide as illustrated in Figure 5.12. Table 5.5 summarizes the module‟s specifications. Calculations for the loading specifications may be found in Appendix C.3 and C.4.

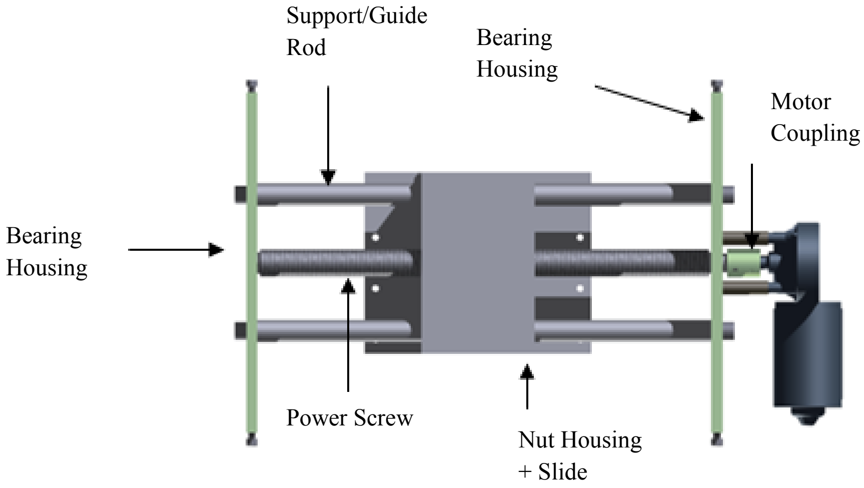


Figure 5.12: Drive mechanism of the Work Table Slide Module

Table 5.5: Specifications of the Work Table Slide Module

Module Data	Work Table Slide Module
Module Code (WTS = Work Table Slide)	MRM – WTS01-300-T3-T5
Module Control Resolution	5.869×10^{-3} mm
Module Range	300 mm
Moving Interface	Type 3
Static Interface(s)	Type 5
Max Speed	174 mm/min
Max Actuation Load	930 N
Max Normal Load on Moving Interface	460 N

The work table slide module is designated as the Y-axis in the drilling configuration. The HTM for this module is given by equation 5.17; the limits are with reference to local frame „i+1‟. Refer to Appendix B.2 for calculations and illustrative diagrams.

$$ {}^{i+1}_{\ i}M_{WT\ Slide} = \begin{bmatrix} 1 & 0 & 0 & 155 \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & -111 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (-150 \le y \le 150) \qquad (5.17) $$

Column Module (Z- Axis)

The column module supports the cutting head in the drilling configuration. The module was created mainly out of aluminium (295-T4) for weight saving, with four silver steel rods forming the support and guide mechanism for the slide (see Figure 5.13b).

Silver steel is a 1% carbon tool steel [60] that was specifically selected for its high strength to create a stable, light weight support structure for the drill cutting head. The modules weight was limited for easy, manual assembly. The drive mechanism of the module consisted of a centrally located ISO Metric M24x3 power screw. The screw is of high tensile steel and runs in a brass nut as illustrated in Figure 5.13.c. The screw is supported by thrust bearings at the top and bottom ends of the column. Table 5.6 summarizes the module‟s specifications.

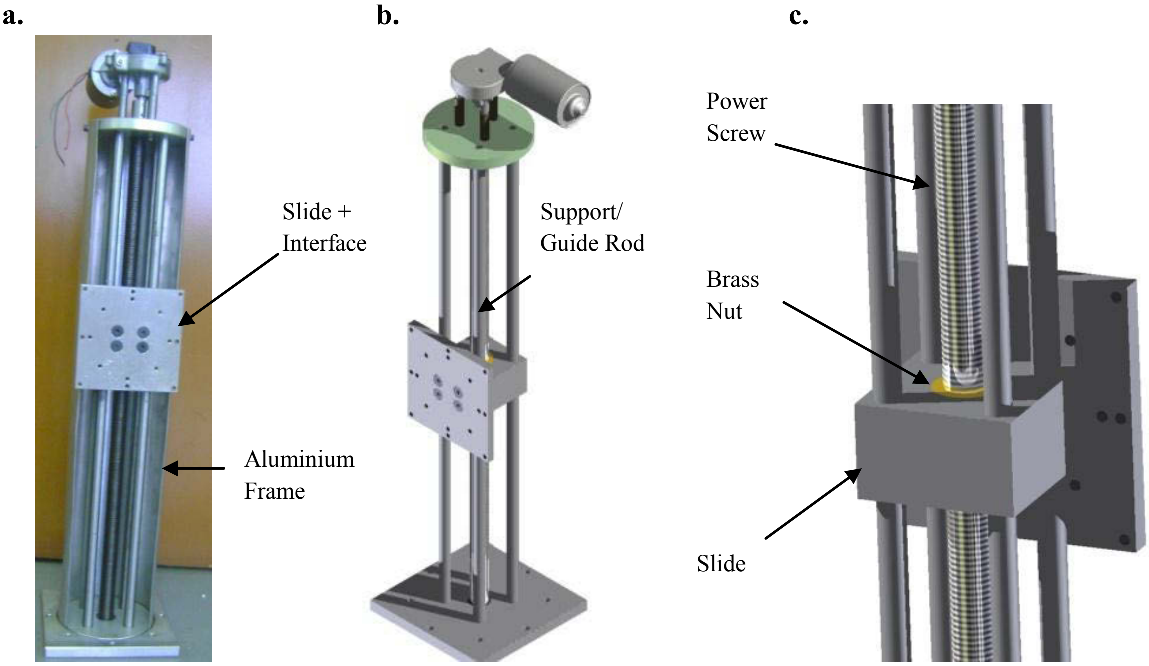


Figure 5.13 MRM Column Module (Z-axis)

a. Column Module – Front view
b. Column Module – Displaying support structure
c. Column Module – Displaying drive mechanism

Table 5.6: Specifications of the Column Module

Module Data	Column Module
Module Code (C=Column)	MRM-C01-562-T2A/2B-T1
Module Control Resolution	5.869×10^{-3} mm
Module Range	600 mm
Moving Interfaces	Type Two A and B
Static Interface	Type One
Max Speed	174 mm/min
Max Actuation Load	2952 N
Max Normal Load on Moving Interface	300 N

The column module is designated as the Z-axis in the drilling configuration. The HTM for this module is given by equation 5.18; the limits are with reference to local frame „i+1‟. Refer to Appendix B.3 for calculations and illustrative diagrams. Calculations for the loading specifications may be found in Appendix C.3 and C.4.

$$^{i+1}_{i}M_{Column} = \begin{bmatrix} 1 & 0 & 0 & -54.5 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (85 \leq z \leq 647) \qquad (5.18)$$

Cross Slide Module (Y-Axis and C-Axis)

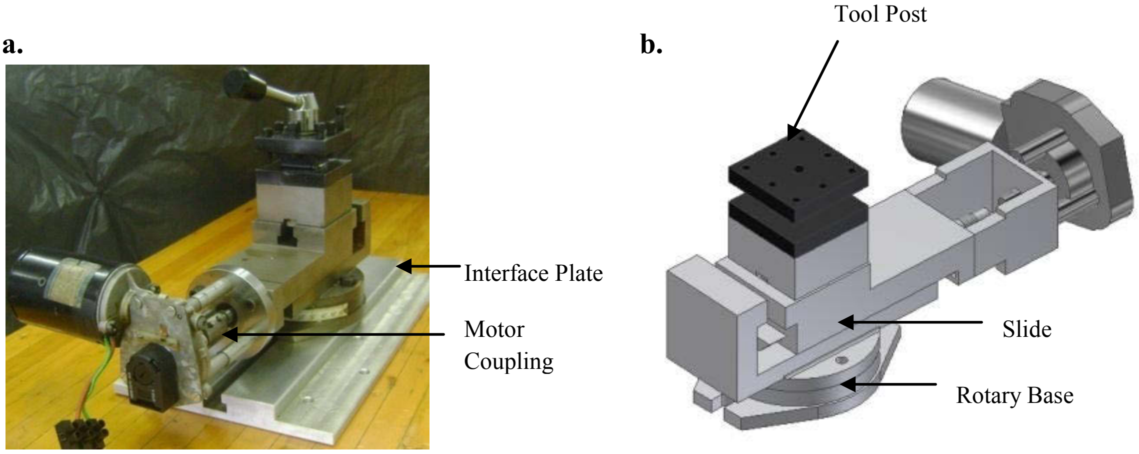


Figure 5.14: Cross Slide Module and Tool Post (Y and C axes)

a. MRM Cross Slide Module – Rear view
b. MRM Cross Slide Module – Illustrative side view

The cross slide module contains a tool post and is responsible for feeding the tool into a rotating work piece in the turning configuration. The module was a COTS unit of hardware that was retrofitted with a servo drive motor. The body of the module is steel and the servo drive system is supported by an aluminium bracket. The steel body is ideal for vibration damping and the support of high machining forces. The drive mechanism consisted of the tool post being driven by a 12x2 metric trapezoidal power screw.

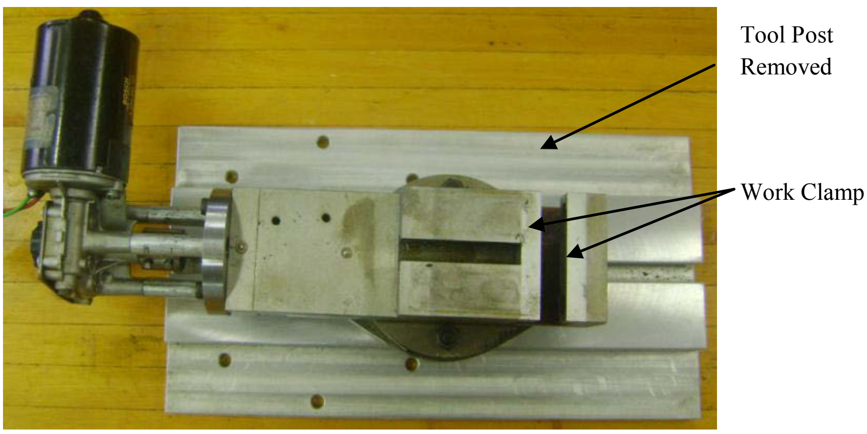


Figure 5.15: MRM Automated Work Clamp

The cross slide module possessed two additional features. The first feature was the ability of the module to be transformed into an automated device for work clamping. This display of reconfigurability is achieved by the design of the tool post to be modular and removable from the base of the module. Figure 5.15 illustrates the reconfigured module with the tool post removed.

The second feature was the ability of the module to rotate about its axis. This effectively created a rotational axis (C-axis). The rotary indexing feature of this module is manually manipulated; the rotation is illustrated in Figure 5.16.b. Table 5.7 summarizes the module‟s specifications. Calculations for the loading specifications may be found in Appendix C.3 and C.4.

a.

b.

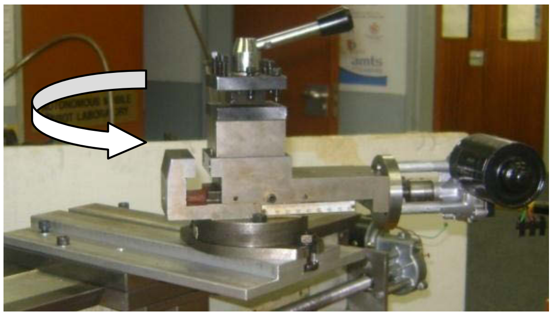


Figure 5.16: Cross Slide Module Displaying Additional Rotary Axis

a. Cross slide module at home position
b. Cross slide module orientated at 45^{o} to the home position

Table 5.7: Specifications of the Cross Slide Module

Module Data	Cross Slide Module
Module Code (CS= Cross Slide)	MRM-CS01-115-T0-T1
Module Control Resolution	3.906 x10^{-3} mm
Module Range (Y axis)	115 mm
Module Range (C axis)	360^{o}
Static Interface	Type One
Max Speed	116 mm/min
Max Actuation Load	250 N
Max Load on Tool (vertical and horizontal)	2500 N

This module provides both the Y and C axes in the turning configuration. The HTM for this module is given by equation 5.19; the limits are with reference to local frame „i+1‟. Refer to Appendix B.4 for calculations and illustrative diagrams.

$$ {}^{i+1}_{i}M_{Cross\ Slide} = \begin{bmatrix} c\alpha & -s\alpha & 0 & 0 \\ s\alpha & c\alpha & 0 & y \\ 0 & 0 & 1 & 168 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (-90 \le y \le 25;\ -360° \le \alpha \le 360°) \qquad (5.19) $$

Idealized Performance of Linear Axes

Performance characteristics of the servo drive system implemented in the MRM axes were presented in Section 5.5.3. By manipulating the performance characteristics of the drive motor a corresponding idealized performance characteristic may be developed for the performance of a module under the action of a resisting load. Rearranging equation 5.10 yields the force that a power screw mechanism is capable of acting against for a given input torque:

$$W = T\left[\frac{d_m}{2}\frac{f\pi d_m + L\cos\alpha_n}{\pi d_m \cos\alpha_n - fL} + \frac{f_c d_c}{2}\right]^{-1} \quad (5.20)$$

Equation 5.20 and the motor performance data have been used to generate Figures 5.17 and 5.18. These figures represent the ideal performance of the linear motion modules with regard to actuation force and speed (Figure 5.17) and the electric current requirements of the modules under corresponding loads (Figure 5.18). These figures have been generated purely from the actuation characteristics of the associated motor and equation 5.20; the forces presented do not necessarily represent the maximum forces sustainable by the modules. Refer to Appendix C.1 for calculations.

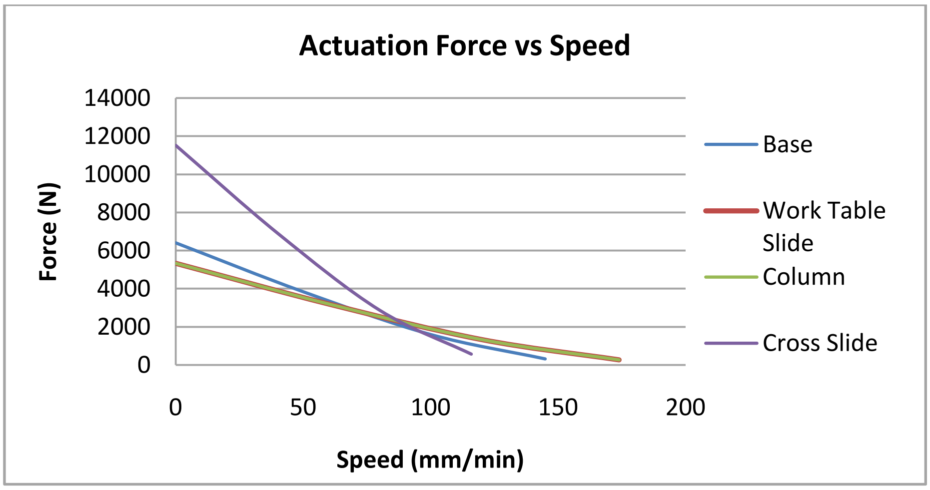


Figure 5.17: Graph of Actuation Force vs Speed for Linear Axes

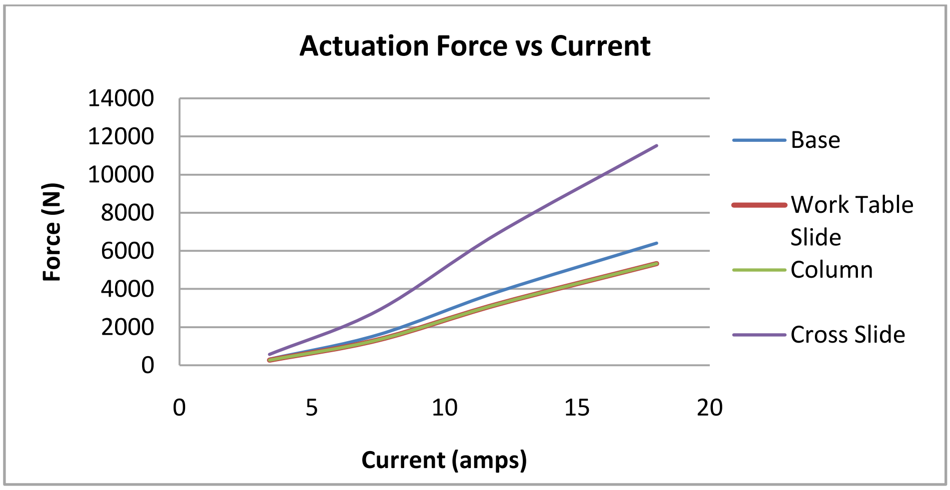


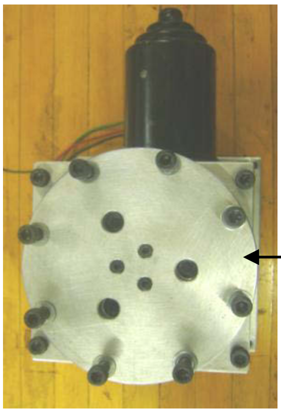
Figure 5.18: Graph of Actuation Force vs Current for Linear Axes

5.5.5 Rotary Axes

Cutting Head Rotary Module (A-Axis)

The "cutting head rotary" module was designed for use in the drilling configuration. The module is an optional rotary axis that is capable of orientating the cutting head in different planes. The frame of the module was created entirely out of aluminium to minimize weight, while providing sufficient strength during drilling. Weight minimization was necessary due to limitations imposed by the actuation torque that was available from module motors.

a.



b.

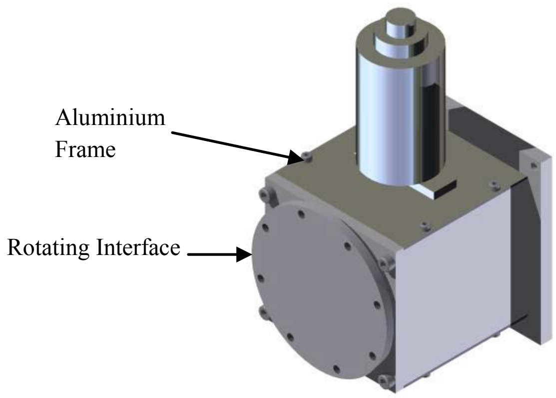
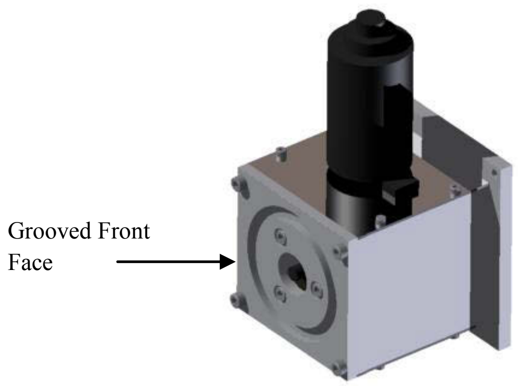


Figure 5.19: The Cutting Head Rotary Module (A-axis)

a. Cutting Head Rotary Module – Front view
b. Cutting Head Rotary Module – Illustrative isometric view

The actuation mechanism of this module consisted of a stepped interface plate rotating in a groove on the front face of the module. The groove provides support for the interface during operation and ensures smooth rotation. The interface plate is directly coupled to the drive motor as illustrated in Figure 5.20.b.

a.



b.

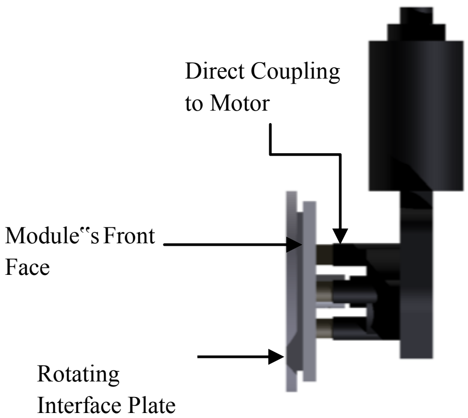


Figure 5.20: Drive Mechanism of the Cutting Head Rotary Module

a. Grooved front face
b. Direct coupling of motor to interface

The DC motor that has been implemented in all axes contains an internal worm gearbox that amplifies the output torque from the armature shaft. The second benefit derived from the internal gearbox is that it behaves as a braking mechanism. The gear component of the box cannot be rotated by an applied load and can only be rotated by the worm mechanism attached to the armature shaft. The direct coupled solution provided a basic, cost effective solution, however for industrial implementations it is recommended that the interface be coupled to the motor via a secondary gearbox. Table 5.8 summarizes the specifications of this module. Calculations for the loading specifications may be found in Appendix C.3 and C.4.

Table 5.8: Specifications of the Cutting Head Rotary Module

Module Data	Cutting Head Rotary Module
Module Code (CHR = Cutting Head Rotary)	MRM-CHR01-360-T2A-T2B
Module Control Resolution	0.703 °
Module Range	± 360°
Moving Interfaces	Type Two A
Static Interface	Type Two B
Max Speed	70 rev/min
Stall Torque	20 N.m
Max Allowable Torque On Moving Interface	12 N.m
Max Normal Load on Moving Interface	250 N

This module has been designated as the A-axis, as it provides rotary motion about the X-axis in the drilling configuration. The HTM for this module is given by equation 5.21; the limits are with reference to local frame „i+1". Refer to Appendix B.5 for calculations and illustrative diagrams.

$$ {}^{i+1}_{i}M_{CH\ Rotary} = \begin{bmatrix} 1 & 0 & 0 & -138 \\ 0 & c\gamma & -s\gamma & 0 \\ 0 & s\gamma & c\gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (-360° \leq \gamma \leq 360°) \qquad (5.21) $$

Tilt Table Module (B-Axis)

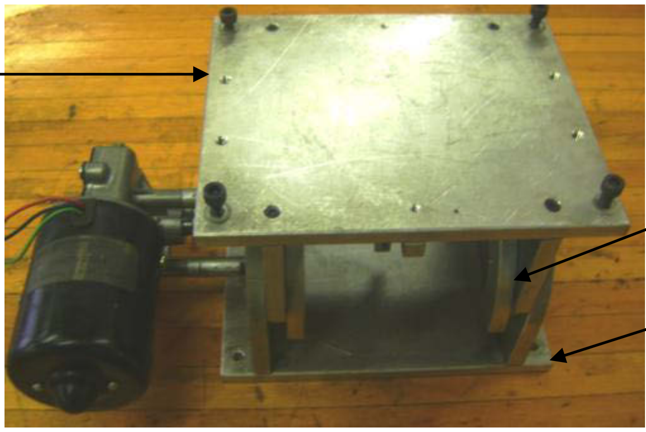


Figure 5.21: The Tilt Table Module (B-axis)

The tilt table module illustrated in Figure 5.21 was designed for use in the drilling configuration. The module is capable of having a work table attached to its upper interface and provides an optional rotary axis. The table tilts the work part relative to the cutting tool to provide different planes of machining. The module was designed entirely out of aluminium, to create a strong light weight mechanism that is easy to reconfigure and easily moved by the drive motors of other modules in the kinematic chain.

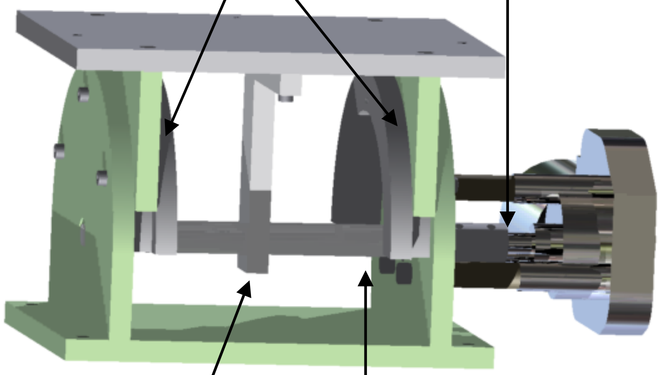


Figure 5.22: Drive Mechanism of the Tilt Table Module

The drive mechanism of the module consisted of the upper interface plate being moved by a leaver arm as illustrated in Figure 5.22. The lever arm is coupled to a drive shaft, which is in turn coupled to the motor. The drive shaft fits into the lever arm and the connection is secured by a shear pin. The shaft is also supported at both ends by two deep groove ball bearings. The rotary motion of the upper interface is guided by two stepped arches at either end of the plate; these arches also support the load placed on this interface, protecting the drive shaft from bending. The DC motor that has been implemented in this axis contained an internal worm gearbox (as in all the other axes). The internal gearbox behaves as a braking mechanism, permitting motion to occur only by the actuation of motor. It should be noted that this mechanism is a direct drive mechanism as there is no torque conversion between the motor and the interface tilting mechanism. Table 5.9 summarizes the specifications of this module. Calculations for the loading specifications may be found in Appendix C.3 and C.4.

Table 5.9: Specifications of the Tilt Table Module

Module Data	Tilt Table Module
Module Code (TT = Tilt Table)	MRM-TT01-90-T3-T3
Module Control Resolution	0.703 ^{o}
Module Range	± 90^{o} to the horizontal
Moving Interface	Type Three
Static Interface	Type Three
Maximum Speed	70 rev/min
Stall Torque	20 N.m
Maximum Allowable Torque On Moving Interface	12 N.m
Max Normal Load on Moving Interface	240 N

The module is designed for attachment to the work table slide module and provides rotary motion about the Y-axis in the drilling configuration; it has therefore been designated as the B-axis of that system. The HTM for this module is given by equation 5.22; the limits are with reference to local frame „i+1". Refer to Appendix B.6 for calculations and illustrative diagrams.

$$ {}^{i+1}_{i}M_{Tilt\ Table} = \begin{bmatrix} c\beta & 0 & s\beta & -50s\beta \\ 0 & 1 & 0 & 0 \\ -s\beta & 0 & c\beta & -50c\beta - 95 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (-45° \leq \beta \leq 45°) \qquad (5.22) $$

Rotary Table Module (C-Axis)

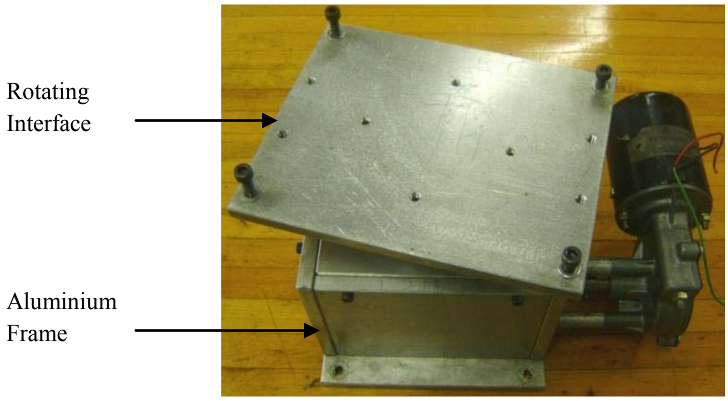


Figure 5.23: Rotary Table Module (C-axis)

The rotary table module illustrated in Figure 5.23 was designed for use in the drilling configuration. The module is capable of having a work table or other modules attached to its upper interface. This module was also designed entirely out of aluminium, to create a strong, light weight mechanism that is easy to reconfigure and easily moved by the drive mechanisms of other modules.

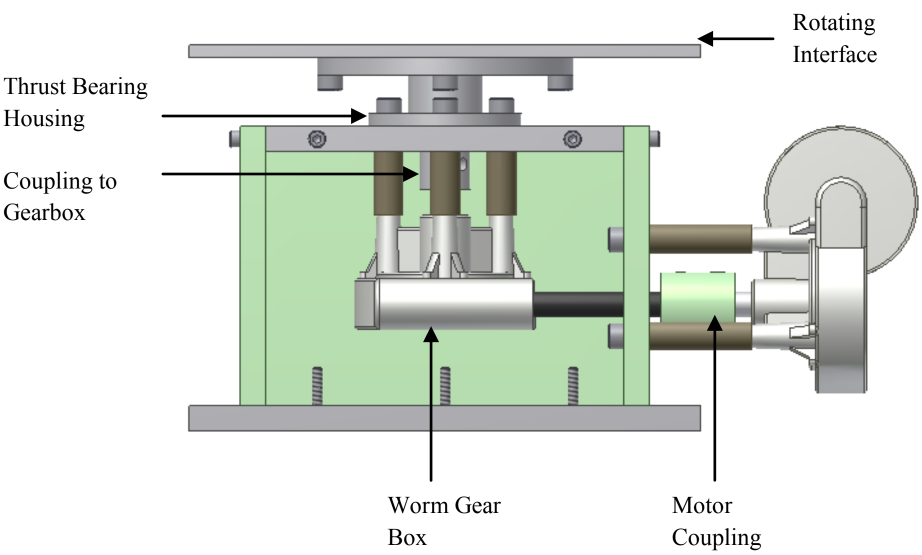


Figure 5.24: Rotary Table Drive Mechanism

The drive mechanism consisted of the upper interface being rotated via a reduction worm gearbox. This interface is supported by a thrust bearing at its base. The worm gearbox is coupled to the drive motor by a 12 mm steel shaft. The worm gearbox in the module and the internal worm gearbox belonging to the motor both prevent the mechanism from being moved by the load, permitting motion to occur only under the control of the motor. Table 5.10 summarizes the specifications of this module. Calculations for the loading specifications may be found in Appendix C.3 and C.4.

Table 5.10: Specifications of the Rotary Table Module

Module Data	Rotary Table Module
Module Code (RT = Rotary Table)	MRM-RT01-360-T3-T3
Module Control Resolution	0.0125 °
Module Range	± 360°
Moving Interfaces	Type Three
Static Interface	Type Three
Maximum Speed	1.25 rev/min
Stall Torque	N/A – Prior failure of gearbox
Maximum Allowable Torque on Moving Interface	20 N.m
Max Normal Load on Moving Interface	250 N

The module provides rotary motion about the Z-axis in the drilling configuration; it has therefore been designated as the C-axis of that system. The HTM for this module is given by equation 5.23; the limits are with reference to local frame „i+1". Refer to Appendix B.7 for calculations and illustrative diagrams

$$ {}^{i+1}_{i}M_{Rot\ Table} = \begin{bmatrix} c\alpha & -s\alpha & 0 & 0 \\ s\alpha & c\alpha & 0 & 0 \\ 0 & 0 & 1 & -152 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (-180° \leq \alpha \leq 180) \qquad (5.23) $$

Idealized Performance of Rotary Axes

The cutting head rotary module and the tilt table module both possessed direct drive mechanisms with no torque conversion between the motor and the driven interface. Ideally (no friction) these modules should display the torque and speed characteristics of the drive motor due to the direct coupling. On the contrary the rotary table module possessed a mechanism where the rotating interface was driven via a secondary worm gearbox. Equations 5.24 and 5.25 relate the speed and torque of the input shaft to the output shaft of a single stage reduction gearbox.

$$ \omega_{output} = \omega_{input} \frac{N_{worm}}{N_{gear}} \qquad (5.24) $$

$$ T_{output} = T_{input} \frac{\omega_{input}}{\omega_{output}} \qquad (5.25) $$

These equations have been used in conjunction with the motor performance data to generate Table 5.11. This table displays the performance characteristic of actuation torque versus speed for the MRM rotary modules.

These values have been generated purely from the actuation characteristics of the associated motor and the relationships presented in equations 5.24 and 5.25. The torques presented do not necessarily represent the maximum loads sustainable by the modules. Refer to Appendix C.2 for calculations.

Table 5.11: Actuation Characteristics of MRM Rotary Axes

Actuation Current (amps)	A-Axis Speed (rev/min)	A-Axis Torque (N.m)	B-Axis Speed (rev/min)	B-Axis Torque (N.m)	C-Axis Speed (rev/min)	C-Axis Torque (N.m)
3.4	58	1	58	1	1.036	56
7.5	40	5	40	5	0.714	280
12	20	12	20	12	0.357	672
18	Stall	20	Stall	20	Stall	1120

5.6 MRM Process Modules (Modular Cutting Heads)

Drilling Head

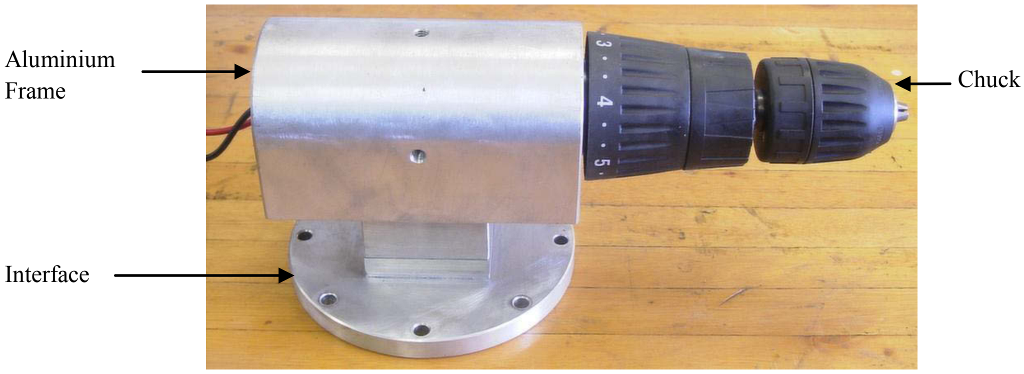


Figure 5.25: MRM Drilling Module

The MRM drilling module illustrated in Figure 5.25 forms the cutting head in the MRM drilling configuration. The module consists of a motor and spindle unit fitted into an aluminium housing. The module is specified to operate at 12 volts and provides 80 watts of power at the spindle. The motor and planetary gearbox arrangement, illustrated in Figure 5.26, is specified to provide a maximum spindle speed of 580 rev/min. The internal planetary gearbox possesses a back-torque limiter (slip clutch) that connects the gearbox to spindle. The slip clutch prevents the motor from stalling which could potentially damage the motor. Table 5.12 summarizes the specifications of this module.

Table 5.12: Specifications for the Drilling Module

Module Data	Drilling Module
Module Code (DH = Drilling Head)	MRM-DH01-12-T0-T2A
Drill Range	0.5 mm – 12 mm
Static Interface	Type Two A
Power	80 watts
Maximum Speed	580 rev/min (Unloaded)
Torque Settings	16

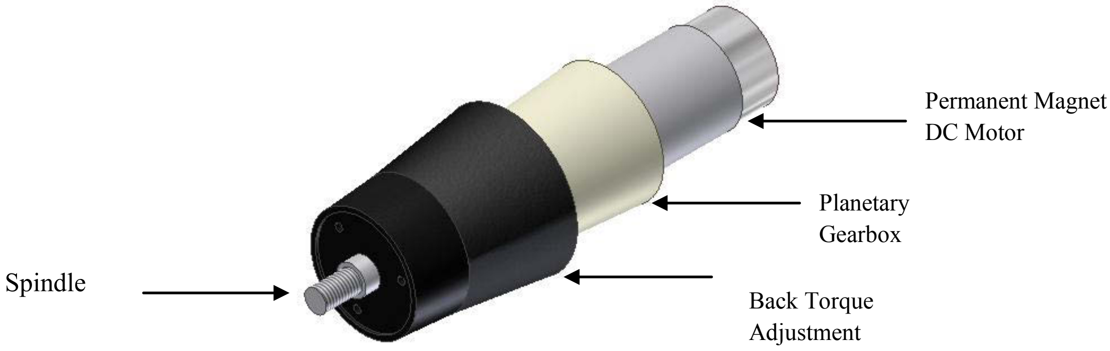


Figure 5.26: MRM Drilling Module Internal Mechanism

The HTM for the kinematic description of this module is given by equation 5.26. Refer to Appendix B.8 for calculations and illustrative diagrams.

$$^{i+1}_{\;\;i}M_{Drill\ Head} = \begin{bmatrix} 1 & 0 & 0 & -75 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -81.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.26}$$

Turning Head

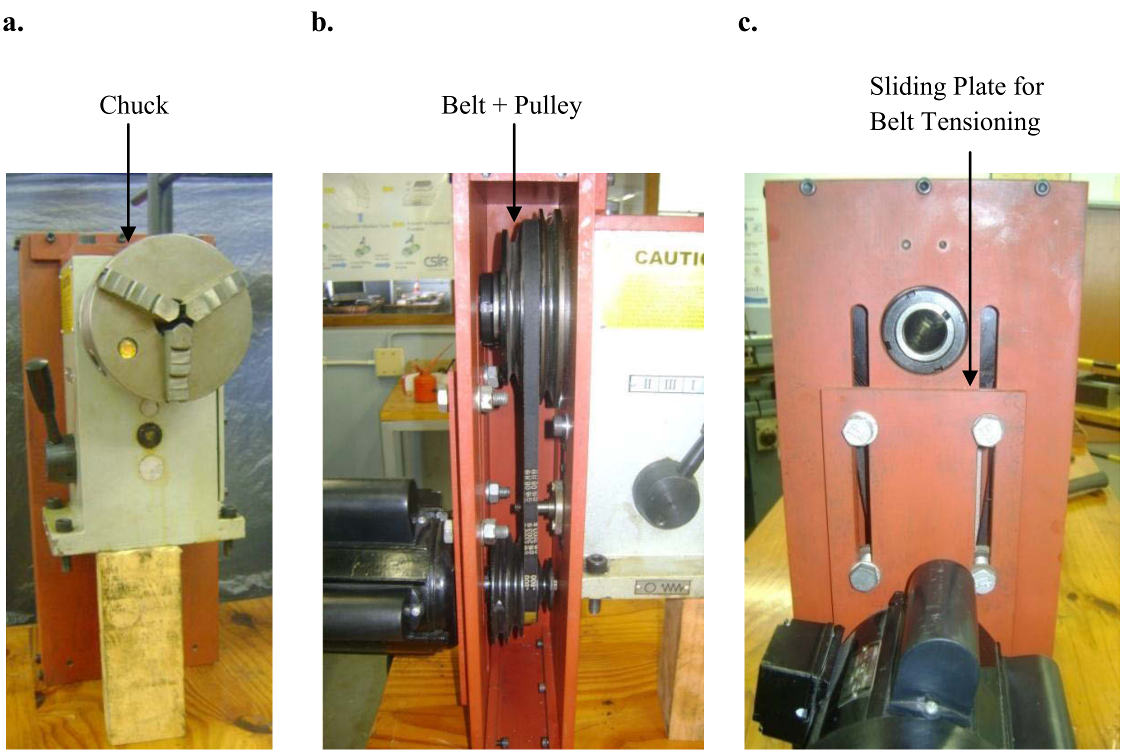


Figure 5.27: MRM Turning Module

a. Turning Module – Displaying chuck
b. Turning Module – Displaying belt drive mechanism
c. Turning Module – Displaying belt tensioning mechanism

The MRM module illustrated in Figure 5.27 is the cutting head in the turning configuration. The modular cutting head consists of a head stock driven by a single phase 220 volt, 0.55kW AC induction motor. The motor drives the spindle/chuck mechanism via a vee-belt drive system as illustrated in Figure 5.27.b. The motor provides a maximum output speed of 1400 rev/min which is manipulated by the belt drive mechanism to provide three speed settings. The speed and torque characteristics of this module are summarized in Table 5.13. The belt position is adjusted by the manipulation of a slide tensioning mechanism illustrated in Figure 5.27.c. The slide tensioning mechanism consists of four bolts that when loosened permit the motor mounting plate to slide allowing the belt to be tensioned or slackened. The headstock mechanism consists of a 3-Jaw chuck, with a maximum diametric capacity of 120 mm. Table 5.14 summarizes the specifications of this module.

Table 5.13: Actuation Characteristics of Turning Module

Motor Power (W)	Motor Speed (rev/min)	Motor Torque (N.m)	Reduction Ratio	Spindle Speed (rev/min)	Spindle Torque (N.m)
550	1400	3.75	30:133	315.79	16.63
550	1400	3.75	50:111	630.63	8.33
550	1400	3.75	67:89	1053.93	4.98

Table 5.14: Specifications of the Turning Module

Module Data	Tilt Table Module
Module Code (TH = Turning Head)	MRM-TH01-120-T0-T4
Swing Over Bed	420 mm diameter
Spindle Hole	24 mm
Chuck Capacity	120 mm
Static Interface	Type Four
Power	0.55 kW
Maximum Actuation Speed	1054 rev/min
Maximum Actuation Torque	16.63 N.m

The HTM for the kinematic description of this module is given by equation 5.27. Refer to Appendix B.9 for calculations and illustrative diagrams.

$$ {}^{i+1}_{i}M_{Turning\ \ Head} = \begin{bmatrix} 1 & 0 & 0 & -192.5 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -212.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.27} $$

5.7 MRM Accessory Modules

Manufactured Accessory Modules

Two accessory modules were created for the MRM platform. The first module is the modular work table illustrated in Figure 5.28.a. The work table was constructed completely out of aluminium to create a light weight module that is comfortably moved by the drive motors of other modules.

Figure 5.28: Manufactured Accessory Modules

a. Modular Worktable
b. Modular Range Extension Arm

The work table was designed to be modular to enable it to be transferred between other automated modules. The work table can be transferred between the work table slide module, the tilt table module and the rotary table module. The second advantage of a modular work table is that it may be interchanged with other work tables. Manufacturers may therefore implement customized worktables that contain features and fixturing devices that are optimized in their functionality as compared to generic work clamps. This possesses the potential to shorten the work setup time on a machine. Table 5.15 summarizes the specifications of this module.

Table 5.15: Specifications of the Work Table Module

Module Data	Tilt Table Module
Module Code (WT = Work Table)	MRM-WT01-160-T0-T3
Dimensions	160 mm x 160 mm (Table Area)
Static Interface	Type Three

The kinematic description of this module is given by equation 5.28. Refer to Appendix B.10 for calculations and illustrative diagrams.

$$ {}_{i}^{i+1}M_{Work\ Table} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -24.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.28} $$

The second accessory module that was created was the range extension arm illustrated in Figure 5.28.b. The arm was created for incorporation into the drilling configuration, partially to compensate for the length the base module (discussed later) and increases the extent of movement of the drilling head by 350 mm. Modular extensions to a machines range should be used with caution as the added physical length amplifies torques within the machine structure. Increased torques can lead to deflections in the machine structure, thereby increasing the first and second order errors in the geometric positioning of the tool. Table 5.16 summarizes the specifications of this module. The kinematic description of this module is given by equation 5.29. Refer to Appendix B.11 for calculations and illustrative diagrams.

Table 5.16: Specifications for Modular Range Extension Arm

Module Data	Tilt Table Module
Module Code (REA=Range Ext Arm)	MRM-REA-370-T0-T2A
Dimensions	370 mm extension
Static Interface	Type Two A

$$ {}^{i+1}_{i}M_{Extension\ \ Arm} = \begin{bmatrix} 1 & 0 & 0 & -370 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.29} $$

COTS Accessory Modules

a.

b.

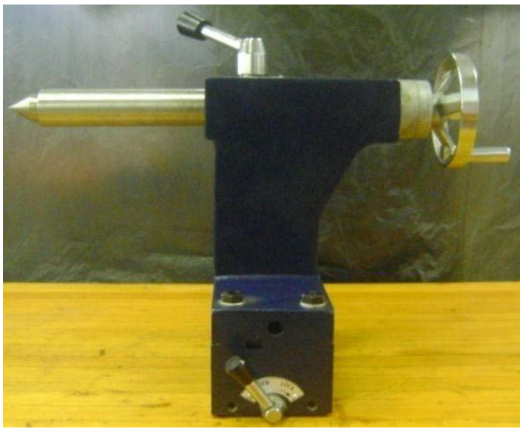


Figure 5.29: COTS Accessory Modules

a. A Modular Steady Rest
b. A Modular Tailstock

Two COTS accessories were incorporated into MRM platforms. The first module is the Steady Rest depicted in Figure 5.29.a. The second COTS module that was incorporated into the MRM is the Tailstock illustrated in Figure 5.29.b. These accessories, which may be considered as commercially available modules, were used in the turning configuration for the support of long work pieces during machining. The modules aid in minimizing the eccentricity of rotating shafts/ billets that would otherwise result in tool breakage or geometric errors on the machined product. The incorporation of COTS hardware into the MRM platform highlights the potential for the extension of the accessory category in the MRM library.

To facilitate the integration of COTS accessories due consideration must be undertaken to ensure that interfacing elements comply with current standards in the machine building industry. The modular Steady Rest and Tailstock both interface with the MRM base module which possesses a standardized „dove tail" slide on which both accessory modules connect.

5.8 Mechanical Assembly and Reconfiguration

5.8.1 Assembling a Kinematically Viable Machine Tool (An Example)

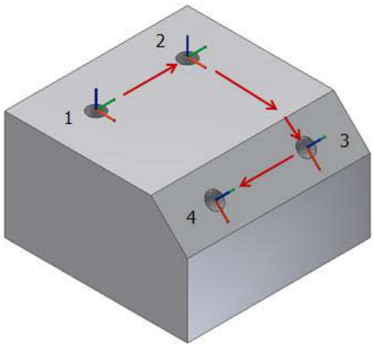


Figure 5.30: An Example Part

The methodology employed in the creation of kinematically viable machine tools was discussed in Section 3.4.2. The first stage in the methodology is to obtain a task matrix from mechanical drawings of the part/parts the machine will be required to produce. The task matrix is obtained by placing reference frames along key points of the tools required trajectory. The first reference frame is placed at the start of the tools trajectory as illustrated in the example of Figure 5.30. The task matrix for this example is given by equations 5.31 (HTM used directly).

$$ {}^{1}_{4}T = {}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & y_1 \\ 0 & 0 & 1 & z_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\beta & 0 & s\beta & x_3 c\beta + x_2 \\ 0 & 1 & 0 & 0 \\ -s\beta & 0 & c\beta & -x_3 s\beta + z_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & y_2 \\ 0 & 0 & 1 & z_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5.30) $$

$$ {}^{1}_{4}T = \begin{bmatrix} c\beta & 0 & s\beta & z_3 s\beta + x_3 c\beta + x_2 \\ 0 & 1 & 0 & y_2 + y_1 \\ -s\beta & 0 & c\beta & z_3 c\beta - x_3 s\beta + z_2 + z_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5.31) $$

The symbols x, y, z represent the respective translations with regard to the various local reference frames and β represents a rotation about a local y axis. The z symbol appears in the homogenous transformation matrices, representing the motion of a drill in and out of the respective holes (not indicated on diagram). Once a task matrix has been obtained, essential motions are identified; these essential motions are represented in a function structure graph as illustrated in Figure 5.31. The function structure graph provides a template for the allocation of modules to a machine tool. This structure usually consists of two branches stemming from the machine base; these branches represent the allocation of DOF to the cutting tool and the work clamping/support system.

The methodology outlined above yielded the MRM configuration illustrated in Figure 5.32. The machine consisted of the base module forming the X-axis, the work table slide module forming the Y-axis, the column forming the Z-axis and the tilt table module forming the B-axis. The kinematic description of this configuration is achieved by mutiplying the HTM‟s of individual modules, from tool holding module to work holding module. The HTM for this MRM configuration is given by equation 5.32.

$$ {}^{1}_{4}T = \begin{bmatrix} c\beta & 0 & s\beta & z_3 s\beta + x_3 c\beta + x_2 \\ 0 & 1 & 0 & y_2 + y_1 \\ -s\beta & 0 & c\beta & z_3 c\beta - x_3 s\beta + z_2 + z_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

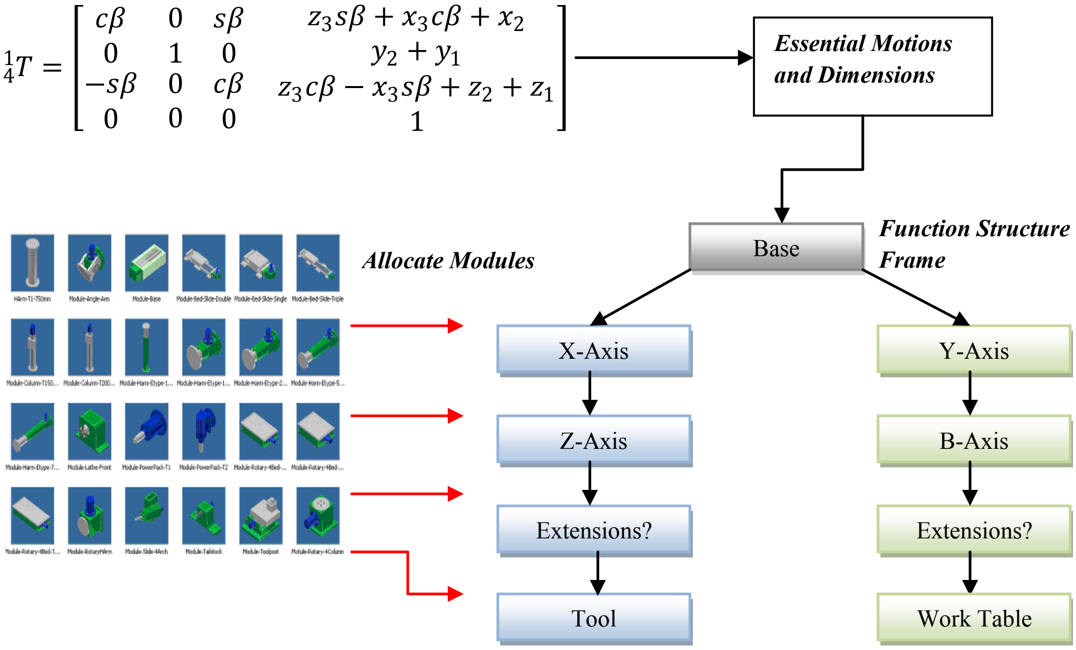


Figure 5.31: Identification of Necessary Motions and Allocation of Modules to Machine Tool

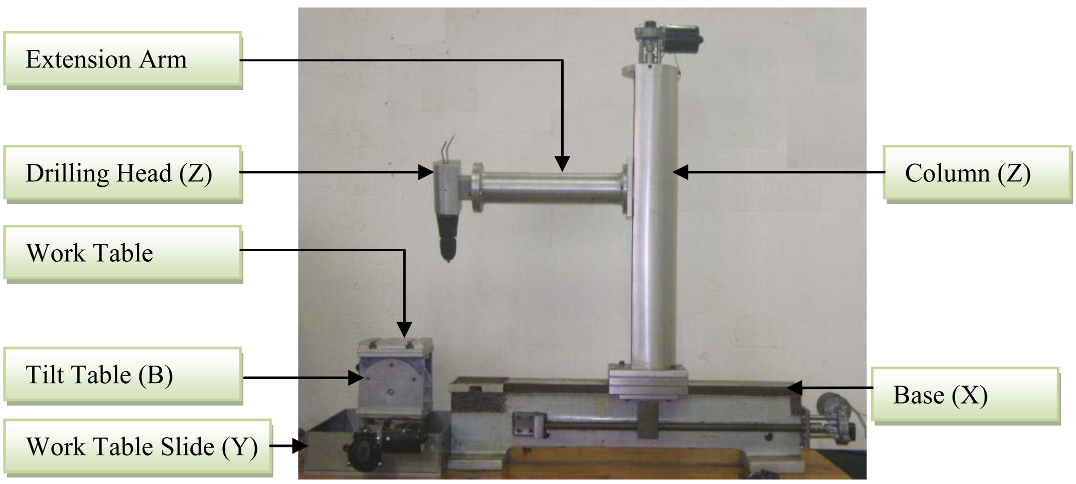


Figure 5.32: A Kinematically Viable Machine Tool for the Production of the Example Part

A comparison between the task matrix (eqation 5.31) and the machine transformation matrix (equation 5.32) shows a driect match in the rotational component of the HTM. A comparison between the translation components does not yield a direct match. However the variables x, y and z and β are present in corresponding terms indicating that the machine is kinematically viable in terms of the types of motions it is able to provide to the cutting head.

$$ {}^{Worktable}_{Drill}T = \begin{bmatrix} c\beta & 0 & s\beta & -344.5c\beta - 27.5s\beta + zs\beta + xc\beta \\ 0 & 1 & 0 & 2.5 + y \\ -s\beta & 0 & c\beta & 344.5s\beta - 119.5 - 27.5c\beta + zc\beta - xs\beta \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5.32) $$

It should be noted that this method does not yield unique MRM configurations. Depending on the set up of local reference frames when generating a task matrix, different MRM configurations may be generated that are also kinematically viable. An example of this is the MRM configuration illustrated in Figure 5.33, which replaces the tilt table modue with the cutting head rotary module to enable drilling on the inclinded surface of the example part. The HTM for this alternate MRM configuration is:

$$ {}^{Worktable}_{Drill}T = \begin{bmatrix} 1 & 0 & 0 & -482.5 + x \\ 0 & c\gamma & -s\gamma & 2.5 + 81.5s\gamma + y \\ 0 & s\gamma & c\gamma & 79.5 - 81.5c\gamma + z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.33} $$

When multiple kineamtically viable configurations are possible, the configuration that provides the most appropriate mechanical properties, axis ranges, speeds and torques is selected.

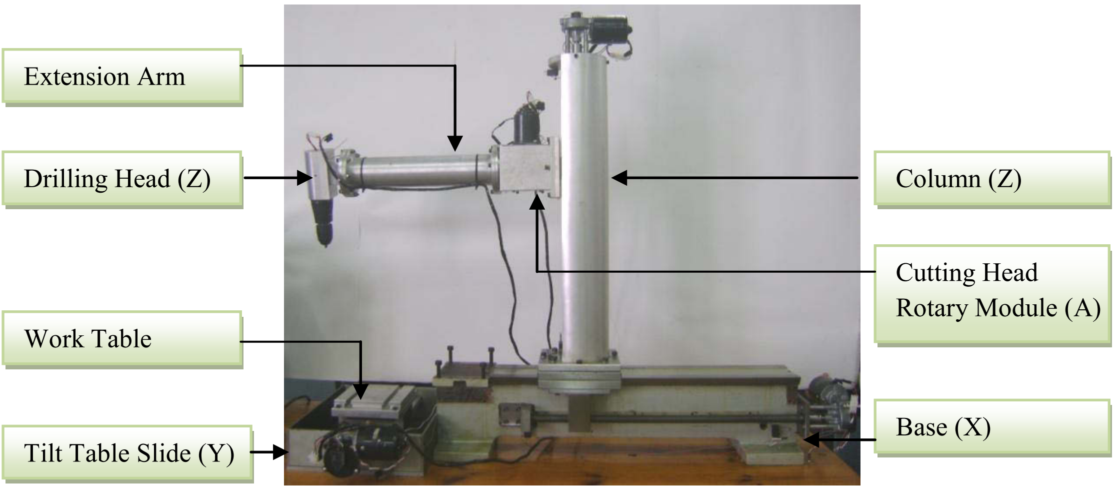


Figure 5.33: A Second Kinematically Viable Machine Tool for the Production of the Example Part

5.8.2 Machine Reconfiguration

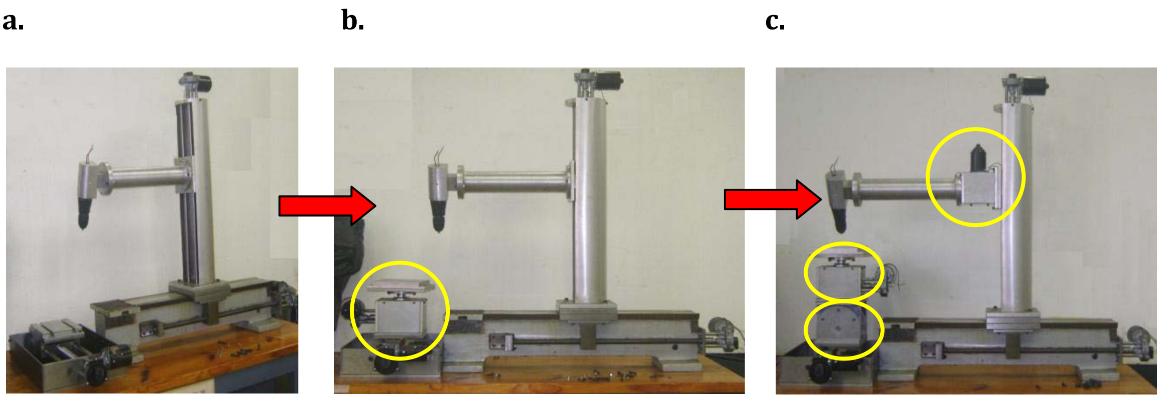


Figure 5.34: Reconfiguration of Machining DOF by Addition of Modules

a. Three DOF configuration (X,Y and Z axes)
b. Four DOF configuration (X,Y, Z and C axes)
c. Six DOF configuration (X,Y,Z, A, B and C axes)

MRM platforms possess the ability to provide a change in processing operations and DOF by the addition or removal of modules from the machine base. The ability to vary a machine"s DOF implies that a manufacturing enterprise may begin operation with machines possessing a minimum level of functionality. As the enterprise becomes more profitable and the product portfolio evolves, the machines in the system may be enhanced by the integration of additional DOF into a base platform. This capability is illustrated in Figure 5.34, where a three DOF machine is upgraded to a four and ultimately a six DOF system (additional modules highlighted in yellow circles).

In a manufacturing operation a change of parts/ part families may occur. Depending on the geometric features of the new part family it may be necessary that different processing operations may be required while previous processes capabilities of the system become irrelevant. In this instance the cutting head of the MRM may be changed to enable a new process, as illustrated in the concept of Figure 4.4. If the kinematic structure of the machine tool does not support a change in cutting heads the MRM structure may be decomposed into its modular elements. The elements may then be used in the construction of new types of machinery. This more extensive form of reconfiguration is illustrated in Figure 5.35 where the drilling machine structure is decomposed and a turning structure is assembled using modules from the decomposed drill and other modules from the MRM library.

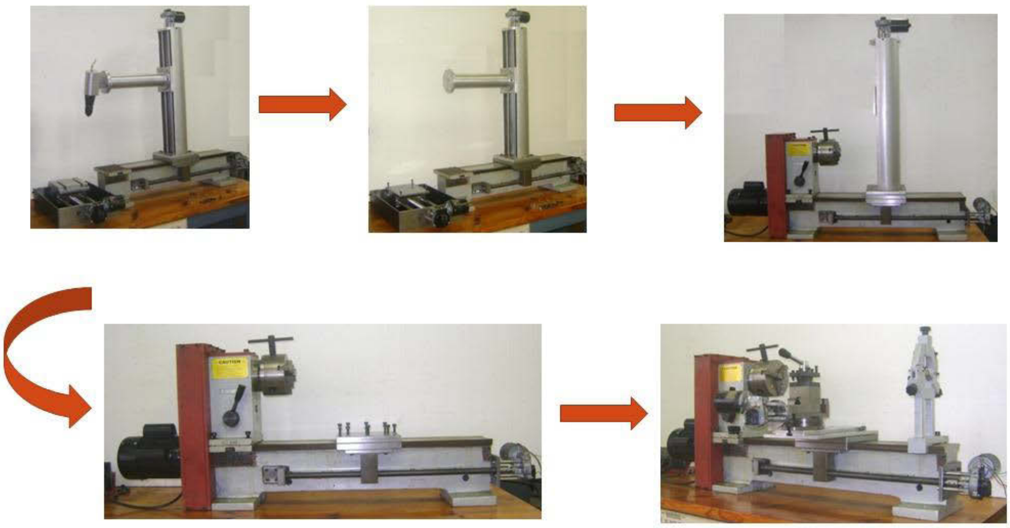


Figure 5.35: Decomposition of Drilling Structure and Assembly of Turning Structure

5.8.3 Module Combinations

MRM modules may be combined in multiple configurations to yield different types of machinery with varying kinematic capabilities. For a specific processing function, the number of unique kinematic combinations, achievable is calculated by equation 5.34 where the number „one" in the formula represents the basic platform; n represents the total number of enhancement modules that may be added to the platform and r represents the number of enhancement modules selected at a time.

$$N = 1 + \sum_{r=1}^{n} \frac{n!}{r!\,(n-r)!} \tag{5.34}$$

The basic configuration of the MRM drilling platform consisted of X, Y and Z axes. This platform could be enhanced with three rotary axes to increase its DOF. Note that the range extension arm was not considered as an enhancement as it was essential to all drilling configurations. The total number of unique kinematic configurations for the drilling process is calculated as follows:

$$N = 1 + \frac{3!}{1!\,(3-1)!} + \frac{3!}{2!\,(3-2)!} + \frac{3!}{3!\,(3-3)!} = 1 + 3 + 3 + 1 = 8$$

The MRM drilling platform possessed eight unique configurations (1 x 3DOF, 3 x 4 DOF, 3 x 5 DOF and 1 x 6 DOF). The turning platform, under the current library of modules was only enabled to display one configuration. The current library of eleven modules was therefore able to yield nine kinematically and functionally different machine configurations. The details of these nine configurations are given in Appendix D.

5.9 Cutting Conditions

5.9.1 Cutting Conditions in Turning

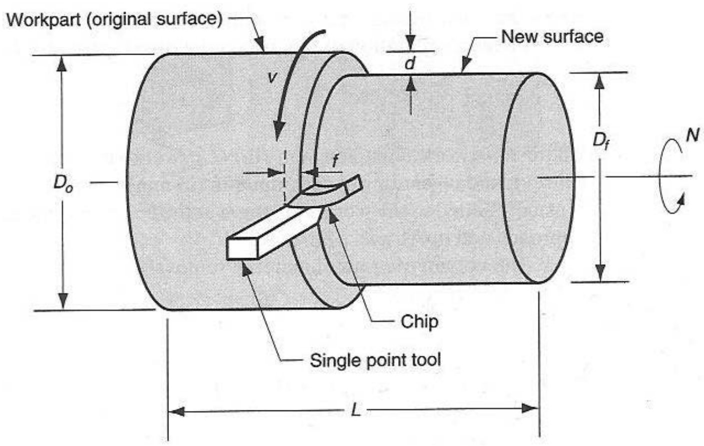


Figure 5.36: A Typical Turning Operation [61]

In machining operations NC programmers are required to select cutting conditions when developing part programs. The common conditions that an operator would be required to select are the depth of cut d (mm), the linear feed rate of the tool f_r (mm/min) and the rotational speed of the machine spindle N (rev/min). The direction of the tool feed and the depth of cut for a typical turning operation are illustrated in Figure 5.36. The appropriate selection of cutting conditions is necessary to optimize the time required for machining while maintaining the surface integrity and geometric tolerances of machined parts. For a turning operation, the time T_m (min) required for a linear cut of length L (mm) between two points on a cylindrical part is determined by equation 5.35. The total time required for a turning operation is the summation of the times required for individual linear cuts.

$$T_m = \frac{L}{f_r} \tag{5.35}$$

The material removal rate R_{MR} (mm^3/min) for a turning operation is calculated by equation 5.36, where V is the tangential velocity (m/s) of the surface being machined (original surface). The tangential velocity of the original surface is calculated by equation 5.37 where D_o is the diameter (m) of this surface as illustrated in Figure 5.36.

$$R_{MR} = V.f.d \tag{5.36}$$

$$V = \pi.N.D_o \tag{5.37}$$

5.9.2 Cutting Conditions in Drilling

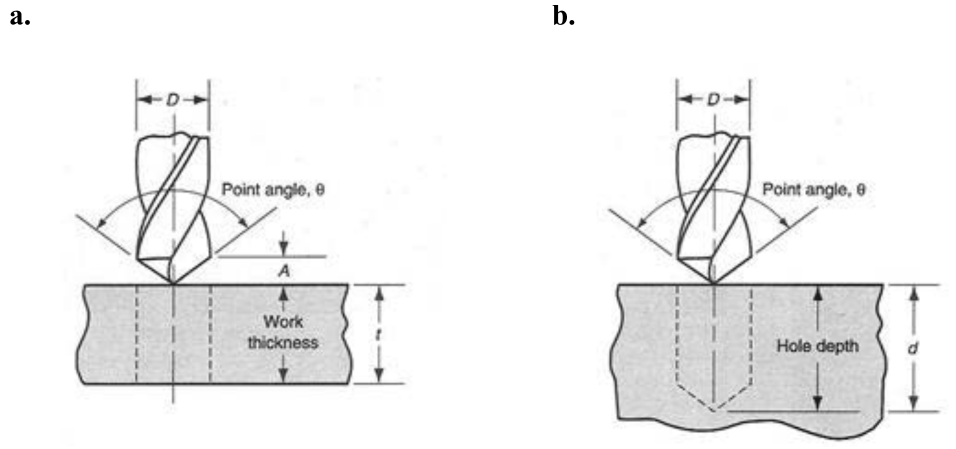


Figure 5.37: Typical Drilling Operations [61]

a. Drilling of a through hole
b. Drilling of a blind hole

In drilling operations the depth of cut d, coincides with the linear tool feed direction. The depth of cut, tool feed rate and spindle speed are specified in NC programs as in turning operations. Drilling operations may be performed to achieve either through holes or blind holes as illustrated in Figure 5.37. Based on the programmed feed rate f_r (mm/min) and the thickness of the work material t (mm), the time required to machine a through hole is calculated by equation 5.38.

$$T_m = \frac{t + A}{f_r} \tag{5.38}$$

The approach allowance A (mm), accounts for the additional length of the drill before it terminates at a point. The approach allowance is calculated by equation 5.39, where D is the drill diameter (mm) and θ is the drill point angle in degrees.

$$A = 0.5\, D\, tan\left(90 - \frac{\theta}{2}\right) \tag{5.39}$$

The time required for the drilling of a blind hole is calculated by equation 5.40, and the material removal rate R_{MR} (mm^3 /min) for both through and blind hole applications is calculated by equation 5.41.

$$T_m = \frac{d}{f_r} \tag{5.40}$$

$$R_{MR} = \frac{\pi D^2 f_r}{4} \tag{5.41}$$

5.10 Forces and Torques in Machining

5.10.1 Forces in Turning

Forces in machining are largely determined by empirical relationships that are based on experiments. In turning operations the resultant force during the cutting process can be resolved into three elementary components:

- P_x : the force acting against the direction of the tool feed
- P_y: the force acting perpendicular to the tool feed in the horizontal plane
- $P_{z:}$: the force in the vertical plane simultaneously acting perpendicular to P_x and P_z

Basu and Pal [62] present the empirical relationship of equation 5.42 for determining P_z; where C_p is a coefficient based on the work material, d is the depth of cut (mm), S is the tool feed (mm/rev) and K is a coefficient based on the tool geometry, coolant and work material. The coefficients x and y are based on the type of material being cut.

$$P_z = C_p . d^x . S^y . K \tag{5.42}$$

The coefficients are determined from tables that have been compiled from extensive experimental testing. The forces P_y and P_x are also empirically related to P_z depending on the type of material being machined and other physical parameters of the cutting process:

$$\frac{P_x}{P_z} \approx 0.3 \; to \; 0.2 \qquad \frac{P_y}{P_z} \approx 0.2 \; to \; 0.1 \tag{5.43}$$

5.10.2 Forces and Torques in Drilling

Forces in drilling are determined empirically as in turning operations. Basu and Pal [62] present the empirical relationship of equation 5.44, for determining the thrust force on a drilling tool; where P is the thrust force (kg), K is a constant that depends on the work material and geometric parameters of a drill, S is the tool feed (mm/rev) and m is a constant depending on the material being machined. The constants are determined from tables developed from experiments.

$$P = K . D . S^m \tag{5.44}$$

The turning moment on a drill is given by equation 5.45; where M_t is the turning moment (kg.mm), and K_t, x and y are empirical constants.

$$M_t = K_t . D^x S^y \tag{5.45}$$

Tables for determining the cutting coefficients and constants are widely available for steel and other common metals. During this research such tables were not located for plastics and waxes. Drilling configurations were therefore designed around a drilling thrust force of 50 N, while turning configurations were designed on $P_x = P_y = P_z = 50$ N.

5.10.3 Force and Torque Propagation

The knowledge of the force and torque exerted on a cutting tool may be used to determine the force and torque propagation throughout a machining structure. The link-wise torque and force propagation is given by:

$$^{i+1}f_{i+1} = {}^{i+1}_{i}R\ {}^{i}f_{i} \tag{5.46}$$

$$^{i+1}n_{i+1} = {}^{i+1}_{i}R\ {}^{i}n_{i} + {}^{i+1}_{i}P \times {}^{i+1}f_{i+1} \tag{5.47}$$

Where f_{i+1} and n_{i+1} are the force and torque exerted on link i+1 by link i. The position (*P*) and rotation (*R*) matrices are derived directly from the HTM"s of individual modules. For an expected cutting force the joint actuation torques and forces are obtainable. The actuation torque required by a rotary axis is determined by equation 5.48 while the actuation force for a linear axis is calculated by equation 5.49, where ${}^{i}\hat{Z}_{i}$ is the joint axis unit vector.

$$\tau_i = {}^{i}n_i^T\ {}^{i}\hat{Z}_i \tag{5.48}$$

$$\tau_i = {}^{i}f_i^T\ {}^{i}\hat{Z}_i \tag{5.49}$$

5.11 Mechanical Error Modelling

5.11.1. First Order Errors

The ability of a MRM to accurately position a cutting tool relative to a work piece is an essential criterion in evaluating the feasibility of implementing this technology. Tool positioning errors are comprised of first and second order components [63]. First order errors result in dimensional inaccuracies in machined components. These errors are attributed to three factors:

(i) Geometric positioning errors between adjacent interfaces.
(ii) Static errors: deflections due to forces on modules, excluding impulse forces.
(iii) Thermal expansion/contraction errors (not considered in this research).
(iv) Mechanical backlash between mating components (discussed in Section 8.8).

Geometric Positioning/ Assembly Errors

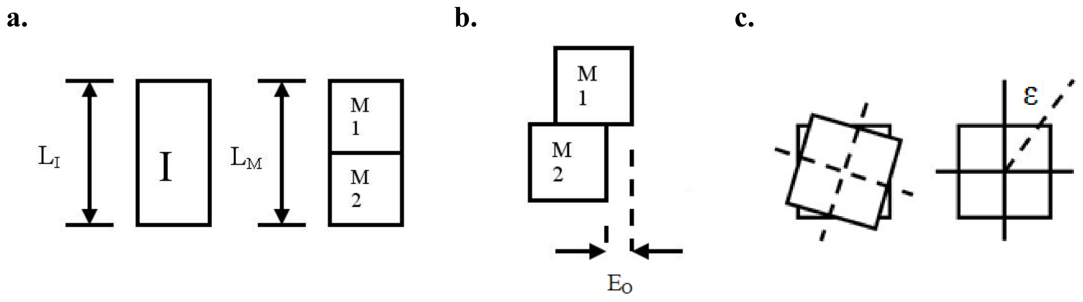


Figure 5.38: MRM Assembly Errors for Interfacing Module Pairs

a. Concatenation error
b. Edge offset error
c. Skewness error

Geometric positioning errors are introduced into an MRM structure during module assembly/ reconfiguration. Although the geometric errors may be very small for properly designed interfaces and connectors with reasonable design tolerances, the accumulation of these minute errors across a significant number of connected modules may be noteworthy.

The first step in the modelling of the accumulated assembly error in an MRM is the identification of the three types of assembly errors illustrated in Figure 5.38. The first error, called the concatenation error E_C is defined by equation 5.50, where L_I is the length of an integrated structure, and L_M is the length of a similar structure having been created out of two modules instead of one integral piece.

$$E_C = L_M - L_I \tag{5.50}$$

The second type of error is an edge offset errors $E_{O\,1}$ or $E_{O\,2}$ if more than one edge is offset. The third error called "Skewness" defined by the angle ε, is a measure of the rotation of module two about the geometric centre of module interfaces one and two.

The second step in the modelling of the accumulated assembly error is the relation of module-wise assembly errors to the reference frames placed on the interfaces of adjacent modules. According to the kinematic modelling method established in Section 5.5.2 the reference frames placed on the mating interfaces should perfectly coincide. The errors E_C, E_{O1}, E_{O2} and ε represent the error in aligning these frames. The error may be kinematically represented by the HTM of equation 5.51 which implements the X-Y-Z Euler angle convention. The mapping of errors E_C, E_{O1}, E_{O2} and ε to Euler parameters x, y, z and α, β, γ is dependent on the orientation of reference frame i+1. Errors must be methodically mapped to corresponding axes on frame i+1 for the successful pairing of errors with Euler parameters.

$$E_{i+1\leftarrow i} = \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma & x \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma & y \\ -s\beta & c\beta s\gamma & c\beta c\gamma & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.51}$$

The total system transformation matrix, including assembly errors is calculated by equation 5.9. Accounting for assembly errors is essential during machine calibration, as it is possible for these errors to be compensated for by the machine controller as opposed to the reassembly of the machine tool. The total system transformation matrix, including assembly errors is given by equation 5.52.

$$^{Work}_{Tool}TE = M_1 E_{1\leftarrow 2} M_2 E_{2\leftarrow 3} \dots M_{n-1} E_{n-1\leftarrow n} \tag{5.52}$$

Static Deflections

Static deflections are caused by operational forces being transmitted throughout the machine structure. These errors contribute to the total first order error and result in geometric inaccuracies in machined parts. The geometric effect of static deflections can be mathematically accounted for in individual modules by altering the HTM that describes the spatial relationship, and orientation of the interface reference frames with regard to each other. Deflections may either cause or contribute to: (i) a linear offset in reference frames or (ii) a rotation of one reference frame relative to the other.

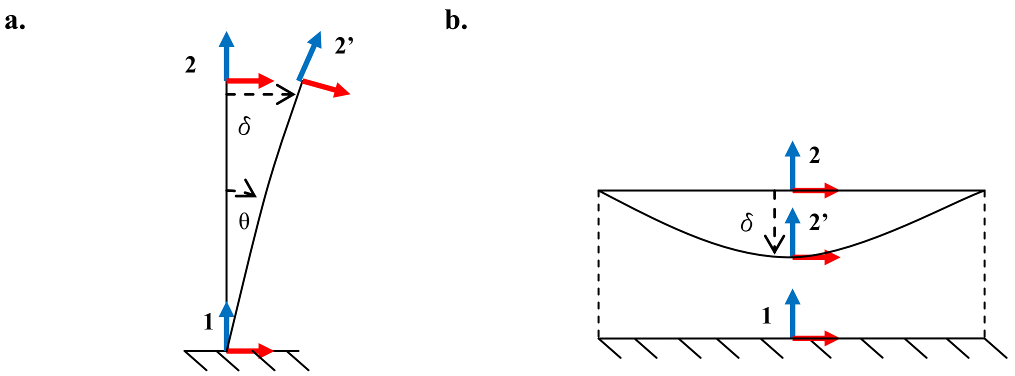


Figure 5.39: Effect of Static Deflections on Kinematic Models

a. A static deflection causing an offset and rotation of frame 2
b. A static deflection causing a deflection of frame 2

Figure 5.39 illustrates the effect of static deflections on the relative position and orientation of reference frames with regard to each other. Static deflections may be determined by established analytical methods or Finite Element Analysis. Once determined, the linear offsets and angles of rotations may be related to Euler parameters (*x, y, z*) and (*γ, β, α*). The new *x, y* and *z* Euler parameters will describe the origin of frame 2‟ with reference to frame 1; while the angles *γ, α* and *β* will describe the orientation of frame 2‟ relative to frame 1. These parameters are then substituted into equation 5.8 to obtain a new HTM for the module $M_n^{'}$. The total system transformation matrix, including assembly errors and static deflections is therefore given by:

$$ {}^{Work}_{Tool}TE_{total} = M_1^{'}E_{1\leftarrow 2}M_2^{'}E_{2\leftarrow 3} \dots M_{n-1}^{'}E_{n-1\leftarrow n} \tag{5.53}$$

The position error vector that characterises the entire first order error in a machine tool is calculated by equation 5.54. The position vector of the tool tip is with relation to the closest reference frame on an associated tool holding module:

$$ {}^{Work\ table}_{Tool}PE_{total} = {}^{Worktable}_{Tool}TE_{total}\begin{bmatrix} x_{tool\ tip} \\ y_{tool\ tip} \\ x_{tool\ tip} \end{bmatrix} - {}^{Worktable}_{Tool}T\begin{bmatrix} x_{tool\ tip} \\ y_{tool\ tip} \\ z_{tool\ tip} \end{bmatrix} \tag{5.54}$$

5.11.2 Second Order Errors

Second order errors are a result of vibrations induced by the impact of a cutting tool‟s teeth with the work surface, regenerative chatter and other vibrations within a machine. These errors are classified as dynamic - *E(t)* - and generally affect the surface integrity of a machined component, machine tool wear, and tool breakage. The magnitude of a second order error depends on module stiffness and damping properties, as well the mass distribution in the machine. These errors are specific to the physical attributes of individual mechanical assemblies, and are difficult to model in a generic manner [63].

5.12 Mechanical Analysis of Drilling Subassembly

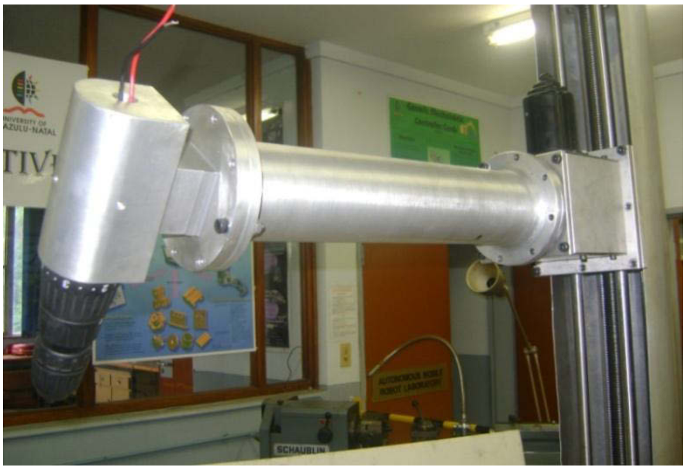


Figure 5.40: Drilling Arm and Column Assembly

MRM modules possess the ability to be assembled in multiple configurations and a total of nine unique configurations were achievable with the current library of modules. Loading calculations for individual modules are located in Appendix C.3 and C.4. Due to the extensive number of modular assembly configurations, only an analysis of the weakest configuration is presented in this section. The subassembly with the least rigidity consists of the drilling head, the range extension arm, the cutting head rotary module and the column module. This subassembly is illustrated in figure 5.40.

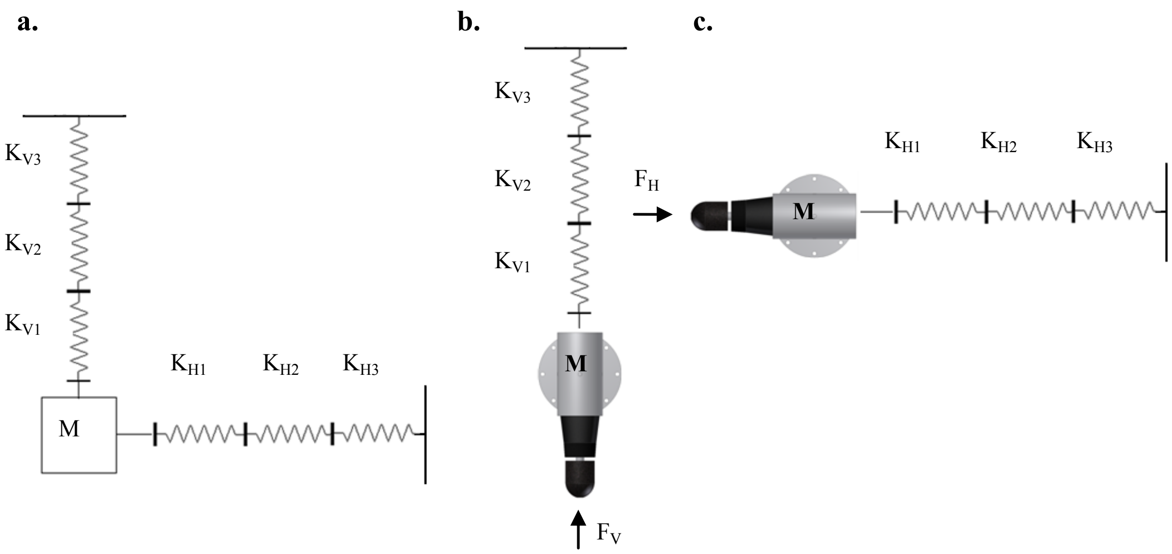


Figure 5.41: Drilling Arm and Column Assembly Represented as Springs in Series

a. The vertical and horizontal stiffness‟s of modules modelled as springs in series
b. The thrust force on the drill when the drilling head is vertically orientated
c. The thrust force on the drill when the drilling head is horizontally orientated

In order that a static and dynamic analysis could be performed on the system, the vertical and horizontal stiffness‟s of individual modules have been modelled as springs in series, as illustrated in Figure 5.41.a. For simplicity the vertical and horizontal subsystems have been decoupled. This simplification will provide a reasonable approximation of the mechanical vibration except at frequencies close to resonance in each mode. The analysis considers the effect of a harmonic thrust force on the drilling head when it is vertically orientated and then horizontally orientated. These scenarios are illustrated in Figures 5.41.b and 5.41.c respectively.

Table 5.17: Module Stiffness's (Refer to Appendix C.5)

	Range Extension Arm (1)	Cutting Head Rotary Module (2)	Column Module (3)
K_V (N.m^{-1})	1.592×10^6	95.908×10^6	1.949×10^6
K_H (N.m^{-1})	1.592×10^6	153.222×10^6	2.597×10^4

Table 5.17 contains the calculated stiffness of the related modules; these calculations are presented Appendix C.5. The stiffness of the column in particular, strictly corresponds to the column slide being in a position of 600 mm above its base. For springs in series the spring rates combine reciprocally; the total vertical and horizontal stiffness of the system are therefore:

$$K_{V\ total} = \left[\frac{1}{1.592\times10^6}+\frac{1}{95.908\times10^6}+\frac{1}{1.949\times10^6}\right]^{-1} = 8.683\times10^5\ N.m^{-1}$$

$$K_{H\ total} = \left[\frac{1}{1.592\times10^6}+\frac{1}{153.222\times10^6}+\frac{1}{2.594\times10^4}\right]^{-1} = 2.552\times10^4\ N.m^{-1}$$

Static Analysis

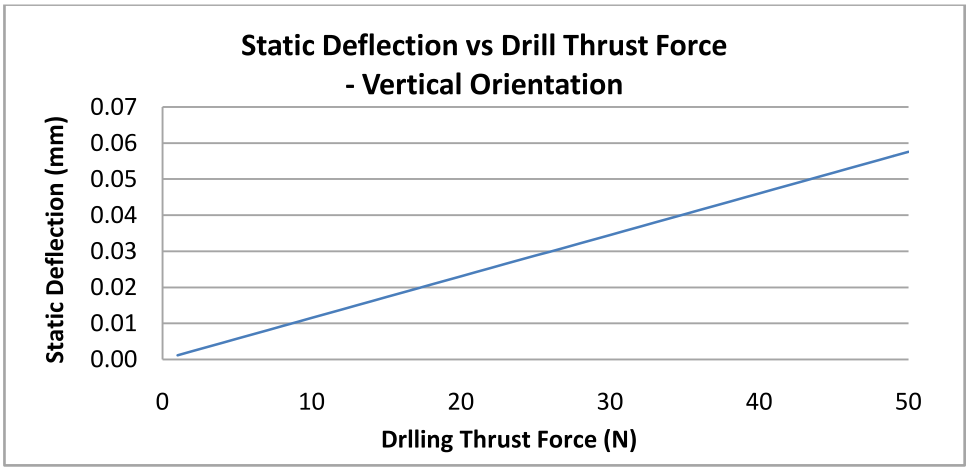


Figure 5.42: Graph of Static Deflection vs Drill Thrust Force for Vertical Drilling

Equation 5.55 presents Hooke‟s Law which relates the deflection of a spring to its stiffness and the force exerted on it. By manipulating Hooke‟s Law the deflection of the drilling head under the action of a static force may be obtained. The deflection of the drilling head is presented in Figures 5.42 and 5.43, for static vertical and horizontal forces.

$$\delta = \frac{F}{K} \tag{5.55}$$

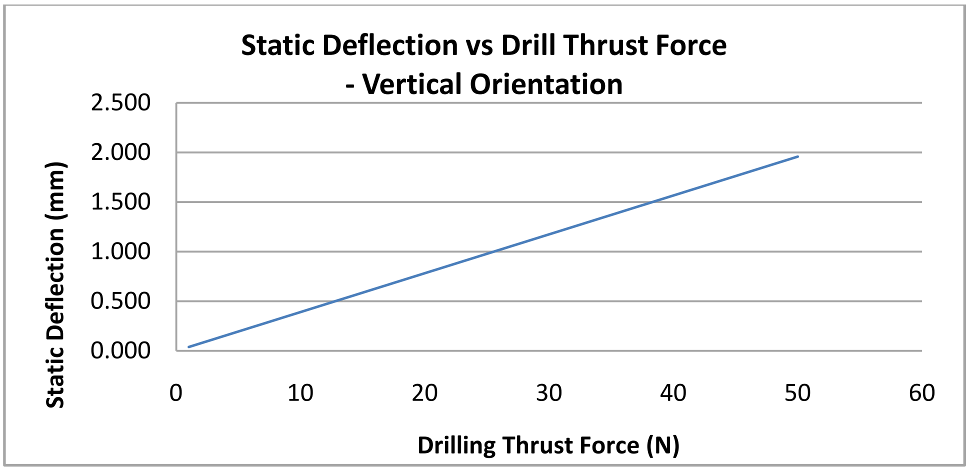


Figure 5.43: Graph of Static Deflection vs Drill Thrust Force for Horizontal Drilling

A vertical thrust force of 50 N leads to a total deflection of 0.058 mm in the vertical plane. The drilling subassembly displayed less rigidity in the horizontal plane and a total deflection of 1.959 mm is expected for a drill thrust force of 50 N. The static deflections due to the thrust force largely affect the accuracy of the depth of holes drilled by the MRM. The reduced rigidity is due to 15 mm sliver steel guide rods that have been used as supporting members in the MRM column module, as opposed a more rigid yet costly dove tail slide system.

Dynamic Analysis at Multiple Frequencies

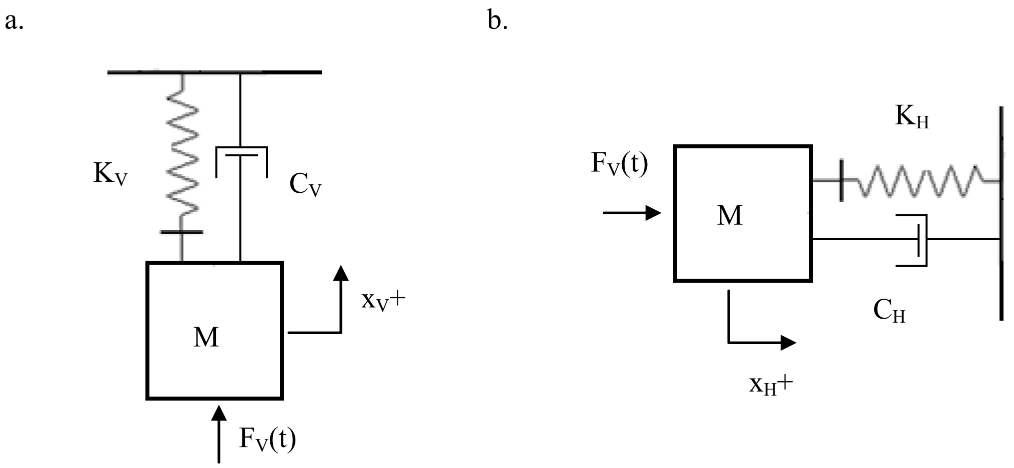


Figure 5.44: Spring-Mass-Damper Systems

a. Spring-Mass-Damper model of drilling assembly – vertical harmonic force
b. Spring-Mass-Damper model of drilling assembly – horizontal harmonic force

The performance of the drilling subassembly under dynamic loading conditions was investigated. The system was modelled as a Spring-Mass-Damper system, and separate investigations were conducted for vertical and horizontal harmonic loading; this is illustrated in Figures 5.44.a and 5.44.b respectively.

For a damped system under the action of a harmonic force, the motion is described by equation 5.56; where m is the mass of the drill module (kg), c is the damping coefficient (N.s/m), k is the stiffness of the system (N/m), F_0 is the magnitude of the harmonic force (N) and ω is the frequency of the harmonic force (rad/s).

$$m\ddot{x} + c\dot{x} + kx = F_0 cos\omega t \tag{5.56}$$

The complete solution to this differential equation for an underdamped system is given by equation 5.57, where X is the amplitude of the response (m), φ is the phase angle (deg), δ is the damping factor and ω_d is the frequency of damped vibrations (rad/s).

$$x(t) = X_0 e^{-\zeta\omega_n t} cos(\omega_d t - \phi_0) + Xcos(\omega t - \phi) \tag{5.57}$$

$$\omega_d = \sqrt{1-\zeta^2}\omega_n \tag{5.58}$$

$$\omega_n = \sqrt{\frac{k}{m}} \tag{5.59}$$

$$\zeta = \frac{C}{C_c} = \frac{C}{2\sqrt{km}} \tag{5.60}$$

$$r = \frac{\omega}{\omega_n} \tag{5.61}$$

The relative performance of a system under a dynamic load with regard to its static loading characteristics is most effectively analysed by obtaining a ratio of the amplitude of the dynamic response to the amplitude of the static response of the system; under the action of force F_0 at different frequencies. The amplitude ratio M is calculated by equation 5.62; where r is the frequency ratio.

$$M = \frac{X}{\delta_{st}} = \frac{1}{\left\{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta\frac{\omega}{\omega_n}\right]^2\right\}^{0.5}} = \frac{1}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}} \tag{5.62}$$

$$\delta_{st} = \frac{F_o}{k} \tag{5.63}$$

The phase angle between the response and the excitation is calculated by equation 5.64.

$$\phi = tan^{-1}\left\{\frac{2\zeta\frac{\omega}{\omega_n}}{1-\left(\frac{\omega}{\omega_n}\right)^2}\right\} = tan^{-1}\left(\frac{2\zeta r}{1-r^2}\right) \tag{5.64}$$

Table 5.18: Physical Characteristics of Drilling Assembly in Horizontal and Vertical Directions

	K (N/m)	C (N.s/m)	m (kg)	ω_n (rad/s)	ζ	ω_d (rad/s)
Vertical	8.683×10^5	5	2.1	643.02	0.0019	643.02
Horizontal	2.552×10^4	5	2.1	110.24	0.0108	110.23

Table 5.18 presents physical characteristics of the drilling subassembly, where the stiffness‟s correspond to the column slide being in a position of 600 mm above its base. Information on the damping characteristics of drill subassembly was not available. The damping coefficients of the system have therefore been set at the conservatively small but finite value of 5 $N.s.m^{-1}$ in both vertical and horizontal cases.

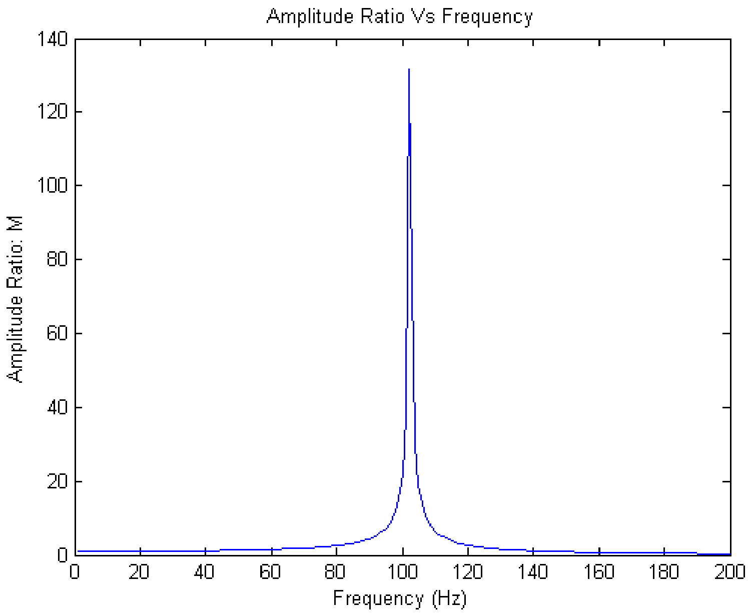


Figure 5.45: Graph of Amplitude Ratio vs Excitation Frequency – Vertical Excitation Force

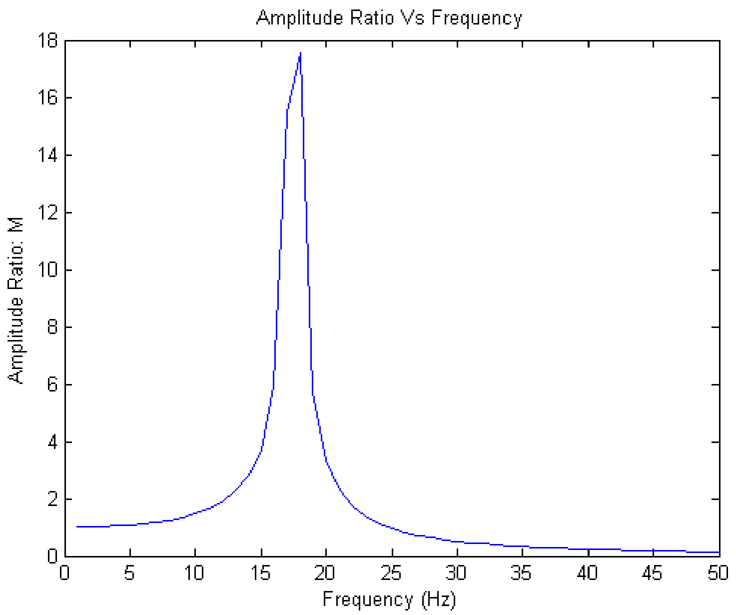


Figure 5.46: Graph of Amplitude Ratio vs Excitation Frequency – Horizontal Excitation Force

The physical characteristics of the system were used in conjunction with equation 5.62 to generate plots of the amplitude ratio at multiple frequencies, for both vertical and horizontal planes (see Figures 5.45 and 5.46). Equation 5.64 was used to generate plots of phase angle versus frequency for the subassembly (see Figures 5.47 and 5.48). The natural frequency of the drilling subassembly for a vertical excitation force is 102.23 Hz, while the natural frequency in the horizontal direction is 17.55 Hz. Excitation at the natural frequency is accompanied by a peak in amplitude ratio as seen in Figures 5.45 and 5.46. If the excitation were to occur twice per drill revolution, the respective resonant drilling speeds would be 3067 rev/min and 527 rev/min.

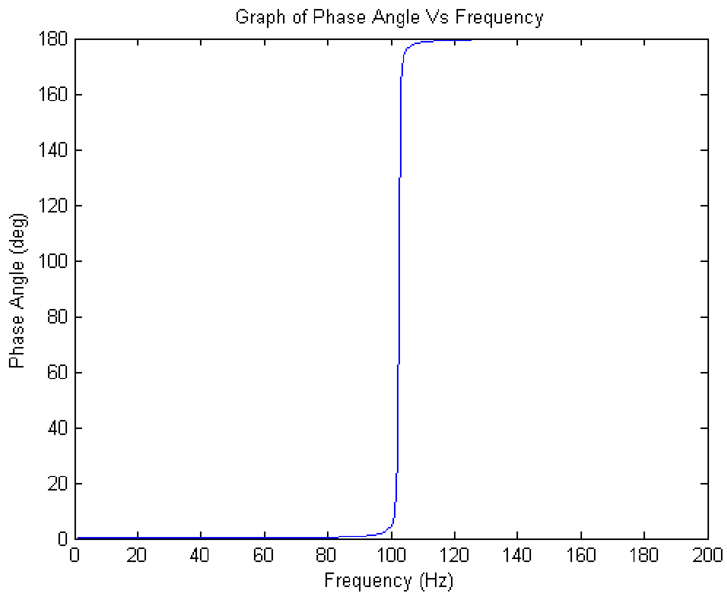


Figure 5.47: Graph of Phase Angle vs Excitation Frequency – Vertical Excitation Force

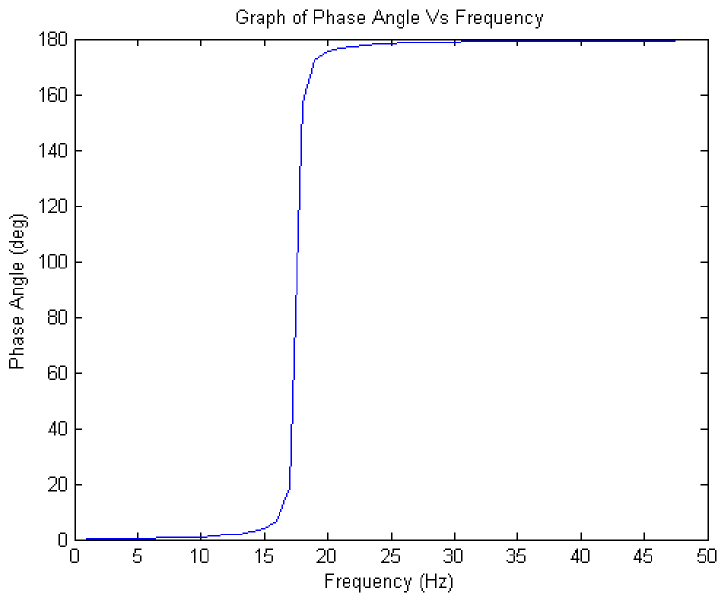


Figure 5.48: Graph of Phase Angle vs Excitation Frequency – Horizontal Excitation Force

Figures 5.47 and 5.48 present the phase angle of the system response at various excitation frequencies. In both vertical and horizontal cases the excitation and the system response are approximately in phase for frequency ratios less than one. For frequencies greater than the natural frequencies of the system the response leads the excitation by approximately 180°. These characteristics are due to the (approximated) small damping capacity of the system.

Simulation Performed at 20 Hz

A simulation was performed to investigate the performance of the drilling subassembly under the action of a 50 N force at 20 Hz. The solving of equation 5.57 for these conditions is presented in Appendix C.6. Table 5.19 presents the results of the solution.

Table 5.19: Vibration Characteristics of Drilling Assembly in Horizontal and Vertical Directions

	X_o (m)	φ_o (deg)	X (m)	φ (deg)	ω_n (rad/s)	ζ	ω (rad/s)
Vertical	8.360×10^{-5}	0.1141	5.987×10^{-5}	0.0442	643.02	0.0019	125.66
Horizontal	6.474×10^{-3}	175.29	6.473×10^{-3}	175.33	110.24	0.0108	125.66

Equation 5.57 was simulated for five seconds at a refresh rate of 5 ms; the results of the simulation are presented in Figures 5.49 and 5.50. The graphs display the displacement of the MRM cutting head with regard to time under the action of the excitation force. Theoretical displacements in excess of 10 mm were demonstrated for horizontal excitation (not practically verified). This is due to the excitation frequency being in close proximity to the natural frequency of the system. The dynamic deflections due to the harmonic excitation are expected to adversely affect the accuracy of the depth of holes drilled by the MRM.

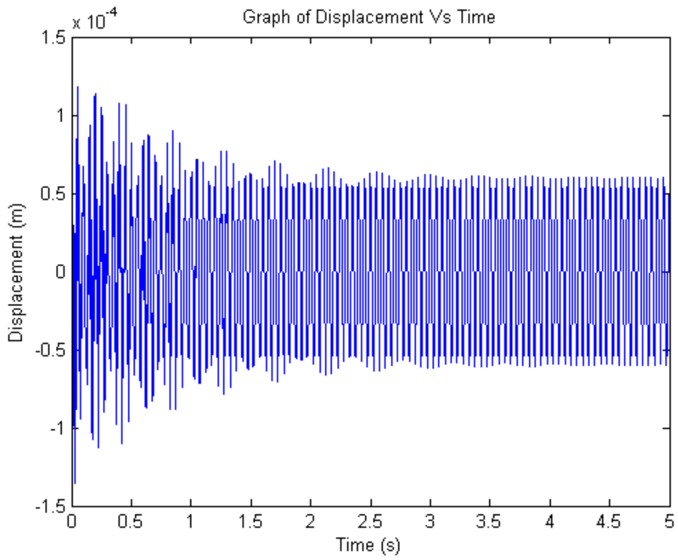


Figure 5.49: Graph of Displacement vs Time – Vertical Excitation Force (50 N)

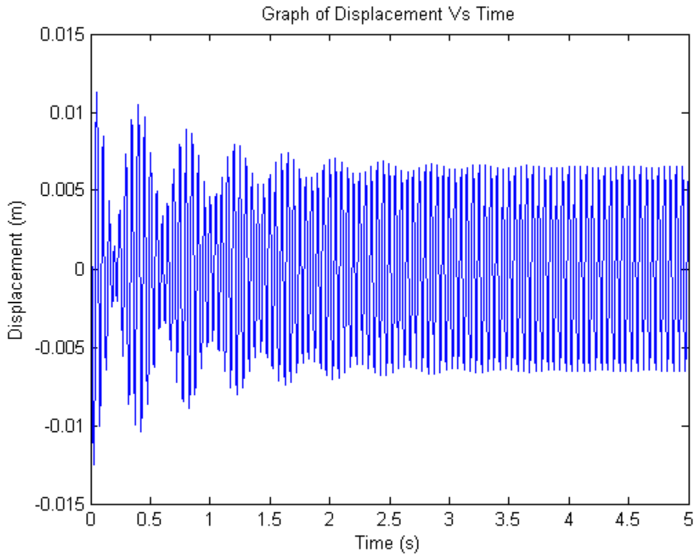


Figure 5.50: Graph of Displacement vs Time – Horizontal Excitation Force (50 N)

5.13. Chapter Summary

This chapter presented the mechanical systems of individual modules; including specifications on their mechanical performance, interconnectivity, speeds, torques and power. An example was presented on the assembly of a kinematically viable machine tool and illustrations were provided on the reconfigurability of the prototype system. The mathematical models governing cutting forces and other cutting conditions were presented in brief. An error modelling technique was also presented for MRMs which accounts for assembly errors and static deflections (first order errors). Finally an analysis of a drilling subassembly was presented. This analysis included a static and dynamic analysis of the systems performance in maintaining positional accuracy under the action of cutting forces.

6. MRM Electronic System

6.1 Electronic System: Design Considerations

The design of an electronic hardware system for the control of MRM modules required the application of the Mechatronic design approach. The focus of the Mechatronic design approach is subsystem design for seamless system integration and balance between the capabilities of the mechanical, electronic and software systems. The following characteristics were identified as essential in the electronic design to support system integration and the mechanical reconfigurability of MRMs:

- **Physical modularity:** the electronic hardware must be modular in parallel to the mechanical hardware to facilitate easy reconfiguration.
- **Scalability:** the electronic system must be scalable to provide an increase in digital processing capacity when mechanical modules are added to a machine.
- **Customization:** the electronic hardware on a platform must be customizable in terms of its ability to enable actuation in different MRM configurations. The number of digital controllers and power amplification units in the electronic system must be exactly matched to the number of actuators present on a platform at all times.
- **Integrability:** modular units of electronic hardware must display "plug-in" capabilities to facilitate quick integration into a platform.
- **Diagnosability:** the electronic control system must facilitate the integration of sensors into a platform and provide feedback to the machine operator.

6.2 MRM Electronic Control System

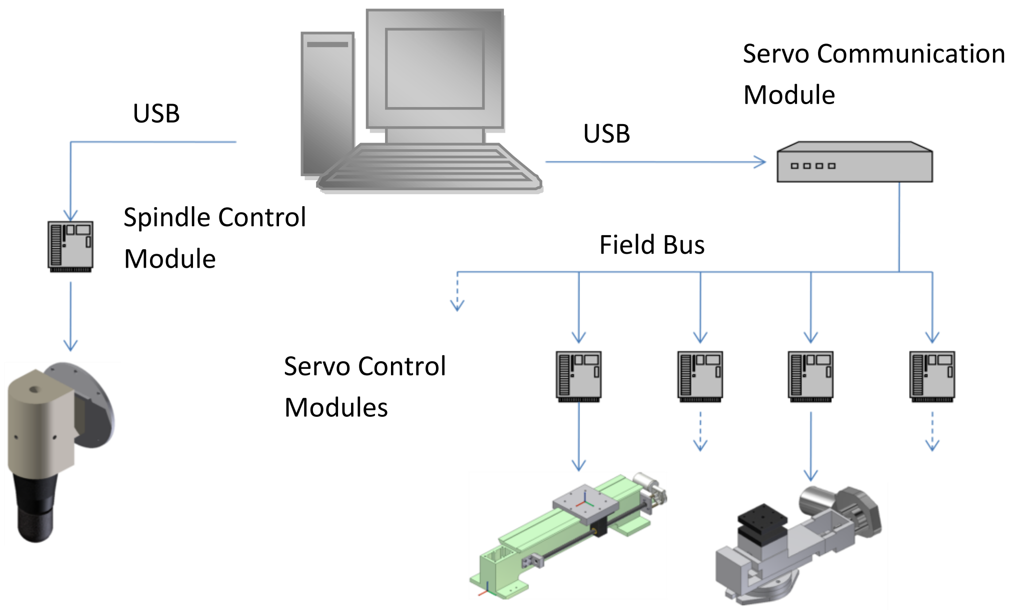


Figure 6.1: MRM Electronic Control System

The electronic control architecture illustrated in Figure 6.1 was selected for implementation in MRMs. At the head of the control system is a Personal Computer (PC). The advent of faster processors for PCs and a general reduction in their prices have increased the use of PC-based controllers in CNC machines. PC based controllers are generally flexible, open and can be easily integrated into multiple manufacturing configurations [47]. A PC was also selected for implementation due to already existing hardware and software support for Universal Serial Bus (USB) and Ethernet communication. Although Ethernet communication was not implemented in this design, it has been identified as an important supporting feature for MRM integration into factory wide networks.

The electronic hardware is divided into two subsystems that are controlled by the host PC; these are the spindle control system and the servo control system. The desktop PC communicates with both subsystems via USB. The USB 2.0 protocol was implemented due to existing software support, data transfer rates of up to 12 Mb/s and the possibility of port expansion [64]. Further advantages of implementing the USB 2.0 standard include its low cost of implementation and its plug-and-play feature.

The host PC communicates directly with a spindle control module via USB. At any instant there is only one *spindle control module* attached to the PC and the USB standard provided an acceptable solution. Communication with *servo control modules* does not occur directly via USB. The variable number of axes that may be implemented on an MRM created the necessity for a network orientated approach for communication with these control modules. Servo instructions are first obtained from the host PC via USB, the *servo communication module* formats these instructions according to the Inter-Integrated Circuit Communication (I2C) protocol. These instructions are then placed onto an I2C network (bus) for transmission to servo control modules.

The I2C protocol was selected based on wide support for the protocol in microcontrollers. The I2C bus is a multi-master bus, implying that any device connected to the bus can initiate a transfer of data. The protocols 7-bit address format permits up to 128 servo control modules to be implemented on the network, bounded otherwise by a bus capacitance limit of 400 pF. Data on the bus can be transferred at rates up to 400 kbits/s [65]; providing sufficient bandwidth for the communication of servo control instructions. It should be noted that any mechanical module requiring servo control may be connected to the I2C network, provided that the data packet protocols discussed in Chapter 7 are strictly adhered to. This will allow auxiliary modules other than the machines axes (motion modules) to be connected and controlled via this network.

6.3 Spindle Control Modules

Power Supply

The function of a spindle control module is to control the actuation of MRM cutting heads, as well as provide diagnostic feedback on the cutting process. Spindle control modules map to process modules on a 1:1 basis. A spindle control module is supplied by 12 V DC power, with a low current and high current supply. The low current 12 V supply is internally regulated to 5 V, and powers the internal digital electronics of the control module. The regulated power also provides a source of power to sensors.

The high current 12 V supply, is used to power an internal relay switch from which motors may draw electricity. The separation of the power supply into a low and high current side was to ensure that the digital electronics are not deprived of power by the motors that are driven by the spindle control module. The total power requirement of a spindle control module is 144 watts, or 24 watts if the onboard relay switch system is unused (see Section 6.7).

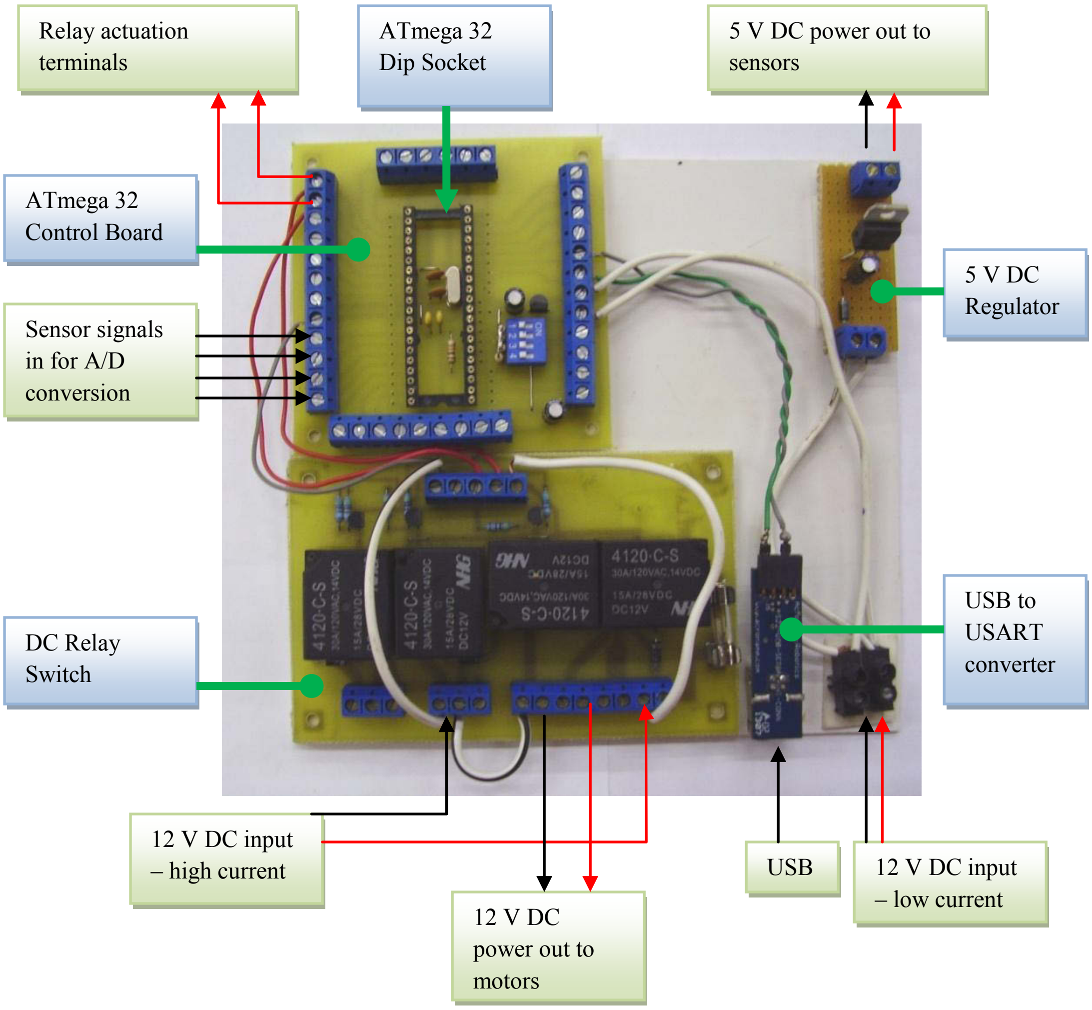


Figure 6.2: Spindle Control Module

USB Communication

The spindle control module receives instructions and provides feedback to the host PC via USB. The module consists of a bi-directional USB to USART converter that is based on a FT232RL chip. The chip is USB 2.0 full speed compatible and requires no USB specific firmware programming; the USB protocol is handled entirely by this device [66]. Serial data that has been received by the FT232RL chip is transmitted via USART to the ATmega 32L control board for manipulation.

ATmega 32L Control Board

The main spindle control board was based on the ATmega 32L microcontroller, which operated at 4MHz. The ATmega 32L is a high performance, low power 8-bit RISC chip.

The range of features on this chip is significant, allowing it to be used in both spindle and servo control modules. Features of the ATmega 32L include (but are not limited to):

- 131 Instructions – most single-clock cycle execution
- Up to 16 MIPS throughput at 16 MHz
- 32 x 8 general purpose working registers
- 32 K Bytes or flash program memory
- 1024 Bytes of EEPROM
- 2 K Bytes internal SRAM
- 8-channel, 10-bit ADC
- Two 8-bit timer/counters
- One 16-bit timer/counter
- Four channel PWM
- Byte Oriented Two Wire Serial Interface
- Programmable serial USART
- External and internal interrupts

A diagram of the ATmega 32L board is located in Appendix E.2.

Sensor Monitoring and A/D Conversion

The Analogue to Digital Conversion (ADC) facility on the ATmega 32L control boards was used to extract sensor data from the MRM cutting heads. The sensor used for vibration monitoring is the ADXL204 dual-axis accelerometer, discussed in Section 6.6.1. Two of the eight available channels were used on the chip for the measurement of vibrations in both vertical and horizontal directions. Sensor signals were decoded with 10-bit ADC. The vibration data is continuously fed back to the host PC via USB, for process monitoring by the machine operator.

Relay Switches and Actuation

Digital speed control was omitted in process modules (modular cutting heads), with spindle speed and torque ratios being manipulated only by the mechanical mechanisms discussed in Section 5.6. Process modules were controlled on a simple on/off basis, with the motors being activated by relay switches. The relay switches were in turn activated by 5 V DC signals applied by two output terminals on the ATmega 32L control board. Two terminals were used to provide forward and reverse functionality on the spindle:

- Terminal One (off), Terminal Two (off): Spindle stopped
- Terminal One (on), Terminal Two (off): Rotate spindle forward/clockwise
- Terminal One (on), Terminal Two (on): Rotate spindle in reverse/anticlockwise

Spindle control modules contained onboard relay switches that are capable of supplying 12 V DC power at a maximum of 10 amps to modular cutting heads. In the instance that a module possessed an AC induction motor an AC power box had to be used in conjunction with the spindle control module, this is presented in Section 6.7.

6.4 The Servo Communication Module

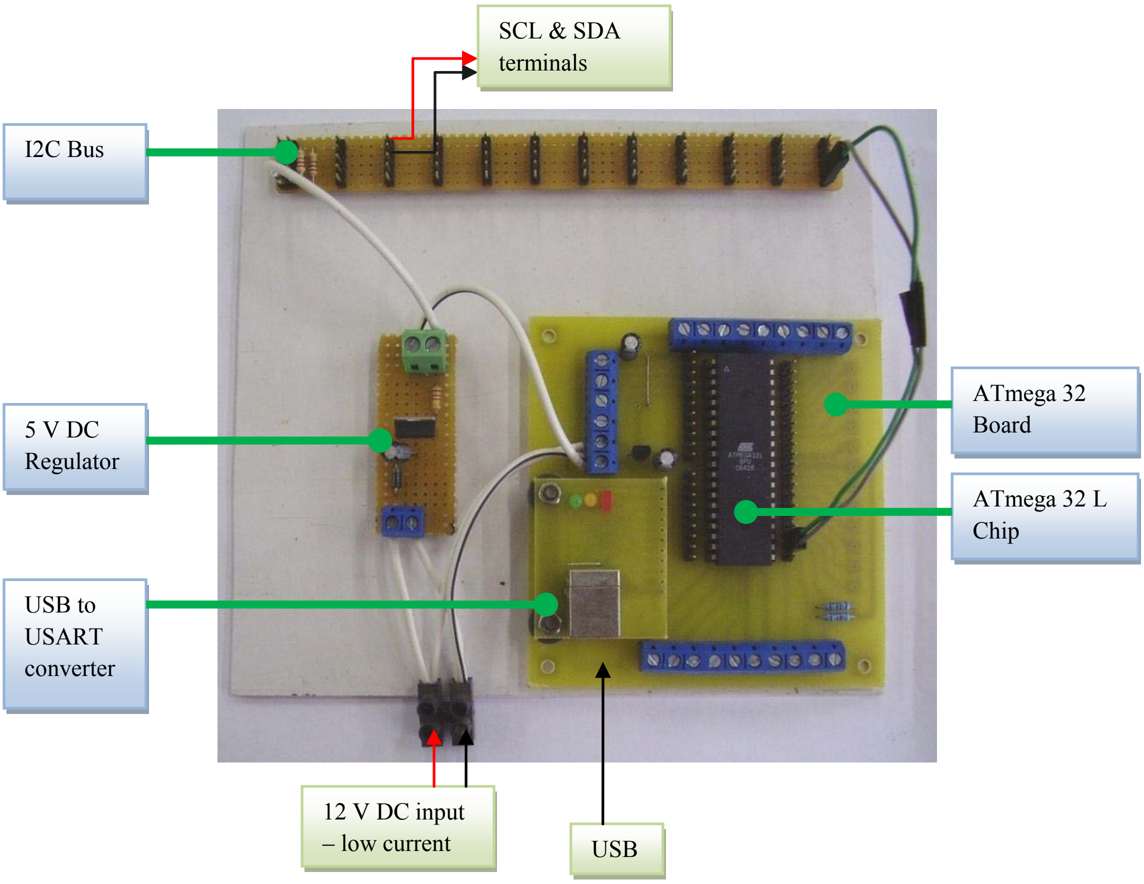


Figure 6.3: Servo Communication Module

Power Supply

The function of a servo communication module is to obtain servo instructions via USB and transmit it via an I2C network to servo control modules. The module is powered by a low current 12 V DC power supply. The 12 V supply is internally regulated to 5 V, and powers an ATmega 32L control board and the I2C bus. An MRM platform requires only one servo communication module to begin operation; however if the data transfer requirements of the system exceeds 400 kbits/s more may be plugged into the system. The total power requirement of a servo communication module is 24 watts.

USB and I2C Communication

The module contains an FT232RL chip and an ATmega 32L chip (presented in Section 6.3). The FT232RL device enabled bi-directional serial communication between the USB port on the host PC and the USART hardware on the ATmega 32L. ATmega 32L was operated at 4MHz and performed the function of obtaining serial data, and placing it into a First-In-First-Out (FIFO) queue for transmission on the I2C network. The Two Wire Interface (TWI) on the ATmega 32L was used for I2C communication. The chip contained internal hardware for arbitration detection, status monitoring and control. Complete details of the I2C module on this chip may be found in [67]. The connection points for I2C slave devices are present on the module as illustrated in Figure 6.3. A diagram of the ATmega 32L board is located in Appendix E.2.

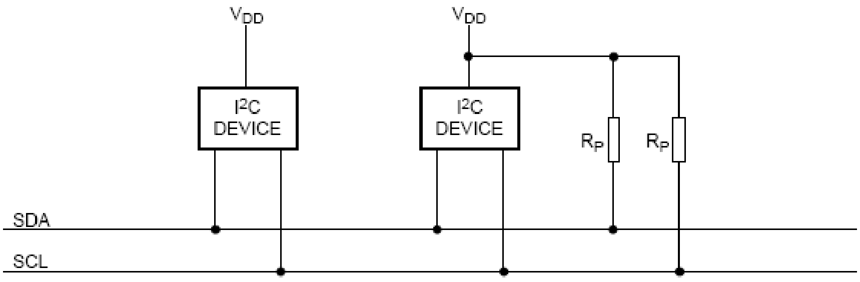


Figure 6.4: I2C Bus Electrical Connection [65]

The I2C bus consisted of a clock (SCL) and data (SDA) line that was connected to each device in the network. To ensure proper operation, 2.7 kΩ pull-up resistors (R_p) were connected between the clock and data lines and a 5V source (V_{DD}). Figure 6.4 illustrates the electrical integration of devices with the I2C bus.

6.5 Servo Control Modules

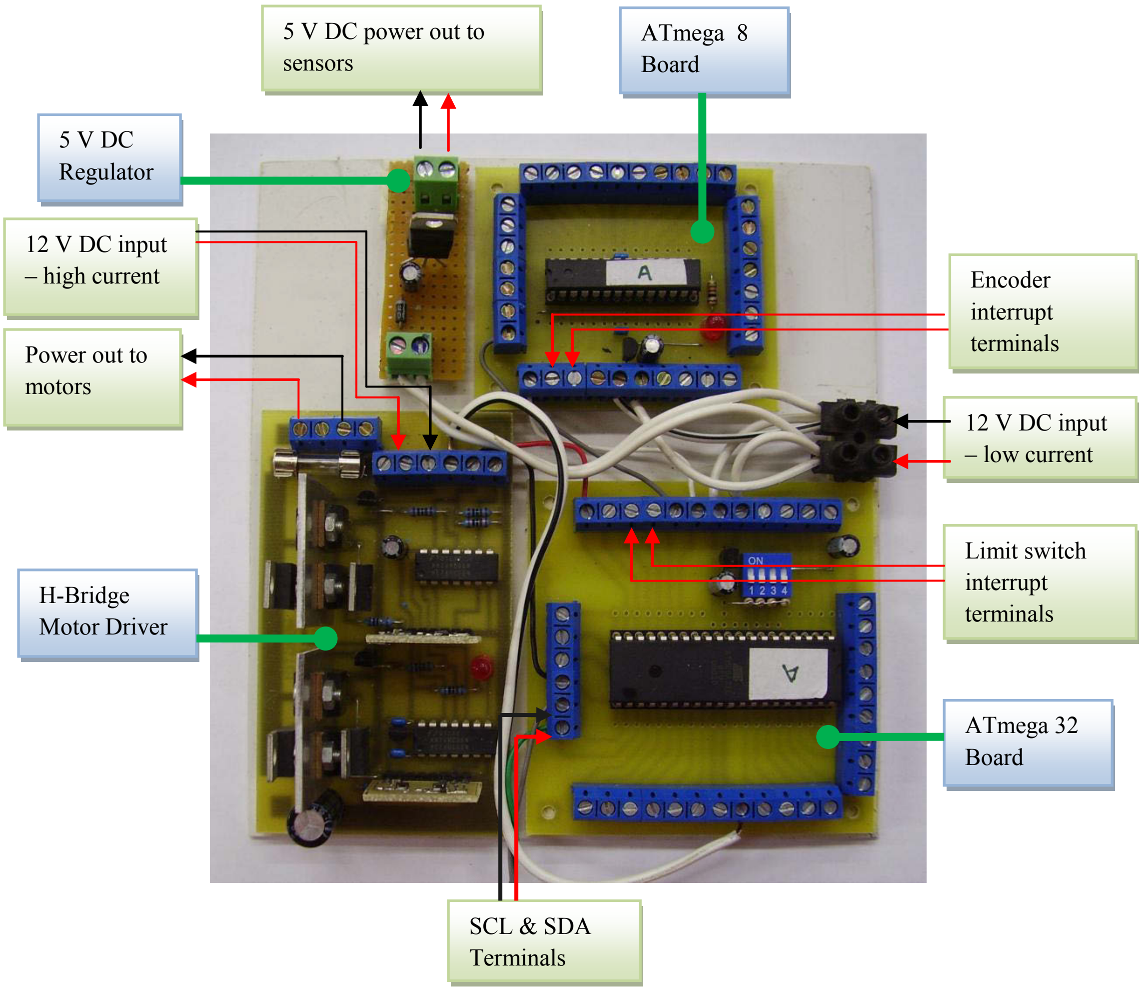


Figure 6.5: Servo Control Module

Power Supply

The function of a servo control module is to perform position and speed control on motion modules (machine axes) according to the instructions received on the I2C network. Servo control modules map to motion modules on a 1:1 basis. The module is supplied by 12 V DC power, with a low current and high current supply. The low current supply is internally regulated to 5 V for use by ATmega 32L and ATmega 8L microcontrollers. The servo control module also provides regulated power to the sensors on an associated mechanical module. The high current 12 V supply, is used to power an onboard H-Bridge motor driver. The H-Bridge in turn supplies pulse width modulated electric power to a servo drive motor. The total power requirement of a servo control module is 174 watts.

ATmega 32L and ATmega 8L Control Boards

Servo control modules contained an ATmega 8L and an ATmega 32L chip. The features of the ATmega 32L were discussed in Section 6.3; features of the ATmega 8L [68] include (but are not limited to):

- 130 Instructions – most single-clock cycle execution
- Up to 16 MIPS throughput at 16 MHz
- 32 x 8 general purpose working registers
- 32 K Bytes or flash program memory
- 512 Bytes of EEPROM
- 1 K Byte internal SRAM
- Two 8-bit timer/counters
- One 16-bit timer/counter
- Programmable serial USART
- External and internal interrupts

The ATmega 32L microcontroller performs the functions of receiving servo instructions, initializing the appropriate servo control routine and finally reporting the status of the operation to the host PC (via the servo communication module). The chip communicates with the second onboard chip, the ATmega 8L, via USART. The ATmega 8L performs the function of encoder monitoring. Diagrams of the ATmega 32L and ATmega 8L boards are located in Appendix E.2.

Pulse Counting on the ATmega 8L Board

The ATmega 8L chip counts the electric pulses from the output channels of optical encoders. Pulse counting occurs on an external interrupt basis, which is the reason why a dedicated chip has been used for this purpose. The ATmega 8L determines the number of pulses detected in a 100 ms interval. The pulse count data is transmitted to the ATmega 32L, which determines the speed and position of an axis based on the information. The transmission is triggered by an internal interrupt that is generated by the 16-bit timer/counter on the ATmega 8L.

Wave Generation on the ATmega 32L Board

The 16-bit timer/counter unit on the ATmega 32L chip was used to generate a Pulse Width Modulation (PWM) signal. The PWM signal is the control signal that is generated by a software servo control routine that is executed on the ATmega 32L board. The PWM channel on the ATmega 32L is connected to an onboard H-Bridge motor driver to enable speed control.

A second output terminal on the ATmega 32L board was also connected to the motor driver to switch the direction of motor actuation (refer to diagrams in Appendix E.2).

Onboard H-Bridge

The H-Bridge motor driver, indicated in Figure 6.5, performed PWM on a 12 volt power source. The unit is capable of supplying up to 10 amps continuously to servo drive motors. At the maximum current rating of 10 amp, a constant load of 9 Nm can be sustained at the output shaft of the motors. In linear axes the motors could theoretically maintain a constant actuation force of up to 1500 N at a current of 10 amp.

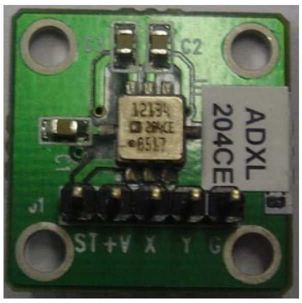
Collision Detection on the ATmega 32L Board

The external interrupt pins on the ATmega 32L were connected to limit switches for collision detection. When a collision occurs a limit switch closes a circuit which applies a 5 V signal to an interrupt pin. The interrupt software routine ends the servo control routine and the operation of the motor. An appropriate status message is then transmitted to the host PC via the servo communication module.

6.6 Sensors

6.6.1 Process Modules

a.



b.

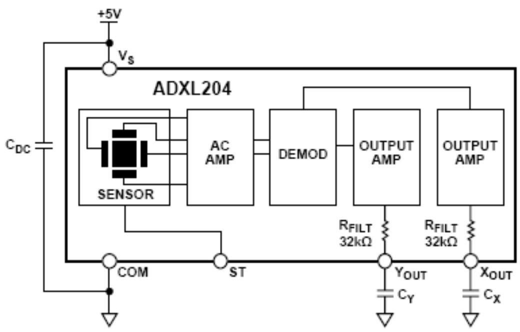


Figure 6.6: ADXL 204 dual axis accelerometer [69]

a. ADXL 204 sensor and circuit board
b. ADXL 204 function block diagram

MRM process modules each contained the ADXL dual axis accelerometer illustrated in Figure 6.6.a. The accelerometer was used to measure the vibrations generated by the cutting process and hence introduce the characteristic of diagnosability into the system. The mechanical vibrations generated during the interaction of the tool with the work piece can provide diagnostic data for the analyses of the stability of machining operations. The data obtained from an accelerometer can also be used to detect the phenomenon of regenerative chatter (second order vibrations). Regenerative chatter causes volatility in the cutting process which leads to the degradation of machined parts and possibly tool breakage.

The ADXL 204 IC is capable of measuring accelerations up to 17 m/s^2 with a bandwidth of 0.5 Hz up to 2.5 kHz. The bandwidth may be manipulated by changing the capacitors C_Y and C_X labelled in Figure 6.6.b. This option is available to narrow the bandwidth and increases the resolution. The commercial board of Figure 6.6.a has factory installed capacitors of 100 nF, setting the bandwidth to 50 Hz and resolution to 2 mg (g = gravity). The current setting enabled vibrations to be measured at spindle speeds up to 3000 rev/min on the basis of a single excitation per revolution. Other significant features of the ADXL 204 included a low current requirement of 700 µA when operated at 5 volt. The sensor unit can withstand temperatures of -40 ^{o}C to 125 ^{o}C and has a shock survival of 3500 g. Further details on the ADXL 204 may be found in [69].

The ADXL 204 interfaces with the servo control module via two of the eight ADC channels present on the ATmega 32L chip (see Section 6.3). The X_{out} and Y_{out} channels indicated in Figure 6.6.b, output a signal between 0 to 5 volt for ADC. The nominal voltage on the device is 2.5 volt, which is the voltage when the device is sensing zero acceleration along an axis. Voltages less than 2.5 volt indicate acceleration in the negative direction of an axis while voltages greater than 2.5 volt indicate a positive acceleration. The 10-bit ADC on the ATmega 32L allowed a measurement resolution of 47 mg.

6.6.2 Motion Modules

Optical Encoders

a.

b.

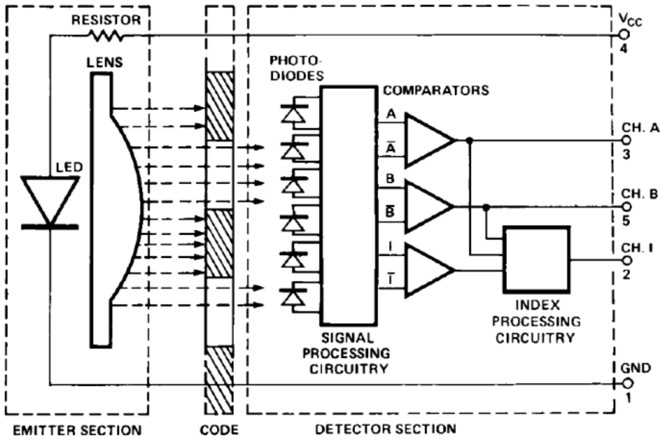


Figure 6.7: The HEDS-5540 Optical Encoder [70]

a. HEDS-5540 optical encoder
b. HEDS-5540 function block diagram

The HEDS-5540 optical encoder was integrated into MRM motion modules to create a servo drive system (see Section 5.5.3). The function block diagram for this device is illustrated in Figure 6.7.b; indicated on this diagram is the pin configuration for the unit. The HEDS-5540 is capable of producing two square waves in quadrature using channels A and B (CH A and CH B), with a third indexing pulse generated once per revolution on channel I (CH I).

The HEDS-5540 is capable of a resolution of 512 pulses per revolution on a single channel, or 1024 pulses per revolution in quadrature. Further features on the HEDS-5540 include a maximum velocity rating of 30000 rpm and acceleration of 250000 rad/s^2. The encoders were also suitably rated at a maximum vibration of 20 g at 1000 Hz, and a maximum temperature of 100 ^{o}C [70].

Although the encoders possess three channels, only one channel (CH A) was used in the MRM design. The device was selected based on cost rather than its level of functionality and proved more cost effective than other single channel encoders. The direction of motion on an axis is predetermined by servo control modules and the decoding of a quadrature signal was not necessary. Channel „A‟ producing 512 pulses per revolution enabled resolutions of up to 0.70^o on rotary axes and 0.003 mm on linear axes. The channel is connected directly to the interrupt terminal on an associated servo control module. The device is also operated on 5 volt DC and derives its power from the regulated power supply unit on servo control modules.

Limit Switches

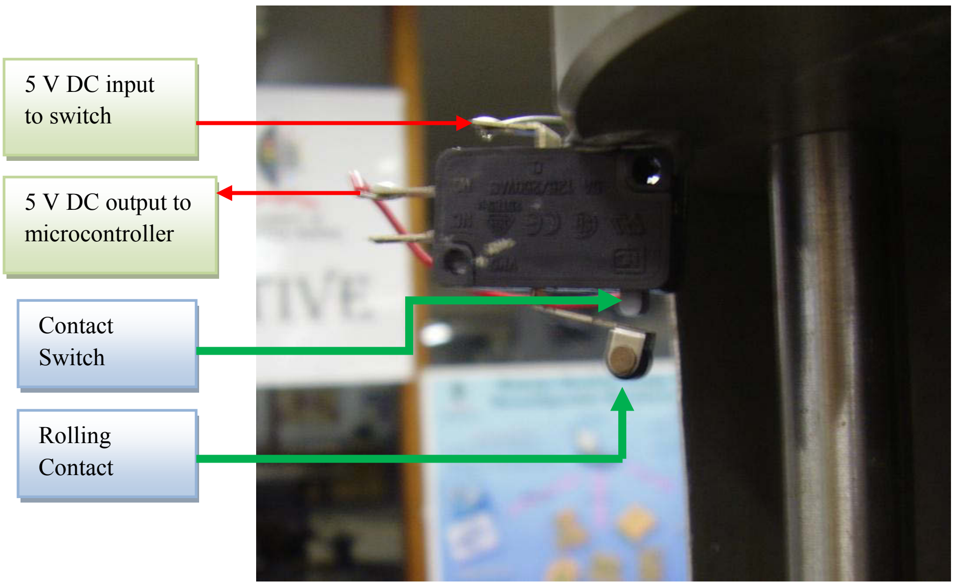
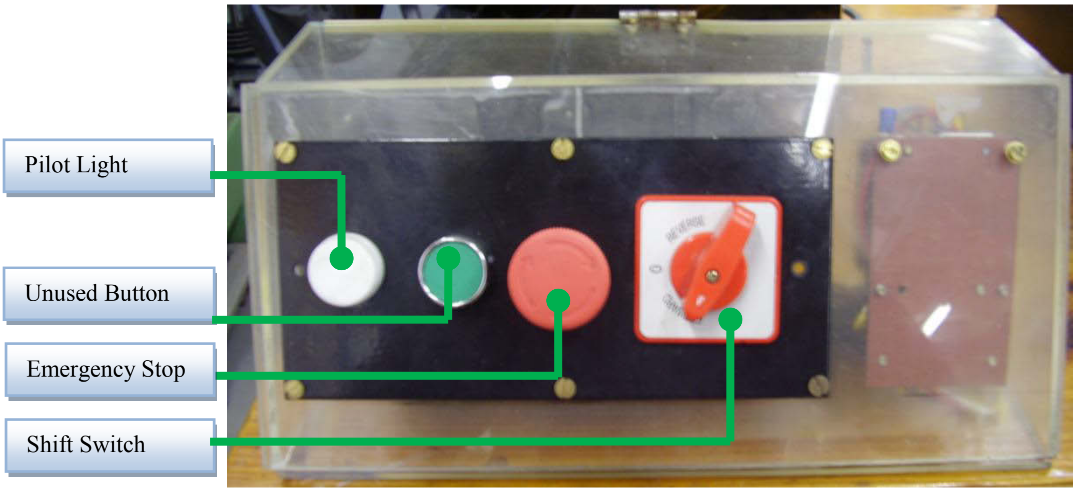


Figure 6.8: Limit Switch on Column Module

Limit switches were used in the MRM design for contact sensing in motion modules. These sensors were necessary to prevent damage to the modules through collisions between the internal mechanical components. A single module would usually contain two switches at either end of its axis. The limit switches were connected in a „normally open‟ configuration, and would close a circuit when contact is made between a moving component and the switch. The sensors are connected to an interrupt terminal on servo control modules and a 5 volt interrupt signal is generated when the circuit is closed. The interrupt software routine then ceases the generation of a PWM signal to the H-Bridge motor drivers, which in turn stops the operation of the motor.

6.7 The AC Power Box

a.



b.

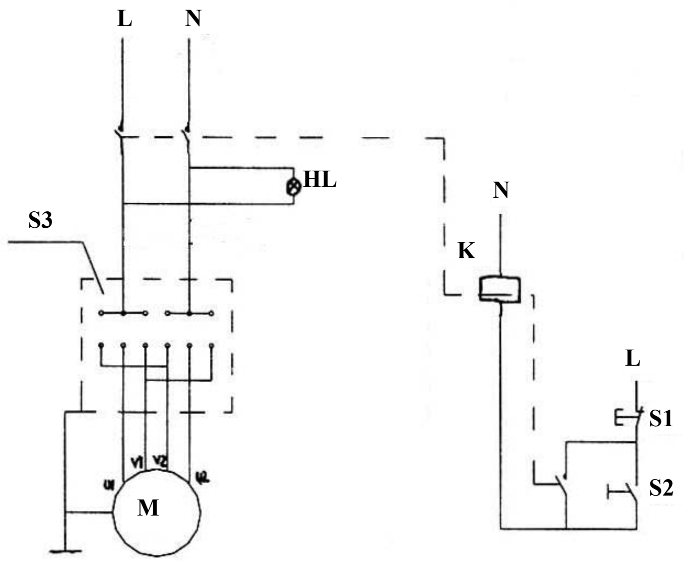


Figure 6.9: Electrical System of the AC Power Box

a. AC Power Box
b. AC Power Box – Schematic of electrical system

Modular cutting heads containing AC induction motors required the use on an AC power box in conjunction with the spindle control module for actuation. The electrical system in this instance bypasses the DC relay switch present on the spindle control module. This relay switch is only capable of supplying 12 V DC power to cutting heads with DC motors (the drilling head specifically). The AC control box, illustrated in Figure 6.9., consists of an alternating current contactor (K), a pilot light (HL), an AC relay switch (S1), an emergency button (S2) and a shift switch (S3).

The pilot light was a safety feature of this system, used to indicate that the electrical components of the system were powered. The second safety feature was the emergency switch, which once pressed, shuts down the operation of the motor.

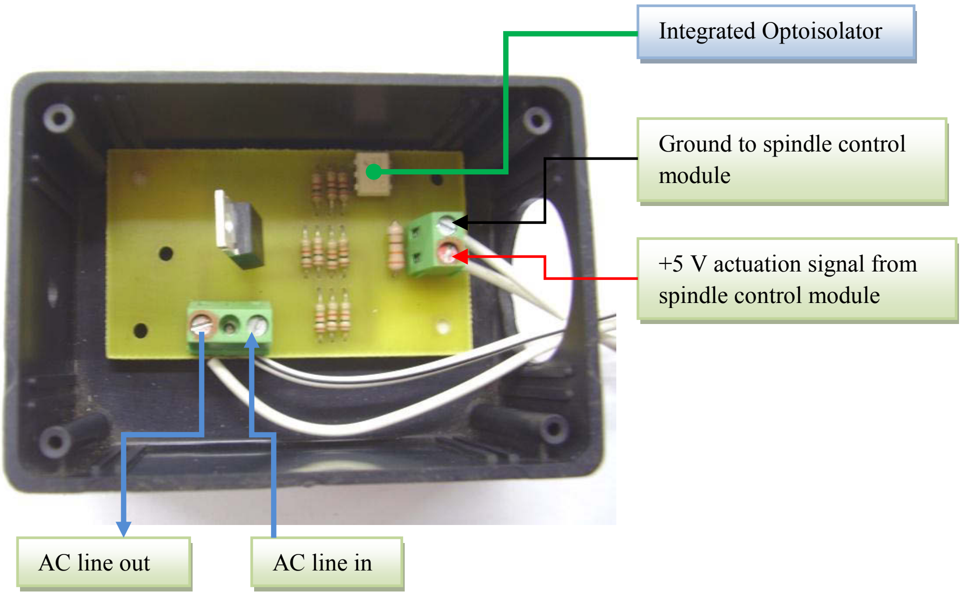


Figure 6.10: AC Relay Switch

The modular turning head was the only module from the current MRM library that contained an AC induction motor. The motor is a single phase, 220 volt, 0.55kW induction motor. The motor is specified to use 20 amps and it was necessary that an AC contactor be used in the safe actuation of the motor. The AC contactor consisted of a low current circuit that is activated and deactivated by the emergency stop button and the AC relay switch. When switches S1, S2 and S3 are "closed" and the low current circuit is active, an electromagnetic system within the contactor activates the high current circuit allowing power to be supplied to the shift switch. If the shift switch has been preset, the motor will begin rotating in the preset direction. Figure 6.11 outlines the sequence of control in the actuation of the motor.

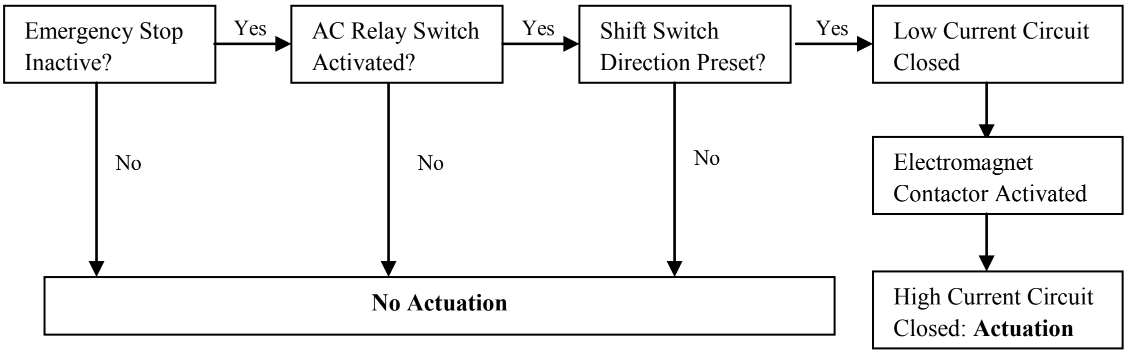


Figure 6.11: Sequence of Control in Motor Actuation

The AC relay switch was included in the design to enable the digital on/off control of process modules. The switch is activated by a 5 V signal from the spindle control module, interfaced via an optoisolator. The integrated optoisolator, shown in Figure 6.10, protects the digital circuitry of the spindle control module from the AC currents that exist in the circuitry of the relay switch. Due to cost restrictions a manual shift switch was used to preset the direction of a motor‟s rotation and hence the direction of the spindle rotation. The shift switch indicated in Figure 6.9.b has forward and reverse settings or alternatively can be set to zero to deactivate the system. This switch need only be set once prior to the digital actuation of motors via the AC relay switch. The system may then continue to be controlled digitally until a change in spindle direction is necessary.

6.8 Power Supply System

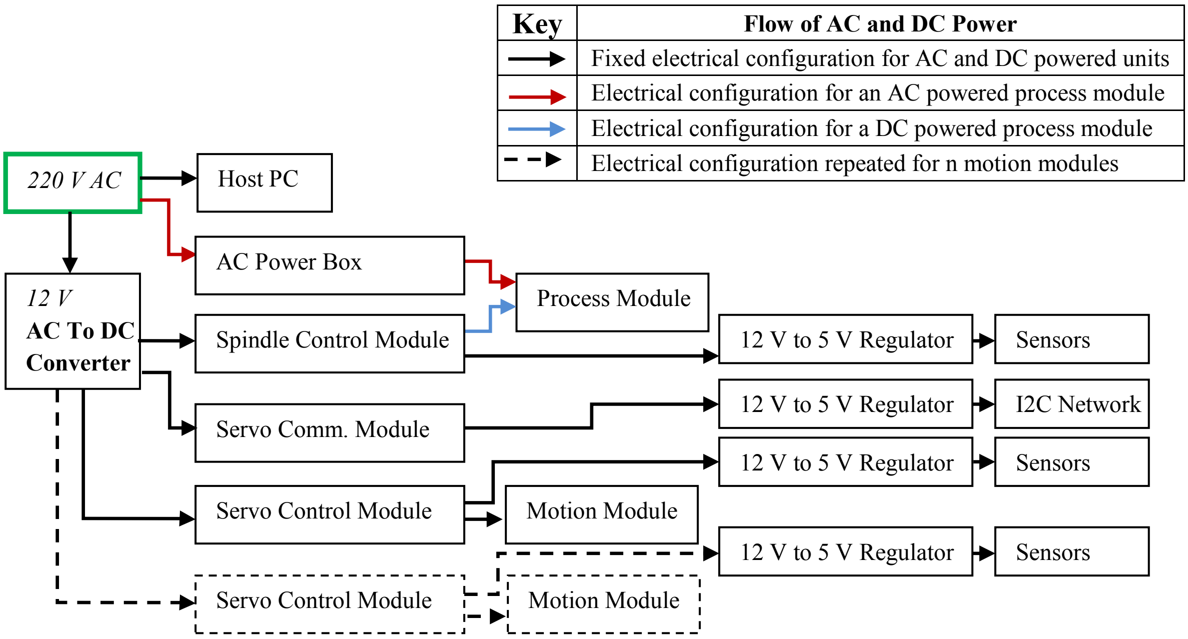


Figure 6.12: Flow of AC and DC Power in a MRM

The MRM electrical system is powered by 220 volt AC at 50 Hz. The total power requirement of an MRM system is dependent on the number of control modules, communication modules and AC power boxes present in the system. The host PC operates directly on AC, including those MRM process modules that contain AC induction motors. Those components of the system that required 12 volt DC power are supplied by AC to DC converters; 20 amp converters were used to meet to high current electrical requirements of the system, while 8 amp "PC power supplies" were used to meet the low current requirements of the system. The hybrid use of AC to DC converters was due to restrictions on costs when developing the system. Figure 6.13 shows the AC to DC converters that were used.

Process modules are operated on AC or DC power depending on the type of motor the module contains. Motion modules (MRM Axes) are powered exclusively by 12 volt DC, as all motion modules contain DC servo drives. The power to these modules is supplied and controlled via an associated servo control module. Sensors and microcontrollers in the system that required 5 volt DC power for operation, derived their power form appropriate DC regulators present on either servo or spindle control boards.

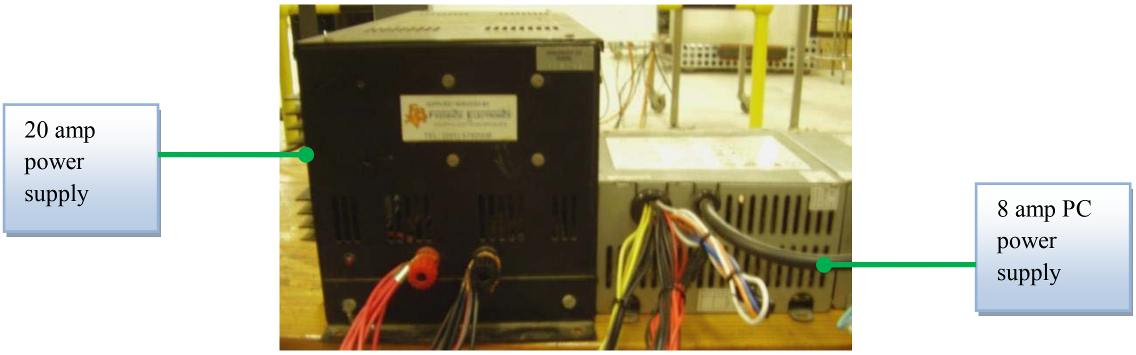


Figure 6.13: AC to DC Converters

6.9 System Integration and Reconfiguration

Figure 6.14: Power and Control Interface between Mechanical and Electronic Modules

Mechanical modules interface with spindle and servo control modules via an eight wire interface: four sensor signal wires, two sensor power wires and two motor power wires. Mechanical modules with AC induction motors contain three additional wires for motor power. The two generic "interfaces" that are formed by these combinations of wires provide a consistent means of connecting mechanical modules to electronic control modules.

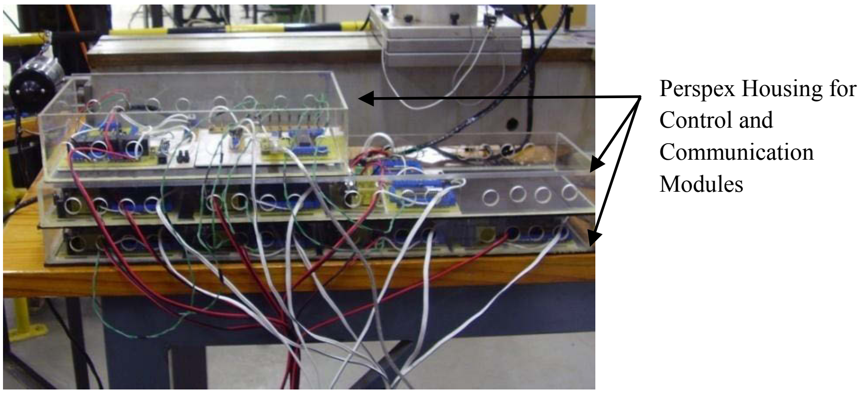


Figure 6.15: Electronic System Assembly

Figure 6.15 illustrates the assembly of the MRM control hardware where spindle and servo control modules are housed in Perspex alongside the mechanical platform. The electronic system is reconfigurable on four levels which ultimately support the mechanical reconfigurability of a MRM.

Level One - Software

The software on spindle and servo control modules may be changed if the module is used to control a different mechanical module. This enables the modules to be reused with minor adaptations. The change in software may be achieved by removing and reprogramming the associated ATmega 32L and 8L chips. Alternatively the chips may be simply swapped for chips containing the correct control programs. These chips are designed to be modular and fit into dip sockets for easy installation and removal.

Level Two - Processing Capacity

MRMs possess the ability to increase their functionality by the integration of additional motion modules into a platform. As the number of motion modules increases the digital processing capacity of the system must be increased. This is always necessary as servo control modules map to motion modules on a 1:1 basis. Additional servo control modules may be added to the electronic system by plugging them into the I2C network, and connecting them to the 12 V power supply system.

Level Three – Communication Bandwidth

Through the process of reconfiguration additional motion modules may be added to the I2C network. If many modules are added to the network, the 400 kbit/s bandwidth of a standard network may be insufficient to cater for the data requirements of all the modules. In this instance additional servo communication modules may be added in parallel to the first by plugging them into the USB ports of the host PC. The upgrade is completed by connecting the modules into the 12 V DC supply system. Additional servo control modules may then be plugged into the I2C networks on the new servo communication modules.

Level Four – Power Supply

The power requirements of an MRM system varies as the number of controllers and actuators present in a system are changed through reconfiguration. In the instance that the power demand of the system cannot be met by the present supply system, additional power sources may be added in parallel. Although modular power supply systems were not developed for the present MRM library of modules, it is recommended that in future implementations, standardized modular power supply units be created for these systems. These power supply units should be designed as “plug-in” units, intended for rapidly assembly in parallel to each other.

6.10 Chapter Summary

This chapter began with a list of desirable characteristics for the MRM control system, such that its design supports system integration and the mechanical reconfigurability if MRMs. The chapter proceeded with a presentation of the entire MRM electronic control system. This was followed by the presentation of constituent control modules, communication modules, sensors and actuation units such as AC power boxes. The four levels of reconfigurability and the integration of the electrical/electronic system with mechanical modules was also discussed.

7. MRM Software System

7.1 Software Design Considerations

The MRM software system was designed with due consideration of the five key characteristics that MRMs must display, these are: modularity, convertibility, customization, integrability and diagnosability. The software system either displays these characteristics directly or provides the support needed for the electronic and mechanical systems to fulfil the required characteristics. The translation of these characteristics into software design requirements was as follows:

- **Modularity:** the MRM software must support the integration of modular electronic hardware into the system.
- **Convertibility:** the software system must support the control of mechanical hardware that is periodically converted for the manufacturing of new products. This specifically entails the ability to program different MRM configurations.
- **Customization:** the software must display the ability to customize its control configuration to match a machines hardware configuration. This includes the activation/deactivation of specific control commands based on the mechanical modules present in a platform.
- **Integrability:** the software system must be designed for the seamless integration of the MRM host PC with distributed control drives containing embedded programs. Integrability is supported by the implementation of well defined communication and control protocols.
- **Diagnosability:** MRM software routines must be implemented for the extraction of sensor data. This also entails the interpretation and formatting of the data for display through the MRM GUI. A status and error reporting system must be built into the GUI.

The MRM software system, in addition to displaying these five characteristics, is recommended to display controller openness and real time control. Controller openness and real time performance are achieved by the development of an open architecture control system, on an operating system with a real time software kernel. The development of a real time open architecture controller for the MRM was beyond the scope of this research.

7.2 Machine Operating System and Development Environment

At the head of the MRM software system was a desktop PC supporting a LINUX operating system. The LINUX operating system was implemented due to the openness of the software thus enhancing the manipulability of the operating system. The host control system was developed and implemented on the Fedora 7 derivative of LINUX.

The development environment that was used in the creation of the host software was Qt Designer by Trolltech ASA [71]. Qt Designer is a C++ Integrated Development Environment (IDE). Qt supports the development of advanced GUI applications, including applications that require Ethernet communication. The Qt application Programming Interface (API) contains approximately 400 classes and 6000 functions, providing an extensive set of building blocks for the development of applications.

The ATmega 8L and ATmega 32L microcontrollers which were implemented on servo control modules, spindle control modules and servo communication modules were programmed in C. The software was created using a package called CodeVision AVR, which is a C compiler, IDE and in-system programmer for the AVR family of microcontrollers [72].

7.3 Software Reference Architecture

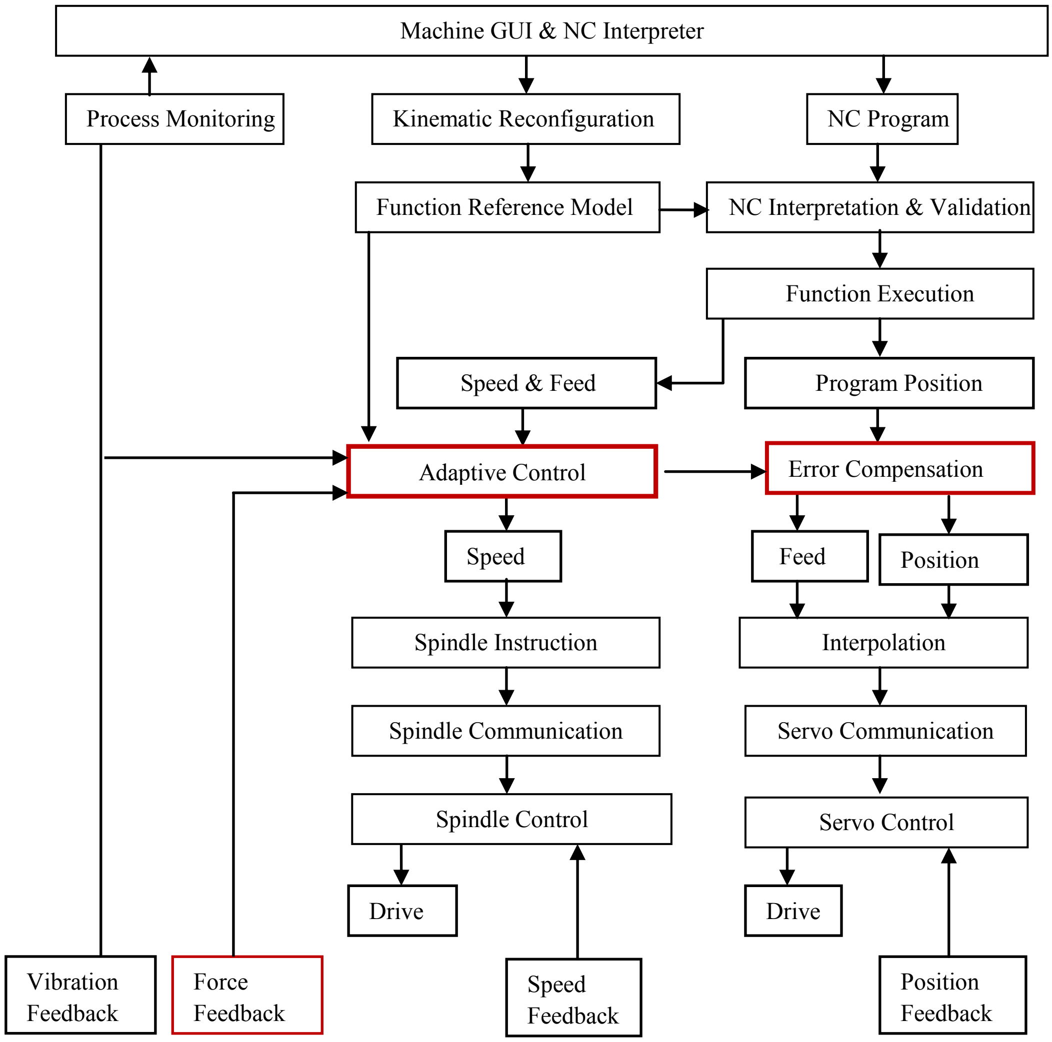


Figure 7.1: MRM Software Reference Architecture

The MRM software system is based on the multi-tier architecture illustrated in Figure 7.1. The reference architecture outlines the necessary software routines and the interaction between these routines for the functional objectives of the software system to be achieved. The primary objectives of the software system are to enable digital control over MRM actuators, provide reconfigurable control settings and provide diagnostic feedback to the user.

At the highest tier of the software system are the functions that are associated with the human-machine interface. These functions include user programming, process monitoring and reconfiguration.

User programs and input configurations are cross referenced and validated by other functions to prevent erroneous user inputs. Validated user commands are then relayed to lower functions in the system that manipulate user instructions for use by servo and spindle control modules.

The focus of the control implementation was on hardware abstraction. Hardware abstraction facilitated the reconfiguration of the mechanical and electronic system and minimized the level of reconfiguration required in the software system. Hardware abstraction was achieved on the host PC by creating well defined control protocols for the management of subordinate hardware units. The hardware abstraction was further supported by concentrating generic software functions on the host PC, while module specific functions were concentrated on distributed control drives. Software functions which are designed to be generic (not module specific) included text interpretation, code validation, error compensation, adaptive control and interpolation. Software functions that were specific to individual mechanical modules included position control, speed control, collision detection and sensor monitoring.

The adaptive control and error compensation functions are outlined in red (in Figure 7.1) as these functions have been identified as essential in MRMs; however the implementation of this in software was out of the scope of this research. The individual software routines that constitute the MRM software architecture are to be discussed in further detail in the proceeding sections of Chapter 7. Figure 7.1 should be referred to during the discussions as guide to the context of software entities in the overall architecture.

7.4 MRM Graphic User Interface

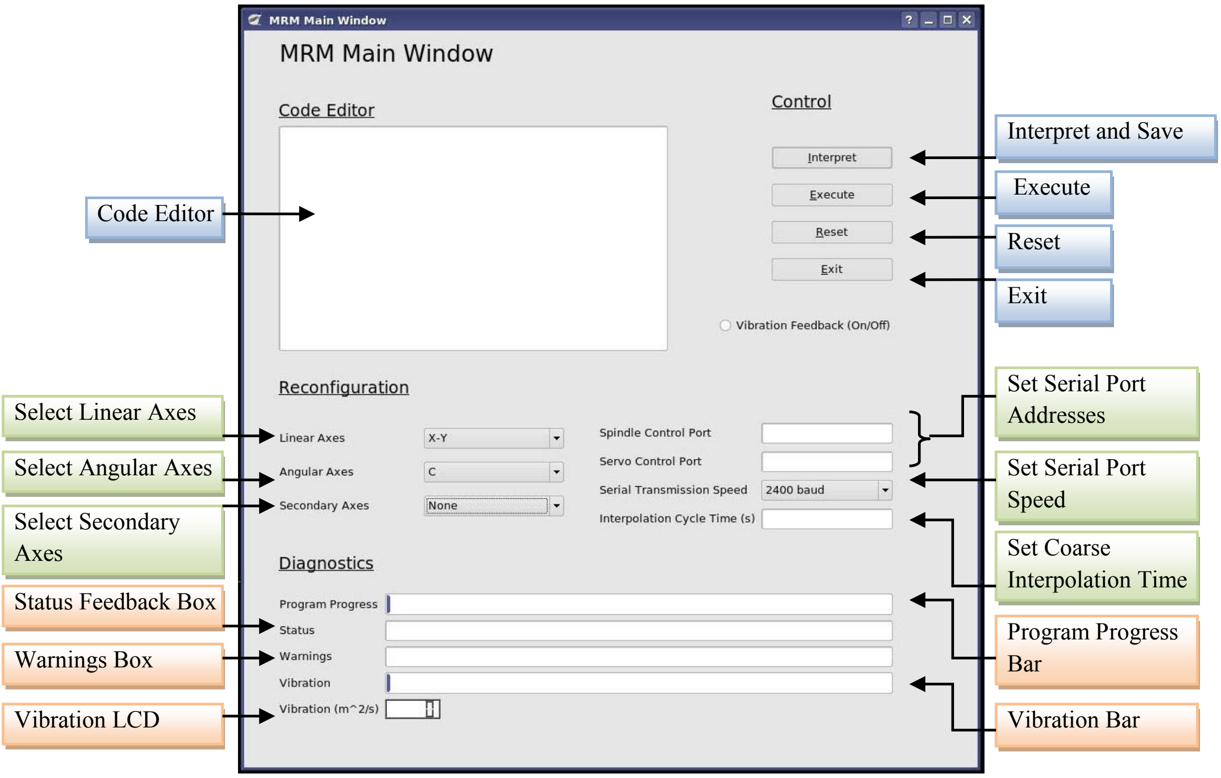


Figure 7.2: MRM User Interface

The first stage in the development of the MRM software system was the development of a GUI. The MRM GUI provides a text window for the entry of user programs. Users enter programs in the text window according to a limited version of conventional NC or G code (ISO 6983). The GUI provides control buttons that enable the user‟s control program/code to be validated and saved. Alternatively a previous program may be executed the from the machine‟s code database file (code.dat – discussed later). Drop down menus have been built into the GUI that allow the machines current control configuration to be selected.

Once a user has selected the machine‟s current control configuration and has entered a valid NC program, the execution of the program is initialized by the „Execute" button. A progress bar in the GUI indicates the progress of the user‟s program as a percentage. A status info box provides the user with reports on the current operation and a warning info box alerts the user with regard to problems that arise during the machines operation. The feedback of information to the user fulfils the diagnosability requirement of the system.

Provision has been made on the machine GUI for the feedback of process data from sensors to the user. In particular a visual and numerical display of the vibration measured from MRM cutting heads is available for user examination via the machine GUI. Mechanical vibration has been chosen as the process variable for diagnostics as these vibrations are the primary indicators of the stability of the machining process. For an industrial implementation the range of diagnostic tools on the MRM may be extended to force and temperature monitoring systems.

7.5 User Programming

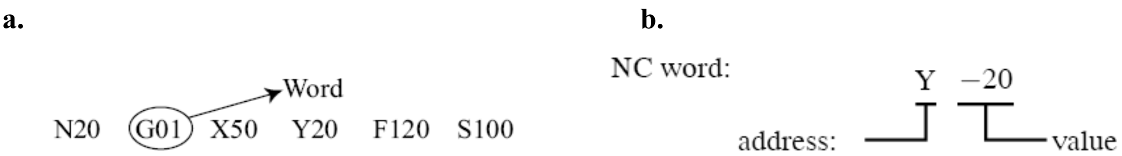


Figure 7.3: Numerical Control Syntax [31]

a. A block of NC code
b. The format of an NC word

The MRM is programmed by the user with a modified and limited set of traditional NC commands (ISO 6983). A part program using this syntax consists of code blocks, individual blocks consist of several „words", and each word consists of an address and a number [31]. Figure 7.3.a illustrates a typical block of NC code and Figure 7.3.b illustrates the format of a typical NC word.

The MRM software was created to recognize a single line of code as a block, without the necessity of using the customary EOB (End of Block) syntax. This limited the length of a block of code to a single line. The MRM GUI may be expanded in size for longer lines/blocks of NC code. Table 7.1 summarizes the addresses and the related functions that were made available for creating control programs for the MRM. For additional information on NC programming please refer to [31].

Table 7.1: NC Commands for MRM Programming

Function	Address	Units
Line Number		
Block Number	N	
Preparatory Functions		
Rapid Positioning	G00	
Linear Interpolation	G01	
Circular Interpolation (CW)	G02	
Circular Interpolation (CCW)	G03	
Coordinate System Origin Setting	G10	
Absolute Distance Mode	G90	
Incremental Distance Mode	G91	
Axis Words		
X – Primary Linear Axis	X	mm
Y – Primary Linear Axis	Y	mm
Z – Primary Linear Axis	Z	mm
U – Secondary Linear Axis (Parallel to X)	U	mm
V – Secondary Linear Axis (Parallel to Y)	V	mm
W – Secondary Linear Axis (Parallel to Z)	W	mm
A – Angular Axis About X	A	deg
B – Angular Axis About Y	B	deg
C – Angular Axis About Z	C	deg
Miscellaneous Words		
Program Stop	M00	
Program End	M02	
Turn Spindle CW	M03	
Turn Spindle CCW	M04	
Stop Spindle Rotation	M05	
Other Words		
Spindle Speed (Manually Manipulated)	S	0 or 1
Feed Rate	F	mm/min
X – Axis Offset for Arcs	I	mm
Y – Axis Offset for Arcs	J	mm
Z – Axis Offset for Arcs	K	mm
Arc Radius	R	mm

7.6 Reconfiguration of the NC Command Set

MRM reconfiguration at a software level involved the activation/ deactivation of commands in view of a machines modular configuration. All MRM configurations contained the base module and a cutting head; the S word address and the X word address were therefore always active. In addition to this all M and G words addresses (Excluding G02 and G03) were active in every configuration as these words are non-specific with regard to a particular module.

Through the process of mechanical reconfiguration the number and types of motion modules changed on a MRM platform. The process of software reconfiguration therefore targeted the activation/deactivation of commands which related directly to an individual axis or commands which were used to control the synchronized motion of two axes.

For simplicity all MRM kinematic configurations were represented in a drop down menu for selection by the operator. The selection of a specific kinematic configuration activated the word addresses associated with that configuration. Table 7.2 summarizes the activation/ deactivation of MRM functions through software reconfiguration, and their associated word addresses.

Table 7.2: MRM Software Reconfiguration – Activation/ Deactivation of Functions

Functions/ Words	Address	Activation
Block Number	N	Always active
Preparatory Functions	G00, G01, G10, G90, G91	Always active
Miscellaneous Words	M00, M02, M03, M04 M05	Always active
Other Words	S, F	Always active
X – Primary Linear Axis	X	Always active
Y or Z – Primary Linear Axes	X, Y, Z	Active when selected
A, B or C - Primary Angular Axes	A, B, C	Active when selected
U, V, W – Secondary Linear Axes	U, V, W	Active when selected
Circular Interpolation (CW)	G02, G03	+2 active linear axes
X, Y or Z – Axis Offset for Arcs	I, J, K	Relevant linear axes are active
Arc Radius	R	+ 2 active linear axes

7.7 Reconfiguration of Driver Module Addresses

The physical addition/removal of spindle driver modules and servo communication modules during reconfiguration required the initialization of module addresses to re-establish communication via USB and I2C. USB communication was initialized by entering the addresses of the servo and spindle ports in text format in the MRM user interface. An example of a USB port address on a Linux operating system would be "/dev/ttyUSB0". USB port speeds were configured through a drop down menu on the GUI from which common data transfer speeds were selected.

The addressing of servo driver modules and their corresponding axes was a simpler process. The I2C addresses of individual axes corresponded on a 1:1 basis with their program word addresses. To illustrate this principle consider an axis which is controlled using the word address „X". The corresponding I2C address of this axis will also be the character 'X', which according to the ASCII standard is reduced to the hexadecimal number 0x58. The number 0x58 is therefore the address of the X-axis on the I2C network. The process of reconfiguring the MRM command set by drop down menus therefore served a dual purpose. Enabling an axis word address further enabled the corresponding axis to be addressed over the I2C network.

7.8 NC interpretation and Validation

MRM programs are entered into the code editor on the machine GUI in text format. All programs must first be interpreted and saved prior to execution; this is done by the activation of the "Interpret and Save" button on the user interface. Text interpretation involved the allocation of individual NC words to appropriate variables in the software. During the process of text interpretation the user"s program is subjected to two stages of filtering. The first stage filters the program for the use of incorrect syntax. The second stage compares the user program to the MRMs current modular configuration.

The drop menus used to initialize the machine‟s modular axes configuration creates a function reference model against which NC functions in the user‟s program are compared. Functions used by the machine operator that are inconsistent and incompatible with the machines modular configuration are rejected and an error message is issued through the GUI.

Valid user programs that have successfully passed through the two stages of filtering are stored in a database file called “code.dat”. Code that has been stored is ready to be executed using the “Execute” button on the user interface. If the “Execute” button is activated without a program entered in the code editor the MRM software will execute old code that has been previously stored in the code database file. This file is overwritten each time the user saves a new program, and is cleared by the activation of the “Reset” button. Only a limited level of functionality was enabled with regard to code storage and retrieval due to the prototypical nature of the platform.

7.9 Execution of User Programs

The clicking of the “Execute” button on the MRM user interface begins the execution of the user‟s program (sample code located in Appendix I). The validated program is retrieved from the code database file (code.dat) and loaded into the host PC‟s dynamic memory by the “Load Program” software routine. If the software is unable to read the code database file or if the file is empty, error messages are generated in the warning text box on the GUI. User programs are loaded a block at a time, and if a block had been successfully loaded, control is passed onto the “Function Selection” software routine; this is illustrated in Figure 7.4.

The Function Selection software routine is the main software entity that manages the active control routines being executed on the MRM platform. Control routines are dictated by the M and G word addressed in the user program, while other word addresses dictate information on tool feed rates, spindle speeds and distances. The function selection software routine first executes all M word instructions. M word addresses contain instructions relating to the general control of the machine, these instructions include: program stop/start/end, direction of spindle rotation and other miscellaneous functions. Each instruction requires additional dedicated software subroutines for its execution. Once an M word has been used to activate a mechanical module, that module will continue operation until another M word has been used to deactivate it. For example, if a spindle has been switched on and instructed to rotate clockwise, it will continue to do so without the M word instruction being repeated in every block of user code. Upon the completion of the M word instructions in a block of code, the execution of G word instructions begins.

G word addresses are primarily concerned with control of the machines axes. These instructions include the initialization of reference coordinate systems, absolute or incremental programming and the mode of motion control (point to point, linear interpolation, circular interpolation). Each of these software routines require additional dedicated software subroutines for their execution. Once a G word has been used, the control routines that are related to that G word maintain precedence until overruled by other G words in subsequent blocks of code. G words do not need to be repeated in every line of code. For example, if absolute coordinate programming has been selected, this mode of control will maintain precedence without the G word instruction being. Once all M and G word instructions have been completed for a block of code, control is passed onto the “Status Update” software routine.

The Status Update routine updates the progress bar on the machine GUI. The progress is indicated as a percentage of the number of code blocks that have been executed with regard to the total number of blocks in the user‟s program. The status box is also updated with information for the machine operator, relating to the current state of the machining process. If all the blocks of code in the program have been executed the software returns control to the operating system until the user activates another function on the user interface.

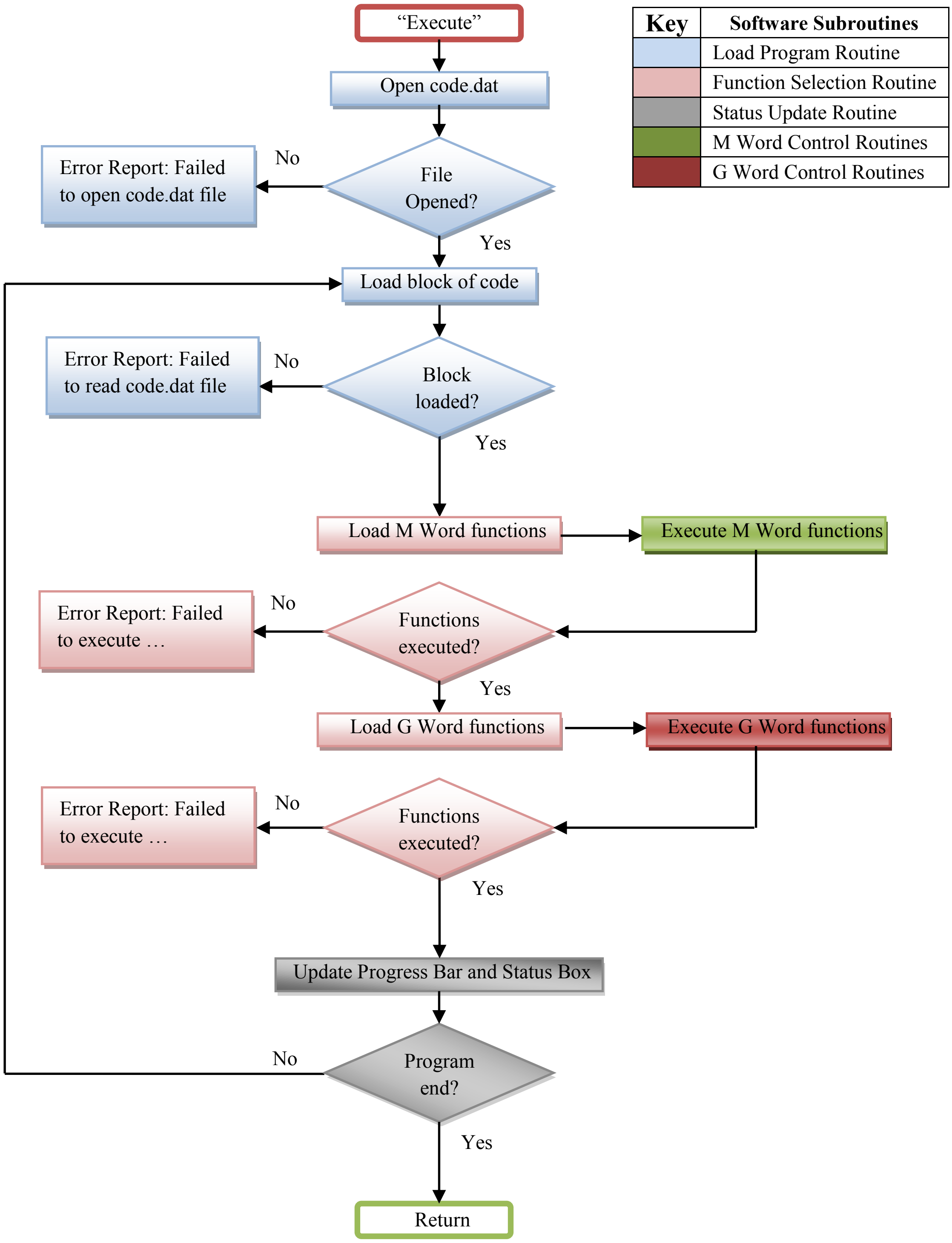


Figure 7.4: Sequence of Operations for Execution of User Programs

7.10 M Word Software Routines

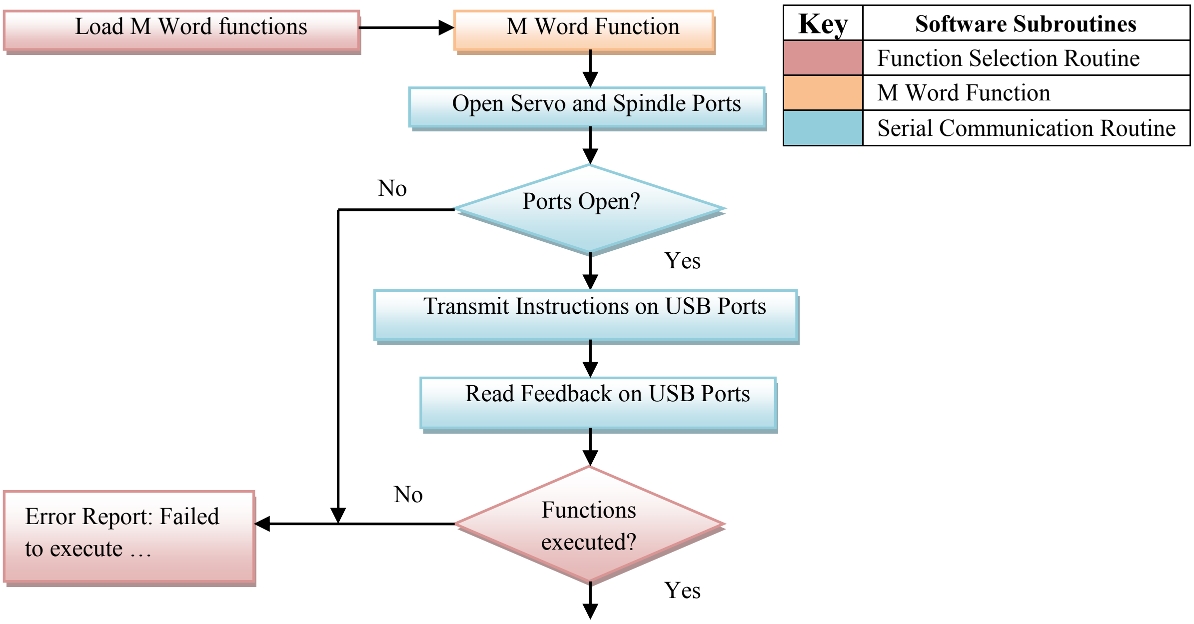


Figure 7.5: Sequence of Events in the Execution of M Word Instructions

Table 7.3: Hexadecimal Values of General Instruction Byte for Various M and G Words

Spindle Control Modules		
M or G Word	**Instruction**	**General Instruction Byte Value (HEX)**
M00	Program Stop	0x01
M02	Program End	0x02
M03	Turn Spindle Clockwise	0x03
M04	Turn Spindle Anticlockwise	0x04
M05	Spindle Stop	0x05
	Servo Control Modules	
M or G Word	**Instruction**	**General Instruction Byte Value (HEX)**
M00	Program Stop	0x01
M02	Program End	0x02

M Word instructions that were enabled in the MRM software system included: Program Stop, Program End, Turn Spindle CW/CCW and Spindle Stop. The execution of these functions involved switching operations on the MRM, as no digital speed control was enabled on the cutting heads. The communication of these instructions to spindle and servo control modules occurred via the respective USB ports and feedback on the completion of these instructions also received via USB on an interrupt basis. Section 7.14 presents the control and data communication protocols for servo and spindle control modules. A single byte was required to transfer M word instructions to both types of control modules. This byte is the "General Instruction" byte in the respective control protocols. Table 7.3 displays the hexadecimal values of the "General Instruction" byte for the various instructions.

7.11 G Word Software Routines

Coordinate Systems and Absolute Programming

The G10 instruction was built into the MRM software however its use in this instance differed from the ISO 6983 convention. MRMs being modular and reconfigurable present a unique challenge in establishing the position of the machine spindle relative to the work table after reconfiguration. The challenge of establishing the position of the machine spindle is solved by issuing the G10 command, causing each individual axis to move to its home position after the machine has been assembled. The position of the spindle relative to the absolute reference coordinate system on the work table is then known by the substitution of the various home locations for individual axes into the machine transformation matrix.

Example: consider the three axis drilling configuration presented in Appendix D.1. The home positions of the various axes are: x = 257.5 mm, y= 0 mm and z = 647 mm

$$
{}^{Worktable}_{Drill}T = \begin{bmatrix} 1 & 0 & 0 & -344.5+x \\ 0 & 1 & 0 & 2.5+y \\ 0 & 0 & 1 & -2+z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -344.5+257.5 \\ 0 & 1 & 0 & 2.5+0 \\ 0 & 0 & 1 & -2+685 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -87 \\ 0 & 1 & 0 & 2.5 \\ 0 & 0 & 1 & 683 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Therefore upon the issuing of the G10 command the position of the drilling spindle relative to the coordinate system on the work table is P(x, y, z) = (-87 mm, 2.5 mm, 645 mm).

To enable absolute programming the position of the spindle relative to the work table must be manually entered by the machine operator into the position database file (Position.dat); after the G10 command has been issued. The position database file maintains a record of the position of the machine spindle relative to the work table and is updated by the software for each movement of the machines axes thereafter. The G10 command need only be issued once after reconfiguration, or when a recalibration of the machine is required. This command is issued in the "General Instruction" byte in the servo control instruction (see Section 7.14).

Table 7.3 (continued): Hexadecimal Values of General Instruction Byte for Various M and G Words

Servo Control Modules		
M or G Word	Instruction	General Instruction Byte Value (HEX)
G10	Return Axis to Home Position	0x0A

Modes of Motion Control

MRM platforms possess the ability to be programmed in either absolute or incremental coordinates (G90 and G91). The motion of the machines axes could be controlled in rapid point to point motions (G00) or constant speed motions (G01, G02, G03). Figure 7.6 illustrates the sequence of operations for the processing of a G Word instruction. Instructions such as G90 and G91 do not require any motion of the machine axes and are activated to control the behaviour of other G Word instructions. Instructions G00 and G10 are associated with rapid motions of the machines axes, and do not require interpolation before the transmission of commands to servo control modules.

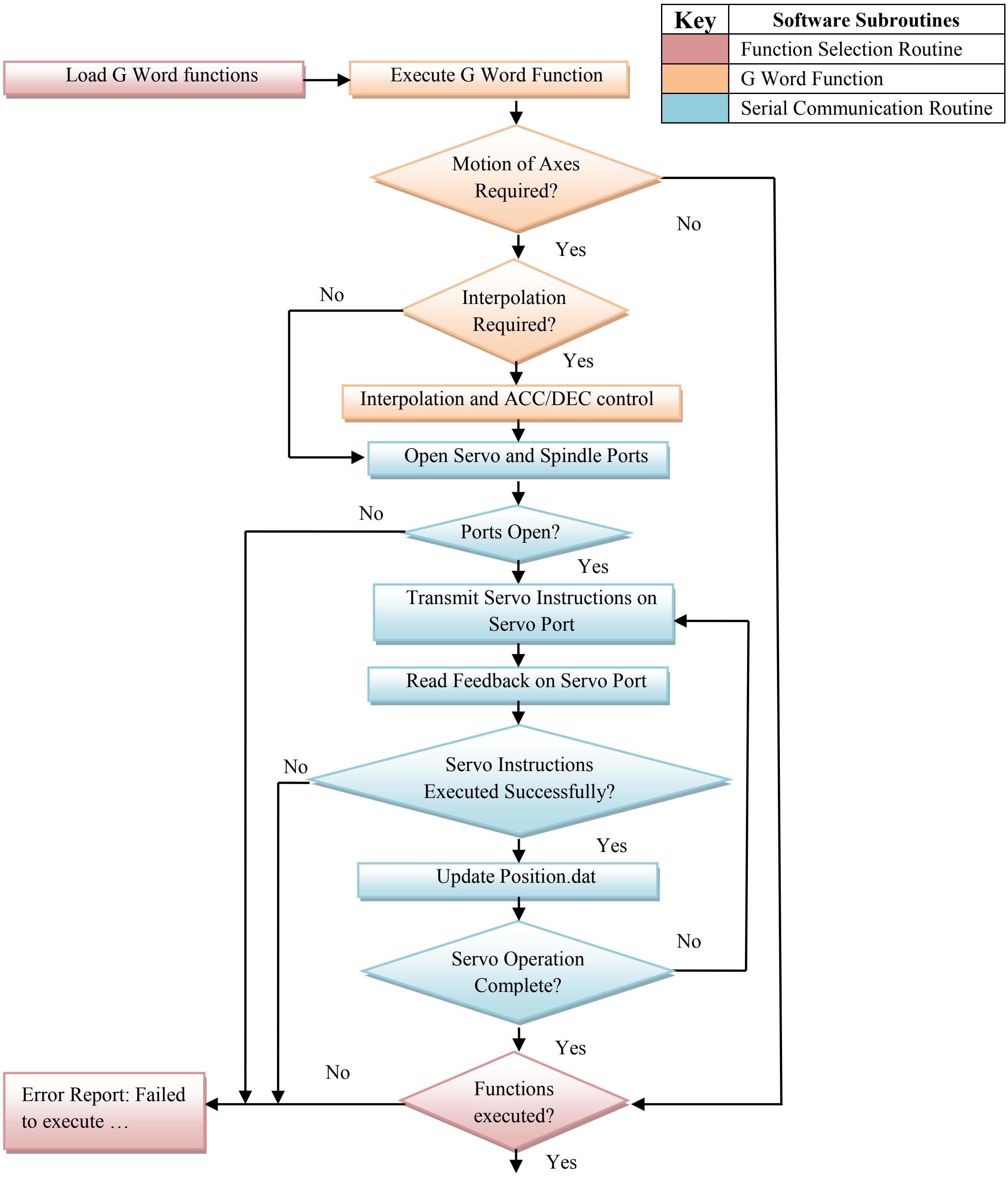


Figure 7.6: Sequence of Events in the Execution of G Word Instructions

Instructions G01, G02 and G03 observe the required feed rate as dictated by the user program. These instructions require the execution of an appropriate interpolation algorithm, to divide the required distance of travel into small linear segments across which a position control algorithm is applied. The smaller segmented target distances are transmitted to the servo control modules for the execution after acceleration and deceleration control is applied.

Servo control instructions are transmitted to control modules via USB, as shown in Figure7.6. Once these low level instructions have been generated by the MRM software, control is transferred to the serial communication software routine that transmits servo instructions and receives feedback on its successful or unsuccessful execution. Feedback is received via USB on an interrupt basis. If the execution of servo instructions is unsuccessful, control is transferred to the function selection subroutine which generates an error message for the machine operator. If the instructions have been successfully transmitted, the serial communication routine updates the position of the axes in the position database file (Position.dat), and continues with the transmission of further servo instructions until all the necessary instructions have been completed.

7.12 Interpolation

A Sampled-Data interpolator was selected for implementation in MRMs. The Reference Word algorithm incorporating the Improved Tustin Method (ITM) was the favoured combination. The ITM is generally preferred for software orientated numerical control designs where floating point arithmetic is possible. The ITM exhibits high accuracy and a relatively low number of iterations in comparison to Euler and Taylor methods [31]. The ITM/Reference Word algorithm involved the linear segmentation of both linear and non linear trajectories.

Linear Interpolation

a. **b.**

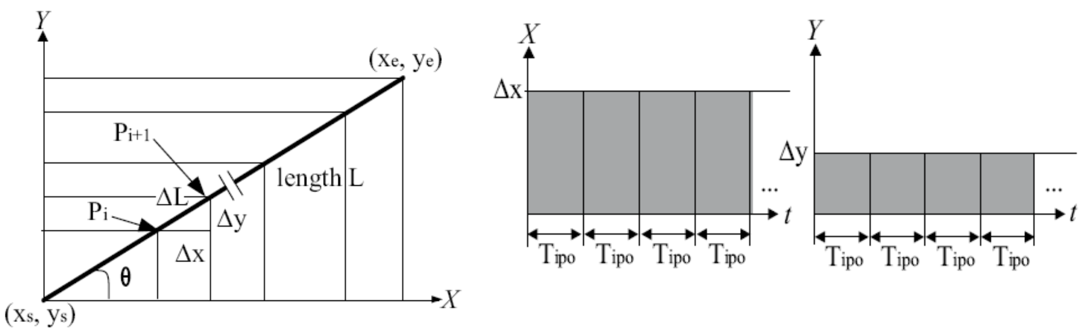


Figure 7.7: Linear Interpolation [31]

a. Total linear path divided into interpolation points P_i
b. Axial increments in X and Y axes for individual interpolation time steps

The G01 command required the process of interpolation to achieve a linear trajectory of the cutting tool. Figure 7.7.a illustrates the principle of interpolation, where a linear trajectory is divided into segments. The division of a trajectory into segments improves the accuracy of the position control. Individual segments may be resolved into axial increments for each axis that is active in the trajectory. Figure 7.7.b illustrates the axial increments for each interpolation cycle time. These increments generate a discreet ramp input to the position control algorithms running on servo drive modules. For a trajectory requiring the synchronized motion of two axes the length of the linear path is calculated by equation 7.1.

$$L = \sqrt{(x_e - x_s)^2 + (y_e - y_s)^2} \qquad (7.1)$$

The length to be travelled per interpolation cycle is calculated by equation 7.2, where T_{ipo} is the interpolation cycle time (s) and *f* is the combined feed rate of the two axes (mm/min):

$$\Delta L = \frac{f.T_{ipo}}{60} \tag{7.2}$$

The axial increments per cycle are calculated by equation 7.3 and the total number of iterations *N*, required to complete the trajectory is calculated by equation 7.4:

$$\Delta X = \Delta L \frac{x_e - x_s}{L} \tag{7.3}$$

$$\Delta Y = \Delta L \frac{y_e - y_s}{L}$$

$$N = \frac{L}{\Delta L} \tag{7.4}$$

The calculation of the total number of iterations often results in a residual length for each axis, as the number *N* has to be in the format of an integer.

$$Res_x = (x_e - x_s) - N.\Delta X \tag{7.5}$$

$$Res_y = (y_e - y_s) - N.\Delta Y$$

The residual length is a form of truncation error, and is compensated for by distributing it evenly among each interpolation cycle. The final axial increments per interpolation cycle are given by equation 7.6:

$$\Delta X_{final} = \Delta X + \frac{Res_x}{N} \tag{7.6}$$

$$\Delta Y_{final} = \Delta Y + \frac{Res_y}{N}$$

The axial increments are stored in a database file called “FIFOtemp.dat”. This is a temporary storage location for the data before acceleration/deceleration control is performed.

Circular Interpolation

The G02 and G03 commands require the process of circular interpolation to achieve a tool trajectory along an arc of radius *R* (mm). The circular trajectory is achieved by dividing the arc into multiple linear segments. The linear axial increments per interpolation cycle time, for a trajectory along an arc of radius *R*, are given by equation 7.7:

$$\Delta X = x(i+1) - x(i) \tag{7.7}$$

$$\Delta Y = y(i+1) - y(i)$$

The calculation of the appropriate linear increments is dependent on the current position of a machines tool tip after each interpolation cycle. This is given by equation 7.8 where *R (i)* is the radius of the interpolated arc from the previous interpolation cycle.

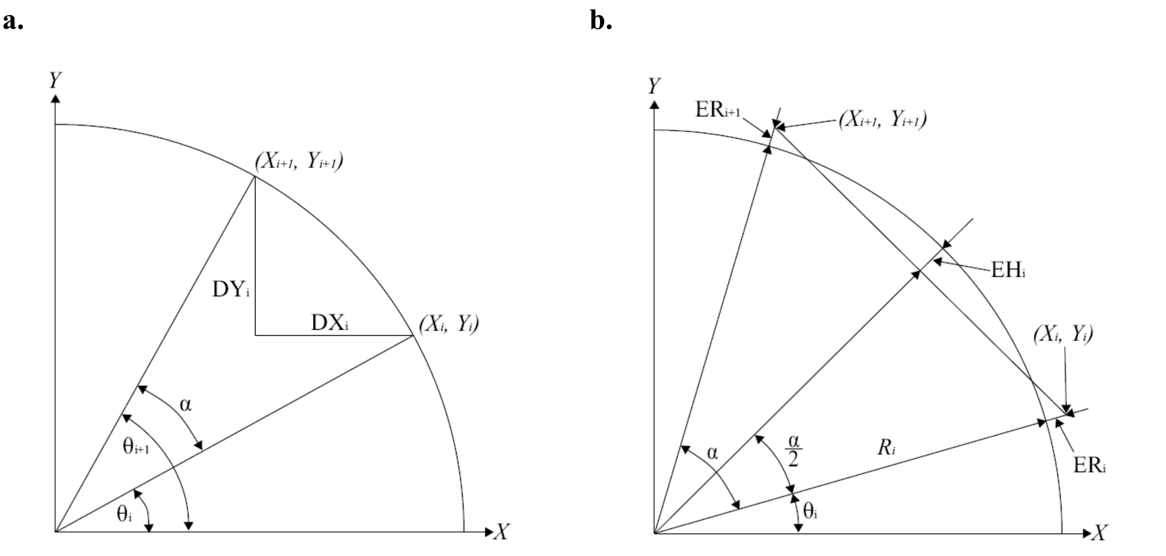


Figure 7.8: Circular Interpolation [31]

a. Interpolation of an arc
b. Radial Error and Chord Height Error

$$x(i+1) = R(i)cos\big(\theta(i+1)\big) \quad (7.8)$$

$$y(i+1) = R(i)sin\big(\theta(i+1)\big)$$

$$R(i) = \sqrt{x(i)^2 + y(i)^2} \quad (7.9)$$

The angular position of the tool tip is calculated by equation 7.10, where α is the angular increment in tool position, for each interpolation cycle. In the Improved Tustin Method α is calculated by equation 7.11 and the number of required iterations by equation 7.12.

$$\theta(i+i) = \theta(i) + \alpha \quad (7.10)$$

$$\alpha = \sqrt{\frac{16}{R-1}} \cong \frac{4}{R} \quad (7.11)$$

$$N = \frac{\theta}{4}\sqrt{R} \quad (7.12)$$

The required feed rates for the individual axes to achieve the synchronized circular motion are given by equation 7.13:

$$f_x = f\frac{x(i+1) - x(i)}{\sqrt{\big(x(i+1) - x(i)\big)^2 + \big(y(i+1) - y(i)\big)}} \quad (7.13)$$

$$f_y = f\frac{y(i+1) - y(i)}{\sqrt{\big(x(i+1) - x(i)\big)^2 + \big(y(i+1) - y(i)\big)}}$$

Once an arc has been linearized into multiple segments with individual feed rate requirements, further linear interpolation must be performed to obtain a final set of axial increments for transmission to servo control modules.

When approximating a circle by multiple linear segments two types of errors occur, these are chord height errors EH and radial errors ER (see Figure 7.8.b). These errors are calculated using equations 7.14 and 7.15:

$$ER(i) = R(i) - R = \sqrt{x(i)^2 + y(i)^2 - R} \qquad (7.14)$$

$$EH(i) = R - R(i)\cos\left(\frac{\alpha}{2}\right) \qquad (7.15)$$

7.13 After Interpolation Acc/Dec Control

a. **b.** **c.**

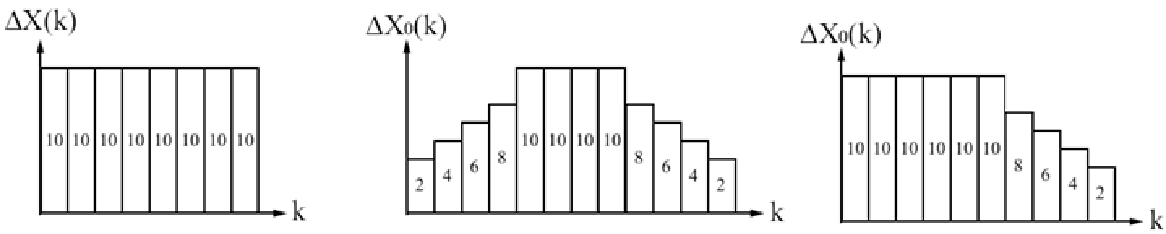


Figure 7.9: Axial Increments Before and After Acc/Dec Control [31]

a. Axial increments before Acc/Dec control
b. Axial increments after Acc/Dec control
c. Only deceleration control performed

The process of acceleration and deceleration (Acc/Dec) control must be preformed after interpolation to ensure the smooth motion of the axes. The interpolation algorithms presented in the previous section provide a steady reference of axial increments to position control algorithms as illustrated in Figure 7.9.a. The position control algorithm runs on servo control modules. A fixed reference of axial increments creates the problem of excessive acceleration at the beginning of a trajectory and causes an overshoot of the target position at the end. Acc/Dec control is performed by ramping up and ramping down the reference input to the position control algorithm, as illustrated in Figure 7.9.b.

The MRM system contained low powered motors. The execution of acceleration control was therefore omitted from the software as excessive accelerations were not a concern for this system. After interpolation the focus of the control system was exclusively on deceleration control to prevent overshoot in the target position that may be caused by inertia. The output from deceleration control only is illustrated in Figure 7.9.c. Deceleration control is performed by obtaining the sum S of the position increments for the final j interpolation cycles. This sum is then spread out over n additional interpolation cycles in a linearly receding pattern.

The sum is obtained by equation 7.16 where k_{final} is the last interpolation cycle number in the original set of axial increments:

$$S = \sum_{a=0}^{j-1} \Delta X(k_{final} - a) \tag{7.16}$$

The sum of the final j increments is used to calculate a declaration constant D that provides the linear decrement in the reference position. Equation 7.17 was used to calculate the deceleration constant for a steady original reference of ΔX.

$$D = \frac{S - \Delta X \times (j + n)}{0.5(j + n)^2} \tag{7.17}$$

The new set of reference positions including linear deceleration control is calculated by 7.18. Note that deceleration control is only applied from interpolation cycle time numbers $(k_{final} - j + 1)$ to $(k_{final} + n)$, where $k_{final} + n$ is the new number of interpolation cycles required to complete the motion of the axes.

$$\Delta X_o(k) = \Delta X + 0.5D(i^2 - (i-1)^2) \qquad (0 \le i \le j + n) \tag{7.18}$$

The final sets of axial increments are stored in a database file called "FIFO.dat". After Acc/Dec control has been performed, control is passed onto the serial communication software routine. This software routine then transmits the axial increments stored in FIFO.dat, as part of the instruction set to servo control modules.

Example

Table 7.4: Deceleration Control Performed After Interpolation

Before Deceleration Control		After Deceleration Control		
k	**ΔX (mm)**	**k**	**i**	**ΔX_o (mm)**
1	4	1	0	4
2	4	2	0	4
3	4	3	0	4
4	4	4	0	4
5	4	5	1	3.75
6	4	6	2	3.25
7	4	7	3	2.75
8	4	8	4	2.25
	0	9	5	1.75
	0	10	6	1.25
	0	11	7	0.75
	0	12	8	0.25
Total	**32 mm**			**32 mm**

As an example, consider the set of original axial increments presented in Table 7.4. For deceleration control it is decided that the sum of the final four increments are to be distributed over an additional four interpolation cycles. This brings the total number of interpolation cycles for the trajectory up to twelve. Deceleration control begins on the fifth cycle and ends on the twelfth, linearly ramping down the axial increments from 4 mm down to 0.25 mm per cycle.

$$S = \sum_{a=0}^{j-1} \Delta X(k_{final} - a) = \sum_{a=0}^{4-1} \Delta X(8 - a) = \Delta X(8) + \Delta X(7) + \Delta X(6) + \Delta X(5) = 16$$

$$D = \frac{S - \Delta X \times (j + n)}{0.5(j + n)^2} = \frac{16 - 4 \times (4 + 4)}{0.5(4 + 4)^2} = -0.5$$

Deceleration begins at cycle number: $k = k_{final} - j + 1 = 8 - 4 + 1 = 5$

Deceleration and trajectory ends at cycle number: $k = k_{final} + n = 8 + 4 = 12$

7.14 Control Protocols and Data Communication

The use of standard instruction and feedback protocols for the control of MRMs created the flexibility for mechanical and electronic control modules to be easily connected and controlled by the system. Motion modules (modular axes) were controlled using a ten byte instruction protocol. The first byte of the instruction packet is the servo control module address to which the subsequent data bytes must be routed. The second byte is used to transmit general instructions to the control module. The final pair of four bytes are instructions on the distance and the interpolation cycle time for the execution of the position control algorithm. Distances and interpolation cycle times are stored in the „C" float data type, enabling a range of values in decimals from ± (3.4×10^{-38} to 3.4×10^{38}).

A seven byte protocol was used for the feedback of information from servo control modules to the host PC. The first byte was used to address the data to the servo communication module. This was necessary as the I2C bus is a multi-master bus and the transmission of feedback to the host PC required the servo communication module to enter into slave receiving mode with a corresponding servo control module as the master. The six successive data bytes that are received by the servo communication module are then transmitted to the host PC via USB. The second byte is the address of the servo control module that is providing the feedback. This address acts as an identification number for the module.

The third byte is general feedback provided by the module. The type of feedback responses include: Instruction Complete, No Actuation and Collision at Axis Limit. The final four bytes are used to transmit the final position of the axis back to the host PC; this is used to update the position database file. Table 7.5 summarises the instruction and feed back protocols for servo control modules. The details of the "General Instruction" and "General Feedback" bytes are contained in Table 7.3 and Table E.3.1 (in Appendix E.3).

Modular cutting heads were controlled by spindle control modules, based on a single instruction byte received from the host PC. Five bytes were used for feedback to the main control program.

Spindle modules are connected directly to the host PC via USB, and required a much more compact control protocols than motion modules. Feedback values from process modules are returned in the „C" float data type. Table 7.6 summarizes the instruction and feed back protocols that were used in conjunction with spindle control modules to manage the MRM cutting heads. The details of the of the "General Instruction" and "General Feedback" bytes are contained in Table 7.3 and Table E.3.1 (in Appendix E.3).

Table 7.5: Instruction and Feedback Protocols for Servo Control Modules

Transmission of Instructions		
Sequence	**Purpose**	**Data Size**
1	Servo Control Module"s I2C Address	1 Byte
2	General Instructions	1 Byte
3	Axial Increment	4 Bytes
4	Interpolation Cycle Time	4 Bytes
Feedback		
Sequence	**Purpose**	**Data Size**
1	Servo Communication Module"s I2C Address	1 Byte
2	Servo Control Module"s I2C Address	1 Byte
3	General Feedback	1 Byte
4	Feedback Value	4 Bytes

Table 7.6: Instruction and Feedback Protocols for Spindle Control Modules

Transmission of Instructions		
Sequence	**Purpose**	**Data Size**
1	General Instructions	1 Byte
Feedback		
Sequence	**Purpose**	**Data Size**
1	General Feedback	1 Byte
2	Feedback Value	4 Bytes

7.15 Servo Communication Module: Software Routines

The servo communication module is responsible for the transmission of data between the host PC and servo control modules. Figure 7.10 places the software functions of the servo communication module into the context of the control system. The diagram also illustrates the sequence of operations performed by the servo communication module for the transmission of data. The servo communication module has four modes of operation: instruction receive mode, instruction transmit mode, feedback receive mode and feedback transmit mode.

Instruction Receive Mode

At the beginning of the execution of a new series of instructions the servo communication module is in receive mode. In this mode the main ATmega 32 chip waits for the issue of servo control instructions from the host PC. These instructions are received by the USART receiver interrupt service routine. The USART data register is eight bits and instructions are received a single byte a time. The service routine obtains the servo control instructions and places them into a character buffer. The first byte of every ten bytes received is the address of a servo control module. These addresses are registered as active by the software.

The hexadecimal number 0xFF was reserved as a flag to indicate that all instructions have been loaded. If the first byte of an anticipated ten byte sequence is found equal to 0xFF, the software routine ceases to buffer data and the servo communication module switches from instruction receive to instruction transmit mode.

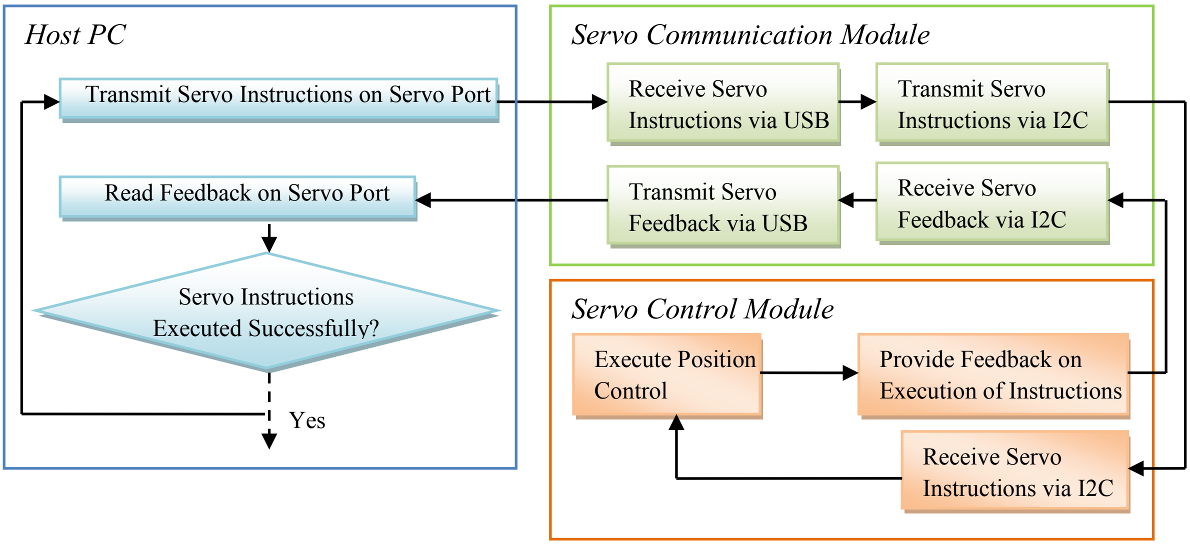


Figure 7.10: Sequence of Operations for the Transmission of Servo Instructions and Feedback

Instruction Transmit Mode

In instruction transmit mode, the software transmits the buffered servo instruction data to the respective servo control modules over the I2C bus. The transmission is initialized by the issue of a START condition on the bus. Next a seven bit slave address is transmitted and one „write" bit, indicating that a transmission of data is to occur. The servo control module that has been addressed issues an acknowledgement on the bus. The servo communication module will then continue to transmit all nine remaining instruction bytes to the servo control module. Upon completion a STOP condition is issued on the bus, and the process is repeated until all servo control modules have received their respective instructions. Once all instructions have been transferred the servo communication module issues a general call on the I2C bus. The binary address 0b0000000 is reserved for the general call, to which all modules respond, irrespective of their individual addresses. The general call is issued to begin the synchronized execution of instructions by the various servo control modules. Once the general call has been issued the servo communication module switches to the feedback receive mode.

Feedback Receive Mode

In feedback receive mode the servo communication module receives feedback from the servo control modules. Individual servo control modules transmit their respective feedback data packets to the communication module over the I2C bus. The first byte of the packet is the servo communication module"s address and a write bit. The direct addressing of the communication module is necessary to prevent other servo control modules on the bus from receiving the data. Once communication has been established the remaining six bytes of feedback are transmitted. The I2C hardware units on the ATmega 32 chips contain inbuilt bus arbitration, allowing servo control modules to transmit feedback data one at a time without interference from other modules.

The second byte received by the servo communication module is the address of the transmitter. This is cross referenced against the register of active addresses. The feedback data is stored in a character buffer and when feedback has been received from all active addresses the module switches to feedback transmit mode.

Feedback Transmit Mode

In feedback transmit mode all buffered feedback from servo control modules is transmitted to the host PC via USART and USB for analysis. Once all data is transmitted the servo communication module is switched back to instruction receive mode. The module is then ready to repeat the processes for the next set of instructions. If feedback has not been received by the host PC for a period equal to two interpolation cycle times an error report is displayed on the machine GUI.

7.16 Servo Control Modules: Software Routines

The software system on servo control modules is concerned with the execution of position control instructions that have been received from the host PC. A position control instruction is composed of an axial increment and a time for the motion to be achieved. The cycle of periodically updating these instructions is known as an interpolation cycle, and the time specified for the increment to be achieved corresponds to the interpolation cycle time. Operations associated with position control include:

- the receiving and interpretation of instructions,
- the periodic execution of the position control algorithm,
- the monitoring of encoder feedback,
- the generation of a PWM signal to H-bridge motor drivers based on the output of the position control algorithm and
- collision detection.

Position Control

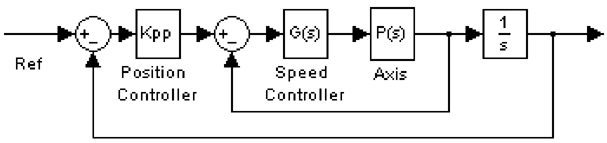


Figure 7.11: Cascade Structure for Closed Loop Servo Control

The position control of an axis is achieved by the cascaded control system of Figure 7.11. The outer loop is the position control loop while the inner loop is the speed control loop. Speed control is therefore inherent in achieving position control, and the feed rates prescribed through user programs are preserved. The efficiency of the cascaded structure for closed loop servo control depends primarily on the speed and stability of the inner control loop. A slow response on the inner loop reduces machining accuracy around circles and corners, where a rapid change in the position reference is expected.

The transfer function for a typical axis *P(s)*, is given by equation 7.19 where *K* is an electromotive constant, *J* is the moment of inertia of the mechanical system about the axis of the motor, *b* is a damping coefficient of the mechanical system, *L* is the motor inductance and *R* is the electrical resistance [73]. The values of these constants for the DC motors used in the MRM platform were unknown, but were not necessary for the control of the system.

$$P(s) = \frac{K}{(Js + b)(Ls + R) + K^2} \tag{7.19}$$

The position control loop in the system contained a proportional controller K_{pp} while a PID controller was implemented on the inner speed control loop. The transfer function of the PID controller is defined by equation 7.20, where K_p, K_i and K_d are the gains of the controller (coarse tuned by the Ziegler-Nichols method and fine tuned by trial).

$$G(s) = K_p + \frac{1}{s} K_i + sK_d \tag{7.20}$$

The controller was reduced to a discrete format for implementation in software. The z-transform of the controller was obtained by determining the z-transforms of the individual terms:

$$K_p \Rightarrow K_p \tag{7.21}$$

$$\frac{K_i}{s} \Rightarrow \frac{K_i T}{1 - z^{-1}} \tag{7.22}$$

$$K_d s \Rightarrow \frac{K_d (1 - z^{-1})}{T} \tag{7.23}$$

The transfer function of the controller in the discrete time domain is given by equation 7.24, where T is the sampling time for the control loop:

$$G(z) = K_p + \frac{K_i T}{1 - z^{-1}} + \frac{K_d (1 - z^{-1})}{T} \tag{7.24}$$

The transfer function may be written in the more convenient form of equation 7.25, where the constants K_0, K_1 and K_2 are calculated by equations 7.26-28.

$$G(z) = \frac{K_0 + K_1 z^{-1} + K_2 z^{-2}}{1 - z^{-1}} \tag{7.25}$$

$$K_0 = K_p + K_i T + \frac{K_d}{T} \tag{7.26}$$

$$K_1 = -K_p - \frac{2K_d}{T} \tag{7.27}$$

$$K_2 = \frac{K_d}{T} \tag{7.28}$$

The error e is the input to the PID controller and u is the output, therefore:

$$G(z) = \frac{u}{e} = \frac{K_0 + K_1 z^{-1} + K_2 z^{-2}}{1 - z^{-1}} \tag{7.29}$$

By manipulating equation 7.29:

$$u(n) - u(n-1) = K_0 e(n) + K_1 e(n-1) + K_2 e(n-2)$$

The output for the PID controller at the n^th^ iteration is therefore calculated by equation 7.30:

$$u(n) = u(n-1) + K_0 e(n) + K_1 e(n-1) + K_2 e(n-2) \tag{7.30}$$

By substituting the constants K_0, K_1 and K_2 into equation 7.30 the output of the controller is then given by equation 7.31:

$$u(n) = u(n-1) + K_p\big(e(n) - e(n-1)\big) + K_i T e(n)$$

$$+\frac{K_d}{T}\big(e(n) - 2\,e(n-1) + e(n-2)\big) \tag{7.31}$$

Equation 7.31 is recursive, where the output of the controller *u(n)* is dependent on the output of the previous iteration *u(n-1)*. Based on the condition that *u(0) = 0* and *e(0)=0*, equation 7.31 is further reduced:

$$u(n) = K_p e(n) + K_i T \sum_{i=1}^{n} e(i) + \frac{K_d}{T}\big(e(n) - e(n-1)\big) \tag{7.32}$$

Equation 7.32 was implemented on servo control modules for position control. The output *u(n)* was used to set the duty cycle of PWM signals to motor drivers , which ultimately regulates the speed of the motors. The variable *e(n)*, which is the input to the PID controller is calculated by equation 7.33 :

$$e(n) = K_{pp}\,.\,E(n) - \frac{\Delta X_m(n-1)}{T} \tag{7.33}$$

E(n) is the error in the existing position of an axis with regard to the reference position that is specified in position control instructions. This is calculated by equation 7.34, where *i* is the iteration number and ΔX_m is the axial increment that was measured for that iteration.

$$E(n) = Ref - \sum_{i=1}^{n-1} \Delta X_m(i) \tag{7.34}$$

The reference input *Ref*, to the position control algorithm is dependent on the type of motion required. Rapid motions are used to move a machine axis from one point to another quickly, without the observance of a target feed rate. In this instance the reference is provided by the step function of equation 7.35. For interpolated motions the program feed rate is observed and the reference is provided by the discrete ramp function of equation 7.36. Figure 7.12 illustrates both step and discrete ramp references as functions of time.

$$Ref = 0 \qquad (t < T_{step}) \tag{7.35}$$

$$Ref = \Delta X_{ideal} \qquad (t \geq T_{step})$$

$$Ref = \sum_{i=1}^{n} \Delta X_o(i) \tag{7.36}$$

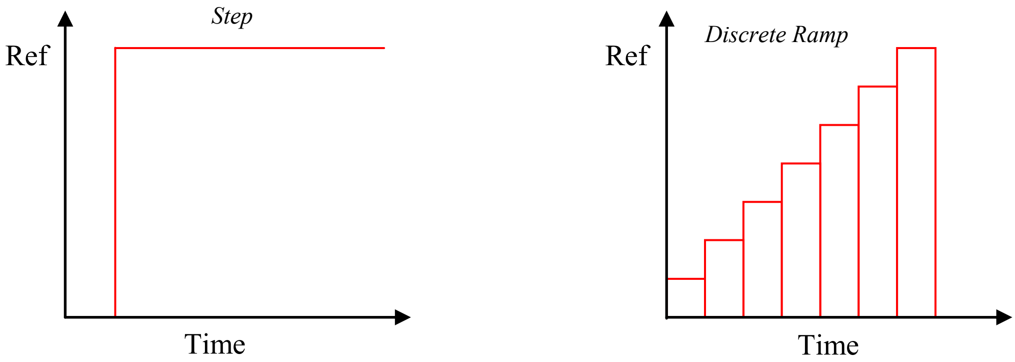


Figure 7.12: Reference to Position Control Loop

Signal Sampling

The ATmega 8L chip on servo control modules was responsible for the monitoring of feedback from position encoders. Encoder pulses were counted on an external interrupt basis and each interrupt incremented the pulse count by one. For all MRM axes, 512 pulses corresponded to one full revolution of a motor shaft. Equation 3.37 and 3.38 relate the pulse count to linear and angular increments respectively, where L is the pitch of a power screw (mm) and N is a reduction ratio.

$$\Delta X_m = L\frac{count}{512} \tag{7.37}$$

$$\Delta\theta_m = 360N\frac{count}{512} \tag{7.38}$$

Pulse counts were transmitted from the ATmega 8L chip to the ATmega 32L chip every 100 *ms* for position calculations. The position control algorithm was therefore executed every 100 *ms* upon the receiving the data. The transmission was driven by a 16-bit timer counter on the ATmega 8L chip that triggered software interrupt. The software interrupt transmitted the updated pulse count via USART.

PWM Signal Generation

The output of the position control algorithm *u(n)* was used to regulate the duty cycle of the PWM signal to H-Bridge motor drivers, thus enabling the control of motor speed and ultimately axis position. Phase and frequency correct PWM was executed on the ATmega 32L chip, by using the 16-bit timer/counter unit. The Input Capture Register (ICR) was used to set the TOP value, which defines the frequency of the PWM signal. The frequency of the PWM is calculated by equation 7.39, where N is a pre-scalar and $f_{clk\_I/O}$ is the operating frequency of the chip [67].

$$f_{PWM} = \frac{f_{clk_I/O}}{2.N.TOP} \tag{7.39}$$

The operating frequency of the chip was 4 *MHz,* which was pre-scaled by eight. The TOP value on the ATmega 32 chip was set to 10000 resulting in a PWM frequency of 25 *Hz.* The Output Compare Register (OCR1A) was used to set the duty cycle of the PWM according to equation 7.40. The equation relates the integer value of the register to *u(n)*, and K is a scaling factor. The duty cycle is then given as a percentage by equation 7.41.

$$OCR1A = K.u(n) \tag{7.40}$$

$$Duty\ Cycle = \frac{OCR1A}{TOP} \times 100\% \tag{7.41}$$

Collision Detection

Collision detection was enabled for individual axes, but not for the system at large. Individual axes contained limit switched that were connected to the external interrupt pins of the ATmega 32L chip. When a collision occurs at the end of an axis range, the limit switch generates a signal on an interrupt pin, initializing the external interrupt service routine. This routine stops the generation of the PWM signal, transmits an error message to the host PC and returns the servo control module to an inactive state ready for the receipt of further instructions.

7.17 Spindle Control Modules: Software Routines

Switching Operations

Spindle control modules activated and deactivated the motors of the MRM cutting heads via relay switches. The software routine associated with the switching operation was uncomplicated as digital speed control was omitted from the system. Two pins on the ATmega 32L microcontroller were used to activate either clockwise or anticlockwise spindle rotation. The states of the pins were varied in software by setting the related port registers to suitable values using appropriate bitwise operations.

ADC and Vibration Monitoring

Spindle control modules were responsible for monitoring the vibrations in MRM process modules during machining operations. The vibration data would ideally be used in adaptive control to alter spindle speeds and tool feed rates to reduce the vibrations to acceptable levels. The creation of adaptive control routines was out of the scope of this research and vibration data was collected only for display on the user interface. A practical analysis of mechanical vibrations in MRMs was also out of the scope of this research (theoretical analysis in Section 5.12). The inclusion of a vibration monitoring system was only to reinforce the principle of diagnosability in MRMs.

The output channels of the ADXL204 dual-axis accelerometer were connected to the Analogue to Digital Converter (ADC) terminals of the local ATmega 32L microcontroller board. Only the axis and channel of interest was connected by manually configuring the electrical connections to the microcontroller. The reading of an ADC port was initialized by a 16-bit timer on the chip, and measurements were obtained at a frequency of 100 Hz. The ADC hardware converted the analogue input voltage to a 10-bit value through successive approximation [67]. The acceleration a of an axis was calculated by equation 7.42, where g is gravity, n is the number of bits dedicated to the ADC, V_{ref} is the ADC reference voltage and V_{nom} is the nominal voltage of the accelerometer.

$$a = g\left(V_{ref}\frac{ADC\_Ouput}{n^2} - V_{nom}\right) \tag{7.42}$$

The accelerations on an axis were converted into an absolute value M. The maximum magnitude registered in a one second cycle was then transmitted to the host PC for update on the user display.

The transmission was triggered by the same software interrupt the initializes the reading of the ADC ports (maximum magnitude per 100 readings = maximum magnitude registered in one second). The data was transferred to the host PC via USART and USB.

Appendix F.5 contains a sample graph of accelerometer measurements obtained from the drilling head, when the spindle was unloaded and allowed to rotate at maximum speed (approximately 580 rev/min).

7.18 Chapter Summary

This chapter presented the software system that was created for MRMs. The focus of the software implementation was on hardware abstraction to minimize the reconfigurability required at a software level. Hardware abstraction was achieved by the definition of control and communication protocols and the appropriate distribution of generic and module specific software functions between the host PC and distributed control drives. Matters of user programming and reconfiguration were addressed and a complete overview of the software system was provided. The algorithms that were implemented on the host PC and control drives were also presented.

8. System Assembly and Performance

8.1 System Assembly and Reconfiguration: An Overview

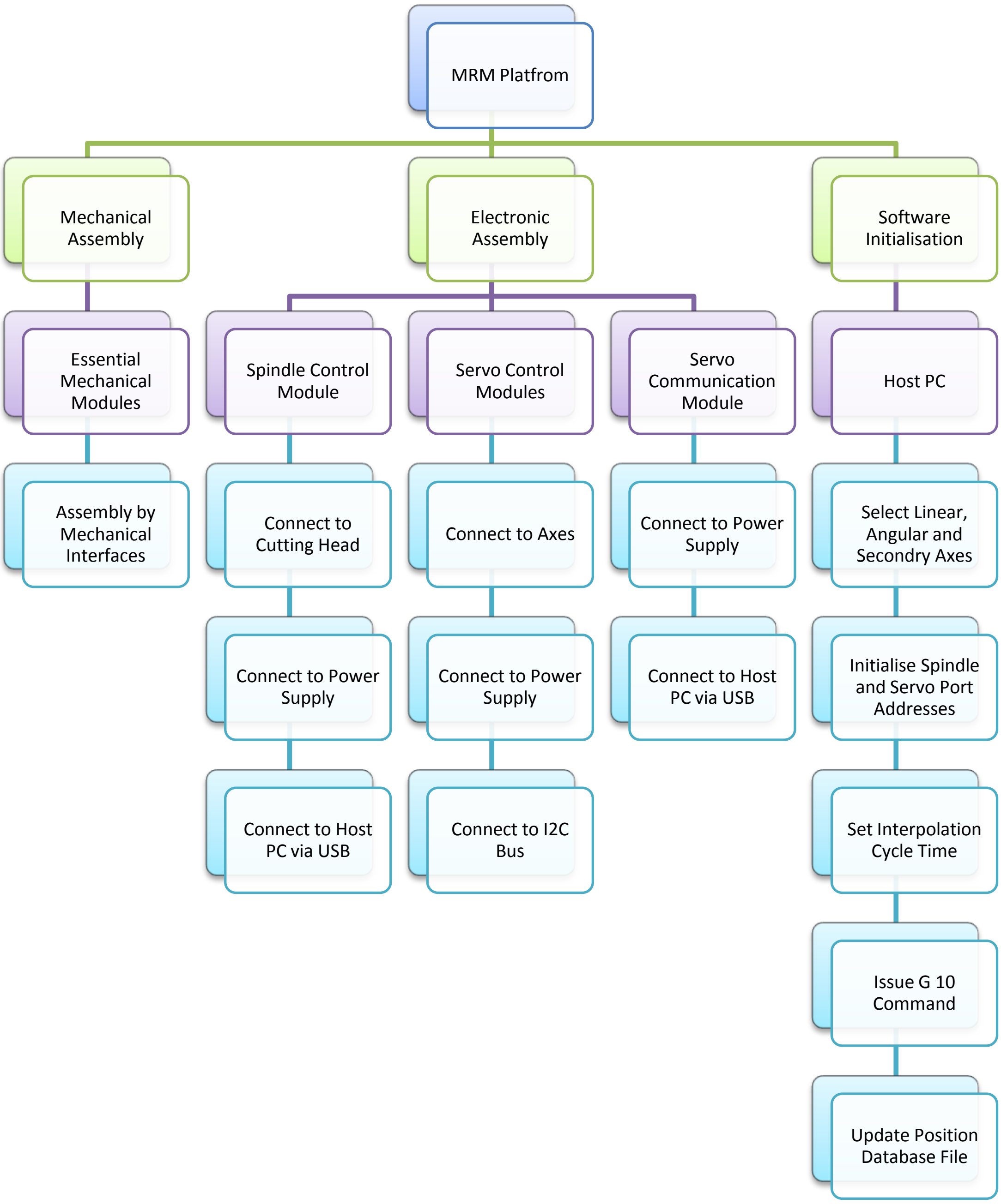


Figure 8.1: A Complete Overview of the MRM Assembly/Reconfiguration Procedure

The assembly of an MRM platform begins with a description of the product that is to be machined. Section 5.8.1 presented a methodology based on the research of Moon and Kota [42], whereby information on the desired tool trajectory is used to identify the essential mechanical modules for the assembly of a kinematically viable machine tool. Once the modules have been identified they are assembled by means if a series of standardized bolted interfaces.

All MRM platforms contain one process module (cutting head), and require a single spindle control module to manage its operation. The spindle control module is connected to the cutting head by means of the standard power and control interfaces: an eight wire connection for DC modules, and an eleven wire connection for AC modules. The spindle control module is then connected to the power supply system and finally to the host PC via USB.

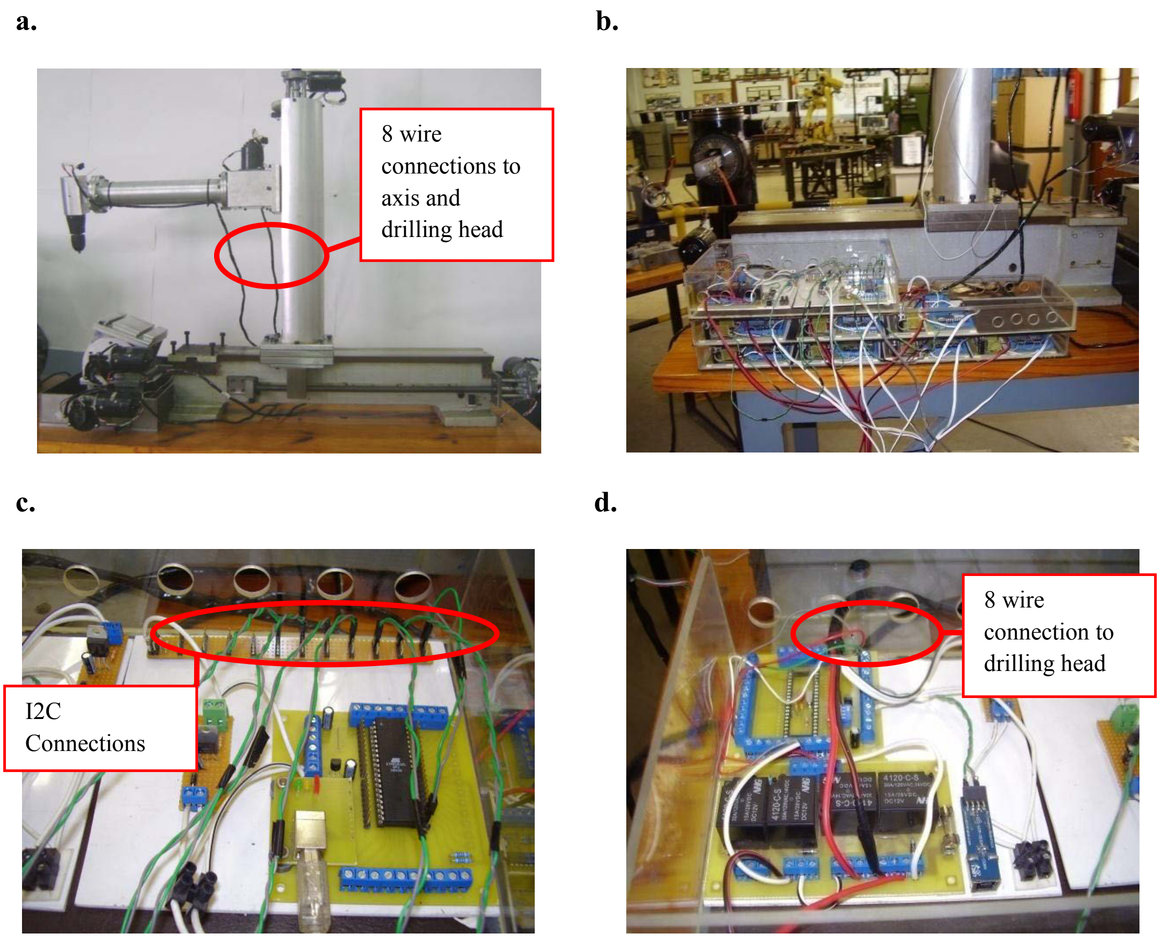


Figure 8.2: Mechanical and Electronic Assemblies

a. Assembled mechanical system showing power and control connections to modules
b. Assembled electronic control system
c. Servo communication module showing connections to I2C network
d. Spindle control module showing incoming eight wire connection form drilling head

Each axis in a MRM requires a servo control module to manage its operation and only the exact number needed should be present on a platform. Servo control modules connect to their respective mechanical modules by means of an eight wire power and control connection. Once connected, servo control modules are then connected to the DC power supply system. Servo control modules are finally plugged into the I2C bus, with the physical connection points being present on an associated servo communication module. All MRM configurations contain at least one servo communication module. The communication module is connected to the power supply system, and interfaced with the host PC via USB, during assembly. Figure 8.2 illustrates aspects of the mechanical and electronic assembly.

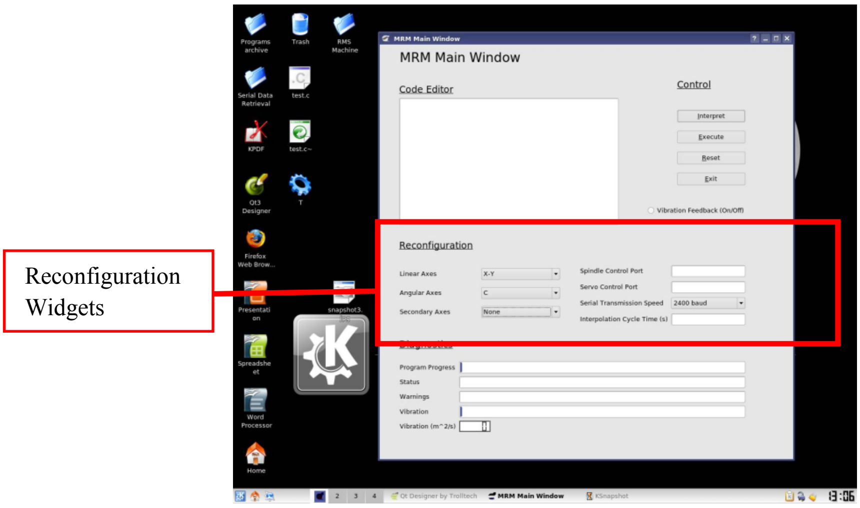


Figure 8.3: Initialization of Machine Configuration on Host PC

After the complete assembly of the mechanical and electrical systems the user is required to reconfigure the active NC command set. This is achieved by selecting the axes configurations from drop down menus on the machine GUI illustrated in Figure 8.3. Thereafter the USB addresses of the servo and spindle ports are set and an interpolation cycle time is specified for the machine. Prior to user programming the G10 command must be entered in the code window and executed. This command causes all axes to move to their respective home positions. The position of the machine spindle relative to the work table is then calculated and manually entered into the position database file, thus enabling absolute programming. This completes the assembly of the platform. During MRM reconfiguration, the procedure is the same as the assembly procedure outlined in Figure 8.1; however individual stages that are not necessary may be omitted. A new MRM configuration must always be initialized in software before operation.

8.2 Pairing of Mechanical and Control Modules

Servo and spindle control modules match to mechanical modules on a 1:1 basis. During MRM assembly, control modules are paired with mechanical modules and those pairs must be maintained throughout successive reconfigurations. Although generic servo and spindle control programs were implemented on distributed control drives, these programs require module specific information to complete their respective functions. For example a servo control module would contain information on the mechanical ratios (gear ratios, screw pitch, etc) of a module as well as PID tuning constants. The ATmega 32L microcontrollers on servo and spindle control modules are programmed with module specific information and if a control module is to be used to manage a different unit of mechanical hardware, the microcontroller must be swapped or reprogrammed with the correct data.

8.3 Machine Calibration

MRMs are reconfigured by the addition and removal of mechanical modules from a platform. To ensure a swift system ramp-up after reconfiguration, techniques must be employed for process debugging and optimization. For tool positioning errors, a kinematic calibration of the machine tool is required.

Machine Calibration typically requires the following steps:

(i) **Modelling**: mathematical model that describes the machines geometry and motion.
(ii) **Measurement**: of the tool position in the workspace.
(iii) **Identification**: understanding the relationship between axial positions and the tool position.
(iv) **Compensation:** implementing the modified control program to ensure accurate task completion.

The mathematical model of a machines geometry and motion is encapsulated in its homogenous transformation matrix. The measurement of the tool or spindle position in the workspace is achieved by traditional laser measurement techniques that are already used in CNC calibration procedures. The discrepancy between the measured tool position and the ideal tool position may be resolved into a set of linear and angular offsets. These offsets are related to individual axes and the true position of an axis is reprogrammed on its associated servo control module.

8.4 System Performance Criteria and Errors

The performance of a machine tool is primarily evaluated with regard to spindle power and the accuracy, repeatability, maximum torque and maximum speed of its axes. The power, torque, speeds and other loading specifications for MRM modules were presented in Chapter 5. This chapter focuses on the performance of the MRM positioning systems for dynamic accuracy, as well as static accuracy and repeatability. An MRM positioning system consists of:

- the host PC which provides position instructions,
- the servo communication module which facilitates the transmission of instructions and enables the synchronized execution of these instructions,
- servo control modules which execute the position control algorithm and
- mechanical axes (motion modules), which position the cutting tool relative to the work part.

The accuracy and repeatability of a machine tool is dependant on the first order mechanical errors and control errors that are introduced during the positioning of the cutting tool. First order mechanical errors are a result of static deflections in the machine structure, errors that have been introduced due to the inaccurate assembly of the machine, backlash between mechanical components and thermal errors. Second order mechanical errors are a result of the dynamic interaction of the cutting tool with the work piece and generally affect the surface finish of a machined part.

Control errors are composed of truncation errors, linearization and tracking errors. Truncation errors are introduced by the limitation of measurement systems and rounding off during calculations. On MRMs truncation errors were introduced by the necessity to reduce axial increments to discrete pulse counts to be achieved by individual axes. Pulse counts are an integer value and the remainder is truncated. The truncation errors on MRMs were therefore limited in size to the increment associated with a single pulse count. This increment is often referred to as the Basic Length Unit (BLU) of an axis.

Linearization errors are a result of the linear approximation of curves. The chord height error and radial error are two particular errors that are characteristic of circular interpolation. The chord height error is an inherent error in the circular interpolation algorithm and its value is an indication of the maximum deviation of the reference path generated by the interpolator, as compared to the ideal tool path. The radial error is in indication of the difference in radii between the measured tool path and an ideal arc. The radial error is also an inherent error in the linear approximation; however when it is computed at the start and end positions of a linear segment it is reflective of a truncation error.

Tracking errors are errors between a reference trajectory and the actual axis/tool trajectory. These errors are a result of the incorrect tuning of the control algorithm, inertia in the mechanical system, uneven friction in slides and irregular loading. These errors are particularly prominent during the acceleration and deceleration of an axis. The effect of tracking errors is overshoot in the target position and a general discrepancy between the ideal and actual position of the cutting tool at time t.

The final significant factor with regard to machine performance is the ability of the positioning system to maintain calibration. A drift in machine calibration occurs due to backlash between mechanical components and the cumulative effect of uncertainty in position measurements. This uncertainty is inherent in measurement systems as the smallest measurable increment in position is limited to one BLU. Calibration errors are characterized by high repeatability and poor accuracy in the positioning system.

8.5 Control Performance: Interpolated Motion

Interpolated motions are motions where reference to the speed control algorithm is incremented by ΔX or $\Delta\theta$ in each interpolation cycle, resulting in a discrete ramped input to the position control algorithm. The objective of this mode of control is to achieve the user prescribed feed rate for the cutting tool. The performance of individual axes for interpolated motions was investigated.

Statistical tools that were used in the analysis included an evaluation of the average value of a set of measurements and the standard deviation. The average and standard deviation of a set of measurements are calculated by equations 8.1 and 8.2 respectively, where x is a generic variable, n is the number of measurements and s is the standard deviation.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{8.1}$$

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{8.2}$$

Linear Axes (Dynamic Analysis)

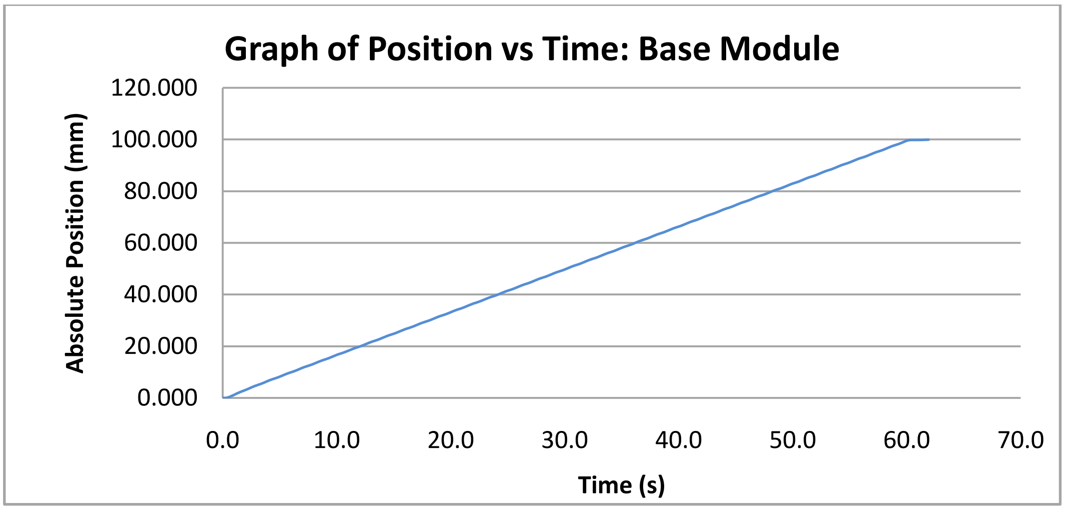


Figure 8.4: Graph of Position vs Time: Base Module (+X Direction)

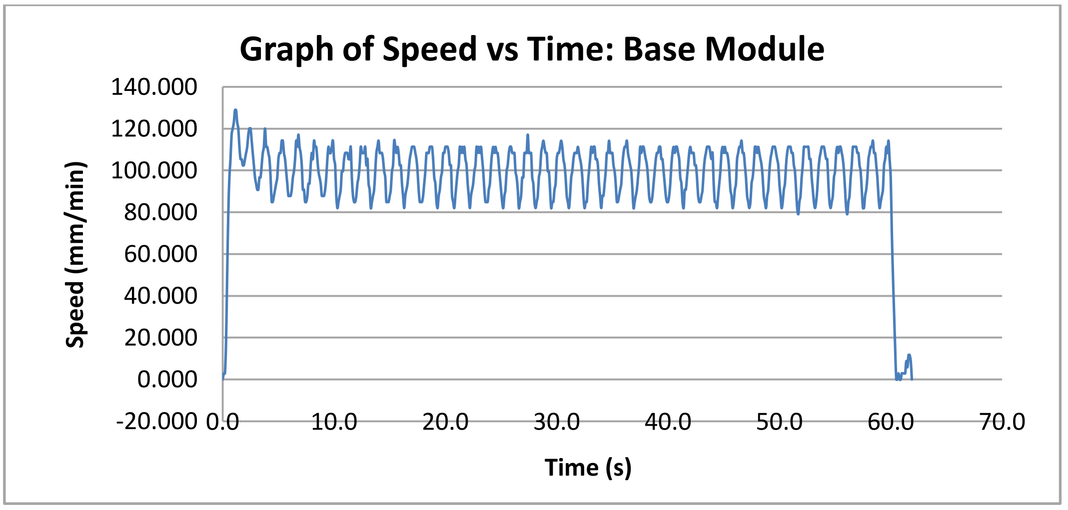


Figure 8.5: Graph of Speed vs Time: Base Module (+X Direction)

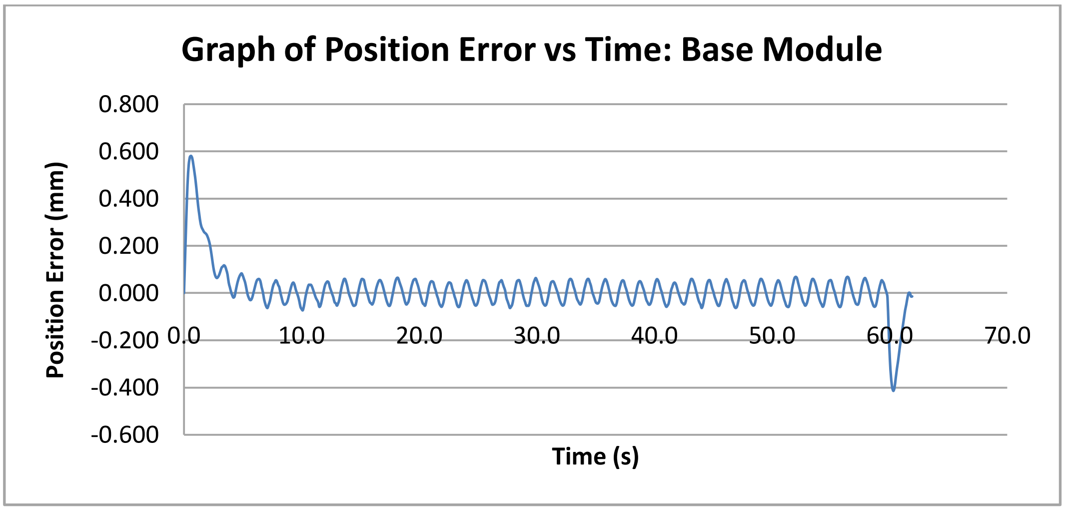


Figure 8.6: Graph of Position Error vs Time: Base Module (+X Direction)

The dynamic performance of the linear axes was investigated for interpolated motion. The graphs presented in Figures 8.4-6 demonstrate the performance of the base module. The interpolation was performed for a distance of 100 mm at an axis feed rate of 100 mm/min. This feed rate was selected for testing as it is the original upper speed specification for linear modules (see Section 4.3). Furthermore it is at higher end of the axis speed range (not the highest speed) and errors are prominent in the accelerated and decelerated regions of the trajectory. Figure 8.4 illustrates the measured position of the axis with regard to time. Figure 8.5 illustrates the measured speed of the axis with regard to time. The speed of the axis oscillated about the reference speed of 100 mm/min. The average speed of the trajectory was 100.15 mm/min with a standard deviation of 10.31 mm/min.

An uneven friction characteristic displayed by the module drive mechanism is the primary cause of the oscillations. The number of oscillations in the curve of Figure 8.5 is equal to the number of power screw revolutions that were required to complete the movement, confirming that the origin is in the mechanical system and not instability in the control system. Figure 8.6 illustrates the position error of the axis (tracking error) with regard to time, where the position error E_p, at interpolation cycle *i,* is defined by equation 8.3. The highest position errors occurred in the accelerated and decelerated regions of the trajectory. These errors were 0.58 mm and -0.41 mm respectively.

$$E_p(i) = \sum_{i=1}^{n} \Delta X_o(i) - \sum_{i=1}^{n} \Delta X_m(i) \qquad (8.3)$$

The test data that was used to generate Figures 8.4-6 is located in Appendix F.6. The performance graphs of other linear axes are also located in Appendix F. Please not that **only a sample** of the test data collected during testing is located in this appendix due to the extensive amount of data that was collected; the test data for other axes is located on the supplementary DVD.

Table 8.1: Speed Control Performance of Linear Modules for Interpolated Motion

Module	Program Speed (mm/min)	Distance (mm)	Average Speed (mm/min)	Avg Speed / Prog Speed	Std Dev: Speed (mm/min)
Base	100	+100	100.15	100.15%	10.31
	100	-100	97.89	97.89%	14.16
	25	+100	23.40	93.60%	4.38
	25	-100	23.42	93.68%	2.63
Work Table Slide	100	+100	96.66	96.66%	21.26
	100	-100	96.01	96.01%	22.45
	25	+100	24.49	97.96%	4.87
	25	-100	24.61	98.44%	3.82
Column	100	+100	96.49	96.49%	18.54
	100	-100	94.47	94.47%	16.94
	25	+100	24.61	98.44%	4.21
	25	-100	24.63	98.82%	4.09
Cross Slide Module	100	+50	96.82	96.82%	13.92
	100	-50	94.95	94.95%	19.25
	25	+50	23.34	93.36%	2.20
	25	-50	23.22	92.88%	2.38

Tables 8.1 and 8.2 summarize the performance of all linear axes in the MRM module library for interpolated motion. Table 8.1 presents data on the performance of linear axes with regard to speed control for higher and lower speeds. The average speeds of the axes were computed for the specified distances. For speeds of 100 mm/min the axes exhibited an average speed that was in a range of 94.47% to 100.15% of the program speed. At the slower speed of 25 mm/min the axes exhibited an average speed of 92.88% to 98.82% of the program speed. Deviations from the user specified speeds are inevitable due to axis acceleration and deceleration. The execution of deceleration control on the MRM platform is an example of an intentional and controlled deviation from the user specified speed. Deviations from the program speed are also caused by the controller compensating for errors such that the target position is achieved in precedence to the prescribed feed rate.

All linear axes displayed an oscillation in speed during operation. The standard deviation represents the average amplitude of these oscillations with regard to the average speed. The standard deviation of the axes speeds is significantly higher at increased speeds. For a program speed of 100 mm/min the standard deviation was in a range of 10.31 mm/min to 22.45 mm/min, while for a program speed of 25 mm/min the standard deviation of the axes speeds was in a range of 2.20 mm/min to 5.87 mm/min. The oscillations exhibited in the speed and position error graphs for all linear axes was attributed to an uneven friction characteristic in the drive mechanisms (see Appendix F.1). The standard deviation may be reduced with the use of higher quality power screws in linear axes as opposed to the low cost ISO metric threaded bar that was used in the present design.

The motors used in the axes were generally underpowered and exhibited rise times in excess of 500 ms when accelerating to target speeds. The lower torques exhibited by the motors at higher speeds contributed to greater deviations from the program feed rate at these speeds.

Table 8.2: Position Control Performance of Linear Modules for Interpolated Motion

Module	Program Speed (mm/min)	Distance (mm)	Max Pos Error (mm/min)	Avg Pos Error (mm/min)	Final Pos Error (mm)
Base	100	+100	0.581	0.053	-0.015
	100	-100	0.439	0.040	-0.015
	25	+100	0.186	0.017	-0.015
	25	-100	0.112	0.011	-0.020
Work Table Slide	100	+100	0.527	0.082	-0.023
	100	-100	0.527	0.089	-0.018
	25	+100	0.158	0.033	0.000
	25	-100	0.182	0.037	-0.012
Column	100	+100	0.586	0.077	-0.023
	100	-100	0.633	0.070	-0.006
	25	+100	0.187	0.030	-0.023
	25	-100	0.211	0.032	-0.018
Cross Slide Module	100	+50	0.453	0.116	-0.023
	100	-50	0.359	0.035	-0.086
	25	+50	0.156	0.007	-0.020
	25	-50	0.148	0.008	-0.008

Table 8.2 presents data on the performance of position control for interpolated motion. The maximum position errors occurred consistently in the accelerated regions of individual trajectories. The maximum position errors for program speeds of 100 mm/min were in a range from 0.0359 mm to 0.633 mm, while for program speeds of 25 mm/min the maximum position errors for individual trajectories were in a range from 0.112 mm up to 0.211mm.

The magnitude of the maximum position errors at the higher speed are attributed to the slow acceleration exhibited by the drive motors. These errors may be reduced by the implementation of higher powered, geared servo motors. The average position errors for individual trajectories were computed as an average of the magnitude (absolute value) of individual position errors during a trajectory. At the higher speed the average position errors for individual trajectories were in a range from 0.035 mm up to 0.116 mm. For the lower speed these errors were in a range from 0.007 mm up to 0.037 mm.

The errors in the final position of the axes at the end of an interpolation were in similar ranges for both lower and higher speeds. These errors are negative indicating that an overshoot of the final target position has occurred. The errors in the final position for individual trajectories were in a range from 0.000 mm up to 0.086 mm. Note that all the errors that have been presented thus far have been determined from data that has been extracted from the control system, this data does not account for mechanical errors.

Rotary Axes (Dynamic Analysis)

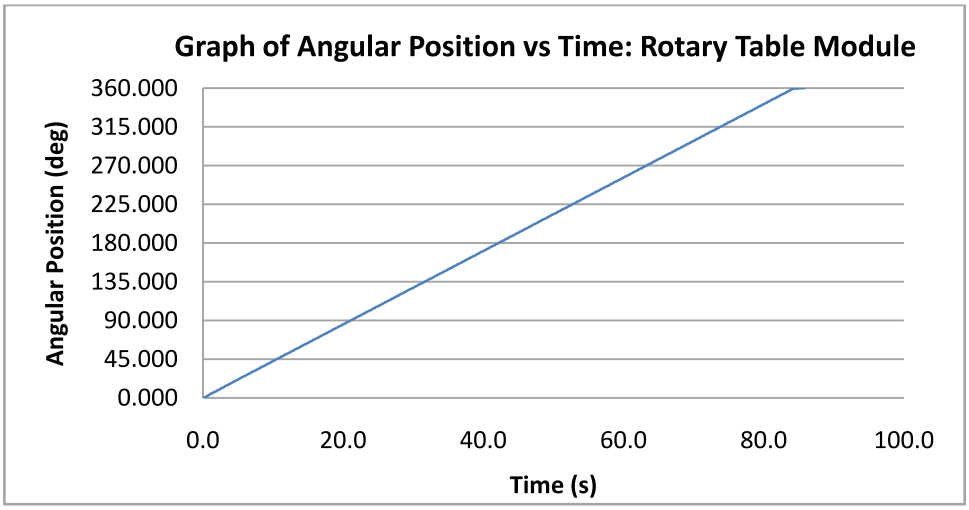


Figure 8.7: Graph of Angular Position vs Time: Rotary Table Module (+C/α Direction)

An investigation of the dynamic performance of rotary axes was performed for interpolated motion. Figures 8.7–9 provide a sample of the performance curves for position control, speed control and position errors generated from the testing of rotary axes. These figures illustrate the performance of the rotary table module for an interpolation of 360^{o} at a target speed of 0.75 rev/min. For this interpolation the rotary table achieved an average speed that was 93.73% of its program speed with a standard deviation of 0.086 rev/min. The maximum error in angular position was 0.086^{o} which occurred in the deceleration phase of the trajectory as illustrated in Figure 8.9. Sample data and the performance graphs of other rotary modules are located in Appendix F2 and F6.

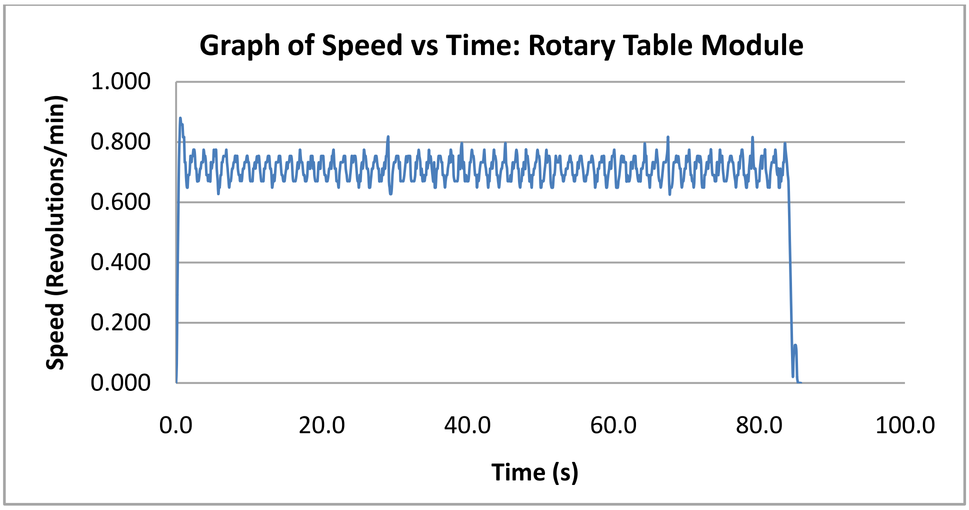


Figure 8.8: Graph of Speed vs Time: Rotary Table Module (+C/α Direction)

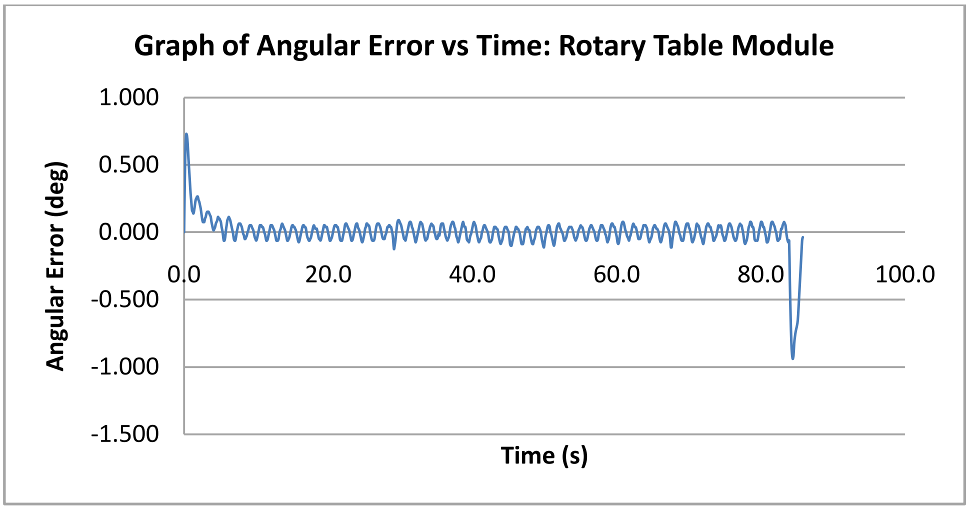


Figure 8.9: Graph of Angular Position Error vs Time: Rotary Table Module (+C/α Direction)

Tables 8.3 and 8.4 summarize the results of individual performance tests on all rotary modules. It should be noted that the performance results provided are only for a single speed per module, as position errors have already been shown to increase with an increase in reference speed, particularly in the acceleration and deceleration regions of a trajectory.

Table 8.3: Speed Control Performance of Rotary Modules for Interpolated Motion

Module	Program Speed (rev/min)	Angle (Degrees)	Average Speed (rev/min)	Avg Speed / Prog Speed	Std Dev: Speed (rev/min)
Cutting Head Rotary	10	+360	8.973	89.73%	2.680
	10	-360	9.109	91.09%	2.516
Tilt Table	15	+90	10.798	71.99%	6.584
	15	-90	10.076	67.17%	7.042
Rotary Table	0.75	+360	0.703	93.73%	0.086
	0.75	-360	0.700	93.33%	0.093

The cutting head rotary module and the tilt table module both possessed direct drive mechanisms, while the rotary table module was driven via a reduction gearbox. A reduction gearbox was necessary in the rotary table module as the axis of motor shaft was perpendicular to the axis of rotation on the module's moving interface. An already available worm gearbox was used in the module to reduce development costs and the reduction ratio limited the maximum rotary speed of this module to 1.07 rev/min. The tilt table module and the cutting head rotary module were both capable of speeds of 60 rev/min, however program speeds of greater than 10 rev/min to 15 rev/min resulted in excessive position errors in interpolated motions. For a program speed of 10 rev/min, the cutting head rotary module achieved an average speed in the region of 90% of its target speed. The standard deviations of 2.680 rev/min and 2.515 rev/min for clockwise and anti-clockwise motion both indicate an uneven friction characteristic in the module's mechanical system.

The tilt table module displayed significantly greater standard deviations in its speed characteristics and only achieved average speeds in the region of 70% of the target speed. Both the cutting head rotary and tilt table modules displayed a "slip-stick" effect in the reaction of the axes to friction. The "slip-stick" effect in the axes indicated that the drive motors did not possess sufficient torque for a direct drive system. On the contrary the rotary table module displayed a low standard deviation in its speed, as this module possessed the advantage of torque amplification which resulted in a relatively smooth trajectory.

Table 8.4: Position Control Performance of Rotary Modules for Interpolated Motion

Module	Program Speed (rev/min)	Angle (Degrees)	Max Pos Error (Degrees)	Avg Pos Error (Degrees)	Final Pos Error (Degrees)
Cutting Head Rotary	10	+360	14.766	5.698	-0.703
	10	-360	12.656	5.742	-0.703
Tilt Table	15	+90	11.250	6.228	-1.406
	15	-90	12.656	6.797	-0.703
Rotary Table	0.75	+360	0.942	0.062	-0.083
	0.75	-360	0.804	0.061	-0.063

The "slip-stick" effect in addition to the low acceleration of the drive motors resulted in large maximum and average position errors for the cutting head rotary module and the tilt table module. The lower operating speed and higher torque of the rotary table resulted in a drastic difference in the positioning accuracy of this axis as compared to the other modules. At increased program speeds the effect of poor acceleration is more pronounced in position accuracy. The cutting head rotary module and tilt table module both possessed direct drive mechanisms and which ultimately made them difficult to control at speeds lower than 5 rev/min. The advantage of improved position control at low speeds was therefore not realized with these modules.

The cutting head rotary module and tilt table module displayed errors in the region of -0.703^{o} to -1.406^{o} in their final positions. These errors are relatively small compared to the errors exhibited during the motion of the axes. This indicated that the system was still effective in stopping the axes once the required encoder pulse counts had been achieved.

8.6 Control Performance: Rapid Point to Point Motion Control

Tests were performed to determine the accuracy of individual axes for point to point motion control. In point to point motion control the axes are moved rapidly to target positions without observing a target feed rate. The objective is to move the axes to the programmed positions as quickly and as accurately as possible. The position control software on servo control modules limited the maximum reference input to the cascade control loop, resulting in axes displaying linearly incrementing position characteristics over larger movements in distance. Figures 8.10 and 8.11 illustrate the position control characteristics for the base module and cutting head rotary module. The sample characteristics illustrate a highly linear profile for the 40 second trajectory of the base module, while a s-shaped characteristic is displayed for the 1.8 second trajectory of the cutting head rotary module.

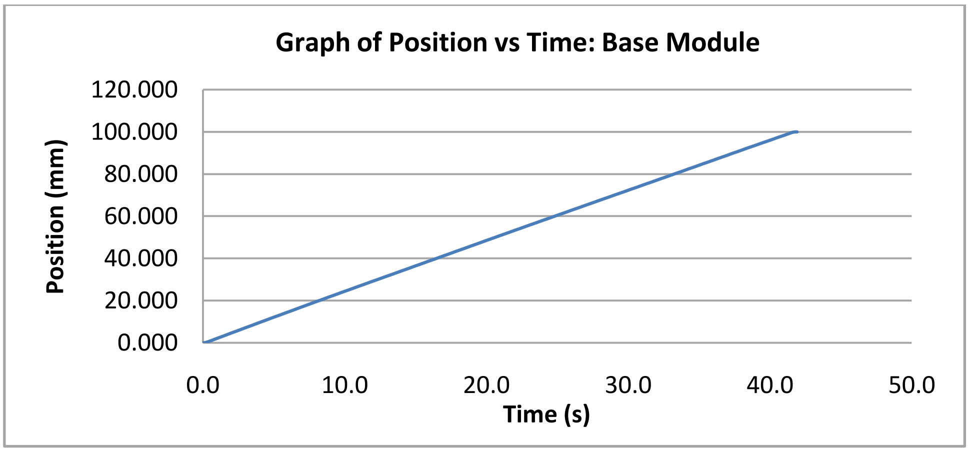


Figure 8.10: Graph of Position vs Time, Point to Point Control of Base Module (+X Direction)

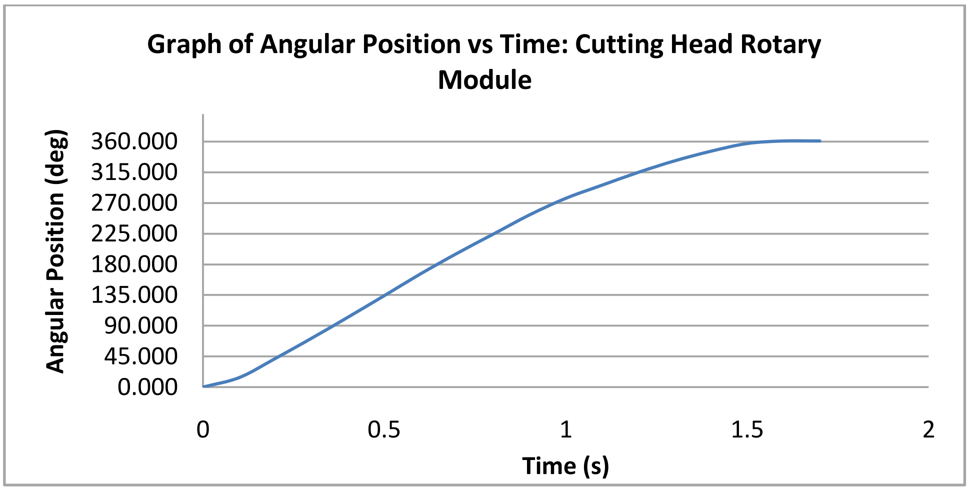


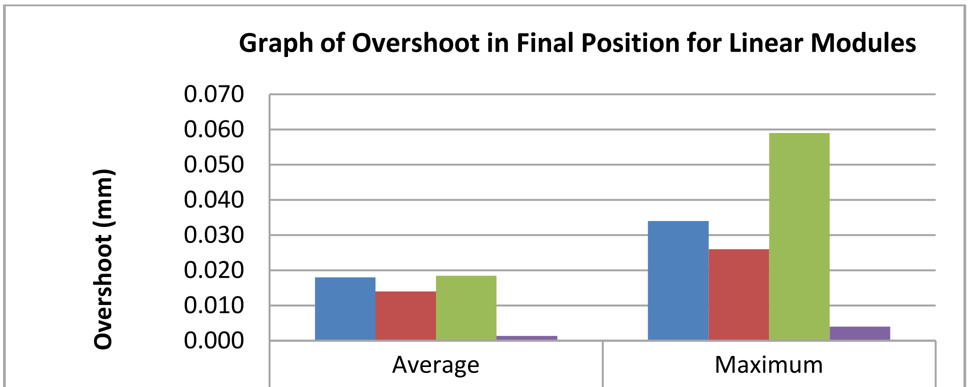
Figure 8.11: Graph of Position vs Time, Point to Point Control of Cutting Head Rotary Module (+A/γ Direction)

The position control software was designed to continue the execution of the control algorithm until a position equal to the target position was achieved or an overshoot of the target position had occurred. Position control errors were therefore always overshoot errors. The H-Bridges used to drive the motors could not provide a rapid change in the direction of motor rotation, and the position control loop was not used to compensate for the overshoot.

Figures 8.12 and 8.13 demonstrate the average and maximum position errors for rapid point to point motion motions in linear and rotary axes respectively. The position errors were calculated by equation 8.4 which determines the difference between the reference position provided by the control system and the position obtained from encoder measurements.

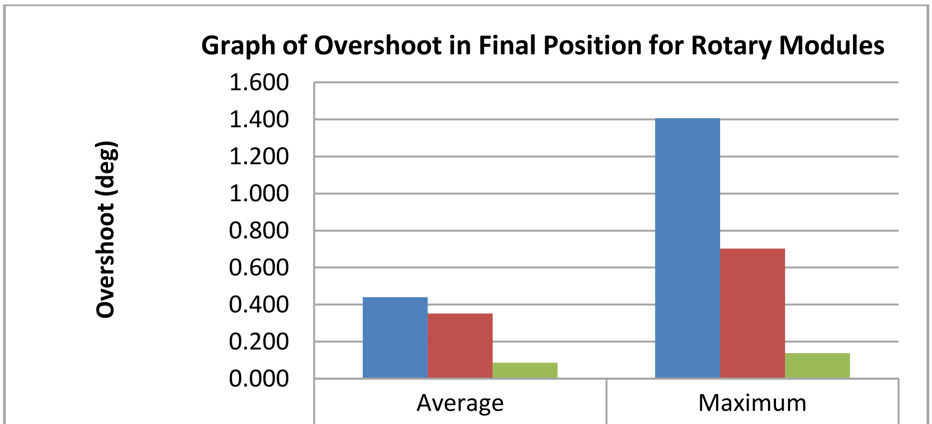
$$E_p\left(t_{final}\right) = \Delta x_{ideal} - \Delta x_{measured} \tag{8.4}$$

The graphs have been generated from eight tests being performed on individual axes across various distances. Refer to Appendix F.3 to locate the data from individual tests, note that this data has been obtained from the control system and does not account for mechanical errors.



	Average	Maximum
Base	0.018	0.034
Work Table Slide	0.014	0.026
Column	0.019	0.059
Cross Slide	0.001	0.004

Figure 8.12: Graph of Overshoot in Final Position for Point to Point Control of Linear Axes



	Average	Maximum
Cutting Head Rotary	0.439	1.406
Tilt Table	0.352	0.703
Rotary Table	0.086	0.138

Figure 8.13: Graph of Overshoot in Final Position for Point to Point Control of Rotary Axes

Tests were performed on linear axes across distances of 25 mm up to 100 mm. The distribution of the overshoot errors showed no specific trend with increases in distance. The overshoot of an axis depended primarily on the inconsistencies of localized friction characteristics close to the target position. The maximum overshoot recorded for a linear axis was 0.059 mm by the column module, while the base module displayed the highest average overshoot error of 0.018 mm. The smallest errors were displayed by the cross slide module, which displayed the smoothest motion from all linear modules due to higher quality in its manufacturing. The cross slide module was a retrofitted commercially acquired unit of hardware.

Tests on rotary axes were performed for rotations of 45^o up to 360^o. The highest overshoot error of 1.406^o was registered by the cutting head rotary module; which also displayed the highest errors on average. The rotary table module possessed a reduction gearbox and operated at relatively low speeds, it therefore displayed the smallest overshoot errors on average.

8.7 Control Performance: Synchronized Motion

Linear Paths (Dynamic Analysis)

An investigation was performed to determine the combined accuracy for the synchronized motion of two axes. The synchronization of axes was performed by the servo communication module, which issued a synchronized start to axes by means of a general I2C call. Figure 8.14 illustrates the resultant position error from the synchronized motion of the base module and work table slide module in a MRM drilling configuration. The axes were required to move the drill spindle across a linear trajectory of 100 mm at a combined feed rate of 100 mm/min (G-code: F100 X70.71 Y70.71). The resultant error from the trajectory was calculated by equation 8.5. The equation does not account for mechanical errors and only presents the error from the perspective of the control system (tracking error).

$$E_{res}(i) = \sqrt{\left(\sum_{i=1}^{n} \Delta X_o(i)\right)^2 + \left(\sum_{i=1}^{n} \Delta Y_o(i)\right)^2} - \sqrt{\left(\sum_{i=1}^{n} \Delta X_m(i)\right)^2 + \left(\sum_{i=1}^{n} \Delta Y_m(i)\right)^2} \quad (8.5)$$

The maximum resultant error in the position of the drill spindle was 0.429 mm and the trajectory was completed with an average position error of 0.069 mm. The average was computed on the magnitude (absolute value) of the errors.

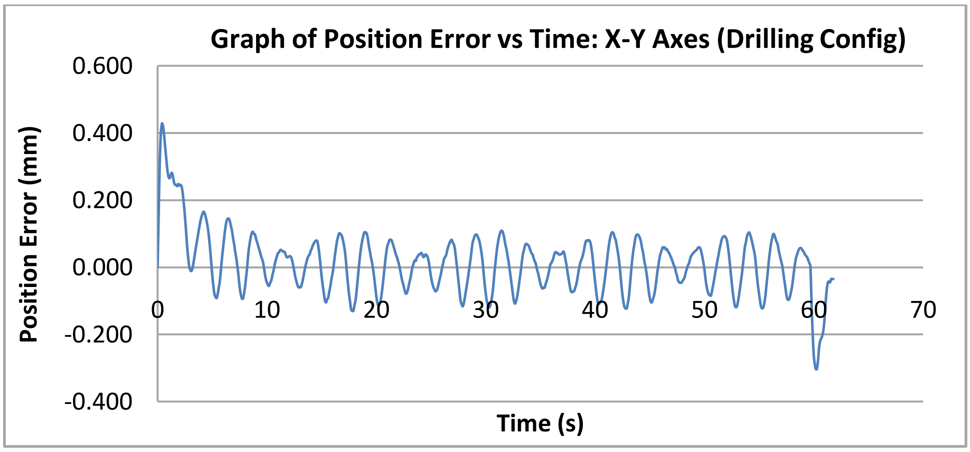


Figure 8.14: Graph of Position Error (Drill Spindle) vs Time, Resultant Position of X and Y Axes

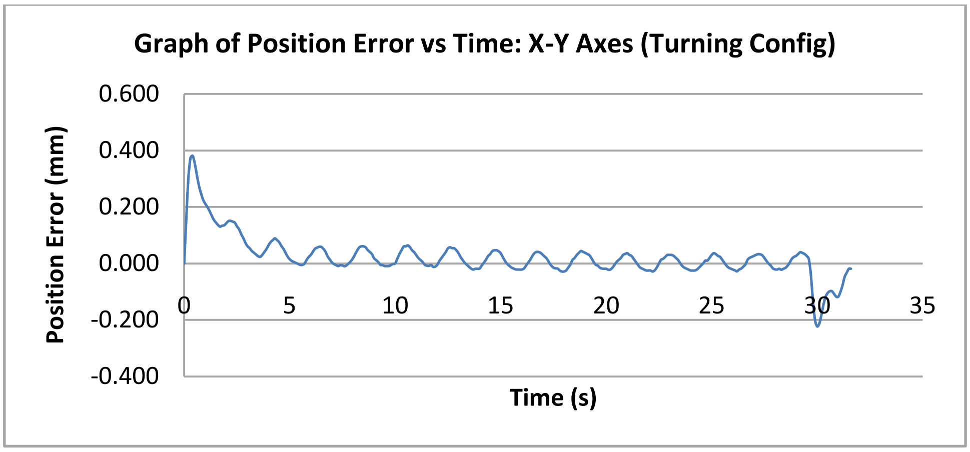


Figure 8.15: Graph of Position Error (Tool Post) vs Time, Resultant Position of X and Y Axes

Figure 8.15 illustrates the resultant position error from the synchronized motion of the base module and cross slide module in the MRM turning configuration. The axes were required to move the tool post (and tool) across a linear trajectory of 50 mm at a combined feed rate of 100 mm/min (G-code: F100 X35.36 Y35.36). The maximum resultant error exhibited for the synchronized motion of these axes was 0.382 mm and the average error was 0.045 mm.

Circular Interpolation (Dynamic Analysis)

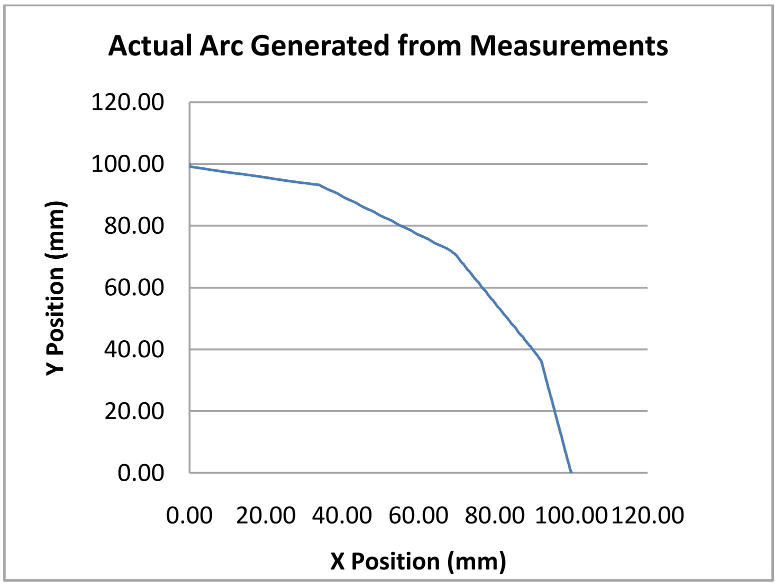


Figure 8.16: Arc Generated by Synchronized Motion of Base Module and Work Table Slide Module

The performance of the MRM control system was investigated for circular interpolation. A test was performed for the interpolation of an arc of radius 100 mm with a subtended angle of 90^o. The test was performed with the base module as the X-axis and the work table slide module as the Y-axis in the 3-DOF drilling configuration. The arc began with the drill spindle at relative position (x=100 mm, y=0 mm) and ended at position (x= 0 mm, y = 100 mm). The arc was linearized according to the circular interpolation algorithm and the linear segments were further interpolated according to the linear interpolation algorithm. Figure 8.16 illustrates the resultant arc that was described by the drill spindle in free space (drill not engaged with work part).

Figure 8.17 illustrates the resultant position error of the drill spindle during the formation of the arc. The position error accounts for tracking errors in the control system and is calculated by equation 8.5. The position error graph is characterized by multiple peaks in the error throughout the trajectory. These peaks occur due to a rapid change in reference input to the position controller at the end of each linear segment in the arc. The arc of Figure 8.16 contained four distinct linear segments resulting in four peaks in the position error characteristic. The magnitude of the errors is highly dependant on the dominant axis (axis required to cover the greater distance) in an individual linear segment and the consistency of the error curve varied throughout the trajectory. The largest error registered for the trajectory was 0.241 mm.

The linearization of an arc generates inherent errors, causing the radius of the arc to deviate from the prescribed radius. The errors are present in the reference to the position control algorithm resulting in the final control error being a composite of both reference and tracking errors.

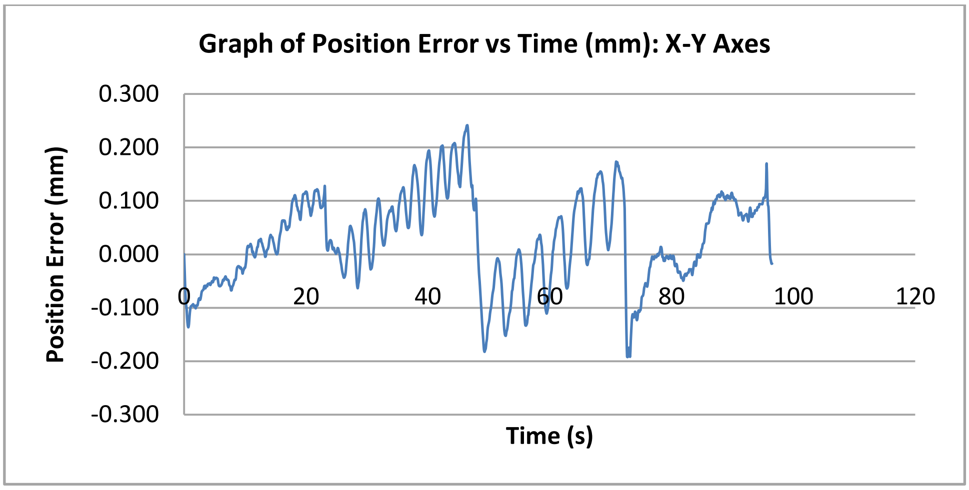


Figure 8.17: Graph of Position Error vs Time, Generation of Arc by X and Y Axes

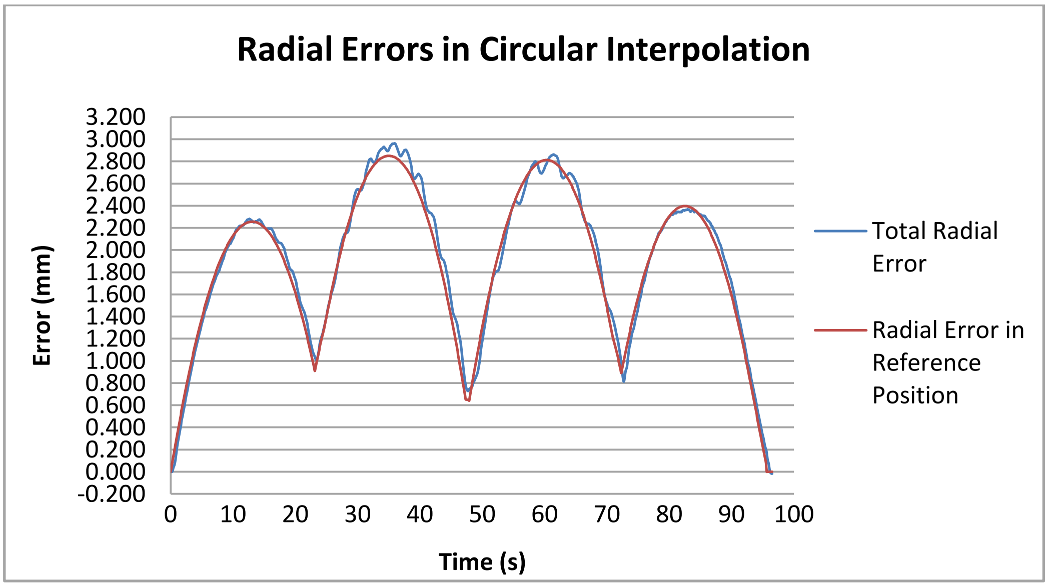


Figure 8.18: Graph of Radial Error vs Time, Generation of Arc by X and Y Axes

Figure 8.18 illustrates the radial errors in the arc with regard to time. The radial error is calculated by equation 7.14; where the equation was used to calculate the error after every iteration of the position control loop. The curve is characterized by four peaks, corresponding to the four linear segments that were used to approximate the arc. The maximum radial error occurs at the middle of each segment resulting in a peak and the error at this point is also referred to as the chord height error (see equation 7.15). Chord height errors as large as 2.850 mm registered in the reference to the controller and the largest total error (reference error + tracking error) in the trajectory was 2.961 mm. The poor accuracy of the interpolated arc was primarily attributed to the circular interpolation algorithm used. For improved accuracy, a moving average fine interpolator may be implemented after the ITM algorithm has performed basic circular interpolation. More advanced algorithms such as the NURBS interpolator may also be implemented for the accurate linearization of curved paths [31].

8.8 Accuracy and Repeatability of Axes

The performance of a machine may be evaluated on the ability of its axes to accurately position the cutting tool and to provide a repeatable measure of accuracy during its operation. Sections 8.5 and 8.7 concentrated on the dynamic performance of the control system specifically, where the investigations explored the ability of the system to track target positions with regard to time for various control instructions. An investigation into the errors in the reference input to the control algorithm was conducted for circular interpolation. The errors resulting from the synchronized motion of two axes were also presented. Thus far, all results presented have only considered the magnitude of errors from the perspective of the control system. These errors did not account for mechanical inaccuracies in the positioning system. The accuracy and repeatability figures calculated in this section will account for mechanical errors, control errors and the control resolution of axes.

Control Resolution

The control resolution CR is defined as the distance that separates two adjacent control points (two encoder pulses) in the motion of an axis [61]. This distance corresponds to the machine BLU which is the smallest measurable increment in distance that may be detected by the control system. The control resolutions of individual axes in the MRM library have been previously presented in Tables 5.4-10. The control resolutions were calculated by equation 8.6, where N is the number of encoder pulses generated per motor revolution and Δx is the axial increment associated with a single revolution.

$$CR = \frac{\Delta x}{N} \tag{8.6}$$

The control resolution represents a limitation in the exactness of position measurements by the control system. The position of an axis will often lie between two control points and the error in the measurement is generally dealt with by adding $0.5CR$ to the position error determined by the control system [61].

Mechanical Errors

Mechanical errors are a result of static deflections, backlash between gears and general play between mating components in the positioning system of an axis.

For the purpose of determining the accuracy and repeatability of MRM modules only the errors resulting from backlash and play between mechanical components was considered. The mechanical errors were determined by measuring the maximum erroneous encoder readings that were generated by the play between components. The final mechanical errors for individual axes were then calculated by equation 8.7, where p is the number of pulses output by the encoders. The truncation effect of the control resolution was not compensated for in this equation and is dealt with later. These calculated errors are presented in Table 8.5

$$max(E_m) = p.CR \tag{8.7}$$

Table 8.5: Mechanical Errors Due to Backlash and Play between Mating Components

Linear Modules	p	CR (mm)	$max(E_m)$ (mm)
Base	1	$4.883x10^{-3}$	$4.883x10^{-3}$
Work Table Slide	1	$5.869x10^{-3}$	$5.869x10^{-3}$
Column	1	$5.869x10^{-3}$	$5.869x10^{-3}$
Cross Slide	1	$3.906\ x10^{-3}$	$3.906\ x10^{-3}$
Rotary Modules	**p**	**CR (deg)**	**$max(E_m)$ (deg)**
Cutting Head Rotary	1	0.703	0.703
Tilt Table	1	0.703	0.703
Rotary Table	8	0.0125	0.1

Accuracy

The accuracy of an axis is defined as the maximum possible error that may occur between the target position specified in a user program and the actual position finally achieved by the axis [61]. The accuracy of CNC systems is commonly determined by equation 8.8 where s is the standard deviation of the error distribution. This equation assumes 100 % accuracy in the ability of the system to position the axis exactly to a prescribed encoder pulse count. The equation also assumes a mean error of zero and that 99.74% of the mechanical errors are within three standard deviations of the final control position.

$$Accuracy = 0.5CR + 3s \tag{8.8}$$

Appropriate equipment and sufficient information to determine the standard deviation of the mechanical error was unavailable. The calculation of accuracy for MRM modules was therefore based on equation 8.9 which calculates the worst instance of accuracy displayed by an axis; this equation is still in agreement to the accepted definition of accuracy in NC machines. The maximum position error E_p is the error in the final position of the axis as measured by the control system.

$$Accuracy = 0.5CR + max(E_m) + max(E_p) \tag{8.9}$$

The repeatability of a positioning system may be defined as the ability of the system to return to a previously programmed position [61]. The repeatability of CNC systems is commonly determined by equation 8.10. However, for MRM axes the repeatability was calculated by equation 8.11 which determines the worst measure of repeatability displayed by each axis.

$$Repeatability = \pm 3s \tag{8.10}$$

$$Repeatability = \pm[max(E_m) + max(E_p)] \tag{8.11}$$

The maximum position error E_p as measured by the control system was determined from multiple tests on individual axes; the results of the individual tests are located in Appendix F.4. These tests were performed at controlled speeds (interpolated motion) for each axis. Table 8.6 presents the accuracy and repeatability data for individual axes. The worst accuracy displayed by linear axes was 0.038 mm and the worst repeatability was $\pm$ 0.035 mm. These figures were displayed by the column module for the +Z direction. The worst case of accuracy and repeatability for rotary axes was displayed by the cutting head rotary module in the –A direction; the accuracy was 3.164^o and the repeatability was $\pm$ 2.812^o. Both the cutting head rotary and tilt table modules displayed poor accuracy and repeatability. The poor performance of these modules is attributed to the direct drive system (no secondary reduction gearbox) used in the modules. It should be noted that accuracy and repeatability figures do not provide any indication of the dynamic performance of an axis, but instead provide performance information with regard to the errors in final axis positions.

Table 8.6: Accuracy and Repeatability of MRM Modules

	Test Conditions						
Linear Modules	**Distance (mm)**	**Speed (mm/s)**	**CR (mm)**	**max(E_m) (mm)**	**max(E_p) (mm)**	**Acc (mm)**	**Rep (mm)**
Base	100	100	0.005	0.005	0.020	0.027	0.024
	-100	100	0.005	0.005	0.015	0.022	0.020
Work Table Slide	100	100	0.006	0.006	0.023	0.032	0.029
	-100	100	0.006	0.006	0.023	0.032	0.029
Column	100	100	0.006	0.006	0.029	0.038	0.035
	-100	100	0.006	0.006	0.023	0.032	0.029
Cross Slide	50	50	0.004	0.004	0.012	0.018	0.016
	-50	100	0.004	0.004	0.012	0.018	0.016
Rotary Modules	**Angle (deg)**	**Speed (rev/min)**	**CR (deg)**	**max(E_m) (deg)**	**max(E_p) (deg)**	**Acc (deg)**	**Rep (deg)**
Cutting Head Rotary	360	40	0.703	0.703	1.406	2.461	2.109
	-360	40	0.703	0.703	2.109	3.164	2.812
Tilt Table	90	30	0.703	0.703	1.406	2.461	2.109
	-90	30	0.703	0.703	1.406	2.461	2.109
Rotary Table	360	0.75	0.013	0.100	0.151	0.257	0.251
	-360	0.75	0.013	0.100	0.113	0.219	0.213

8.9 Chapter Summary

This chapter presented an overview of MRM assembly and reconfiguration. A calibration procedure for MRMs was also outlined. Investigations into the performance of position systems were presented. A positioning system consisted of the host PC, the servo communication module, servo control modules and MRM axes. Investigations were conducted into the static and dynamic positioning accuracy of individual modules and the synchronised motion of multiple axes. Tests were performed for rapid point to point motions, linear interpolated motions and circular interpolated motion. The accuracy and repeatability of individual axes was determined; which accounted for control errors, mechanical errors and the control resolution of modules.

9. Discussion

9.1 Performance Summary: Mechanical Systems

The primary objective of creating the MRM platform was to develop a new class of machine tools that are designed from the outset to display reconfigurability in their functionality. Development costs limited the design of the MRM library of modules to the machining of soft materials such as wax and plastic only. The power available at the machine spindle for drilling and turning was 80 watts and 550 watts respectively. The power available at each axis in the system was 100 watts. The power of the machine spindles and axes were sufficient for the drilling and turning of the specified materials.

All linear axes were capable of speeds of 100 mm/min and all rotary axes were capable of a speed of 1 rev/min, thus meeting the minimum design expectations of the system. The force requirement from the system for the drilling and turning of plastics and waxes was specified at 50 N. All MRM modules were capable of actuation loads in excess of 250 N and normal loads in excess of 240 N on their moving interfaces. These were usually conservative estimations that permitted deflections less than 0.20 mm in individual modules. All MRM configurations were capable of sustaining machining forces of 50 N. The assembly most inclined to large static deflections and vibrations was the drilling subassembly presented in Section 5.12. This particular configuration of modules included the drilling head, the range extension arm, the cutting head rotary module and the column module. For a vertical force of 50 N (N.B column slide 600 mm above its base) a total deflection of 0.058 mm in the position of the machine spindle was predicted by calculations. This subassembly displayed significantly less rigidity in the horizontal plane and a total deflection of 1.959 mm was estimated for a force of 50 N on the drilling head. Of all nine possible MRM configurations this was the worst anticipated deflection in the position of the cutting head/tool for the specified force. This particular configuration was still able to sustain the 50 N drilling force for rotations of $\pm 30^{o}$ in the position of the drilling head (from a vertical position), while still maintaining a deflection of less than 1 mm in the position of the cutting tool.

The dynamic performance of the mechanical system was investigated. The investigation was also performed on the drilling subassembly presented in Section 5.12; as this was the mechanically weakest assembly of all MRM module combinations tested. The system was found to have a resonant frequency of 100 Hz for a vertical excitation force and 15 Hz for a horizontal excitation force on the drilling head (N.B column slide 600 mm above its base). These frequencies correspond to drilling speeds of 6134 rev/min and 1054 rev/min if the excitation were to occur once per revolution. If the excitation were to occur twice per drill revolution, the respective resonant drilling speeds would be 3067 rev/min and 527 rev/min. The drilling head has an unloaded speed of 580 rev/min; however once loaded the speed of the drill is expected to be safely below the resonant speeds (only 80 watts available at spindle). For normal drilling operations (not vibration assisted drilling) vibrations along the axis of the drill are ideally not expected as there is a continuous engagement of the cutting edge of the tool with the work piece. In reality vibrations are induced by inconsistencies in the work piece and damaged tools. The MRM system therefore possesses sufficient mechanical integrity for the machining of wax and plastics which have a generally even consistency.

The performance of the MRM library of modules may be further improved. The column module contained a low cost sliding mechanism consisting of four silver steel rods. For the investigation of Section 5.12, the column module was the module with the least stiffness. In series, spring stiffness's are combined reciprocally and the low total stiffness resulted in the large deflection of 1.959 mm for a force of 50 N on the drilling head in the horizontal direction. The performance of this module under static and dynamic loading may be improved by the use of a traditional dove tail slide mechanism in place of the current system. The work table slide module is another module, which should ideally possess a dove tail slide mechanism in place of the existing steel rod sliding mechanism. Additional mechanical problems resulting from the modularization of production machines are discussed in Section 9.5.

9.2 Performance Summary: Positioning Systems

Dynamic Performance: Interpolated Motion of Individual Axes

Positioning systems consist of the host PC, the servo communication module, servo control modules and the machine axes. An investigation into the dynamic performance of positioning systems was conducted in Section 8.5, for interpolated motion. For program speeds of 100 mm/min, linear axes displayed a maximum tracking error of 0.633 mm. This error is the discrepancy between a reference position and a measured position with regard to time. Rotary axes with reduction gearboxes (rotary table module) displayed a maximum tracking error of 0.942^{o} at a speed of 0.75 rev/min. Rotary axes with direct drive mechanisms (tilt table and cutting head rotary module) were capable of higher speeds, and errors as large as 14.776^{o} were registered at speeds of 10 rev/min. Dynamic tracking errors increased with an increase in operating speeds in both linear and rotary motion modules. The motors used in motion modules were generally under powered and exhibited poor acceleration when achieving target speeds. The highest dynamic errors were generally exhibited during the acceleration phase of interpolations as the drive motors did not possess sufficient power to effectively track the reference.

Across entire trajectories, linear axes displayed average dynamic errors as large as 0.116 mm and rotary axes displayed average dynamic errors as large as 6.797^{o}. A significant contributing factor to the deviation of the measured position from the target position, in the steady region of axis trajectories, was uneven friction characteristics in module drive mechanisms and sliding systems. In both linear and rotary modules the uneven friction characteristics were attributed to the poor quality manufacturing of the mechanisms. The modules that were most affected be uneven friction were the tilt table module and the cutting head rotary module. The direct drive mechanisms in both these modules provided insufficient torque at test speeds to provide smooth operation in view of the uneven friction characteristics displayed by their sliding mechanisms. The modules were prone to the "slip-stick" effect caused by uneven friction, resulting in comparatively large dynamic errors after the acceleration phase of the trajectory. The internal gearboxes of the drive motors were inadequate and the performance of these modules would improve with a redesign that includes a secondary reduction gearbox.

Static Performance: Point to Point Rapid Motion of Individual Axes

Point to point rapid motion is concerned with the rapid positioning of axes, without the observance of a target speed. The performance of positioning systems under this mode of motion control is not concerned with the dynamic positioning accuracy of the system, but rather the accuracy in the final static position of an axis after a trajectory.

Section 8.6 presented the results of tests performed on individual axes for point to point, rapid motions. The error in the final position of an axis was calculated by obtaining the difference between the reference position and the measured position at the end of a trajectory. The calculations did not consider the effect of mechanical play and backlash between mating components. The largest position error exhibited by a linear axis was 0.059 mm, which was displayed by the column module. The largest error exhibited by a rotary axis was 1.406^{o}, which was displayed by the cutting head rotary module. Both these modules displayed the worst cases of uneven friction in their respective categories.

Dynamic Performance for Synchronized Motions –Linear Paths

The performance of the MRM axes for synchronized motions was presented in Section 8.7. A test was performed for the synchronized motion of the base module and work table slide module in the 3-DOF drilling configuration. For a linear path and a resultant speed of 100 mm/min (70.71mm/min per axis), the maximum dynamic position error from the combined motion was 0.429 mm; which occurred during the acceleration of the two axes. The average position error for the drill spindle was 0.069 mm. A similar test was performed in the turning configuration, with the resultant motion of the tool post being provided by the base module and cross slide module. For a linear path and a resultant speed of 100 mm/min, the maximum dynamic position error was 0.382 mm and the average error was 0.045 mm.

Dynamic Performance for Synchronized Motions –Circular Paths

A performance investigation was conducted on the 3-DOF drilling configuration for circular interpolated motion. The ideal arc to be followed by the drill spindle was of radius 100 mm and a subtended angle of 90^{o}. The base module and the work table slide module were to provide a resultant feed rate of 100 mm/min along the arc. The results of the test showed a maximum dynamic position (tracking) error of 0.241 mm. The trajectory was characterized by four peaks in the dynamic position error, corresponding to the end of the four linear segments that were used to approximate the arc. These peaks in error signify a rapid change in the reference to the position control loop and the slow response of the drive motors in tracking this change.

A reference word algorithm incorporating the Improved Tustin Method was used to perform the circular interpolation in software. The ITM algorithm was selected as it is known to provide better accuracy and require less iterations than Euler and Taylor methods [31]. The ITM algorithm resulted in chord height errors as large at 2.850 mm in the reference input to the control algorithm. The performance of the ITM with regard to circular interpolation was poor, as a fine interpolator was not included in the existing software system. The performance of the system may therefore be improved by the addition of a moving average fine interpolator to the software system. The comprehensiveness of the software may also be improved by the incorporation of the NURBS interpolator, which is used for the linear approximation of more complex curved paths.

Accuracy and Repeatability

Accuracy and repeatability tests were performed for individual axes at controlled speeds (interpolated motion). Six tests were performed for each axis in either direction of motion and the results of the individual tests are presented in Appendix F.5. Section 8.8 presented the accuracy and repeatability figures for each axis; these figures accounted for mechanical and control errors, as well as possible errors in position measurements.

The worst accuracy displayed by linear axes was 0.038 mm and the worst repeatability was ± 0.035 mm. These figures were displayed by the column module at a speed of 100 mm/min in the +Z direction. For rotary axes with reduction gearboxes the worst accuracy and repeatability figures were 0.257^o and ± 0.251^o respectively, displayed by the rotary table module for a speed of 0.75 rev/min in the +Y direction. Rotary axes without secondary reduction gearboxes displayed a worst case accuracy and repeatability of 3.164^o and ± 2.812^o respectively. These figures were displayed by the cutting head rotary module for a speed of 40 rev/min in the –A direction.

The modules with the worst relative performance in their respective categories were the cutting head rotary module, the tilt table module and the column module. All of these modules were prone to the negative effects of uneven friction characteristics in their drive and sliding mechanisms. The torque provided by the drive motors at the respective test speeds was also insufficient to smooth the motion of the axes. The only modules that failed to meet the required accuracy and repeatability specifications were the cutting head rotary module and the tilt table module. The combination of uneven friction characteristics, the slip-stick effect and the low power of the motors were the dominant contributors to this discrepancy. Appendix H contains the final specifications that were achieved by the various MRM modules and assemblies.

9.3 Comparative Analysis of the Properties of MRMs

The motivation for the design of MRMs was the inadequacies of other types of machine tools in their applicability to reconfigurable manufacturing. These inadequacies included poor expansion flexibility, rigid mechanical and control architectures and either excessive or limited functionality. The Arch Type RMT presented in Section 3.3 is the only known reconfigurable machining platform that has been built by either industry or academia to date. The machine was built on a party family approach to reconfigurability. The design of MRMs deviated from this approach due to the rigidity of the mechanical architecture and the risk of such machinery becoming redundant if drastic changes in products are expected.

Table 9.1: Comparative Analysis of DMTs, CNCs, RMTs and MRMs

Characteristics	DMTs	CNCs	RMTs	MRMs
Design Orientation	Part	Generic	Part Family	Generic, Reconfigure to Part Family
Mechanical Hardware	Fixed Design	Fixed Design	Fixed Design	Modifiable Design
Control Hardware	Fixed Design	Fixed Design	Fixed Design	Scalable Design
Control Software	No software or Fixed Design	Fixed Designs or Open Architecture Control	Open Architecture Control	Open Architecture Control
Flexibility of Design	Part Design	Generic Design	Part Family Design	Generic design
Reconfigurability – Machining Processes	Not Applicable	Retooling of spindle	Reorientation of Machine Spindle	Interchangeable Cutting Heads
			Retooling of Spindle	Reorientation of Machine Spindle
				Retooling of Spindle
Reconfigurability – Machine Axes	Not Applicable	Not Applicable	Reorientation of Machine Axes	Interchangeable Machine Axes
Customization of Machine to Process	Very High	Low	High	Moderately High
Predicted Relative Cost	Low	High	Low – Moderate	Moderate

MRMs were designed for the manufacturing of general products as in the case of CNC machines; however the modularity of the system permits its flexibility to be customized as in the case of DMTs and RMTs. A comparative analysis of MRMs is provided in Table 9.1, this comparison is between the properties of MRMs, DMTs, CNCs and RMTs. MRMs display a clear advantage over other types of machines in terms of the modifiable mechanical architecture, the scalable nature of the control system and the interchangeability of axes and cutting heads. The property of customizable and expandable flexibility in MRMs has resulted in the prediction of a relatively moderate cost in comparison to CNCs.

9.4 MRMs in Reconfigurable Manufacturing Systems

9.4.1 Reconfigurable Functionality in MRMs

The MRM library of modules consisted of twelve units of hardware that were ultimately used to create nine machines that displayed distinctly different combinations of cutting processes and kinematic abilities. In addition to the manufactured hardware, commercial off the shelf enhancements such as steady rests and tail stocks could be integrated with MRM platforms to provide additional levels of functionality. The full range of modules is documented in Appendix B. All MRM configurations created with the library of modules are documented in Appendix D.

MRMs address the necessity for reconfigurable functionality in RMSs by providing a variation in processing operations and DOF through the structural reconfiguration of a machining platform. A change in processing operations enables different part features to be produced while a change in DOF enables different tool paths. Reconfigurability of this nature holds three important implications:

(i) The flexibility of individual machines may be expanded, thus enabling RMSs to produce different part families with a minimum investment in additional hardware.
(ii) MRMs need only possessed the exact level of functionality required to complete an operation, any excess modules may be removed and distributed to other machines in the system.
(iii) Unused machines may be decomposed into modules and reassembled into other machines that are needed in the system.

9.4.2 Initial Capital Investment in Hardware

MRMs are machines that are able to display expandable machine flexibility. The implication is that manufacturers may begin the operation of a system with the minimal level of functionality required at the outset. As the product portfolio of the system evolves, the machines in the system may be enhanced with additional modules. From an economic perspective this means that manufacturing systems may be initialized at a minimum cost and the flexibility of the system may be gradually increased at a later stage as the system begins to pay back the initial capital investment. Moreover, the increase in flexibility is derived from the upgrading of existing machines as opposed to the purchasing of new machines, therefore promising cost savings in hardware investments.

9.4.3 Scalable System Capacity

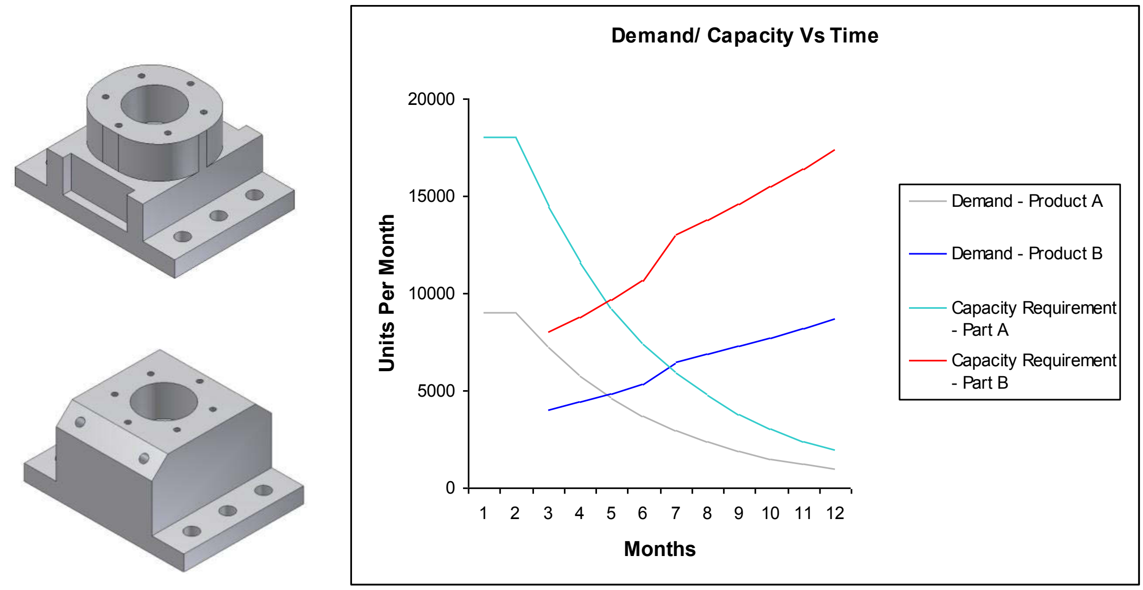


Figure 9.1: Example Demand Characteristics: Part A (above), Part B (below) [74]

In manufacturing systems producing multiple product types, a redistributing of system resources between operations will often be required as the demand characteristics of the individual products vary over a period of time. Changes in demand characteristics are most profound when new products are launched into markets. Consider the example of Figure 9.1 which illustrates two parts belonging to two different products. Part A corresponds to Product A, which is being phased out of production. Part B corresponds to Product B, which is replacing the old product.

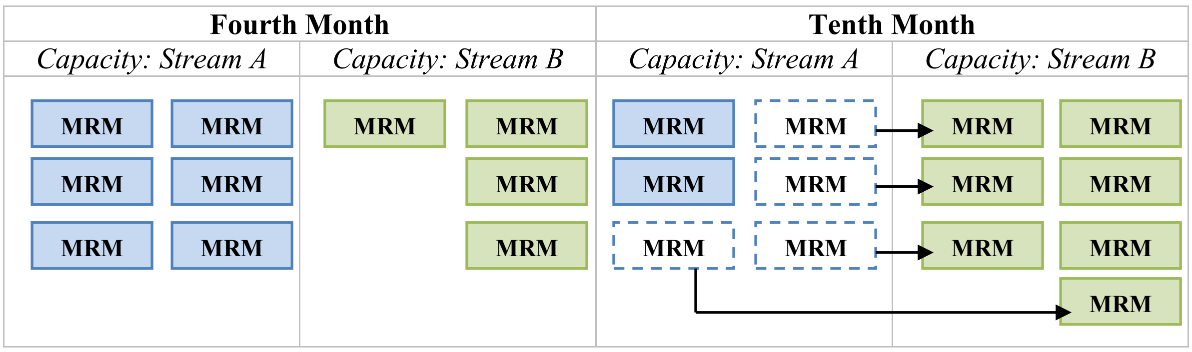


Figure 9.2: Reconfiguration of Production Stream Capacity by the Reconfiguration and Redistribution of MRMs

During the phase of introducing the new product the demand for the older product will decline while the demand for the new product will increase as illustrated. Part A requires a 3-axis drilling machine for the machining of holes on its various flat surfaces while Part B requires a 4-axis drilling machine to cater for the machining of additional holes on inclined surfaces. In the case presented a manufacturer would reallocate a portion of the system resources previously used in the production of A to the production of B based on the demand characteristic.

This is achieved by reconfiguring the 3-axis drilling machines into 4-axis drilling machines by the addition of modules to the platforms. The 4-axis machines are then allocated to the production stream of product B. Figure 9.2 illustrates how the process of reconfiguration may used to vary the capacities of both production streams by the redistribution of system resources.

9.4.4 High Product Variety and Product Customization

MRMs are able to display expandable mechanical flexibility. An expansion in machine flexibility further implies an expansion in the process flexibility of the manufacturing system. Process flexibility is concerned with the set of part types that can be produced by current process configurations. MRMs will therefore enable systems to cope with a higher part variety over a period of time; this is presently a significant challenge in modern manufacturing.

MRMs possess the potential to aid in product customization, which was also identified as a significant challenge in modern manufacturing. Specific product configurations may require unique machine configurations for their production. In this instance an MRM may be suitably reconfigured to match a customized derivative of a product platform. This eliminates the need to purchase an unpopular machine for the customized product. This is a particularly unattractive scenario as the machine may only be used for a limited run of products. With MRMs the manufacturer need only invest in a specialized module to impart the required functionality to the system. The machine may then be reconfigured for other operations once a customized product feature is no longer required.

The modularity of MRMs may in future, grant manufacturers the platform to develop customized modules for their machines (as opposed to purchasing them). This will further enhance product customization and enable manufacturers to optimize MRMs to meet their specific requirements. A customized MRM is expected to be quicker to assemble than the building of customized machines. User customization will require the drafting and publication of open standards for the interfacing and control of MRM modules.

9.4.5 Expansion Flexibility and System Life Span

The expandable machine flexibility, process flexibility and the ability of MRMs to aid in capacity scaling imply high expansion flexibility for RMSs. DMSs are limited in their expansion flexibility due to the rigid nature of the systems, while FMSs would usually require the purchasing of new types of machines to alter the functionality available in the system. The lifespan of RMSs are therefore expected to be significantly longer than DMSs, and the cost of extending its lifespan much lower than FMSs, if MRM technology is refined and implemented.

9.4.6 MRMs and the Five Essential Characteristics of RMSs

The five essential characteristics of RMSs are modularity, convertibility, customization, integrability and diagnosability. These characteristics are to be enabled in RMSs by the technologies implemented in these systems. In MRMs these characteristics were imparted to the system at multiple levels. The Mechatronic engineering approach was applied to the design of MRMs and necessary features in the mechanical, electronic and software systems were identified as early as the conceptual design phase. The individual subsystems either display each of the five characteristics directly, or support other subsystems in displaying these characteristics.

Table 9.2 summarizes how features in the various subsystems of an MRM support the five essential characteristics of RMSs.

Table 9.2: MRMs and the Five Essential Characteristics of RMSs

	Mechanical System	Electronic System	Software System
Modularity	• Modularized axes and cutting heads.	• Modularized control hardware and networked axes.	• The concentration of generic software functions on the host PC and the location of module specific control functions on distributed control drives promoted mechanical and electronic modularity.
Convertibility	• Reconfiguration of modular assemblies to convert machines to produce new products.	• Modular control hardware supported the conversion of the mechanical platform.	• A fully comprehensive G-Code command set inbuilt to support a large variety of mechanical configurations.
Customization	• The functionality of the mechanical system could be customized by allowing only the necessary modules to be present on a platform.	• The electronic control system was modular and scalable, ensuring that only those modules necessary for the control of the current MRM configuration are present in the control system.	• The selection of active axis combinations by drop down menus customized the active G-Code command set. • Commands that were inconsistent with the selected combination were rejected by the text interpreter.
Integrability	• Mechanical modules possessed a series of standard mechanical interfaces for integration with each other. • Standardized 8 and 11 wire connections were used to provide a consistent power and control interface between mechanical and control modules.	• Standardized 8 and 11wire connections for interfacing of control modules with the mechanical platform. • The use of standardized communication protocols such as I2C supported the integration of control modules into networks. • USB communication provided a standard means of interfacing distributed control dives with the host PC.	• The software system supported the USB communication protocol. • The ability to configure USB port addresses for spindle and servo control further enhanced the integrability of hardware with the host PC. • For modular axes the G-Code word addresses corresponded on a 1:1 basis with their I2C addresses, supporting the easy addressability of servo control modules.
Diagnosability	• All automated mechanical modules contained sensors.	• Limit switches for collision detection. • Accelerometers for the measurement of vibrations.	• The MRM GUI contained a warning box, status box, progress bar and LCD for the display of diagnostic information to the user.

9.5 Problems Associated with MRMs

9.5.1 Geometric Proportions of Machine Slides

The use of the range extension arm for drilling configurations increased the susceptibility of those MRM assemblies to static and dynamic deflections. The use of the range extension arm was necessary to compensate for the distance of the column module from the work table slide module. This distance was a result of the geometric proportions of the base module, which was also used for the turning configuration. The dimensions of the base module were suitable for turning configurations which require a long base, but particularly inappropriate for drilling configurations.

Imbalances in the geometric proportions of machines axes are a problem that will have to be addressed before MRM technology becomes practically implementable in industries. A particular range of axes lengths may be more suitable for some cutting processes than for others and the use of a generic set of axes will result in a general decline in the optimality of MRMs for specific processes. Imbalances in the dimensions of axes may be diminished by creating libraries of modules centered on cutting processes that are grouped together on the basis of geometric commonality in the typical parts they machine.

Turning operations are generally concerned with long cylindrical work parts while work parts in drilling are either non-prismatic or possess small length to diameter ratios. The work parts in drilling operations are clamped onto a rectangular work table and an example of a more complementary group of processes would be drilling, vertical milling and some boring operations (operations with a rotating boring bar). These processes may be combined to create a more suitable set of modules, where the dimensional imbalances in the final machine configurations are minimal. Moreover the machines may be reconfigured with a less drastic disassembly and reassembly process.

9.5.2 Mass Distribution in MRM Structures

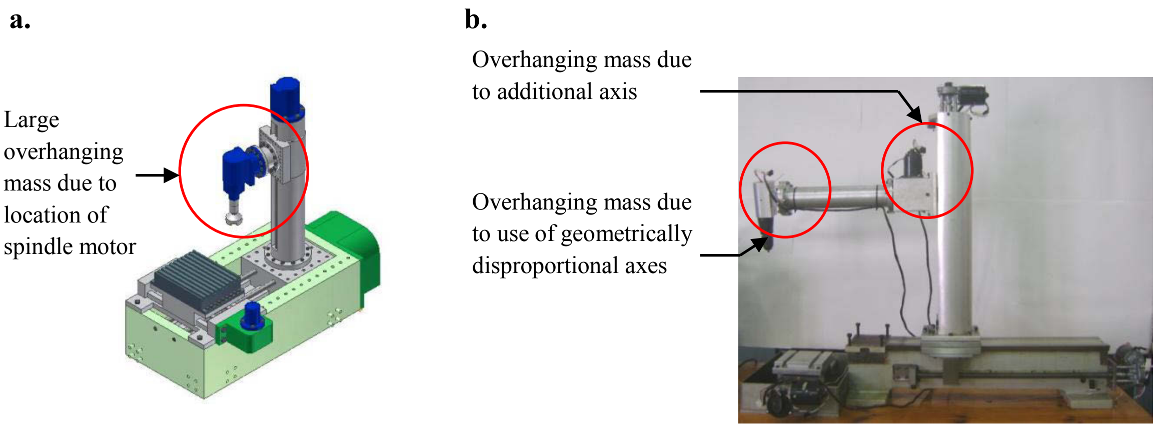


Figure 9.3: Unfavourable Mass Distributions in MRMs

a. Overhanging mass in a 3-axis milling machine
b. Overhanging masses in a 3-axis drilling machine

MRM axes and cutting heads each possess a single drive motor. The motors are housed within the framework of individual modules and cannot be placed elsewhere due to the modularity of the machine structures. This results in an unfavorable mass distribution in machines with regard to deflections. Larger masses are found in overhanging positions as illustrated in Figure 9.3.a due to the necessity to locate the drive motor at the point of actuation. In CNCs and DMTs the drive motor for the machine spindle is usually located in a more stable position with greater mechanical support and power is transmitted from the motor to the spindle via a belt drive mechanism. Figure 9.3.b illustrates a scenario where an overhanging mass is introduced by the addition of a rotary axis to the system. In more conventional machining structures an axis of this nature would have been created as an integrated part of the machine column, minimizing the overhang. Lastly, Figure 9.3.b illustrates how an unfavorable mass distribution may be introduced in a machine structure as a result of the use of geometrically disproportional axes (as discussed in Section 9.4.1). Larger overhanging masses not only affect the static performance of the machine but also adversely affect the dynamic performance. For a given structural stiffness a larger mass closer to the cutting head reduces the natural resonant frequency of the system. MRMs are therefore susceptible to larger vibrations than CNCs or DMTs.

9.5.3 Module Weights, Stiffness and Actuation Power

MRM modules were created largely out of aluminum due to the low power of drive motors. This was a drawback that was introduced by restrictions in development costs. The light weights of the modules allowed the existing MRM system to be reconfigured manually within a maximum of one hour. As a consequence the use of aluminum reduced the stiffness of modules and their resonant frequencies, thus providing less rigidity to structures supporting the work piece and cutting tool. This reduced the performance of the system with regard to static and dynamic deflections.

MRM modules may be created out of stiffer materials such as steel or cast iron. The consequence of this will be heavier modules which will be more difficult to assemble manually. For full scale industrial machines the use of lifting equipment will be required for the assembly and reconfiguration of MRMs. This increases the complexity, cost and time invested in the reconfiguration of an MRM platform. The upgrading of a platform by the integration of a heavier module will diminish the performance of the system, as the drive motors in lower modules such as a base module will have to have to cope with additional weight in the machining structure. This presents the potential for the power balance in the system to be negatively affected and some modules will be found to be underpowered in the new MRM configuration. The underpowered modules will ultimately provide poor dynamic performance during position control, resulting in inaccuracies in machined parts. Slower actuation speeds may also reduce the throughput (units/time) achievable on these machines resulting in a drop in productivity and profits for a manufacturer.

9.5.4 Power Supply Systems

MRM platforms may be upgraded by the integration of additional mechanical and control modules into an existing system. The increase in the number of actuators, sensors and electronic circuits in a platform ultimately increases the demand on the electrical power supply system. MRMs may be created with excess capacity to provide additional power when necessary; alternatively research may be conducted into the development of a scalable power supply system.

Both alternatives are not cost effective and may even result in MRMs being more expensive than highly flexible CNC systems. A power supply with excess capacity is uneconomical while a scalable power supply system would be expected to cost more because of the added complexity in the technology.

9.5.5 Problems Associated with Reconfigurations

The process of reconfiguration requires that an MRM be taken "offline" from the manufacturing system. This implies a loss in productivity for the system during the time that is taken for reconfiguration. If the machine is in series with other machines in a production stream, this implies a standstill in production for the entire stream. The cost savings derived by modular upgrades of machines may be outweighed by the financial losses associated with the loss in productivity in the system.

Modular machines are expected to be prone to assembly errors if the reconfiguration process is not performed with precision. In order to minimize assembly errors the reconfiguration process is expected to be slow and the accurate alignment of module interfaces is of utmost importance. An MRM will have to be recalibrated after every reconfiguration and the calibration may be performed by using traditional CNC laser calibration systems. The entire reconfiguration, calibration and ramp-up processes for the MRMs are expected to be lengthy for industrial grade machines. This reduces the attractiveness of MRMs as a machining solution.

9.6 Chapter Summary

This chapter presented summaries and discussions on the performance of the library of MRM modules and the systems that were assembled from them. The performance of mechanical systems and positioning systems were reviewed and design improvements were recommended. The applicability of MRMs in RMSs was discussed and important benefits of MRMs were highlighted. The chapter concluded with an analysis of the problems associated with MRMs.

10. Conclusion

This research was motivated by the need to develop new production technologies that will enable the objectives of rapidly scalable system capacity and adjustable functionality to be achieved in reconfigurable manufacturing. Modular reconfigurable machines were proposed in this research as a possible solution to the machining requirements of RMSs. The modular nature of these machines permits a change in machining functions and degrees of freedom on a platform, thus enabling adjustable functionality in RMSs. The modular nature of the machines further permits the reconfiguration and redistribution of hardware resources in a system, thus enabling the synergistic scaling of production capacities in manufacturing streams or cells within the system. The variable machining functionality and the ability to assist in scaling production capacities will enable MRMs to form part of the solution that addresses the primary challenges of coping with high product variety and product customization. The modularity of MRMs also creates the potential for the machines to be cost effectively used in the initialization of manufacturing configurations that are needed for the short term manufacturing of small product batches.

MRMs possess the expandable machine flexibility needed in RMSs, thus favoring their implementation above dedicated machine tools. MRMs also exhibit the features of convertibility and customization allowing a machine to be adjusted in its functionality to suit new product portfolios. MRMs therefore possess the potential to cost less than CNC machines, which have comprehensive inbuilt functionality and may have features that may never be used by a manufacturer. Although CNC machines are designed with high flexibility, a CNC may still not possess the functionality required by a manufacturer. In this instance a new CNC machine will have to be purchased or the job may have to be outsourced to another manufacturer who possesses suitable machines. The expandable flexibility in MRMs therefore creates a second advantage over CNC machines, as they may be upgraded as necessary. The expansion flexibility in MRMs increases the expansion flexibility of RMSs and the lifespan of a RMS is expected to be longer and more economical to extend than either DMSs or FMSs.

The MRM modules created during this research could be assembled into a drilling or turning center. The turning configuration displayed two automated axes and one manually adjustable axis. The drilling configuration was able to display a variation from three up to six automated DOF. The twelve modular units of hardware that formed the library of modules were used to create nine unique machine configurations in total. A high level of reconfigurability with limited hardware is therefore displayed in MRM technology.

A modular distributed control system was created for MRMs. The modularity of the system complimented the mechanical modularity and the computing capacity of the system was scalable. The number of mechanical modules controlled by the system could be increased with an increase in the number of distributed control drives connected to the system. The use of standard communication protocols such as USB and I2C promoted the modularity and easy reconfigurability of the control system. The concentration of generic software functions on the host PC and the location of module specific control functions on distributed control drives created a hardware abstraction that further promoted mechanical and electronic modularity. Theoretically the hardware abstraction supports the augmentation of a platform with mechanical and electronic control modules from multiple vendors by providing a consistent style of integration with the rest of the control system.

The facility for a manufacturer to augment his machine tools with modules from multiple vendors would ultimately result in a more competitive machine tool market. The potential to reconfigure and upgrade machine tools cost effectively, exists with MRMs a technology for future manufacturing.

The MRM software system on the host PC was created with full inbuilt functionality. The level of reconfigurability in the software system was limited to the selection of axes and the configuring of port addresses. Collision detection was only enabled locally between a mechanical module and a control module, and the host PC was only informed of collisions after a machining process had begun. For preemptive collision detections on the part of the host PC, a more extensive reconfiguration of the software system is required. A software system with full inbuilt functionality is also bound to be uneconomical if the technology is made commercially available. Further research must be conducted into the development of a modular open architecture control system for MRMs.

The MRM platform developed in this research was limited to the machining of wax and soft materials. The machine displayed a lack of stiffness in certain machine configurations and low powered motors resulted in a decreased performance compared to similar machines that are commercially available. Low cost sliding mechanisms, power screws and other low cost drive mechanisms limited the performance of the machine. The overall performance of the mechanical system was sufficient to achieve the objectives of the research and the performance of the present MRM platform may be significantly improved with additional monetary investments. Improvements that have been identified include the implementation of more suitable and higher quality mechanical components such as recirculating ball screws in linear axes; bevel and spur gearboxes in rotary axes and higher quality DC servo motors in all axes. The use of cast dove tail slide systems and bifurcated structures would also increase the stiffness of linear axes. Stiffer and heavier materials such as steel and cast iron would further increase the rigidity and vibration damping characteristics of individual modules. This would be complimented by an increase in the power capacities of all drive motors in modular axes.

Through the research performed on the existing library of modules, problems in MRMs have been identified. Some of these problems may be solved with improved design while others are an inherent and fundamental consequence of a modularized structure. Dimensional imbalances in machining structures are introduced when uncomplimentary machining processes are grouped together to create a set of modules. This problem was displayed by the current system where the use of a range extension arm was required to compensate for the uncomplimentary dimensions of the base module in drilling configurations. The range extension arm increased the susceptibility of the drilling configurations to large static and dynamic mechanical deflections. Imbalances in the dimensions of axes may be diminished by creating sets of modules centered on cutting processes that are grouped together on the basis of geometric commonality in the typical part shapes they machine (prismatic/non-prismatic, large length to breadth ratio/small length to breadth ratio, large length to diameter ratio/small length to diameter ratio, etc).

The second problem that has been identified in MRMs is an unfavorable mass distribution in the machine structure. The effect of this problem may be diminished to an extent by improved mechanical design; however the necessity to locate drive motors at the point of actuation creates a fundamental structural disadvantage with regard to the mass distribution.

The third problem that was identified is the potential to drastically upset the balance of the structural rigidity and mechanical power available in the system by the integration of additional mechanical modules. This is a fundamental problem and modules may have to be designed with generally high powered motors and high stiffness; which will ultimately reduce the economic viability of the technology. The fourth problem that was identified was the need to increase the electrical power supply to the system as the number of modules in the system increases. Power supplies may be either created with excess capacity or further research may be performed on the development of modular scalable power supplies. A modular power supply system would be expected to cost more than a standard power supply system of equivalent capacity. The economic viability of both solutions appears fundamentally poor at present.

The final problem that was identified is the complexity of the reconfiguration process for MRMs. Reconfigurations entail alterations to the mechanical, electronic, software and electrical power supply systems of a machine. The level of complexity will require the use of companies that possess lifting equipment, calibration equipment and trained personnel to complete the reconfigurations. The reconfiguration process is therefore expected to be costly and time consuming. MRMs have to be taken offline from a system to be reconfigured and the profit losses associated with the machine downtime further reduce the economic viability and practicality of the technology. It should be noted that the automated reconfiguration of a machine is an impractical solution to this problem. If a machine is to display automated transformability into different configurations this would imply that the machine would have to be created with full inbuilt functionality. This is a logical contradiction to the intentions of a modular structural design. In addition to containing full inbuilt functionality, an automated transforming machine would have to contain additional motors and mechanisms to enable the transformability. Such machines would be inherently expensive and therefore not applicable as reconfigurable technology in RMSs.

Further research must be conducted on solving the problems identified, before MRMs become industrially implementable and economically attractive machines. Novel solutions will have to be developed as many of the problems that were highlighted appear to be of a fundamental nature and plausible solutions are not easily identified. An investment into the further research of MRM technology is justified by the promising benefits of enhanced reconfigurability in system functionality and production capacity for RMSs.

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Appendix A

A.1 Interface Type One

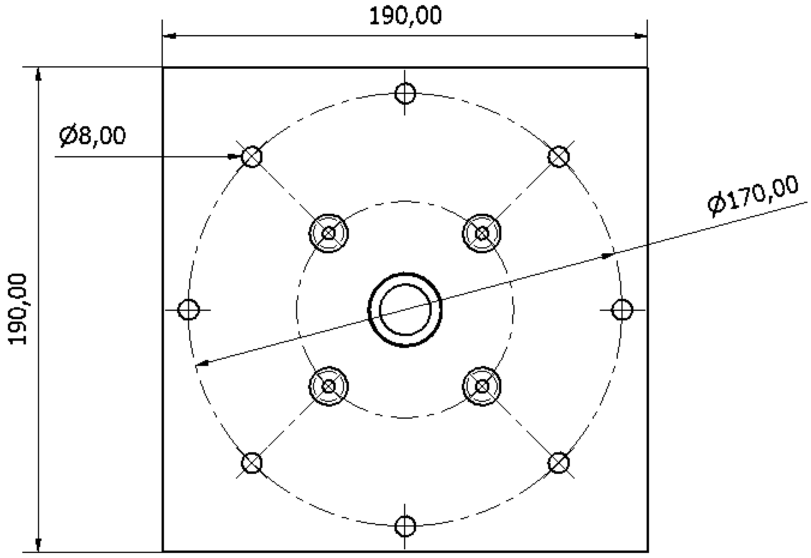


Figure A.1: Dimensional Specifications of Interface One

Table A.1.1: Physical Specifications and Data for Interface One

Interface Name	Plate Material	Yield Strength S_y (MPa)	Ultimate Tensile Strength S_U (MPa)	Shear Strength S_{shear} (MPa)
One	Aluminum 295-T4	165	250	162
Modulus of Elasticity E (GPa)	**Plate Thickness h (mm)**	**Interface Thickness L_{Int} (mm)**	**Thread Height t (mm)**	**Grip Length g (mm)**
72	12	24	12	24

Table A.1.2: Physical Specifications and Data for Interface Connectors – Interface One

Interface Name	Bolt Size (Hexagon Socket Head)	SAE Class	Proof Strength S_P (MPa)	Yield Strength S_y (MPa)	Ultimate Tensile Strength S_U (MPa)
One	M8x1.25	12.9	970	1100	1220
Shear Strength S_{shear} (MPa)	**Modulus of Elasticity E (GPa)**	**Stressed Area A_t (mm^2)**	**Minor Diameter d_r (mm)**	**Bolt Length L_{bolt} (mm)**	**Bolt Tightening Factor k_i**
756	207	36.6 mm^2	6.47	25	0.7

Thread Stripping

Thread stripping will first occur on the interface plate

$$F_e = \pi d(0.75t)S_{shear} = \pi \times 0.008 \times (0.75 \times 0.012) \times 162 \times 10^6 = 36643\ N$$

$$F_{e\ total} = 8 \times 36643 = 293144\ N$$

Joint Separation

$F_i = k_i A_t S_p = 0.7 \times 36.6 \times 10^{-6} \times 970 \times 10^6 = 24851\, N$

$A_c = d^2 + 0.68dg + 0.065g^2$

$A_c = 0.008^2 + 0.68 \times 0.008 \times 0.024 + 0.065 \times 0.024^2 = 2.32 \times 10^{-4}\, m^2$

$$k_b = \frac{A_t E}{L_{bolt}} = \frac{36.6 \times 10^{-6} \times 207 \times 10^9}{0.025} = 3.03 \times 10^8\, N.m^{-1}$$

$$k_c = \frac{A_c E}{L_{int}} = \frac{2.32 \times 10^{-4} \times 72 \times 10^9}{0.024} = 6.96 \times 10^8\, N.m^{-1}$$

$$F_e = \frac{k_b + k_c}{k_c} F_i = \frac{3.03 + 6.96}{6.96} 24851 = 35669\, N$$

$F_{e\ total} = 8 \times 35669 = 285352\, N$

Recommended Bolt Tightening Torque

$T = 0.2 F_i d = 0.2 \times 24851 \times 0.008 = 39.76\, N.m$

Maximum Shear Force per Bolt

$F = AS_{shear} = \frac{\pi}{4} \times 0.008^2 \times 756 \times 10^6 = 38000\, N$

A.2 Interface Type Two

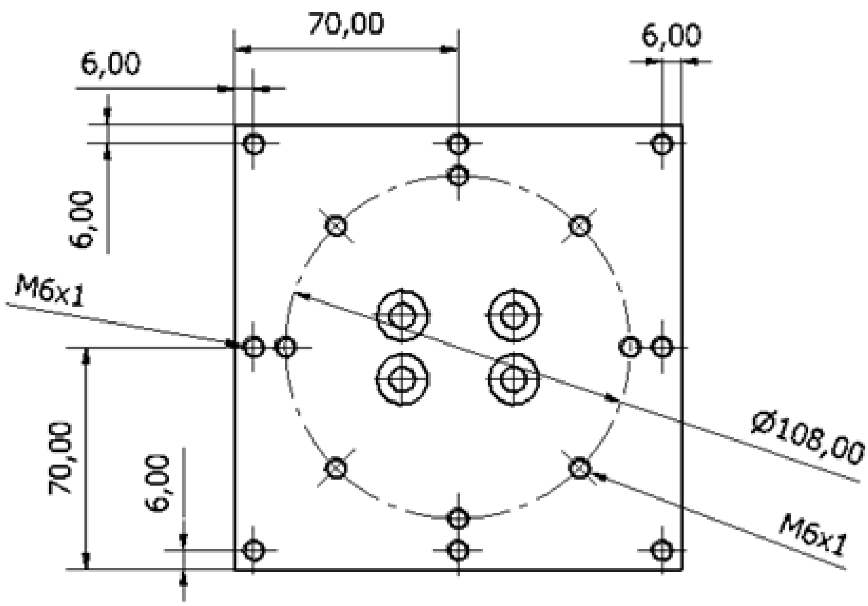


Figure A.2: Dimensional Specifications of Interface Two

Table A.2.1: Physical Specifications and Data for Interface Two

Interface Name	Plate Material	Yield Strength S_y (MPa)	Ultimate Tensile Strength S_U (MPa)	Shear Strength S_{shear} (MPa)
Two	Aluminum 295-T4	165	250	162
Modulus of Elasticity E (GPa)	**Plate Thickness h (mm)**	**Interface Thickness L_{Int} (mm)**	**Thread Height t (mm)**	**Grip Length g (mm)**
72	10	20	10	20

Table A.2.2: Physical Specifications and Data for Interface Connectors – Interface Two

Interface Name	Bolt Size (Hexagon Socket Head)	SAE Class	Proof Strength S_P (MPa)	Yield Strength S_y (MPa)	Ultimate Tensile Strength S_U (MPa)
Two	M6x1	12.9	970	1100	1220
Shear Strength S_{shear} (MPa)	**Modulus of Elasticity E (GPa)**	**Stressed Area A_t (mm^2)**	**Minor Diameter d_r (mm)**	**Bolt Length L_{bolt} (mm)**	**Bolt Tightening Factor k_i**
756	207	20.1 mm^2	4.77	20	0.7

Note: Interface A = Inner Pattern; Interface B = Outer Pattern

Thread Stripping

Thread stripping will first occur on the interface plate

$$F_e = \pi d(0.75t)S_{shear} = \pi \times 0.006 \times (0.75 \times 0.01) \times 162 \times 10^6 = 22902\ N$$

$$F_{e\ total} = 8 \times 22902 = 183217\ N$$

Joint Separation

$$F_i = k_i A_t S_p = 0.7 \times 20.1 \times 10^{-6} \times 970 \times 10^6 = 13648\ N$$

$$A_c = d^2 + 0.68dg + 0.065g^2$$

$$A_c = 0.006^2 + 0.68 \times 0.006 \times 0.020 + 0.065 \times 0.020^2 = 1.44 \times 10^{-4}\ m^2$$

$$k_b = \frac{A_t E}{L_{bolt}} = \frac{20.1 \times 10^{-6} \times 207 \times 10^9}{0.02} = 2.08 \times 10^8\ N.m^{-1}$$

$$k_c = \frac{A_c E}{L_{int}} = \frac{1.44 \times 10^{-4} \times 72 \times 10^9}{0.02} = 5.18 \times 10^8\ N.m^{-1}$$

$$F_e = \frac{k_b + k_c}{k_c} F_i = \frac{2.08 + 5.18}{5.18} 13648 = 19128\ N$$

$$F_{e\ total} = 8 \times 19128 = 153024\ N$$

Recommended Bolt Tightening Torque

$$T = 0.2 F_i d = 0.2 \times 13648 \times 0.006 = 16.38\ N.m$$

Maximum Shear Force per Bolt

$F = AS_{shear} = \frac{\pi}{4} \times 0.006^2 \times 756 \times 10^6 = 21375\ N$

A. 3 Interface Type Three

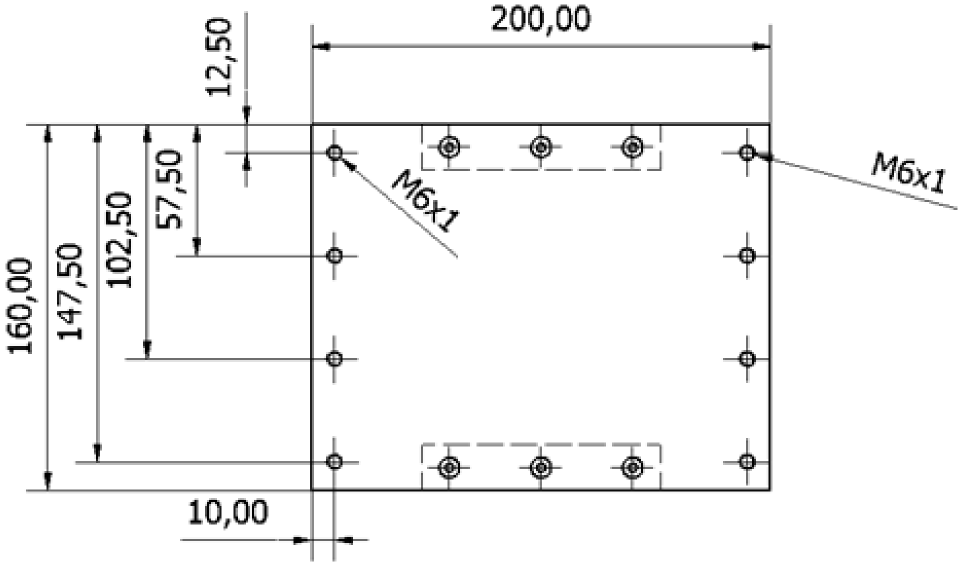


Figure A.3: Dimensional Specifications of Interface Three

Table A.3.1: Physical Specifications and Data for Interface Three

Interface Name	Plate Material	Yield Strength S_y (MPa)	Ultimate Tensile Strength S_U (MPa)	Shear Strength S_{shear} (MPa)
Three	Aluminum 295-T4	165	250	162
Modulus of Elasticity E (GPa)	**Plate Thickness h (mm)**	**Interface Thickness L_{Int} (mm)**	**Thread Height t (mm)**	**Grip Length g (mm)**
72	10	20	10	20

Table A.3.2: Physical Specifications and Data for Interface Connectors – Interface Three

Interface Name	Bolt Size (Hexagon Socket Head)	SAE Class	Proof Strength S_P (MPa)	Yield Strength S_y (MPa)	Ultimate Tensile Strength S_U (MPa)
Three	M6x1	12.9	970	1100	1220
Shear Strength S_{shear} (MPa)	**Modulus of Elasticity E (GPa)**	**Stressed Area A_t (mm^2)**	**Minor Diameter d_r (mm)**	**Bolt Length L_{bolt} (mm)**	**Bolt Tightening Factor k_i**
756	207	20.1 mm^2	4.77	20	0.7

Thread Stripping

Thread stripping will first occur on the interface plate

$$F_e = \pi d(0.75t)S_{shear} = \pi \times 0.006 \times (0.75 \times 0.01) \times 162 \times 10^6 = 22902\ N$$

$$F_{e\ total} = 8 \times 22902 = 183217\ N$$

Joint Separation

$$F_i = k_i A_t S_p = 0.7 \times 20.1 \times 10^{-6} \times 970 \times 10^6 = 13648\ N$$

$$A_c = d^2 + 0.68dg + 0.065g^2$$

$$A_c = 0.006^2 + 0.68 \times 0.006 \times 0.020 + 0.065 \times 0.020^2 = 1.44 \times 10^{-4}\ m^2$$

$$k_b = \frac{A_t E}{L_{bolt}} = \frac{20.1 \times 10^{-6} \times 207 \times 10^9}{0.02} = 2.08 \times 10^8\ N.m^{-1}$$

$$k_c = \frac{A_c E}{L_{int}} = \frac{1.44 \times 10^{-4} \times 72 \times 10^9}{0.02} = 5.18 \times 10^8\ N.m^{-1}$$

$$F_e = \frac{k_b + k_c}{k_c} F_i = \frac{2.08 + 5.18}{5.18} 13648 = 19128\ N$$

$$F_{e\ total} = 8 \times 19128 = 153024\ N$$

Recommended Bolt Tightening Torque

$$T = 0.2F_i d = 0.2 \times 13648 \times 0.006 = 16.38\ N.m$$

Maximum Shear Force per Bolt

$$F = AS_{shear} = \frac{\pi}{4} \times 0.006^2 \times 756 \times 10^6 = 21375\ N$$

A. 4 Interface Type Four

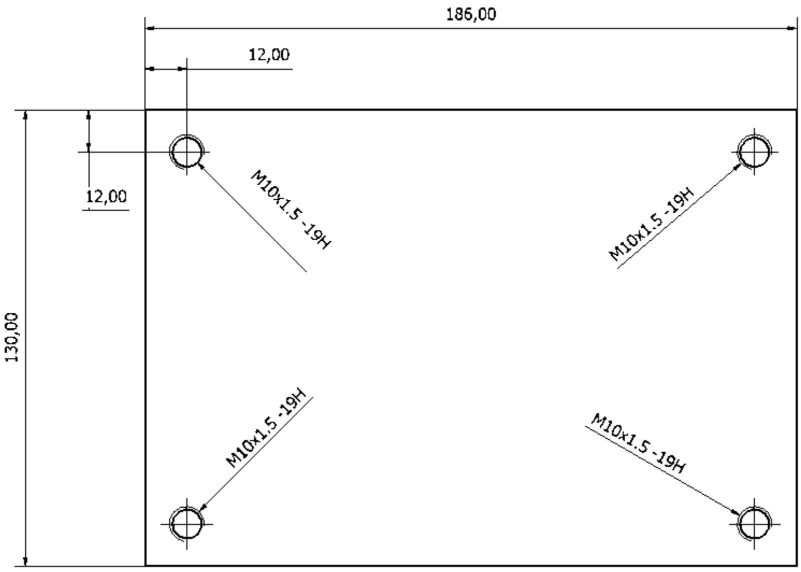


Figure A.4: Dimensional Specifications of Interface Four

Table A.4.1: Physical Specifications and Data for Interface Four

Interface Name	Plate Material	Yield Strength S_y (MPa)	Ultimate Tensile Strength S_U (MPa)	Shear Strength S_{shear} (MPa)
Four	Cast Iron ASTM 20	-	152	179
Modulus of Elasticity E (GPa)	**Plate Thickness h (mm)**	**Interface Thickness L_{Int} (mm)**	**Thread Height t (mm)**	**Grip Length g (mm)**
97	19	38	19	38

Table A.4.2: Physical Specifications and Data for Interface Connectors – Interface Four

Interface Name	Bolt Size (Hexagon Socket Head)	SAE Class	Proof Strength S_P (MPa)	Yield Strength S_y (MPa)	Ultimate Tensile Strength S_U (MPa)
Four	M10x1.5	8.8	600	660	830
Shear Strength S_{shear} (MPa)	**Modulus of Elasticity E (GPa)**	**Stressed Area A_t (mm^2)**	**Minor Diameter d_r (mm)**	**Bolt Length L_{bolt} (mm)**	**Bolt Tightening Factor k_i**
515	207	58.0 mm^2	8.16	40	0.9

Thread Stripping

Thread stripping will first occur on the interface plate

$$F_e = \pi d(0.75t)S_{shear} = \pi \times 0.01 \times (0.75 \times 0.019) \times 179 \times 10^6 = 80134\ N$$

$$F_{e\ total} = 4 \times 80134 = 320536\ N$$

Joint Separation

$$F_i = k_i A_t S_p = 0.9 \times 58.0 \times 10^{-6} \times 600 \times 10^6 = 31320\ N$$

$$A_c = d^2 + 0.68dg + 0.065g^2$$

$$A_c = 0.01^2 + 0.68 \times 0.01 \times 0.038 + 0.065 \times 0.038^2 = 4.52 \times 10^{-4}\ m^2$$

$$k_b = \frac{A_t E}{L_{bolt}} = \frac{58.0 \times 10^{-6} \times 207 \times 10^9}{0.04} = 3.00 \times 10^8\ N.m^{-1}$$

$$k_c = \frac{A_c E}{L_{int}} = \frac{4.52 \times 10^{-4} \times 97 \times 10^9}{0.038} = 11.54 \times 10^8\ N.m^{-1}$$

$$F_e = \frac{k_b + k_c}{k_c} F_i = \frac{3.00 + 11.54}{11.54} 31320 = 39217\ N$$

$$F_{e\ total} = 4 \times 39217 = 156868\ N$$

Recommended Bolt Tightening Torque

$$T = 0.2F_i d = 0.2 \times 31320 \times 0.01 = 62.64\ N.m$$

Maximum Shear Force per Bolt

$F = AS_{shear} = \frac{\pi}{4} \times 0.01^2 \times 515 \times 10^6 = 40448\ N$

A.5 Interface Type Five

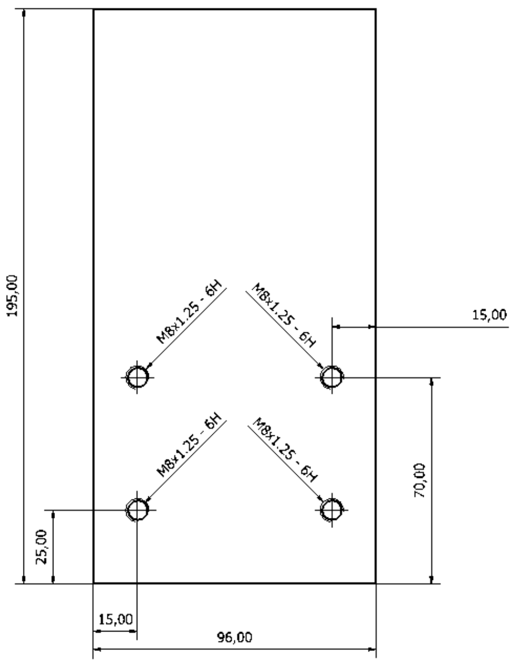


Figure A.5: Dimensional Specifications of Interface Five

Table A.5.1: Physical Specifications and Data for Interface Five

Interface Name	Plate Material	Yield Strength S_y (MPa)	Ultimate Tensile Strength S_U (MPa)	Shear Strength S_{shear} (MPa)
Four	Cast Iron ASTM 20	-	152	179
Modulus of Elasticity E (GPa)	**Plate Thickness h (mm)**	**Interface Thickness L_{Int} (mm)**	**Thread Height t (mm)**	**Grip Length g (mm)**
97	6	25	19	25

Table A.5.2: Physical Specifications and Data for Interface Connectors – Interface Five

Interface Name	Bolt Size (Hexagon Socket Head)	SAE Class	Proof Strength S_P (MPa)	Yield Strength S_y (MPa)	Ultimate Tensile Strength S_U (MPa)
Four	M8x1.25	8.8	600	660	830
Shear Strength S_{shear} (MPa)	**Modulus of Elasticity E (GPa)**	**Stressed Area A_t (mm^2)**	**Minor Diameter d_r (mm)**	**Bolt Length L_{bolt} (mm)**	**Bolt Tightening Factor k_i**
515	207	36.6 mm^2	6.47	25	0.9

Thread Stripping

Thread stripping will first occur on the interface plate

$$F_e = \pi d(0.75t)S_{shear} = \pi \times 0.008 \times (0.75 \times 0.019) \times 179 \times 10^6 = 64107\ N$$

$$F_{e\ total} = 4 \times 64107 = 256429\ N$$

Joint Separation

$$F_i = k_i A_t S_p = 0.9 \times 36.6 \times 10^{-6} \times 600 \times 10^6 = 19764\ N$$

$$A_c = d^2 + 0.68dg + 0.065g^2$$

$$A_c = 0.008^2 + 0.68 \times 0.008 \times 0.025 + 0.065 \times 0.025^2 = 2.41 \times 10^{-4}\ m^2$$

$$k_b = \frac{A_t E}{L_{bolt}} = \frac{36.6 \times 10^{-6} \times 207 \times 10^9}{0.025} = 3.03 \times 10^8\ N.m^{-1}$$

$$k_c = \frac{A_c E}{L_{int}} = \frac{2.41 \times 10^{-4} \times 97 \times 10^9}{0.025} = 9.35 \times 10^8\ N.m^{-1}$$

$$F_e = \frac{k_b + k_c}{k_c} F_i = \frac{3.03 + 9.35}{9.35} 19764 = 26168\ N$$

$$F_{e\ total} = 4 \times 26168 = 104672\ N$$

Recommended Bolt Tightening Torque

$$T = 0.2F_i d = 0.2 \times 19764 \times 0.008 = 31.62\ N.m$$

Maximum Shear Force per Bolt

$$F = AS_{shear} = \frac{\pi}{4} \times 0.008^2 \times 515 \times 10^6 = 25886\ N$$

Appendix B

B.1 Base Module

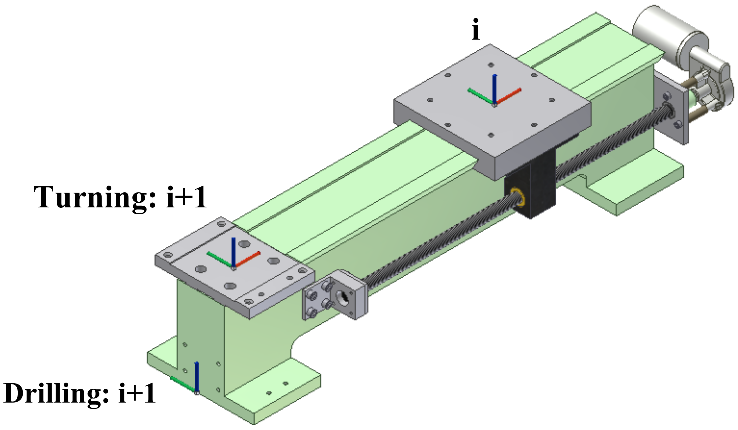


Figure B.1: Base Module Displaying Local Reference Frames

Table B.1.1: Parameters Relating Frame i to i+1 on Base Module (Drilling)

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	variable
β	0	y	-2.5
α	0	z	215

$$^{i+1}_{i}M_{Base-Drilling} = \begin{bmatrix} c0c0 & c0s0s0 - s0c0 & c0s0c0 + s0s0 & x \\ s0c0 & s0s0s0 + c0c0 & s0s0c0 - c0s0 & -2.5 \\ -s0 & c0s0 & c0c0 & 215 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & 2.5 \\ 0 & 0 & 1 & 215 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Limits: $257.5 \leq x \leq 757.5$

Home: $x = 257.5\ mm$

Table B.1.2: Parameters Relating Frame i to i+1 on Base Module (Turning)

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	variable
β	0	y	-2.5
α	0	z	19

$$^{i+1}_{i}M_{Base-Turning} = \begin{bmatrix} c0c0 & c0s0s0 - s0c0 & c0s0c0 + s0s0 & x \\ s0c0 & s0s0s0 + c0c0 & s0s0c0 - c0s0 & -2.5 \\ -s0 & c0s0 & c0c0 & 19 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & 2.5 \\ 0 & 0 & 1 & 19 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Limits: $192.5 \leq x \leq 692.5$

Home: $x = 192.5\ mm$

B.2 Work Table Slide Module

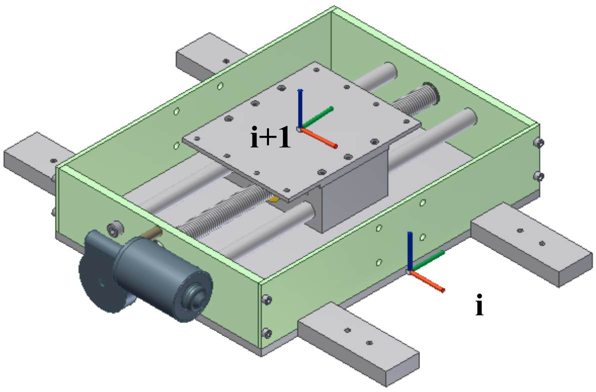


Figure B.2: Work Table Slide Module Displaying Local Reference Frames

Table B.2: Parameters Relating Frame i to i+1 on Work Table Slide Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	155
β	0	y	variable
α	0	z	-111

$$ {}^{i+1}_{\ i}M_{WT\ Slide} = \begin{bmatrix} c0c0 & c0s0s0 - s0c0 & c0s0c0 + s0s0 & 155 \\ s0c0 & s0s0s0 + c0c0 & s0s0c0 - c0s0 & y \\ -s0 & c0s0 & c0c0 & -111 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 155 \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & -111 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Limits: $-150 \leq y \leq 150$

Home: $y = 0\ mm$

B.3 Column Module

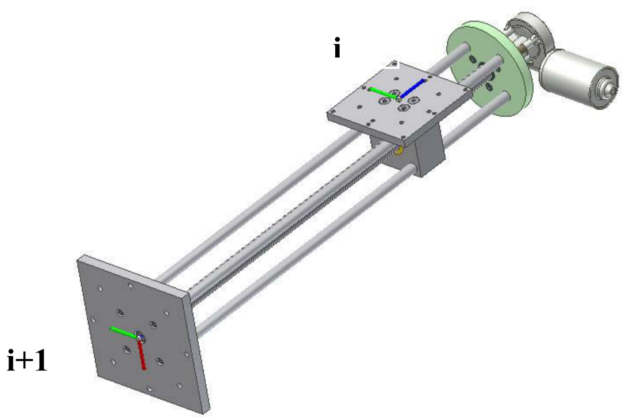


Figure B.3: Column Module Displaying Local Reference Frames

Table B.3: Parameters Relating Frame i to i+1 on Column Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	-54.5
β	0	y	0
α	0	z	variable

$$ {}^{i+1}_{i}M_{Column} = \begin{bmatrix} c0c0 & c0s0s0 - s0c0 & c0s0c0 + s0s0 & -54.5 \\ s0c0 & s0s0s0 + c0c0 & s0s0c0 - c0s0 & 0 \\ -s0 & c0s0 & c0c0 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -54.5 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Limits: $85 \leq z \leq 685$

Home: $z = 685\ mm$

B.4 Cross Slide Module

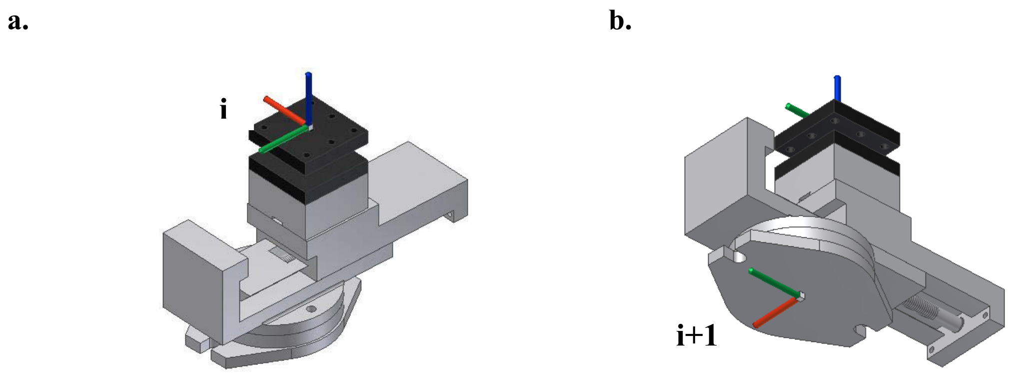


Figure B.4: Cross Slide Module Displaying Local Reference Frames

a. Reference frame i
b. Reference frame i+1

Table B.4: Parameters Relating Frame i to i+1 on Cross Slide Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	0
β	0	y	variable
α	variable	z	168

$$ {}^{i+1}_{i}M_{Cross\ Slide} = \begin{bmatrix} c\alpha c0 & c\alpha s0s0 - s\alpha c0 & c\alpha s0c0 + s0s0 & 0 \\ s\alpha c0 & s\alpha s0s0 + c\alpha c0 & s\alpha s0c0 - c\alpha s0 & y \\ -s0 & c0s0 & c0c0 & 168 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c\alpha & -s\alpha & 0 & 0 \\ s\alpha & c\alpha & 0 & y \\ 0 & 0 & 1 & 168 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Limits: $-90 \leq y \leq 25$

Home: $y = 0\ mm$

B.5 Cutting Head Rotary Module

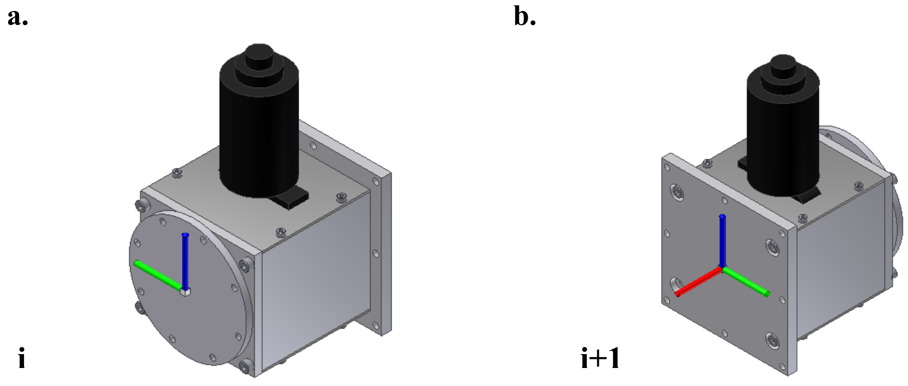


Figure B.5: Cross Slide Module Displaying Local Reference Frames

a. Reference frame i
b. Reference frame i+1

Table B.5: Parameters Relating Frame i to i+1 on Cutting Head Rotary Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	variable	x	-138
β	0	y	0
α	0	z	0

$$ {}^{i+1}_{i}M_{CH\ Rotary} = \begin{bmatrix} c0c0 & c0s0s\gamma - s0c\gamma & c0s0c\gamma + s0s\gamma & -138 \\ s0c0 & s0s0s\gamma + c0c\gamma & s0s0c\gamma - c0s\gamma & 0 \\ -s0 & c0s\gamma & c0c\gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -138 \\ 0 & c\gamma & -s\gamma & 0 \\ 0 & s\gamma & c\gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Limits: $-360° \leq \gamma \leq 360°$

Home: $\gamma = 0°$

B.6 Tilt Table Module

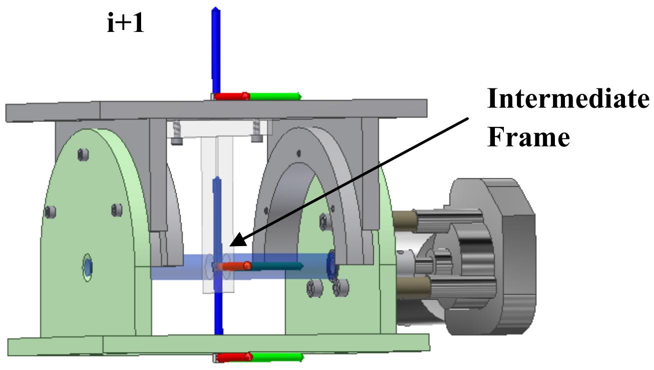


Figure B.6: Tilt Table Module Displaying Local Reference Frames

Table B.6.1: Parameters Relating Frame i to the Intermediate Frame on Tilt Table Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	0
β	variable	y	0
α	0	z	-50

T

Table B.6.2: Parameters Relating the Intermediate Frame to i+1 on Tilt Table Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	variable	x	-138
β	0	y	0
α	0	z	0

$$^{int}_{i}M = \begin{bmatrix} c0c\beta & c0s\beta s0 - s0c0 & c0s\beta c0 + s0s0 & 0 \\ s0c\beta & s0s\beta s0 + c0c0 & s0s\beta c0 - c0s0 & 0 \\ -s\beta & c\beta s0 & c\beta c0 & -50 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c\beta & 0 & s\beta & -50s\beta \\ 0 & 1 & 0 & 0 \\ -s\beta & 0 & c\beta & -50c\beta \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{i+1}_{int}M = \begin{bmatrix} c0c0 & c0s0s0 - s0c0 & c0s0c0 + s0s0 & 0 \\ s0c0 & s0s0s0 + c0c0 & s0s0c0 - c0s0 & 0 \\ -s0 & c0s0 & c0c0 & -95 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -95 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{i+1}_{i}M_{Tilt\ Table} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -95 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\beta & 0 & s\beta & -50s\beta \\ 0 & 1 & 0 & 0 \\ -s\beta & 0 & c\beta & -50c\beta \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c\beta & 0 & s\beta & -50s\beta \\ 0 & 1 & 0 & 0 \\ -s\beta & 0 & c\beta & -50c\beta - 95 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Limits: $-45° \leq \beta \leq 45°$

Home: $\beta = 0°$

B.7 Rotary Table Module

a. **b.**

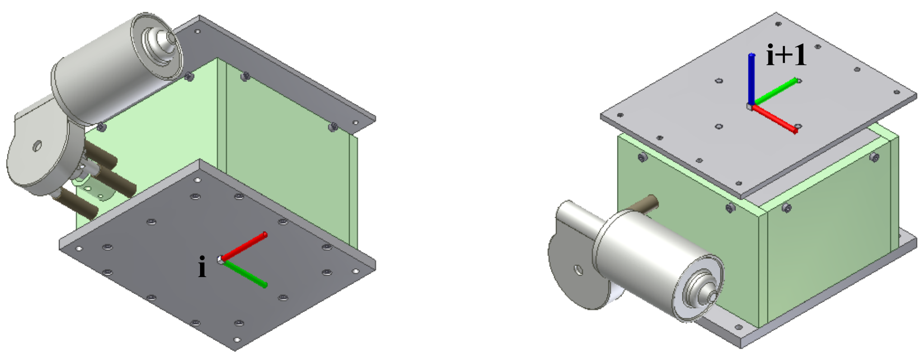


Figure B.7: Rotary Table Module Displaying Local Reference Frames

a. Reference frame i
b. Reference frame i+1

Table B.7: Parameters Relating Frame i to i+1 on Rotary Table Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	0
β	0	y	0
α	variable	z	-152

$$ {}_{i}^{i+1}M_{Rot\ Table} = \begin{bmatrix} c\alpha c0 & c\alpha s0s0 - s\alpha c0 & c\alpha s0c0 + s\alpha s0 & 0 \\ s\alpha c0 & s\alpha s0s0 + c\alpha c0 & s\alpha s0c0 - c\alpha s0 & 0 \\ -s0 & c0s0 & c0c0 & -152 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c\alpha & -s\alpha & 0 & 0 \\ s\alpha & c\alpha & 0 & 0 \\ 0 & 0 & 1 & -152 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Limits: $-180° \leq \alpha \leq 180°$

Home: $\alpha = 0°$

B.8 Drilling Module

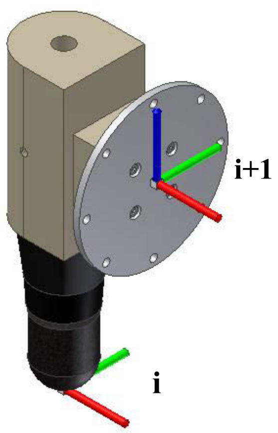


Figure B.8: Drilling Module Displaying Local Reference Frames

Table B.8: Parameters Relating Frame i to i+1 on Drilling Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	-75
β	0	y	0
α	0	z	-81.5

$$ {}_{i}^{i+1}M_{Drill\ Head} = \begin{bmatrix} c0c0 & c0s0s0 - s0c0 & c0s0c0 + s0s0 & -75 \\ s0c0 & s0s0s0 + c0c0 & s0s0c0 - c0s0 & 0 \\ -s0 & c0s0 & c0c0 & -81.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -75 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -81.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

B.9 Turning Module

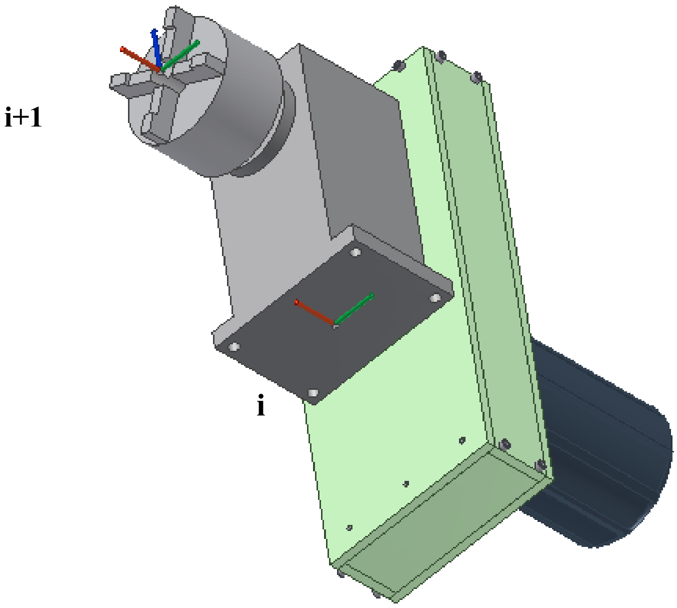


Figure B.9: Turning Module Displaying Local Reference Frames

Table B. 9: Parameters Relating Frame i to i+1 on Turning Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	-192.5
β	0	y	0
α	0	z	-212.5

$$ {}^{i+1}_{\;\;i}M_{Turn\ Head} = \begin{bmatrix} c0c0 & c0s0s0 - s0c0 & c0s0c0 + s0s0 & -192.5 \\ s0c0 & s0s0s0 + c0c0 & s0s0c0 - c0s0 & 0 \\ -s0 & c0s0 & c0c0 & -212.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -192.5 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -212.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

B.10 Work Table Module

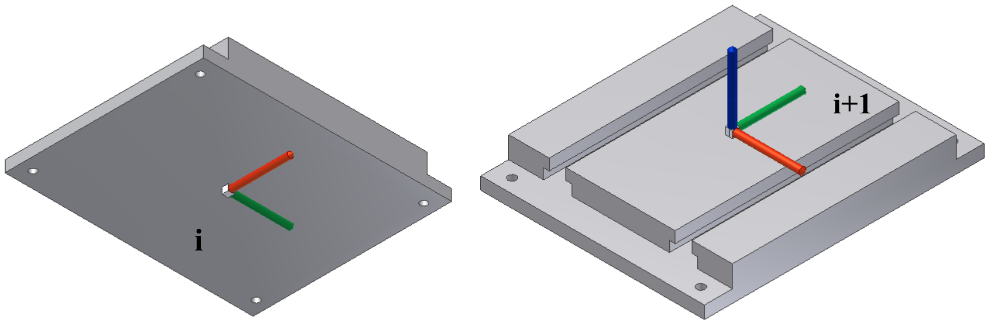


Figure B.10: Work Table Module Displaying Local Reference Frames

Table B.10: Parameters Relating Frame i to i+1 on Work Table Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	0
β	0	y	0
α	0	z	-24.5

$$ {}^{i+1}_{\ \ i}M_{Work\ Table} = \begin{bmatrix} c0c0 & c0s0s0 - s0c0 & c0s0c0 + s0s0 & 0 \\ s0c0 & s0s0s0 + c0c0 & s0s0c0 - c0s0 & 0 \\ -s0 & c0s0 & c0c0 & -24.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -24.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

B.11 Range Extension Module (Arm)

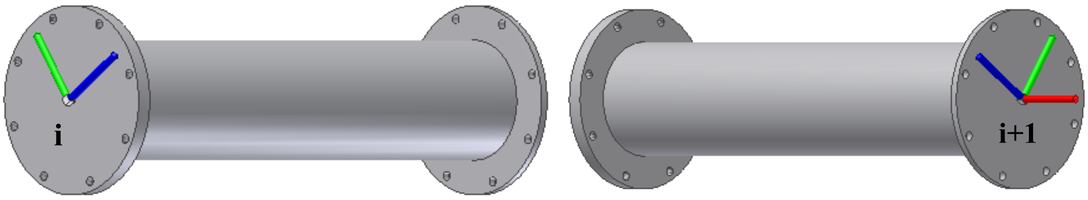


Figure B.11: Range Extension Module (Arm) Displaying Local Reference Frames

Table B.11: Parameters Relating Frame i to i+1 on Range Extension Module

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	-370
β	0	y	0
α	0	z	0

$$ {}^{i+1}_{\ \ i}M_{Extension\ \ Arm} = \begin{bmatrix} c0c0 & c0s0s0 - s0c0 & c0s0c0 + s0s0 & -370 \\ s0c0 & s0s0s0 + c0c0 & s0s0c0 - c0s0 & 0 \\ -s0 & c0s0 & c0c0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -370 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

B.12 Cross Slide Interface Plate

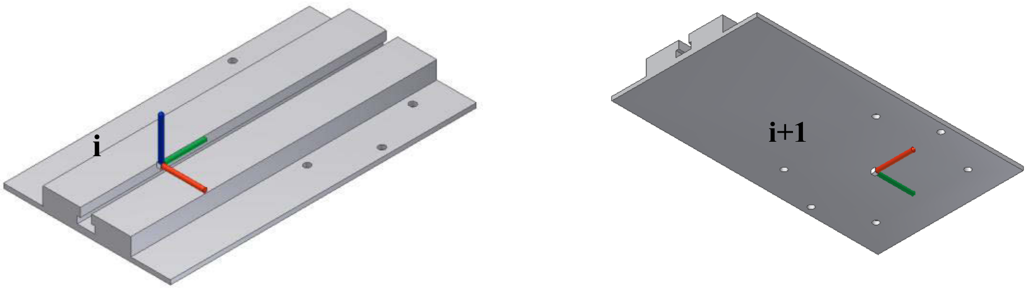


Figure B.12: Cross Slide Interface Plate Displaying Local Reference Frames

Table B.12: Parameters Relating Frame i to i+1 on Cross Slide Interface Plate

X-Y-Z Euler Angles	Degrees	X-Y-Z Offsets	mm
γ	0	x	0
β	0	y (v)	variable
α	0	z	25

$$ {}_{i}^{i+1}M_{Interface\ \ Plate} = \begin{bmatrix} c0c0 & c0s0s0 - s0c0 & c0s0c0 + s0s0 & 0 \\ s0c0 & s0s0s0 + c0c0 & s0s0c0 - c0s0 & v \\ -s0 & c0s0 & c0c0 & 25 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & v \\ 0 & 0 & 1 & 25 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Limits: $0 \leq v \leq 80$

Appendix C

C.1 Power Screw Calculations

Base Module (X-Axis)

Table C.1.1: Power Screw Characteristics of MRM Base Module

d_m (mm)	f	L (mm)	α (Degrees)	f_c	d_c (mm)
18.45	0.25	2.5	30	0.0015	17

Relationship between torque and linear load with direction of motion opposing direction of load:

$$W = T\left[\frac{d_m}{2}\frac{f\pi d_m + L\cos\alpha_n}{\pi d_m\cos\alpha_n - fL} + \frac{f_c d_c}{2}\right]^{-1}$$

$$W = T\left[\frac{0.01845}{2}\frac{0.25\times\pi\times0.01845 + 0.0025\times\cos 30}{\pi\times0.01845\times\cos 30 - 0.25\times0.0025} + \frac{2\times0.0015\times0.017}{2}\right]^{-1}$$

$$W = 320.00\,T$$

Table C.1.2: Power Screw Actuation Characteristics of MRM Base Module

Motor Speed (rev/min)	Motor Current (amps)	Motor Torque (N.m)	Actuation Speed (mm/min)	Actuation Force (N)
58	3.4	1	145	320
40	7.5	5	100	1600
20	12	12	50	3840
Stall	18	20	0	6400

Work Table Slide Module (Y-Axis)

Table C.1.3: Power Screw Characteristics of MRM Work Table Slide Module

d_m (mm)	f	L (mm)	α (Degrees)	f_c	d_c (mm)
22.15	0.25	3	30	0.0015	17

Relationship between torque and linear load with direction of motion opposing direction of load:

$$W = T\left[\frac{d_m}{2}\frac{f\pi d_m + L\cos\alpha_n}{\pi d_m\cos\alpha_n - fL} + \frac{f_c d_c}{2}\right]^{-1}$$

$$W = T\left[\frac{0.02215}{2}\frac{0.25\times\pi\times0.02215 + 0.003\times\cos 30}{\pi\times0.02215\times\cos 30 - 0.25\times0.003} + \frac{2\times0.0015\times0.017}{2}\right]^{-1}$$

$$W = 266.93\,T$$

Table C.1.4: Power Screw Actuation Characteristics of MRM Work Table Slide Module

Motor Speed (rev/min)	Motor Current (amps)	Motor Torque (N.m)	Actuation Speed (mm/min)	Actuation Force (N)
58	3.4	1	174	266.93
40	7.5	5	120	1334.65
20	12	12	60	3203.16
Stall	18	20	0	5338.60

Column Module (Z-Axis)

Table C.1.5: Power Screw Characteristics of MRM Column Module

d_m (mm)	f	L (mm)	α (Degrees)	f_c	d_c (mm)
22.15	0.25	3	30	0.0015	15

Relationship between torque and linear load with direction of motion opposing direction of load:

$$W = T\left[\frac{d_m}{2}\frac{f\pi d_m + L\cos\alpha_n}{\pi d_m\cos\alpha_n - fL} + \frac{f_c d_c}{2}\right]^{-1}$$

$$W = T\left[\frac{0.02215}{2}\frac{0.25\times\pi\times 0.02215 + 0.003\times\cos 30}{\pi\times 0.02215\times\cos 30 - 0.25\times 0.003} + \frac{2\times 0.0015\times 0.015}{2}\right]^{-1}$$

$$W = 267.14\,T$$

Table C.1.6: Power Screw Actuation Characteristics of MRM Column Module

Motor Speed (rev/min)	Motor Current (amps)	Motor Torque (N.m)	Actuation Speed (mm/min)	Actuation Force (N)
58	3.4	1	174	267.14
40	7.5	5	120	1335.70
20	12	12	60	3205.68
Stall	18	20	0	5342.80

Cross Slide Module (Y-Axis and C-Axis)

Table C.1.7: Power Screw Characteristics of MRM Cross Slide Module

d_m (mm)	f	L (mm)	α (Degrees)	f_c	d_c (mm)
10.75	0.25	2	15	N/A	N/A

Relationship between torque and linear load with direction of motion opposing direction of load:

$$W = T\left[\frac{d_m}{2}\frac{f\pi d_m + L\cos\alpha_n}{\pi d_m\cos\alpha_n - fL} + \frac{f_c d_c}{2}\right]^{-1}$$

$$W = T\left[\frac{0.01075}{2}\frac{0.25\times\pi\times 0.01075 + 0.002\times\cos 15}{\pi\times 0.01075\times\cos 15 - 0.25\times 0.002} + 0\right]^{-1}$$

$$W = 576.01\,T$$

Table C.1.8: Power Screw Actuation Characteristics of MRM Cross Slide Module

Motor Speed (rev/min)	Motor Current (amps)	Motor Torque (N.m)	Actuation Speed (mm/min)	Actuation Force (N)
58	3.4	1	116	576.01
40	7.5	5	80	288.05
20	12	12	40	692.12
Stall	18	20	0	11520.20

C.2 Actuation Characteristics of Rotary Axes

For the “Work Table Rotary “module:

$$\omega_{output} = \omega_{input} \frac{N_{worm}}{N_{gear}} = \frac{\omega_{input}}{56}$$

$$T_{output} = T_{input} \frac{\omega_{input}}{\omega_{output}} = 56\, T_{input}$$

All other rotary axes possessed direct drive systems.

Table C.2.1: Actuation Characteristics of MRM Rotary Axes

Motor Speed (rev/min)	Motor Current (amps)	Motor Torque (N.m)	A-Axis Torque (N.m)	B-Axis Torque (N.m)	C-Axis Speed (rev/min)	C-Axis Torque (N.m)
58	3.4	1	1	1	1.036	56
40	7.5	5	5	5	0.714	280
20	12	12	12	12	0.357	672
Stall	18	20	20	20	Stall	1120

C.3 Module Actuation Loading Calculations

Module Actuation Loading and Torque/Force Amplification

The specification of the maximum load that a module can sustain along its axis of actuation is primarily constrained by the load that will cause the drive motor to stall during operation. The torque and force amplification created by power screws and gearboxes may lead to excessive deflections or mechanical fracture before the drive motor stalls. In these instances the maximum load specification must be reduced to below the stall load. The cutting head rotary module and the tilt table module both possessed direct drive mechanisms with no other torque amplification systems; the maximum load that these modules are specified to sustain has therefore been set equal to the stall torque of the motor (20 N.m). The rotary table module possessed a worm gearbox; this gearbox was the mechanical equivalent of the internal worm gearboxes possessed by the drive motors. The maximum load that the rotary table module can sustain was therefore also limited to 20 N.m of torque. The calculations presented in the following subsections relate exclusively to the load specifications for linear axes.

Base Module (X-Axis)

Failure mode: Thread stripping calculation.

Table C.3.1: Physical Specifications of Power Screw Nut on Base Module

Nut Material	Nut Height (mm)	Thread Specification	Shear Strength S_{shear} (MPa)
Brass	50	M20x2.5	206

$$F_e = \pi d(0.75t)S_{shear} = \pi \times 0.020 \times (0.75 \times 0.05) \times 206 \times 10^6 = 485.376\, kN$$

Failure mode: Failure of shear pin in motor coupling.

Table C.3.2: Physical Specifications of Shear Pin and Shaft on Base Module

Pin Material	Pin Diameter (mm)	Motor Shaft Diameter (mm)	Pin Shear Strength S_{shear} (MPa)
Steel	4 mm	12 mm	206

$$A_{Shear} = 2 \times \pi \frac{d^2}{4} = 2 \times \pi \times \frac{0.004^2}{4} = 25.133 \times 10^{-6}\, m^2$$

$$F_{Shear} = S_{Shear} \times A_{Shear} = 206 \times 10^6 \times 25.133 \times 10^{-6} = 5177.398\, N$$

$$T_{Shear} = F_{Shear} \times \frac{d_{shaft}}{2} = 5177.398 \times \frac{0.012}{2} = 31.064\, N.m$$

This is greater than the motor stall torque; therefore the force related to this toque is too high to be used as a limit.

Failure mode: Shear failure of bolts on slide/ power screw attachment system.

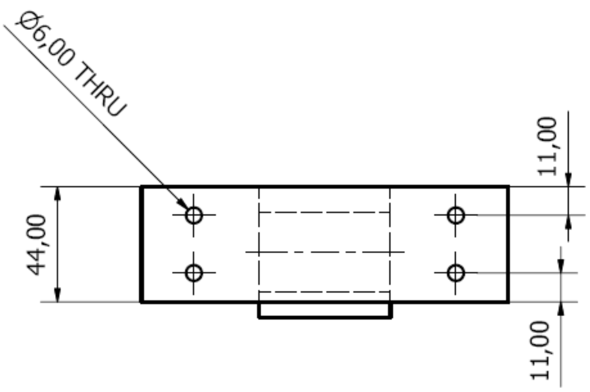


Figure C.3.1: Slide - Power Screw Attachment Bracket

Table C.3.3: Physical Specifications of Bolts on Slide Attachment Bracket

Bolt Size	SAE Class	Shear Strength S_{shear} (MPa)
M6x1	12.9	756

$$F_{Shear} = AS_{shear} = \frac{\pi}{4} \times 0.006^2 \times 756 \times 10^6 = 21375\ N$$

$$F_{Total} = F_{shear} \times 4 = 85500\ N$$

Failure mode: Bearing failure under axial load.

Bearing: Deep Groove Ball Bearing *SKF 61803*
Static radial load rating: $C_o = 930\ N$
Axial load rating: $F_{axial} = 0.5\ C_o = 465\ N$
Two bearings: $F = 930\ N$

Summary of Failure modes:

Table C.3.4: Summary of Failure Modes on Base Module

Summary	
Power Screw Thread Stripping	485.376 kN
Motor Stall	6400 N
Shear Pin on Motor Shaft	$F_{shear} > F_{stall}$
Shear of Bolts on slide attachment	85500 N
Bearing Failure	930 N

Work Table Slide Module (Y-Axis)

Failure mode: Thread stripping calculation.

Table C.3.5: Physical Specifications of Power Screw Nut on Work Table Slide Module

Nut Material	Nut Height (mm)	Thread Specification	Shear Strength S_{shear} (MPa)
Brass	50	M24x3	206

$$F_e = \pi d(0.75t)S_{shear} = \pi \times 0.024 \times (0.75 \times 0.05) \times 206 \times 10^6 = 582.451\ kN$$

Failure mode: Failure of shear pin on motor coupling; pin specifications and calculations same as in base module.

$F_{Shear} > F_{Stall}$

Failure mode: Bearing failure under axial load, bearing specification same as in base module.

$F = 930\ N$

Summary of Failure modes:

Table C.3.6: Summary of Failure Modes on Work Table Slide Module

Summary	
Power Screw Thread Stripping	582.451 kN
Motor Stall	5338.6 N
Shear Pin on Motor Shaft	$F_{shear} > F_{stall}$
Bearing Failure	930 N

Column Module (Z- Axis)

Failure mode: Thread stripping calculation; thread specifications and calculations same as in work table slide module.

$F_e = 582.451\ kN$

Failure mode: Failure of shear pin on motor coupling; pin specifications and calculations same as in base module.

$F_{Shear} > F_{Stall}$

Failure mode: Thrust Bearing failure under axial load.

Bearing: Thrust Ball Bearing *SKF 51102*
Static axial load rating: $C_o = 11200\ N$
Dynamic axial load rating: $C = 9360\ N$

Failure mode: Deflection of column support rods and power screw.

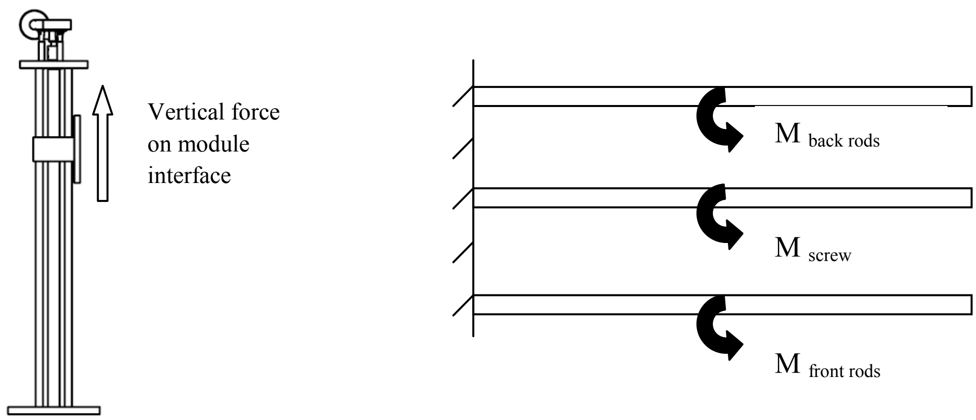


Figure C.3.2: Loading on Support Rods and Power Screw for Pure Vertical Force on Sliding Interface

The loading scenario on the support rods and power screw is presented in Figure C.3.2 for a pure vertical force on the column"s sliding interface. The axial stress on the screw and rods has been neglected as its effect on the deflection of the members is expected to be small. The primary loads that contribute to the deflection of the members are the moments generated by the force. The deflection of a beam under the action of a moment M_o at a distance „a" from its supported end is given by equation C.3.1. Figure C.3.3 illustrates the loading scenario for a single rod.

$$\delta_B = \frac{M_o a}{2EI}(2L - a) \qquad (C.3.1)$$

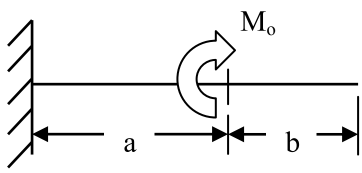


Figure C.3.3: Loading on a Single Beam

For the loading scenario of Figure C.3.2:

$M_{front\ rods} = R \times F = 0.02445F$

$M_{screw} = R \times F = 0.0545F$

$M_{back\ rods} = R \times F = 0.08445F$

Manipulating equation C.3.1:

$$\delta_B = \frac{M_o a}{2EI}(2L - a) = \frac{FRa}{2EI}(2L - a) = F\left[\frac{Ra}{2EI}(2L - a)\right] \qquad (C.3.2)$$

The stiffness of a beam at a distance “a” from the support is given by equation C.3.3:

$$K_B = \frac{F}{\delta_B} = \left[\frac{Ra}{2EI}(2L - a)\right]^{-1} \qquad (C.3.3)$$

For springs in parallel:

$$K_{Total} = K_1 + K_2 + \cdots + K_n \qquad (C.3.4)$$

The total effective stiffness of the column in for the loading scenario of Figure C.3.2 is given by equation C.3.5:

$$K_{Total} = 2K_1 + K_2 + 2K_3 \qquad (C.3.5)$$

Where:

$$K_1 = \left[\frac{0.02445a}{2E_{rod} I_{rod}}(2L_{rod} - a)\right]^{-1}$$

$$K_2 = \left[\frac{0.0545a}{2E_{screw} I_{screw}}(2L_{screw} - a)\right]^{-1}$$

$$K_3 = \left[\frac{0.08445a}{2E_{rod} I_{rod}}(2L_{rod} - a)\right]^{-1}$$

Table C.3.7: Physical Characteristics of Column Support Elements

	d (mm)	E (GPa)	a (mm)	L (mm)
Rods	15.00	207	600	700
Screw	24.00	207	600	700

By the parallel axis theorem (distance between two axes r = 0.0425 m):

$$I_{rod} = \frac{\pi d^4}{64} + Ar^2 = \frac{\pi \times 0.015^4}{64} + \left(\frac{\pi 0.015^2}{4}\right) \times 0.0425^2 = 321.676 \times 10^{-9}\ m^4$$

$$I_{screw} = \frac{\pi d^4}{64} = \frac{\pi \times 0.024^4}{64} = 16.286 \times 10^{-9}\ m^4$$

$$K_1 = \left[\frac{0.02445 \times 0.6}{2 \times 207 \times 10^9 \times 321.676 \times 10^{-9}}(2 \times 0.7 - 0.6)\right]^{-1} = 11.347 \times 10^6\ N.m^{-1}$$

$$K_2 = \left[\frac{0.0545 \times 0.6}{2 \times 207 \times 10^9 \times 16.286 \times 10^{-9}}(2 \times 0.7 - 0.6)\right]^{-1} = 257.737 \times 10^3\ N.m^{-1}$$

$$K_3 = \left[\frac{0.08445 \times 0.6}{2 \times 207 \times 10^9 \times 321.676 \times 10^{-9}}(2 \times 0.7 - 0.6)\right]^{-1} = 3.285 \times 10^6\ N.m^{-1}$$

$$K_{Total} = 2 \times 11.347 \times 10^6 + 257.737 \times 10^3 + 2 \times 3.285 \times 10^6 = 29.522 \times 10^6\ N.m^{-1}$$

The maximum tolerable deflection for the column structure has been set at 0.1 mm. The force associated with this deflection is:

$$F = K_{Total} \times \delta = 29.522 \times 10^6 \times 0.1 \times 10^{-3} = 2952.20\ N$$

Failure mode: Buckling of column under compressive load. This calculation is limited to the critical load that would lead to buckling on the central power screw. The calculation ignores the support effects of the four guide rods, thus providing a conservative limit to the compressive forces that may be allowed in the module.

$$P_{cr} = \frac{\pi^2 EI}{L^2} = \frac{\pi^2 \times 207 \times 10^9 \times 16.286 \times 10^{-9}}{0.7^2} = 21.614 \times 10^6\ N$$

Summary of Failure modes:

Table C.3.8: Summary of Failure Modes on Column Module

Summary	
Power Screw Thread Stripping	582.451 kN
Motor Stall	5342.8 N
Shear Pin on Motor Shaft	$F_{shear} > F_{stall}$
Bearing Failure	9360 N
Deflection of Column (0.1 mm)	2952.2 N
Buckling of Column	21.641 MN

Cross Slide Module (Y-Axis and C-Axis)

Failure mode: Thread stripping calculation.

Table C.3.9: Physical Specifications of Power Screw Nut on Cross Slide Module

Nut Material	Nut Height (mm)	Thread Specification	Shear Strength S_{shear} (MPa)
Brass	20	Trapezoidal 12x2	206

$$F_e = \pi d(0.75t)S_{shear} = \pi \times 0.012 \times (0.75 \times 0.02) \times 206 \times 10^6 = 116.490\ kN$$

Failure mode: Failure of shear pin on motor coupling; pin specifications and calculations same as in base module.

$F_{Shear} > F_{Stall}$

Failure mode: Failure of motor gearbox due to an axial thrust force. The axial thrust forces on the motor shaft are sustained by a thin steel plate which forms the back cover of the worm gearbox. This cover keeps the worm and gear in mesh by restricting the movement of the gear shaft. Finite element analysis was performed on the plate to determine a tolerable maximum thrust force on the motor shaft. The force was applied as a point load at the central point of contact between the shaft and the plate. Fixed constraints were applied to the three fastening points on the plate. The results of the analysis resulted in the maximum force being set to 250 N, which has an associated deflection of 0.1221 mm. Further details of the analysis are found below.

Table C.3.10: Material Properties of Steel Plate

Carbon Steel	
Young's Modulus	2.e+005 MPa
Poisson's Ratio	0.29
Mass Density	7.87e-006 kg/mm³
Tensile Yield Strength	350.0 MPa
Tensile Ultimate Strength	420.0 MPa

Table C.3.11: Loading and Constraints Definition

Load and Constraint Definitions			
Name	**Type**	**Magnitude**	**Vector**
Force 1	Surface Force	250.0 N	0.0 N 0.0 N 250.0 N
Fixed Constraint 1	Edge Fixed Constraint	0.0 mm	0.0 mm 0.0 mm 0.0 mm

Table C.3.12: Structural Results

Structural Results		
Name	Minimum	Maximum
Equivalent Stress	0.3424 MPa	177.3 MPa
Maximum Principal Stress	-9.362 MPa	182.6 MPa
Minimum Principal Stress	-189.6 MPa	36.49 MPa
Deformation	0.0 mm	0.1221 mm
Safety Factor	1.974	N/A

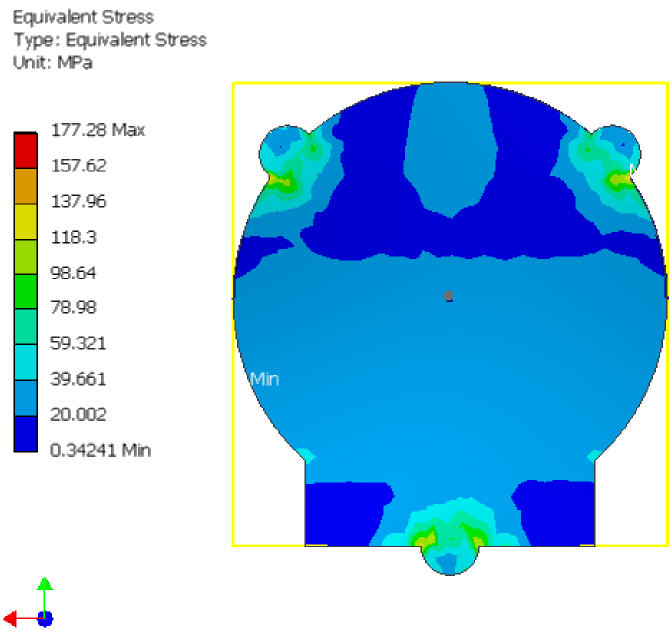


Figure C.3.4: Equivalent Stress on Motor Plate

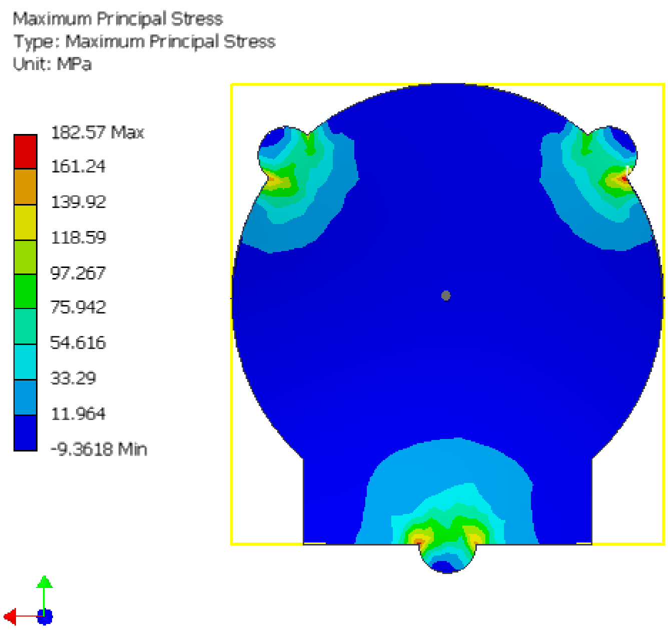


Figure C.3.5: Maximum Principle Stress on Motor Plate

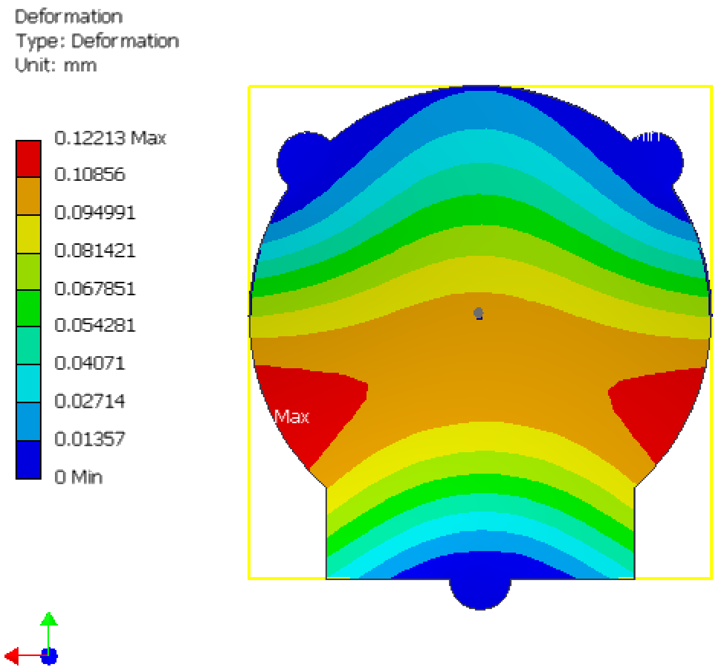


Figure C.3.6: Deformation of Motor Plate

Summary of Failure modes:

Table C.3.13: Summary of Failure Modes on Cross Slide Module

Summary	
Power Screw Thread Stripping	116.490 kN
Motor Stall	11520.2 N
Shear Pin on Motor Shaft	$F_{shear} > F_{stall}$
Deflection of Motor Back Plate	250 N

C.4 Normal Loading Calculations

The calculations presented in this section were used to determine the maximum perpendicular/normal loads that a module can sustain on its moving interface. The loading for selected modules are as follows:

- For the work table rotary module and cutting head rotary module, the maximum load is limited by the maximum thrust load that can be sustained by the motor gearboxes. This force is 250 N, as calculated in section C.3.
- Not determined for the base module as prior failure of other MRM modules in all configurations are expected prior to the failure of the base module under the action of a normal load on its slide.

Work Table Slide Module (Y-Axis)

Failure mode: Deflection of power screw and supporting rods under a normal load. The loading scenario is illustrated in Figure C.4.1.

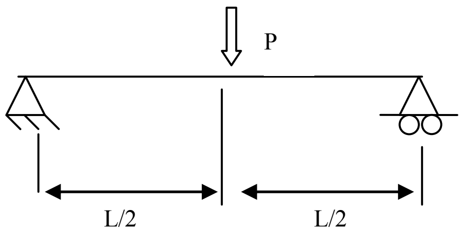


Figure C.4.1: Loading on Work Table Slide Power Screw and Support Rods

For the loading scenario of Figure C.4.1:

$$\delta = \frac{PL^3}{48EI} \tag{C4.1}$$

Therefore:

$$K = \frac{P}{\delta} = \frac{48EI}{L^3} \tag{C4.2}$$

Table C.4.1: Physical Characteristics of Work Table Slide Support Elements

	d (mm)	E (GPa)	L (mm)
Rods	20	207	410
Screw	24.00	207	410

$$I_{rod} = \frac{\pi d^4}{64} = \frac{\pi \times 0.02^4}{64} = 7.834 \times 10^{-9}\ m^4$$

$$I_{screw} = \frac{\pi d^4}{64} = \frac{\pi \times 0.024^4}{64} = 16.286 \times 10^{-9}\ m^4$$

$$K_{rod} = \frac{48EI}{L^3} = \frac{48 \times 207 \times 10^9 \times 7.834 \times 10^{-9}}{0.41^3} = 1.129 \times 10^6\ N.m^{-1}$$

$$K_{screw} = \frac{48EI}{L^3} = \frac{48 \times 207 \times 10^9 \times 16.286 \times 10^{-9}}{0.41^3} = 2.349 \times 10^6\ N.m^{-1}$$

$$K_{Total} = 2 \times 1.129 \times 10^6 + 2.349 \times 10^6 = 4.607 \times 10^6\ N.m^{-1}$$

The maximum tolerable deflection for the structure has been set as 0.1 mm. The force associated with this deflection is:

$$F = K_{Total} \times \delta = 455.6 \times 10^3 \times 0.1 \times 10^{-3} = 460.700\ N$$

Column Module (Z-Axis)

Failure mode: Deflection of power screw and supporting rods under a normal load. The loading scenario is illustrated in Figure C.4.2

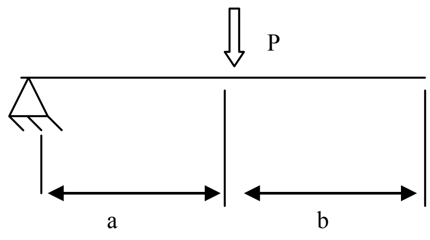


Figure C.4.2: Loading on Column Power Screw and Support Rods

For the loading scenario of Figure C.4.1:

$$\delta = \frac{Pa^2}{6EI}(3L - a) \quad \text{(C4.1)}$$

Therefore:

$$K = \frac{P}{\delta} = \frac{6EI}{a^2(3L - a)} \quad \text{(C4.2)}$$

For physical properties of the module and relevant lengths refer to Table C.3.7

$$I_{rod} = \frac{\pi d^4}{64} + Ar^2 = 321.676 \times 10^{-9}\, m^4$$

$$I_{screw} = \frac{\pi d^4}{64} = 16.286 \times 10^{-9}\, m^4$$

$$K_{rod} = \frac{6EI}{a^2(3L - a)} = \frac{6 \times 207 \times 10^9 \times 321.676 \times 10^{-9}}{0.6^2(3 \times 0.7 - 0.6)} = 7.399 \times 10^5\, N.m^{-1}$$

$$K_{screw} = \frac{6EI}{a^2(3L - a)} = \frac{6 \times 207 \times 10^9 \times 16.286 \times 10^{-9}}{0.6^2(3 \times 0.7 - 0.6)} = 3.746 \times 10^4\, N.m^{-1}$$

$$K_{Total} = 4 \times 7.399 \times 10^5 + 3.746 \times 10^4 = 2.997 \times 10^6\, N.m^{-1}$$

The maximum tolerable deflection for the structure has been set as 0.1 mm. The force associated with this deflection is:

$$F = K_{Total} \times \delta = 2.997 \times 10^6 \times 0.1 \times 10^{-3} = 300.05\, N$$

Cross slide Module (Y-Axis and C-Axis)

Failure Mode: Failure of motor gearbox by associated force.

The load restriction on the motor is a force of 250 N along the axis of the output shaft from its gearbox. This corresponds to P_y = 250 N (see Section 5.10.1). Based on the approximation of equation 5.4.3:

$$\frac{P_y}{P_z} \approx 0.2 \; to \; 0.1$$

The maximum allowable vertical load on a cutting tool that is associated with the cross slide module has been approximated as:

$$P_z = \frac{P_y}{0.1} = \frac{250}{0.1} = 2500 \; N$$

Tilt Table (B-Axis)

Failure Mode: Shearing of pin connecting drive shaft to leaver arm.

Table C.4.2: Physical Specifications of Shear Pin and Shaft in Tilt Table Module

Pin Material	Pin Diameter (mm)	Drive Shaft Diameter (mm)	Pin Shear Strength S_{shear} (MPa)	Length of Leaver Arm (mm)
Steel	4 mm	12 mm	206	85

$$A_{Shear} = 2 \times \pi \frac{d^2}{4} = 2 \times \pi \times \frac{0.004^2}{4} = 25.133 \times 10^{-6} \; m^2$$

$$F_{Shear} = S_{Shear} \times A_{Shear} = 206 \times 10^6 \times 25.133 \times 10^{-6} = 5177.398 \; N$$

$$T_{Shear} = F_{Shear} \times \frac{d_{shaft}}{2} = 5177.398 \times \frac{0.015}{2} = 38.830 \; N.m$$

$$T_{Shear} > (T_{Stall} = 20 \; N.M)$$

Mass associated if tilt table is tilted 90° from a horizontal position:

$$M = \frac{T}{g \times L} = \frac{20}{9.81 \times 0.085} = 24 \; kg$$

This mass has been selected for the maximum normal load, because if loaded while interface is horizontal (creating a normal load), and then moved by 90° it will cause the drive motor to stall.

C.5 Stiffness Calculations for Drilling Assembly

The calculations in this section pertain to the drilling subassembly of Figure 5.40

Range Extension Arm

Position and Rotation Matrices (see Appendix B.11):

$$ {}^{i+1}_{i}M_{Drill\ Head} = \begin{bmatrix} 1 & 0 & 0 & -75 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -81.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{i+1}_{i}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{i+1}_{i}P = \begin{bmatrix} -75 \\ 0 \\ -81.5 \end{bmatrix} $$

Torque and Force Propagation

$$ {}^{i+1}f_{i+1} = {}^{i+1}_{i}R\ {}^{i}f_i = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ F_t \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ F_t \end{bmatrix} $$

$$ {}^{i+1}n_{i+1} = {}^{i+1}_{i}R\ {}^{i}n_i + {}^{i+1}_{i}P \times {}^{i+1}f_{i+1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} -75 \\ 0 \\ -81.5 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ F_t \end{bmatrix} = \begin{bmatrix} 0 \\ 75F_t \\ 0 \end{bmatrix} $$

The loading scenario will therefore be a force of F_t (N) and a torque of $75F_t$ (N.mm) on the interface between the drilling head and the range extension arm.

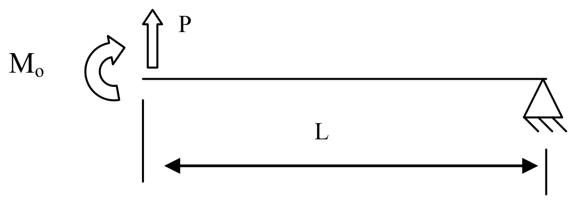


Figure C.5.1: Loading on Range Extension Arm for both Vertical and Horizontal Scenarios

Table C.5.1: Physical Specifications of Range Extension Arm

Material	E (GPa	L (mm)	d_o (mm)	d_i (mm)
Aluminum	72	350	76.2	69.84

By superposition, the deflection due to the combined load is given:

$$ \delta = \frac{PL^3}{3EI} + \frac{M_o L^2}{2EI} \qquad (C.5.1) $$

Therefore:

$$\delta = \frac{2PL^3 + 3M_oL^2}{6EI}$$

$$\delta = \frac{2F_tL^3 + 3 \times 0.075F_tL^2}{6EI}$$

$$\delta = \frac{F_t(2L^3 + 0.225L^2)}{6EI}$$

$$K = \frac{F_t}{\delta} = \frac{6EI}{2L^3 + 0.225L^2} \qquad (C.5.2)$$

Moments of inertia for machining arm (Cross section: thin circular ring)

$$I_x = I_y = \frac{\pi\left(d_o^4 - d_i^4\right)}{64} \qquad (C.5.3)$$

Substituting dimensions from Table C.5.1

$$I_x = I_y = \frac{\pi\left(d_o^4 - d_i^4\right)}{64} = \frac{\pi(0.0762^4 - 0.06984^4)}{64} = 487.119 \times 10^{-9}\ m^4$$

$$K = \frac{6EI}{2L^3 + 0.225L^2} = \frac{6 \times 72 \times 10^9 \times 487.119 \times 10^{-9}}{2 \times 0.370^3 + 0.225 \times 0.370^2} = 1.592900 \times 10^6\ N.m^{-1}$$

$$K_{H1} = K_{V1} = 1.592 \times 10^6\ N.m^{-1}$$

Cutting Head Rotary Module

Position and Rotation Matrices (see Appendix B.5):

$$^{i+1}_{\ \ i}M_{Extension\ \ Arm} = \begin{bmatrix} 1 & 0 & 0 & -370 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{i+1}_{\ \ i}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$^{i+1}_{\ \ i}P = \begin{bmatrix} -370 \\ 0 \\ 0 \end{bmatrix}$$

Torque and Force Propagation

$$^{i+1}f_{i+1} = {}^{i+1}_{\ \ i}R\ {}^{i}f_i = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ F_t \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ F_t \end{bmatrix}$$

$$^{i+1}n_{i+1} = {}^{i+1}_{i}R\ {}^{i}n_i + {}^{i+1}_{i}P \quad \times {}^{i+1}f_{i+1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 75F_t \\ 0 \end{bmatrix} + \begin{bmatrix} -370 \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ F_t \end{bmatrix} = \begin{bmatrix} 0 \\ 445F_t \\ 0 \end{bmatrix}$$

The loading scenario will therefore be a force of F_t (N) and a torque of $445F_t$ (N.mm) on the interface between the drilling head and the range extension arm. Refer to Figure C.5.1.

Table C.5.2: Physical Specifications of Cutting Head Rotary Module

Material	E (GPa)	L (mm)	h_o (mm)	h_i (mm)	b_o (mm)	b_i (mm)
Aluminum	72	110	108	100	116	96

By super position:

$$\delta = \frac{2PL^3 + 3M_oL^2}{6EI}$$

Substituting loads:

$$\delta = \frac{2PL^3 + 3M_oL^2}{6EI}$$

$$\delta = \frac{(2F_tL^3 + 3 \times 0.445F_tL^2)}{6EI}$$

$$\delta = \frac{F_t(2L^3 + 1.335L^2)}{6EI}$$

$$K = \frac{F_t}{\delta} = \frac{6EI}{2L^3 + 1.335L^2} \qquad (C.5.4)$$

Moments of inertia for cutting head rotary module (Cross section: rectangular ring)

$$I_x = \frac{b_o h_o^3 - b_i h_i^3}{12} \qquad (C.5.5)$$

$$I_y = \frac{h_o b_o^3 - h_i b_i^3}{12} \qquad (C.5.6)$$

Substituting dimensions from Table C.5.2

$$I_x = \frac{b_o h_o^3 - b_i h_i^3}{12} = \frac{0.116 \times 0.108^3 - 0.096 \times 0.100^3}{12} = 4.1772 \times 10^{-6}\ m^4$$

$$I_y = \frac{h_o b_o^3 - h_i b_i^3}{12} = \frac{0.108 \times 0.116^3 - 0.100 \times 0.096^3}{12} = 6.6753 \times 10^{-6}\ m^4$$

$$K_{V2} = \frac{6EI}{2L^3 + 1.335L^2} = \frac{6 \times 72 \times 10^9 \times 4.1772 \times 10^{-6}}{2 \times 0.110^3 + 1.335 \times 0.110^2} = 95.908 \times 10^6\ N.m^{-1}$$

$$K_{H2} = \frac{6EI}{2L^3 + 1.335L^2} = \frac{6 \times 72 \times 10^9 \times 6.6735 \times 10^{-6}}{2 \times 0.110^3 + 1.335 \times 0.110^2} = 153.222 \times 10^6\ N.m^{-1}$$

Column Module

Position and Rotation Matrices (see Appendix B.3):

$$ {}^{i+1}_{i}M_{CH\ Rotary} = \begin{bmatrix} 1 & 0 & 0 & -138 \\ 0 & c\gamma & -s\gamma & 0 \\ 0 & s\gamma & c\gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{i+1}_{i}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{bmatrix} $$

$$ {}^{i+1}_{i}P = \begin{bmatrix} -138 \\ 0 \\ 0 \end{bmatrix} $$

Torque and Force Propagation

$$ {}^{i+1}f_{i+1} = {}^{i+1}_{i}R\ {}^{i}f_{i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ F_t \end{bmatrix} = \begin{bmatrix} 0 \\ -F_t s\gamma \\ F_t c\gamma \end{bmatrix} $$

$$ {}^{i+1}n_{i+1} = {}^{i+1}_{i}R\ {}^{i}n_{i} + {}^{i+1}_{i}P \times {}^{i+1}f_{i+1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{bmatrix} \begin{bmatrix} 0 \\ 445F_t \\ 0 \end{bmatrix} + \begin{bmatrix} -138 \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} 0 \\ -F_t s\gamma \\ F_t c\gamma \end{bmatrix} $$

$$ = \begin{bmatrix} 0 \\ 583F_t c\gamma \\ 583F_t s\gamma \end{bmatrix} $$

<u>Vertical Orientation</u>

For a vertically orientated drilling head γ = 0, therefore:

$$ {}^{i+1}f_{i+1} = \begin{bmatrix} 0 \\ 0 \\ F_t \end{bmatrix} $$

$$ {}^{i+1}n_{i+1} = \begin{bmatrix} 0 \\ 583F_t \\ 0 \end{bmatrix} $$

Based on the load on the interface for γ = 0, the loading on the rods and screw has been simplified to:

$$ M_{front\ rods} = R \times F = (0.583 + 0.02445)F = 0.60745F $$

$$ M_{screw} = R \times F = (0.583 + 0.0545)F = 0.6375F $$

$$ M_{back\ rods} = R \times F = (0.583 + 0.08445)F = 0.66745 $$

The loading scenario on the members is that of figure C.5.3.

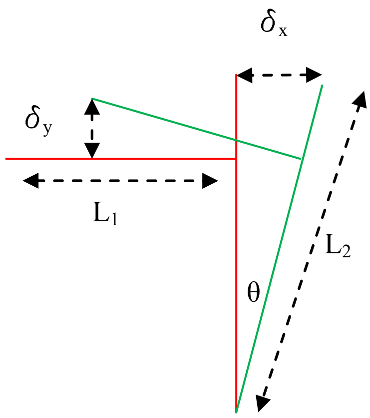


Figure C.5.2: Deflections Caused by Loading on Column Members

$$\delta_y = \frac{L_1}{L_2}\delta_x = \frac{L_1}{L_2}\frac{M_o a}{2EI}(2L-a) \qquad (C.5.7)$$

$$\delta_y = \frac{L_1}{L_2}\frac{RFa}{2EI}(2L-a)$$

For individual members L_1=R and L_2 = L:

$$K = \frac{F}{\delta_y} = \frac{2LEI}{R^2 a(2L-a)} \qquad (C.5.8)$$

$$K = \frac{F}{\delta_y} = \frac{2LEI}{R^2 a(2L-a)} \qquad (C.5.9)$$

Table C.5.3: Physical Specifications of Column Support Elements

	d (mm)	E (GPa)	a (mm)	L (mm)	R (mm)
Front Rods	15.00	207	600	700	607.45
Screw	24.00	207	600	700	637.50
Back Rods	15.00	207	600	700	667.45

$$I_{rod} = \frac{\pi d^4}{64} + Ar^2 = \frac{\pi \times 0.015^4}{64} + \left(\frac{\pi 0.015^2}{4}\right) \times 0.0425^2 = 321.676 \times 10^{-9}\ m^4$$

$$I_{screw} = \frac{\pi d^4}{64} = \frac{\pi \times 0.024^4}{64} = 16.286 \times 10^{-9}\ m^4$$

$$K_1 = \frac{2LEI}{R^2 a(2L-a)} = \frac{2 \times 0.7 \times 207 \times 10^9 \times 321.676 \times 10^{-9}}{0.60745^2 \times 0.6 \times (2 \times 0.7 - 0.6)} = 5.26326 \times 10^5\ N.m^{-1}$$

$$K_2 = \frac{2LEI}{R^2 a(2L-a)} = \frac{2 \times 0.7 \times 207 \times 10^9 \times 16.286 \times 10^{-9}}{0.63750^2 \times 0.6 \times (2 \times 0.7 - 0.6)} = 2.4194 \times 10^4\ N.m^{-1}$$

$$K_3 = \frac{2LEI}{R^2 a(2L-a)} = \frac{2 \times 0.7 \times 207 \times 10^9 \times 321.676 \times 10^{-9}}{0.66745^2 \times 0.6 \times (2 \times 0.7 - 0.6)} = 4.35952 \times 10^5\ N.m^{-1}$$

The elements act as springs in parallel:

$$K_{total} = 2 \times 5.26326 \times 10^5 + 2.4194 \times 10^4 + 2 \times 4.35952 \times 10^5 = 1.94875 \times 10^6\ N.m^{-1}$$

$$K_{V3} = 1.94875 \times 10^6\ N.m^{-1}$$

<u>Horizontal Orientation</u>

For a horizontally orientated drilling head γ = 90°, therefore:

$$^{i+1}f_{i+1} = \begin{bmatrix} 0 \\ -F_t \\ 0 \end{bmatrix}$$

$$^{i+1}n_{i+1} = \begin{bmatrix} 0 \\ 0 \\ 583F_t \end{bmatrix}$$

Based on the load on the interface for γ = 90°, the total torque about the center of the module is:

$$M_o = R \times F = 0.6375F_t$$

The power screw is located at the center; however by nature it cannot resist this torque. The torque is balanced by the guide rods which provide a normal reaction force. The guide rods and the power screw resist the horizontal force F_t. This is illustrated in Figure C.5.3 (Red: Force due to torque about center; Green: Force due to F_t)

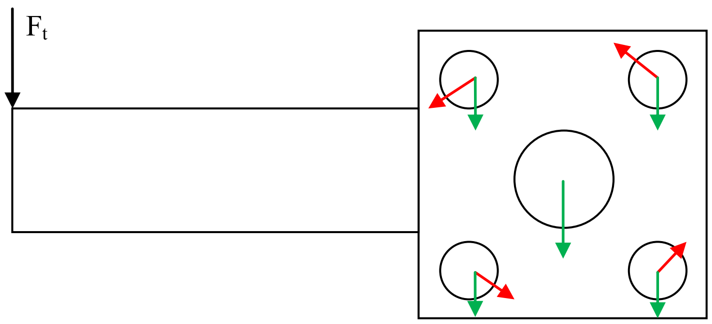


Figure C.5.3: Schematic Diagram of Loading on Column Power Screw and Guide Rods

For simplicity the effect of the torque and the effect of the force F_t shall be dealt with separately. The torque M_o will have the effect of rotating the system about its center as illustrated in Figure C.5.4.a, while the force F_t will have the effect of causing a deflection of the module in the horizontal plane as illustrated in Figure C.5.4.b. The total deflection of the cutting head, due to the loading on the column is illustrated in Figure C.5.4.c.

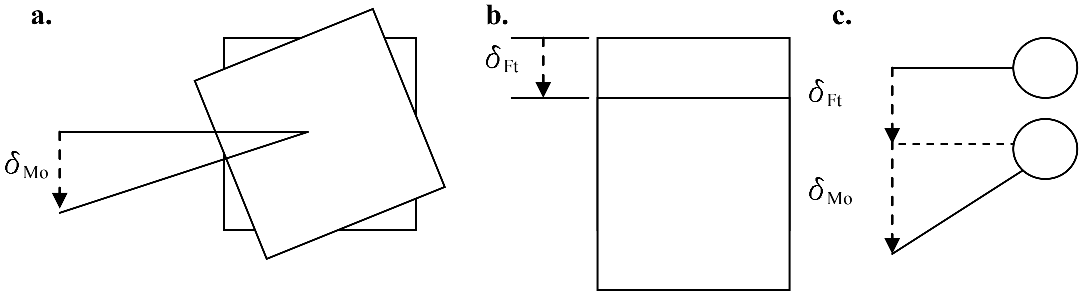


Figure C.5.4: Deflection and Rotation of Column Module

a. Rotation of column module due to torque M_o generated by thrust force on drill
b. Deflection of column module due to force thrust force F_t
c. Combined deflection of drilling head due to thrust force

Rotation Due to Torque

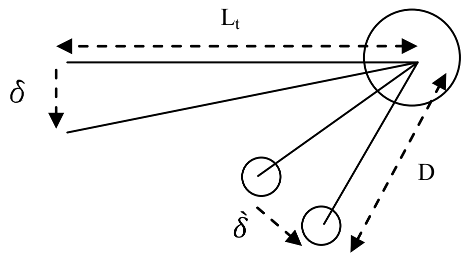


Figure C.5.5: Deflection of Individual Guide Rods in Relation to Deflection of Drilling Head

The rotation of the column module about its center is a result of the deflections of individual guide rods under the forces generated by the torque M_o. The force on an individual rod, causing this deflection is F‘‘, where:

$$F` = \grave{K}\grave{\delta} \qquad (C.5.10)$$

The torque M_o represented as the sum of the individual torques generated by F‘‘:

$$M_o = F_t L_t = 4\grave{F}D \qquad (C.5.11)$$

Relating the deflection of the drilling head to the deflection of an individual guide rod:

$$\grave{\delta} = \frac{D}{L_t}\delta \qquad (C.5.12)$$

Substituting equation C.5.10 into equation C.5.11

$$F_t L_t = 4\grave{K}\grave{\delta}D \qquad (C.5.13)$$

Substituting equation C.5.12 into equation C.5.13

$$\mathrm{F_t} = 4\grave{\mathrm{K}}\delta\frac{\mathrm{D}^2}{\mathrm{L_t^2}}$$

$$K = \frac{F_t}{\delta} = \frac{4\grave{K}D^2}{L_t^2} \qquad (C.5.14)$$

For an individual rod (See Figure C.4.2 and equation C.4.2):

$$\grave{K} = \frac{6EI}{a^2(3L_{rod} - a)} \qquad (C.5.15)$$

Therefore:

$$K = \frac{24EID^2}{a^2L_t^2(3L_{rod} - a)} \qquad (C.5.14)$$

Table C.5.4: Physical Parameters Relating to Torque Applied on Column

E (GPa)	D (mm)	d (mm)	a (mm)	L_{rod} (mm)	L_t (mm)
207	42.5	15.00	600	700	637.5

$$I_{rod} = \frac{\pi d^4}{64} + Ar^2 = \frac{\pi \times 0.015^4}{64} + \left(\frac{\pi 0.015^2}{4}\right) \times 0.0601^2 = 6.408 \times 10^{-7}\, m^4$$

$$K = \frac{24EID^2}{a^2L_t^2(3L_{rod} - a)} = \frac{24 \times 207 \times 10^9 \times 6.408 \times 10^{-7} \times 0.0425^2}{0.6^2 \times 0.6375^2(3 \times 0.7 - 0.6)} = 2.620 \times 10^4\, N.m^{-1}$$

Deflection Due to Drilling Thrust Force

The loading on individual members is as per Figure C.4.2

Table C.5.5: Physical Parameters Relating to Drilling Thrust Force on Column

	d (mm)	E (GPa)	a (mm)	L (mm)
Front Rods	15.00	207	600	700
Screw	24.00	207	600	700
Back Rods	15.00	207	600	700

$$I_{rod} = \frac{\pi d^4}{64} + Ar^2 = \frac{\pi \times 0.015^4}{64} + \left(\frac{\pi 0.015^2}{4}\right) \times 0.0425^2 = 321.676 \times 10^{-9}\, m^4$$

$$I_{screw} = \frac{\pi d^4}{64} = \frac{\pi \times 0.024^4}{64} = 16.286 \times 10^{-9}\, m^4$$

$$K_1 = \frac{6EI}{a^2(3L_{rod} - a)} = \frac{6 \times 207 \times 10^9 \times 321.676 \times 10^{-9}}{0.6^2(3 \times 0.7 - 0.6)} = 739.855 \times 10^3\, N.m^{-1}$$

$$K_2 = \frac{6EI}{a^2(3L_{screw} - a)} = \frac{6 \times 207 \times 10^9 \times 16.286 \times 10^{-9}}{0.6^2(3 \times 0.7 - 0.6)} = 37.458 \times 10^3\ N.m^{-1}$$

The members act as springs in parallel

$$K = 4 \times 739.855 \times 10^3 + 37.458 \times 10^3 = 2.997 \times 10^6\ \mathrm{N.m^{-1}}$$

<u>Total Horizontal Stiffness</u>

The spring rates combine reciprocally:

$$K_{H3} = \left[\frac{1}{2.620 \times 10^4} + \frac{1}{2.997 \times 10^6}\right]^{-1} = 2.5973 \times 10^4\ \mathrm{N.m^{-1}}$$

C.6 Mechanical Vibration Analysis

Table C.6.1: Physical Parameters used in Vibration Analysis – Vertical Direction

F_o	K_V (N.m^{-1})	m (kg)	C (N.S.m^{-1})	x_o (m)	$\dot{x}_o$(m.s^{-1})	f (Hz)
50 N	8.683×10^5	2.1	5	-2.373×10^{-5}	0	20

Table C.6.2: Physical Parameters used in Vibration Analysis – Horizontal Direction

F_o	K_H (N.m^{-1})	m (kg)	C (N.S.m^{-1})	x_o (m)	$\dot{x}_o$(m.s^{-1})	f (Hz)
50 N	2.552×10^4	2.1	5	0	0	20

The total response x(t) for a damped system under a harmonic force is calculated by equation C.6.1:

$$x(t) = X_0 e^{-\zeta\omega_n t} cos(\omega_d t - \phi_0) + Xcos(\omega t - \phi) \qquad (C.6.1)$$

For the initial conditions of the system:

$$x_o = X_0 cos(\phi_0) + Xcos(\phi) \qquad (C.6.2)$$

$$\dot{x}_0 = -\zeta\omega_n X_0 cos(\phi_0) + \omega_d X_0 sin(\phi_0) + \omega X sin(\phi) \qquad (C.6.3)$$

Refer to Section 5.12 for additional equations. Note that the stiffness‟s presented in Tables C.6.1-2 correspond to the column slide being in a position of 600 mm above its base.

Vertical Harmonic Force

Initial displacement based purely on weight of drill head:

$$x_o = -\frac{Weight}{k} = \frac{2.1 \times 9.81}{8.683 \times 10^5} = -2.373 \times 10^{-5}\ m$$

$$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{8.683 \times 10^5}{2.1}} = 643.02\ rad.s^{-1}$$

$$\delta_{st} = \frac{F_o}{k} = \frac{50}{8.683 \times 10^5} = 5.758 \times 10^{-5}\ m$$

$$\zeta = \frac{C}{2\sqrt{km}} = \frac{5}{2\sqrt{8.683 \times 10^5 \times 2.1}} = 0.0019$$

$$\omega_d = \sqrt{1-\zeta^2}\omega_n = \sqrt{1-0.0019^2} \times 643.02 = 643.02\ rad.s^{-1}$$

$$\omega = 2\pi f = 2\pi \times 20 = 125.66\ rad.s^{-1}$$

$$r = \frac{\omega}{\omega_n} = \frac{125.66}{643.02} = 0.1954$$

$$X = \frac{\delta_{st}}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}} = \frac{5.758 \times 10^{-5}}{\sqrt{(1-0.1954^2)^2 + (2 \times 0.0019 \times 0.1954)^2}} = 5.987 \times 10^{-5}\ m$$

$$\phi = tan^{-1}\left(\frac{2\zeta r}{1-r^2}\right) = tan^{-1}\left(\frac{2 \times 0.0019 \times 0.1954}{1-0.1954^2}\right) = 0.0442°$$

Using the initial conditions with equation C.6.2

$$x_o = X_0 cos(\phi_0) + X cos(\phi) = -2.373 \times 10^{-5}\ m$$

$$x_o = X_0 cos(\phi_0) + 5.987 \times 10^{-5} cos(0.0442) = -2.373 \times 10^{-5}\ m$$

$$X_0 cos(\phi_0) = -8.360 \times 10^{-5}$$

Using the initial conditions with equation C.6.3

$$\dot{x}_0 = -\zeta\omega_n X_0 cos(\phi_0) + \omega_d X_0 sin(\phi_0) + \omega X sin(\phi) = 0$$

$$-0.0019 \times 643.02 \times -8.360 \times 10^{-5} + 643.02 \times X_0 sin(\phi_0) + 125.66 \times 5.987 \times 10^{-5} sin(0.0442) = 0$$

$$X_0 sin(\phi_0) = -1.679 \times 10^{-7}$$

$$X_0 = \left[\left(X_0 sin(\phi_0)\right)^2 + \left(X_0 cos(\phi_0)\right)^2\right]^{0.5} = [(-1.679 \times 10^{-7})^2 + (-8.360 \times 10^{-5})^2]^{0.5}$$

$$X_0 = 8.360 \times 10^{-5}\ m$$

$$tan\,\phi_0 = \frac{X_0 sin(\phi_0)}{X_0 cos(\phi_0)} = \frac{= -1.679 \times 10^{-7}}{-8.360 \times 10^{-5}} = 2.008 \times 10^{-3}$$

$$\phi_0 = 0.1151°$$

Horizontal Harmonic Force

$$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{2.552 \times 10^4}{2.1}} = 110.24\ rad.s^{-1}$$

$$\delta_{st} = \frac{F_o}{k} = \frac{50}{2.552 \times 10^4} = 1.959 \times 10^{-3}\ m$$

$$\zeta = \frac{C}{2\sqrt{km}} = \frac{5}{2\sqrt{2.552 \times 10^4 \times 2.1}} = 0.0108$$

$$\omega_d = \sqrt{1-\zeta^2}\omega_n = \sqrt{1-0.0108^2} \times 110.24 = 110.23\, rad.s^{-1}$$

$$\omega = 2\pi f = 2\pi \times 20 = 125.66\, rad.s^{-1}$$

$$r = \frac{\omega}{\omega_n} = \frac{125.66}{110.14} = 1.1409$$

$$X = \frac{\delta_{st}}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}} = \frac{1.959 \times 10^{-3}}{\sqrt{(1-1.1409^2)^2 + (2 \times 0.0108 \times 1.1409)^2}} = 6.473 \times 10^{-3}\, m$$

$$\phi = tan^{-1}\left(\frac{2\zeta r}{1-r^2}\right) = tan^{-1}\left(\frac{2 \times 0.0108 \times 1.1409}{1-1.1409^2}\right) = -4.670°$$

The phase angle is in the second quadrant:
$\phi = 175.33°$

Using the initial conditions with equation C.6.2

$$x_o = X_0 cos(\phi_0) + X cos(\phi) = 0\, m$$

$$x_o = X_0 cos(\phi_0) + 6.473 \times 10^{-3} cos(175.33) = 0\, m$$

$$X_0 cos(\phi_0) = 6.452 \times 10^{-3}$$

Using the initial conditions with equation C.6.3

$$\dot{x}_0 = -\zeta\omega_n X_0 cos(\phi_0) + \omega_d X_0 sin(\phi_0) + \omega X sin(\phi) = 0$$

$$-0.0108 \times 110.24 \times 6.452 \times 10^{-3} + 110.23 X_0 sin(\phi_0) + 125.66 \times 6.473 \times 10^{-3} sin(175.33) = 0$$

$$X_0 sin(\phi_0) = -5.311 \times 10^{-4}$$

$$X_0 = \left[\left(X_0 sin(\phi_0)\right)^2 + \left(X_0 cos(\phi_0)\right)^2\right]^{0.5} = [(-5.311 \times 10^{-4})^2 + (6.452 \times 10^{-3})^2]^{0.5}$$

$$X_0 = 6.474 \times 10^{-3}\, m$$

$$tan\,\phi_0 = \frac{X_0 sin(\phi_0)}{X_0 cos(\phi_0)} = \frac{-5.311 \times 10^{-4}}{6.452 \times 10^{-3}} = -8.232 \times 10^{-2}$$

$$\phi_0 = -4.7060°$$

The phase angle is in the second quadrant:
$\phi_0 = 175.29°$

Appendix D

D.1 Three Axis Drilling Configuration

Axes – X, Y and Z

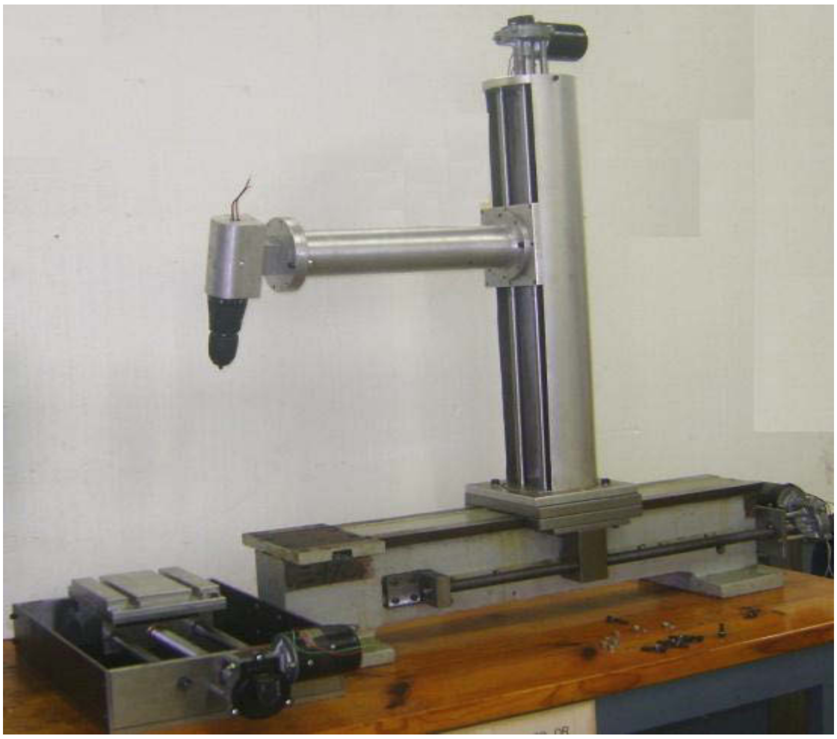


Figure D.1: Three Axis Drilling Machine (X, Y and Z)

Table D.1: Bill of Modules for Three Axis Drilling Machine (X, Y, and Z)

Bill of Modules	Module	Module Code (MRM-Type-Range-Moving Interface-Static Interface)
Motion Modules	Base	MRM-B01-500-T1-T4/5
	Work Table Slide	MRM -WTS01-300-T3-T5
	Column	MRM-C01-562-T2A/2B-T1
Process Module	Drilling Head	MRM-DH01-12-T0-T2A
Accessory Modules	Work Table	MRM-WT01-160-T0-T3
	Range Ext Arm	MRM-REA-370-T0-T2A

$$^{Worktable}_{Drill}T = \begin{bmatrix} 1 & 0 & 0 & -344.5 + x \\ 0 & 1 & 0 & 2.5 + y \\ 0 & 0 & 1 & -2 + z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

D.2 Four Axis Drilling Configurations

Axes – X, Y, Z and A

Figure D.2: Four Axis Drilling Machine (X, Y, Z and A)

Table D.2: Bill of Modules for Four Axis Drilling Machine (X, Y, Z and A)

Bill of Modules	Module	Module Code (MRM-Type-Range-Moving Interface-Static Interface)
Motion Modules	Base	MRM-B01-500-T1-T4/5
	Work Table Slide	MRM -WTS01-300-T3-T5
	Column	MRM-C01-562-T2A/2B-T1
	Cutting Head Rot	MRM-CHR01-360-T2A-T2B
Process Module	Drilling Head	MRM-DH01-12-T0-T2A
Accessory Modules	Work Table	MRM-WT01-160-T0-T3
	Range Ext Arm	MRM-REA-370-T0-T2A

$$ {}^{Worktable}_{Drill}T = \begin{bmatrix} 1 & 0 & 0 & -482.5 + x \\ 0 & c\gamma & -s\gamma & 2.5 + 81.5s\gamma + y \\ 0 & s\gamma & c\gamma & 79.5 - 81.5c\gamma + z \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Axes – X, Y, Z and B

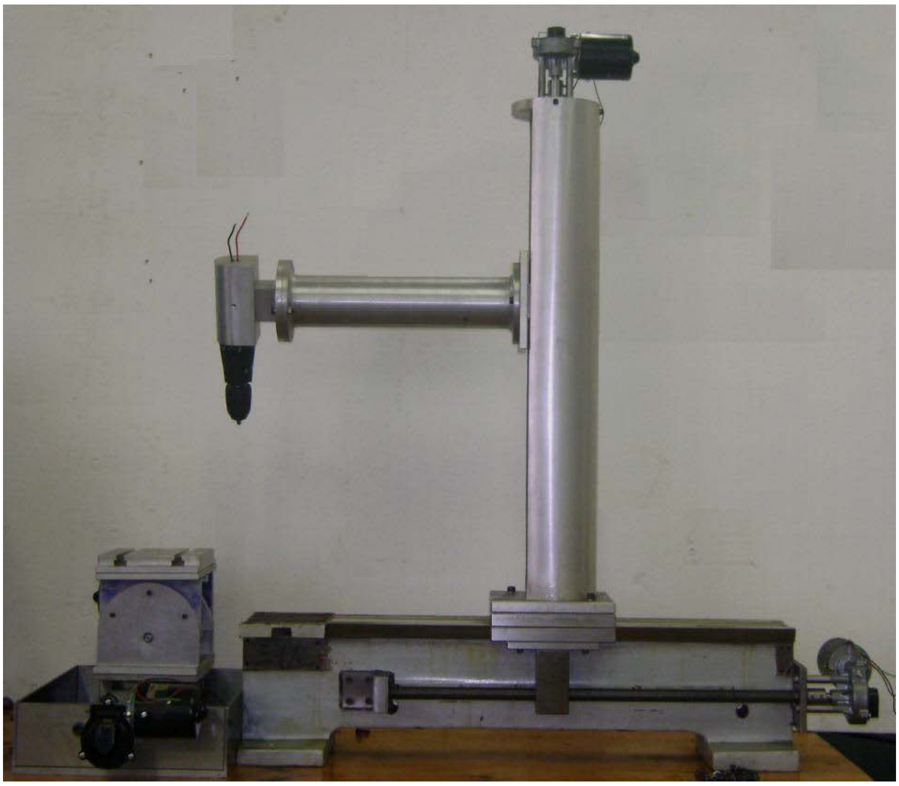


Figure D.3: Four Axis Drilling Machine (X, Y, Z and B)

Table D.3: Bill of Modules for Four Axis Drilling Machine (X, Y, Z and B)

Bill of Modules	Module	Module Code (MRM-Type-Range-Moving Interface-Static Interface)
Motion Modules	Base	MRM-B01-500-T1-T4/5
	Work Table Slide	MRM -WTS01-300-T3-T5
	Column	MRM-C01-562-T2A/2B-T1
	Tilt Table	MRM-TT01-90-T3-T3
Process Module	Drilling Head	MRM-DH01-12-T0-T2A
Accessory Modules	Work Table	MRM-WT01-160-T0-T3
	Range Ext Arm	MRM-REA-370-T0-T2A

$$ {}^{Worktable}_{Drill}T = \begin{bmatrix} c\beta & 0 & s\beta & -344.5c\beta - 27.5s\beta + zs\beta + xc\beta \\ 0 & 1 & 0 & 2.5 + y \\ -s\beta & 0 & c\beta & 344.5s\beta - 119.5 - 27.5c\beta + zc\beta - xs\beta \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Axes – X, Y, Z and C

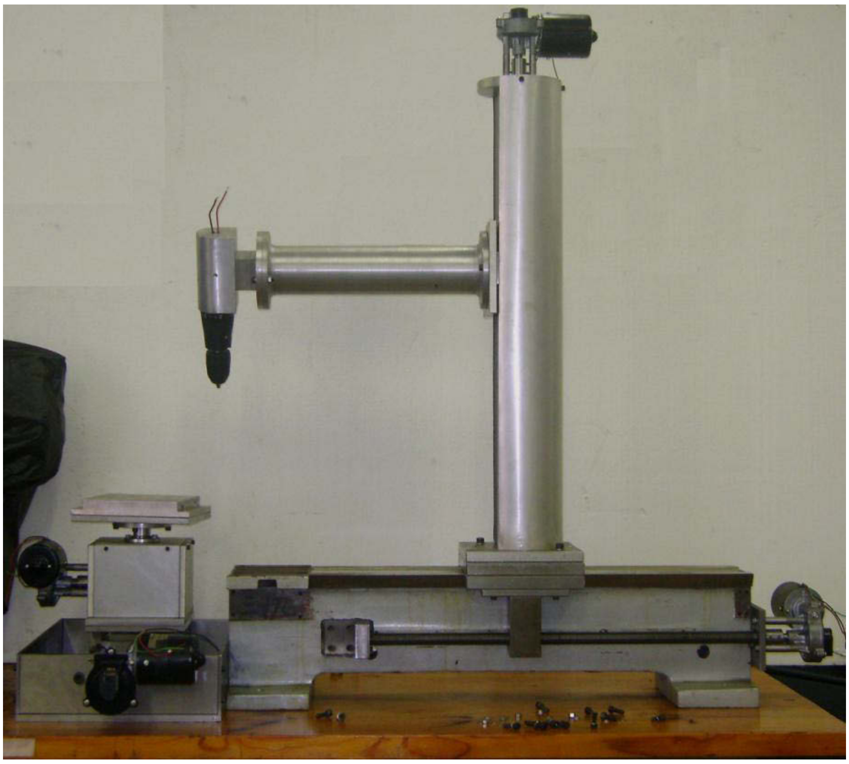


Figure D.4: Four Axis Drilling Machine (X, Y, Z and C)

Table D.4: Bill of Modules for Four Axis Drilling Machine (X, Y, Z and C)

Bill of Modules	Module	Module Code (MRM-Type-Range-Moving Interface-Static Interface)
Motion Modules	Base	MRM-B01-500-T1-T4/5
	Work Table Slide	MRM -WTS01-300-T3-T5
	Column	MRM-C01-562-T2A/2B-T1
	Rotary Table	MRM-RT01-360-T3-T3
Process Module	Drilling Head	MRM-DH01-12-T0-T2A
Accessory Modules	Work Table	MRM-WT01-160-T0-T3
	Range Ext Arm	MRM-REA-370-T0-T2A

$$^{Worktable}_{Drill}T = \begin{bmatrix} c\alpha & -s\alpha & 0 & -344.5c\alpha + xc\alpha - 2.5s\alpha - ys\alpha \\ s\alpha & c\alpha & 0 & -344.5s\alpha + xs\alpha + 2.5c\alpha + yc\alpha \\ 0 & 0 & 1 & -154 + z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

D.3 Five Axis Drilling Configurations

Axes – X, Y, Z, A and B

Figure D.5: Five Axis Drilling Machine (X, Y, Z, A and B)

Table D.5: Bill of Modules for Five Axis Drilling Machine (X, Y, Z, A and B)

Bill of Modules	Module	Module Code (MRM-Type-Range-Moving Interface-Static Interface)
Motion Modules	Base	MRM-B01-500-T1-T4/5
	Work Table Slide	MRM -WTS01-300-T3-T5
	Column	MRM-C01-562-T2A/2B-T1
	Cutting Head Rot	MRM-CHR01-360-T2A-T2B
	Tilt Table	MRM-TT01-90-T3-T3
Process Module	Drilling Head	MRM-DH01-12-T0-T2A
Accessory Modules	Work Table	MRM-WT01-160-T0-T3
	Range Ext Arm	MRM-REA-370-T0-T2A

$$ {}^{Worktable}_{Drill}T = \begin{bmatrix} c\beta & s\beta c\gamma & s\beta c\gamma & -482.5c\beta - 81.5s\beta c\gamma + zs\beta + xc\beta + 54s\beta\beta \\ 0 & c\gamma & -s\gamma & 2.5 + 81.5s\gamma + y \\ -s\beta & c\beta s\gamma & c\beta c\gamma & 482.5s\beta - 119.5 - 81.5c\beta c\gamma + zc\beta - xs\beta + 54c\beta \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Axes – X, Y, Z, A and C

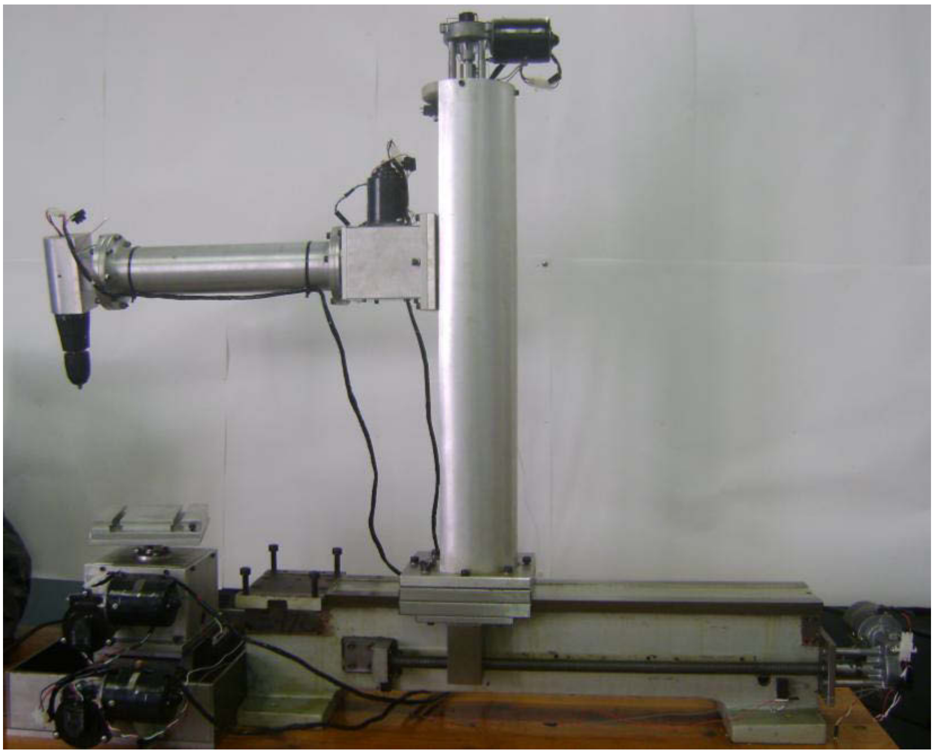


Figure D.6: Five Axis Drilling Machine (X, Y, Z, A and C)

Table D.6: Bill of Modules for Five Axis Drilling Machine (X, Y, Z, A and C)

Bill of Modules	Module	Module Code (MRM-Type-Range-Moving Interface-Static Interface)
Motion Modules	Base	MRM-B01-500-T1-T4/5
	Work Table Slide	MRM -WTS01-300-T3-T5
	Column	MRM-C01-562-T2A/2B-T1
	Cutting Head Rot	MRM-CHR01-360-T2A-T2B
	Rotary Table	MRM-RT01-360-T3-T3
Process Module	Drilling Head	MRM-DH01-12-T0-T2A
Accessory Modules	Work Table	MRM-WT01-160-T0-T3
	Range Ext Arm	MRM-REA-370-T0-T2A

$$^{Worktable}_{Drill}T = \begin{bmatrix} c\alpha & -s\alpha c\gamma & s\alpha s\gamma & -482.5c\alpha - 81.5s\alpha s\gamma + xc\alpha - 2.5s\alpha - ys\alpha \\ s\alpha & c\alpha c\gamma & -c\alpha s\gamma & -482.5s\alpha + 81.5c\alpha s\gamma + xs\alpha + 2.5c\alpha + yc\alpha \\ 0 & s\gamma & c\gamma & -72.5 - 81.5c\gamma + z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Axes – X, Y, Z, B and C

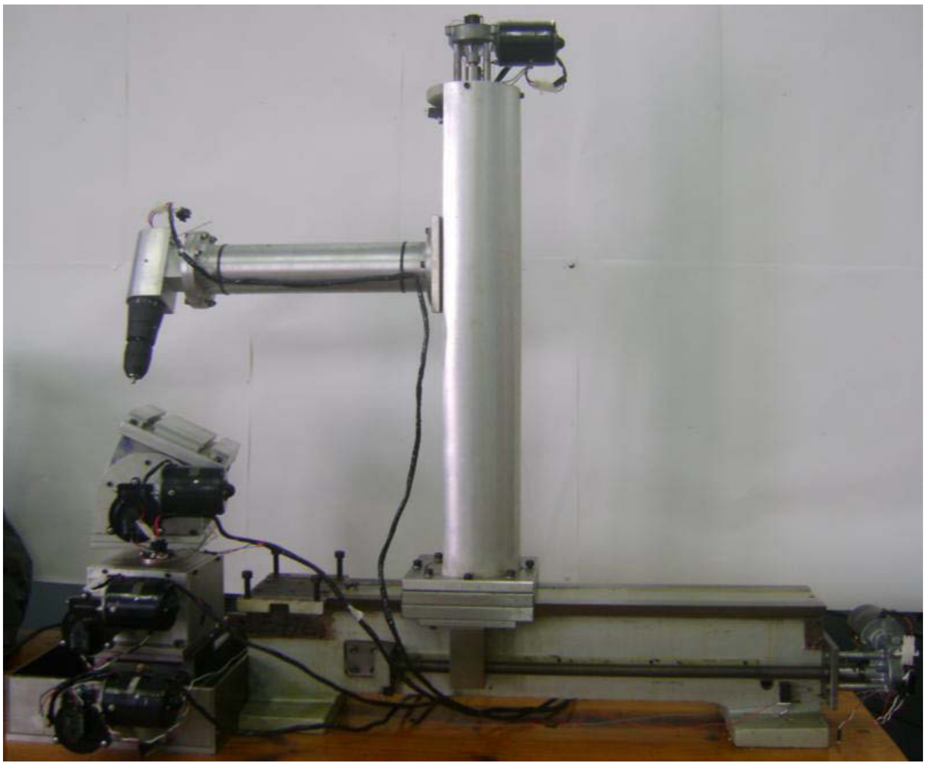


Figure D.7: Five Axis Drilling Machine (X, Y, Z, B and C)

Table D.7: Bill of Modules for Five Axis Drilling Machine (X, Y, Z, B and C)

Bill of Modules	Module	Module Code (MRM-Type-Range-Moving Interface-Static Interface)
Motion Modules	Base	MRM-B01-500-T1-T4/5
	Work Table Slide	MRM -WTS01-300-T3-T5
	Column	MRM-C01-562-T2A/2B-T1
	Tilt Table	MRM-TT01-90-T3-T3
	Rotary Table	MRM-RT01-360-T3-T3
Process Module	Drilling Head	MRM-DH01-12-T0-T2A
Accessory Modules	Work Table	MRM-WT01-160-T0-T3
	Range Ext Arm	MRM-REA-370-T0-T2A

$$^{Worktable}_{Drill}T =$$

$$\begin{bmatrix} c\beta c\alpha & -c\beta s\alpha & s\beta & -344.5c\beta c\alpha - 179.5s\beta + s\beta Z + xc\beta c\alpha - 2.5c\beta s\alpha - yc\beta s\alpha \\ s\alpha & c\alpha & 0 & -344.5s\alpha + xs\alpha + 2.5c\alpha + yc\alpha \\ -s\beta c\alpha & s\beta s\alpha & c\beta & 344.5s\beta c\alpha - 119.5 - 179.5c\beta + zc\beta - xs\beta c\alpha + 2.5s\beta s\alpha + ys\beta s\alpha \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

D.4 Six Axis Drilling Configuration

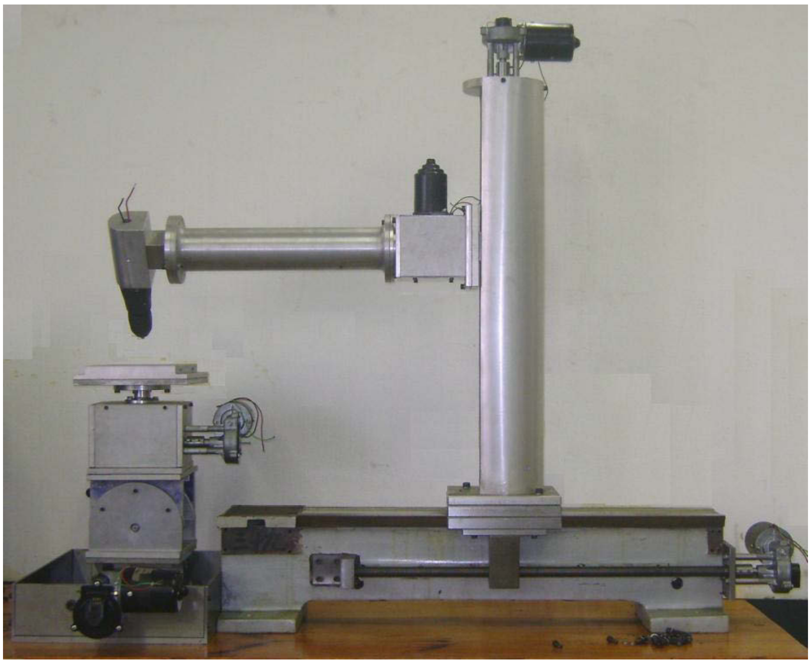


Figure D.8: Six Axis Drilling Machine (X, Y, Z, A, B and C)

Table D.8: Bill of Modules for Six Axis Drilling Machine (X, Y, Z, A, B and C)

Bill of Modules	Module	Module Code (MRM-Type-Range-Moving Interface-Static Interface)
Motion Modules	Base	MRM-B01-500-T1-T4/5
	Work Table Slide	MRM -WTS01-300-T3-T5
	Column	MRM-C01-562-T2A/2B-T1
	Cutting Head Rot	MRM-CHR01-360-T2A-T2B
	Tilt Table	MRM-TT01-90-T3-T3
	Rotary Table	MRM-RT01-360-T3-T3
Process Module	Drilling Head	MRM-DH01-12-T0-T2A
Accessory Modules	Work Table	MRM-WT01-160-T0-T3
	Range Ext Arm	MRM-REA-370-T0-T2A

$$
{}^{Worktable}_{Drill}T = \begin{bmatrix} c\beta c\alpha & -c\beta s\alpha c\gamma + s\beta s\gamma & c\beta s\alpha s\gamma + s\beta c\gamma & K_1 \\ s\alpha & c\alpha c\gamma & -c\alpha s\gamma & K_2 \\ -s\beta c\alpha & s\beta s\alpha c\gamma + c\alpha s\gamma & -s\beta s\alpha s\gamma + c\beta c\gamma & K_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$K_1 = -482.5c\beta c\alpha - 81.5c\beta s\alpha s\gamma - 81.5s\beta c\gamma + zs\beta + xc\beta c\alpha - 2.5c\beta s\alpha - 98s\beta - yc\beta s\alpha$

$K_2 = -965/2 * s\alpha + 163/2 * c\alpha s\gamma + xs\alpha + 2.5c\alpha + yc\alpha$

$K_1 = 482.5s\beta c\alpha - 119.5 + 81.5s\beta s\alpha s\gamma - 81.5c\beta c\gamma + zc\beta - xs\beta c\alpha + 2.5s\beta s\alpha - 98c\beta + ys\beta s\alpha$

D.5 Turning Configuration

Axes – X, Y and C

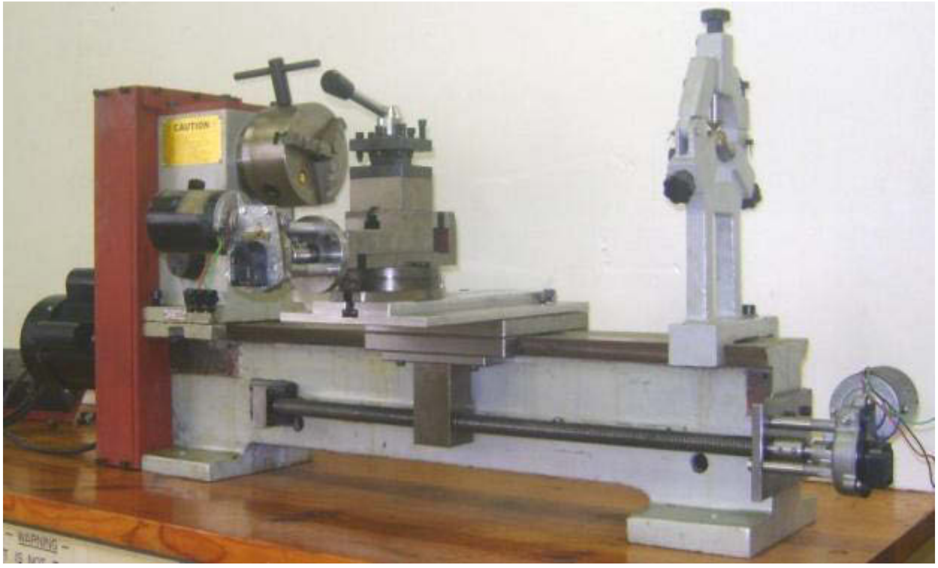


Figure D.9: Three Axis Lathe (X, Y and C)

Table D.9: Bill of Modules for Three Axis Lathe (X, Y and C)

Bill of Modules	Module	Module Code (MRM-Type-Range-Moving Interface-Static Interface)
Motion Modules	Base	MRM-B01-500-T1-T4/5
	Cross Slide	MRM-CS01-115-T0-T1
Process Module	Turning Head	MRM-TH01-120-T0-T4
Accessory Modules	Cross Slide Interface Plate	MRM-CSIP01-80-T0-T1

$$ {}^{Chuck}_{Tool\ Post}T = \begin{bmatrix} c\alpha & -s\alpha & 0 & x-192.5 \\ s\alpha & c\alpha & 0 & 2.5+y+v \\ 0 & 0 & 1 & 0.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Appendix E

E.1 Pin Configurations of Microcontrollers and IC's

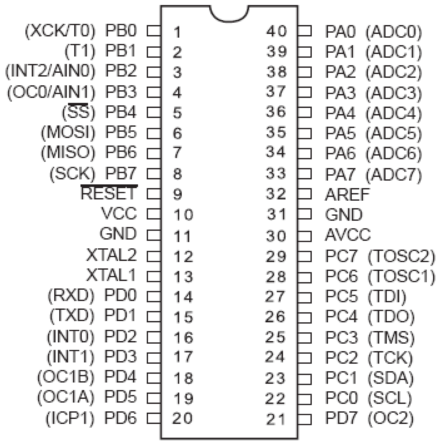


Figure E.1.1: Pin Out of the ATmega 32L Microcontroller [38]

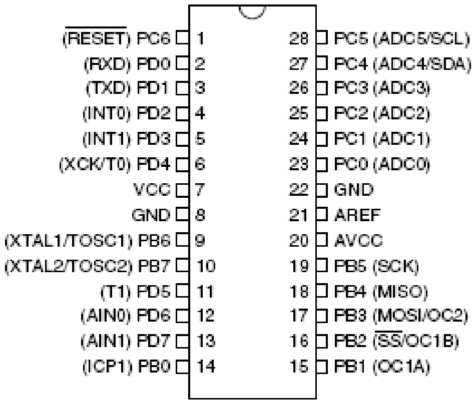


Figure E.1.2: Pin Out of the ATmega 8L Microcontroller [39]

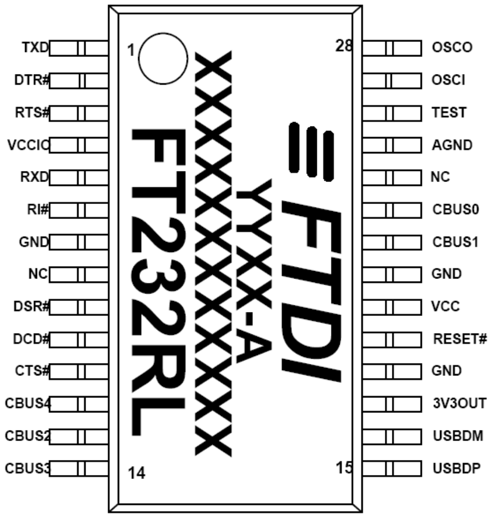


Figure E.1.3: Pin Out of the FT232RL USB USART IC [66]

E.2 Layouts of Component Boards

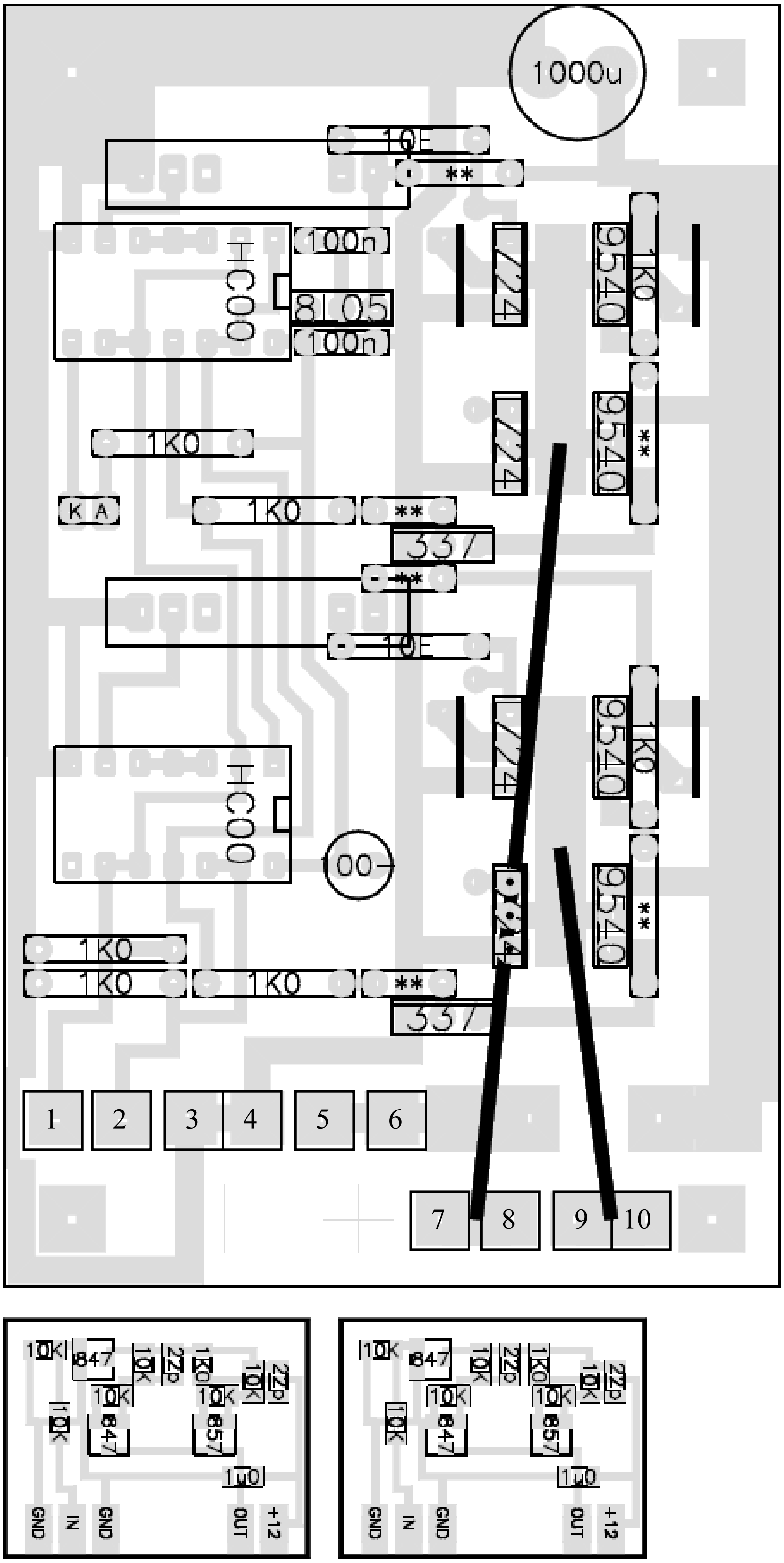


Figure E.2.1: Layout of the H-Bridge Motor Driver Used in Servo Control Modules

Table E.2.1: Configuration of Terminals on H-Bridge Motor Driver

Terminal	Function
1	PWM terminal, connected to microcontroller
2	Direction terminal, connected to microcontroller
3&4	12 DC input, negative terminal
5&6	12 DC input, positive terminal
7&8	Output to motor, positive terminal
9&10	Output to motor, negative terminal

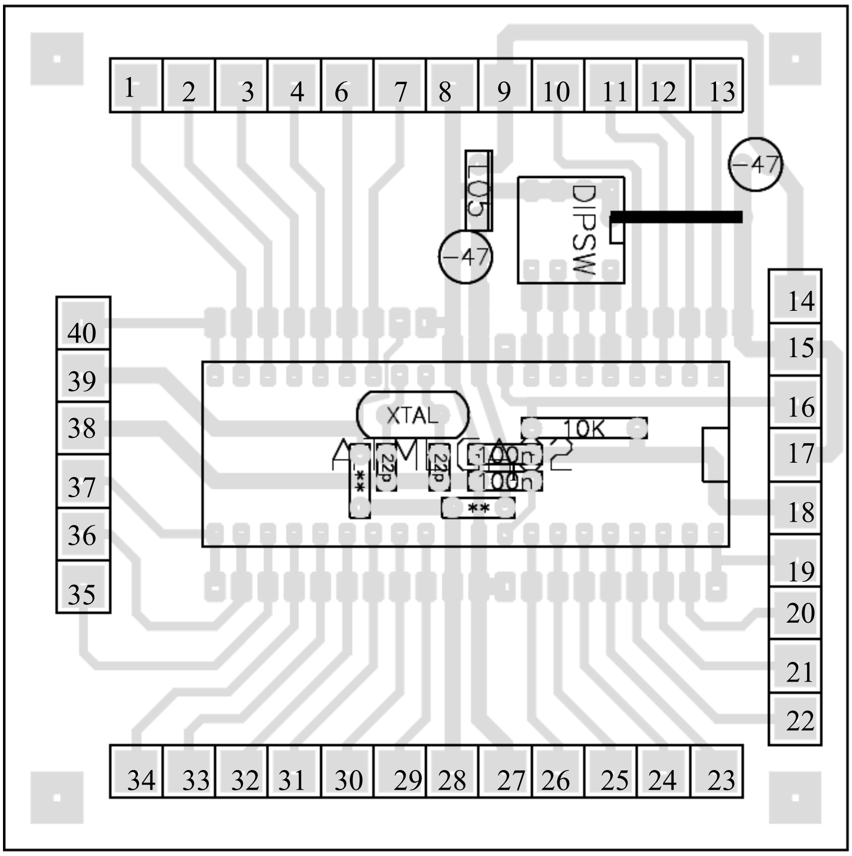


Figure E.2.2: Layout of the ATmega 32L Microcontroller Board Used in Servo and Spindle Control Modules

Table E.2.2: Configuration of Terminals on the ATmega 32L Board Used in Servo and Spindle Control Modules

Terminal	Function	
	Spindle Control	Servo Control
1	Unused	PWM output
2	Unused	PWM output (spare)
3	Unused	Limit switch interrupt terminal
4	Unused	Limit switch interrupt terminal
5	USART transmit	USART transmit
6	USART receive	USART receive
7	Ground	Ground
8	Vcc	Vcc

Table E.2.2 (Continued): Configuration of Terminals on the ATmega 32L…

Terminal	Function	
	Spindle Control	Servo Control
9-18	Unused	Unused
19-26	ADC channels	ADC channels (optional use)
27	Ground	Ground
28	AVcc	AVcc
29-32	Unused	Unused
33-34	I/O terminals for relay switching	Unused
35	Unused	I2C data terminal
36	Unused	I2C clock terminal
37-40	Unused	Unused

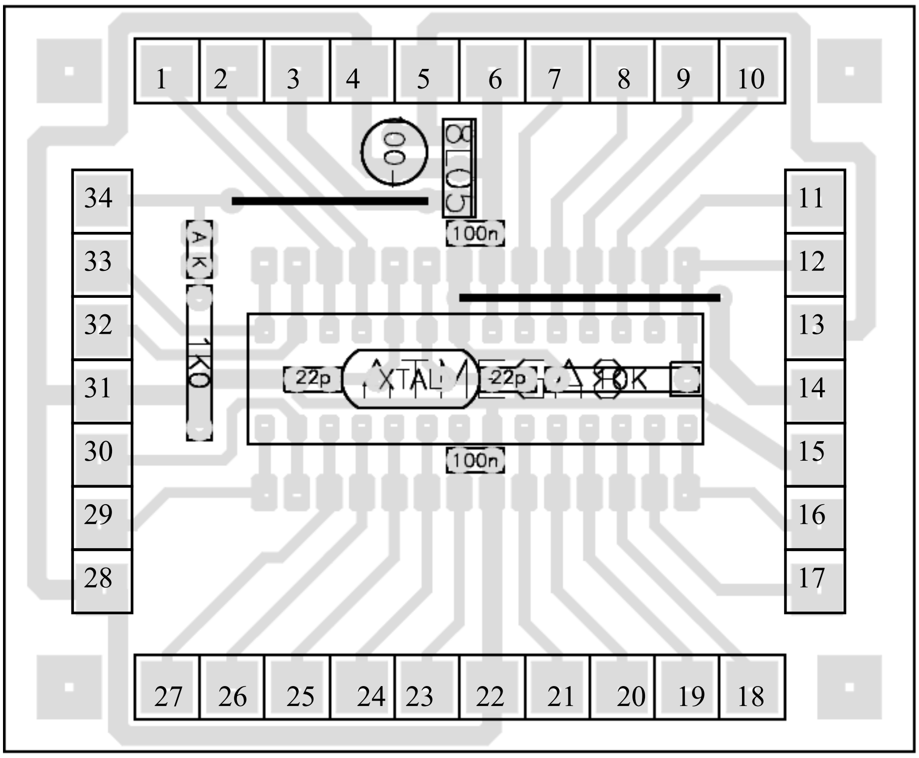


Figure E.2.3: Layout of the ATmega 8L Microcontroller Board Used in Servo Control Modules

Table E.2.3: Configuration of Terminals on the ATmega 8L Board Used in Servo Control Modules

Terminal	Function
1-4	Unused
5	Vcc
6	Ground
7	Unused
8-9	Encoder interrupt terminals
10	USART transmit
11	USART receive
12	Unused
13-21	ADC channels (optional)

Table E.2.3 (Continued): Configuration of Terminals on the ATmega 8L Board…

Terminal	Function
22	Ground
23-34	Unused

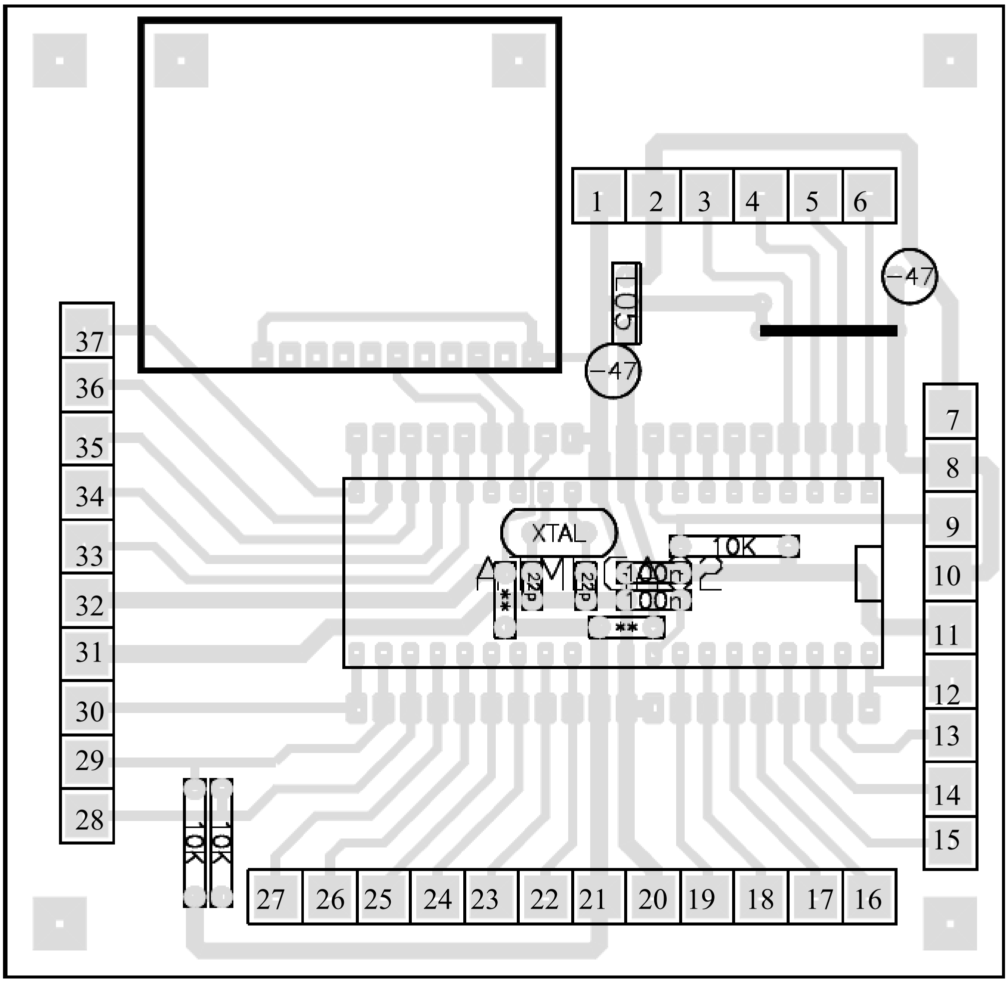


Figure E.2.4: Layout of the ATmega 32L +USB Microcontroller Board Used in Servo Communication Modules

Table E.2.4: Configuration of Terminals on the ATmega 32L +USB Microcontroller Board

Terminal	Function
1	Ground
2	Vcc
3-19	Unused
20	Ground
21-27	Unused
28	I2C data terminal
29	I2C clock terminal
30-37	Unused

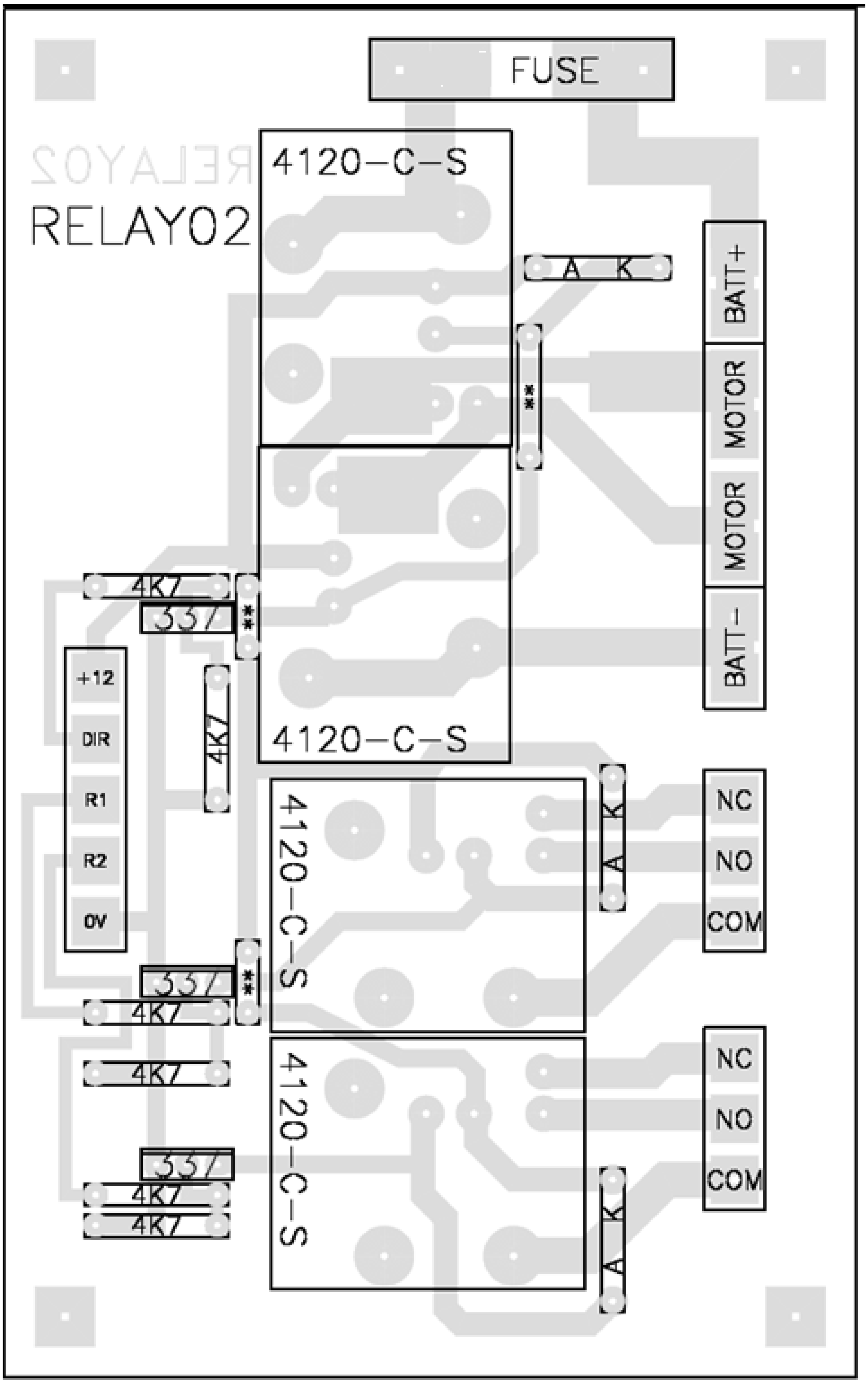


Figure E.2.5: Layout of the DC Relay Switch used in Spindle Control Modules

Table E.2.5: Configuration of Terminals on the DC Relay Switch used in Spindle Control Modules

Terminal	Function
	All Functions Indicated on Diagram

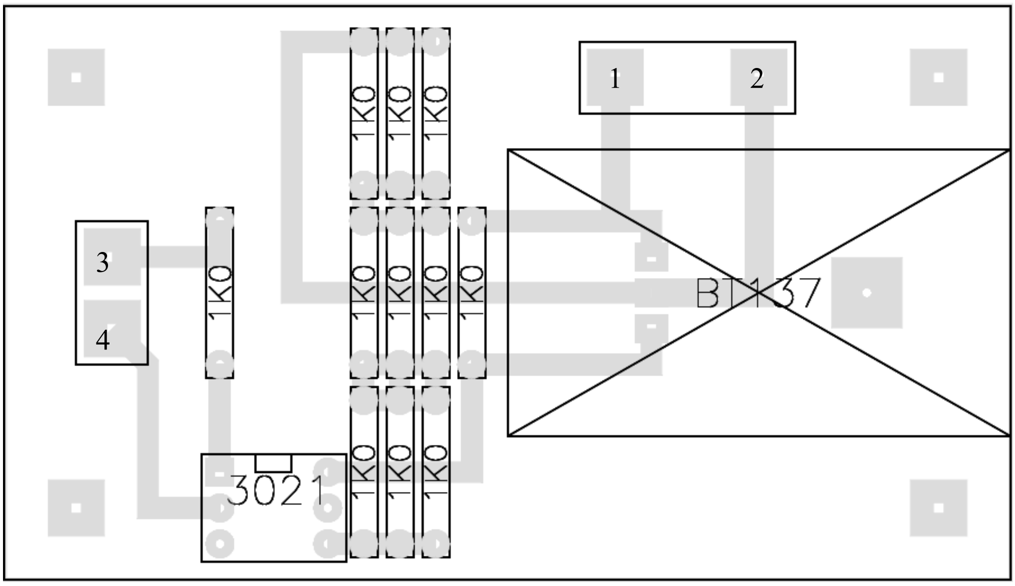


Figure E.2.6: Layout of the AC Relay Switch used in the AC Power Box

Table E.2.6: Configuration of Terminals on the AC Relay Switch used in the AC Power Box

Terminal	Function
1	AC line in
2	AC line out
3	Actuation Terminal
4	Ground

E.3 General Feedback Byte

Table E.3.1: Hexadecimal Values of the General Feedback Bytes

Spindle Control Modules	
Instruction	General Feedback Byte Value (HEX)
Successful Execution of Instruction	0x01
Instruction Incomplete	0x02
Servo Control Modules	
Instruction	General Feedback Byte Value (HEX)
Successful Execution of Instruction	0x01
Collision at Lower Limit	0x02
Collision at Upper Limit	0x03
No Actuation	0x04

Appendix F

F.1 Interpolation: Linear Axes

Base Module (- X Direction)

Linear interpolation performed for a distance of 100 mm at a feed rate of 100 mm/min.

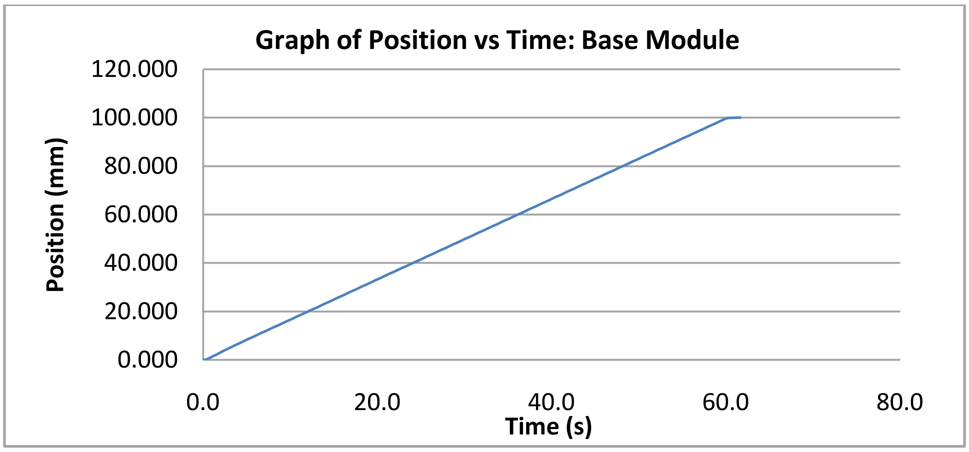


Figure F.1.1: Graph of Measured Position vs Time: Base Module (-X Direction)

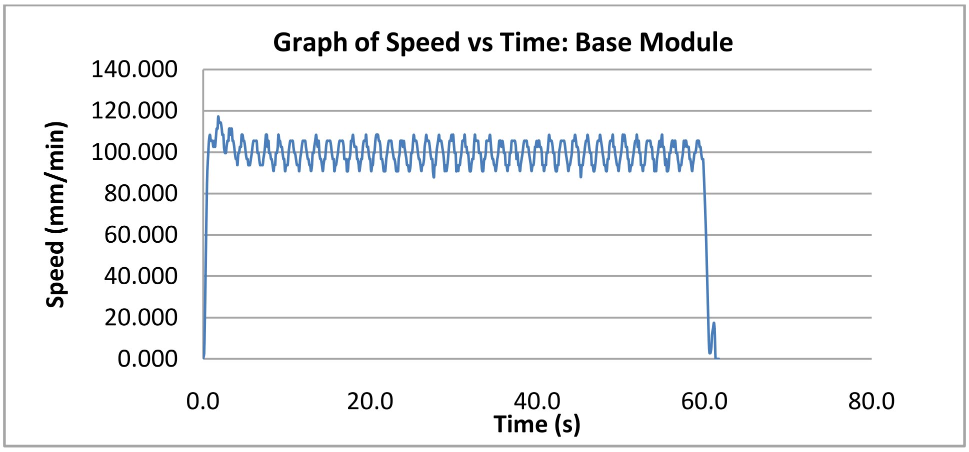


Figure F.1.2: Graph of Measured Speed vs Time: Base Module (-X Direction)

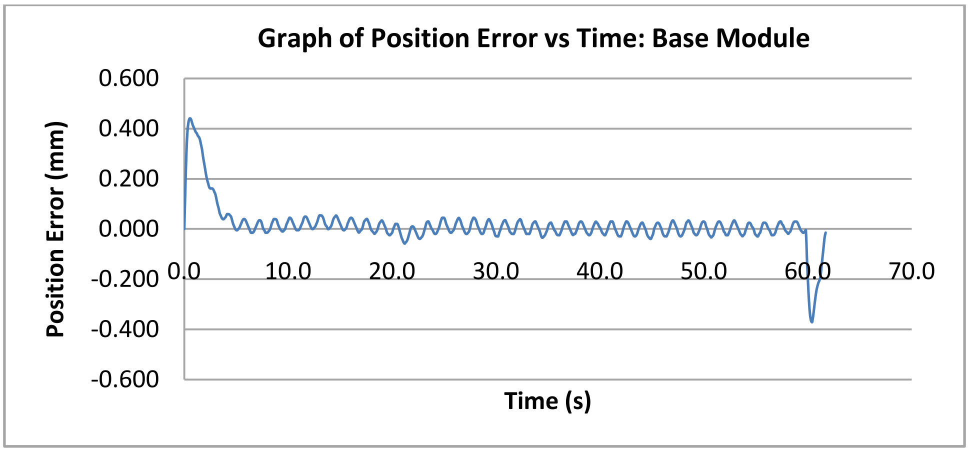


Figure F.1.3: Graph of Position Error vs Time: Base Module (-X Direction)

Work Table Slide Module (+ Y Direction)

Linear interpolation performed for a distance of 100 mm at a feed rate of 100 mm/min.

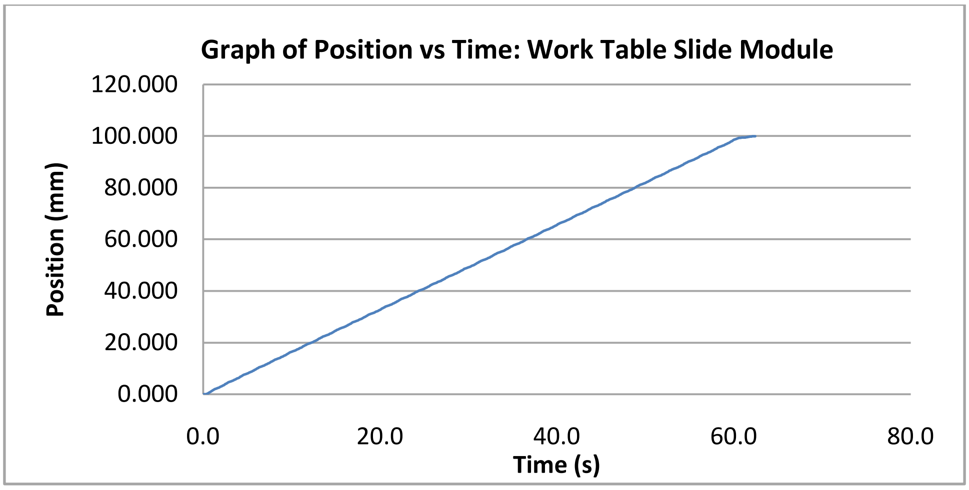


Figure F.1.4: Graph of Measured Position vs Time: Work Table Slide Module (+Y Direction)

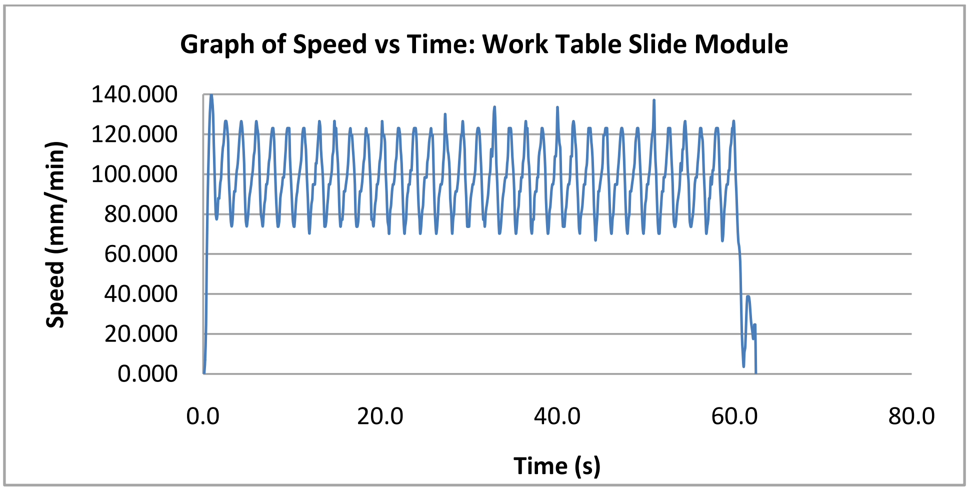


Figure F.1.5: Graph of Measured Speed vs Time: Work Table Slide Module (+Y Direction)

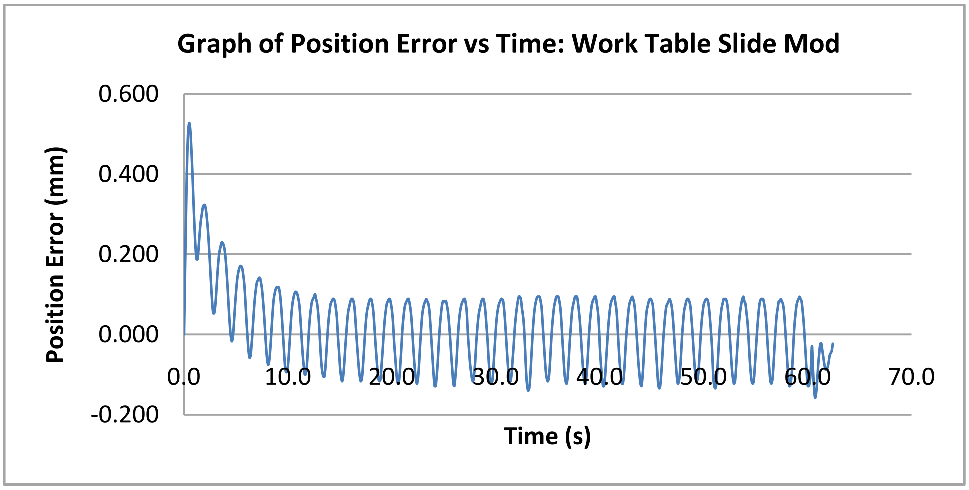


Figure F.1.6: Graph of Position Error vs Time: Work Table Slide Module (+Y Direction)

Work Table Slide Module (- Y Direction)

Linear interpolation performed for a distance of 100 mm at a feed rate of 100 mm/min.

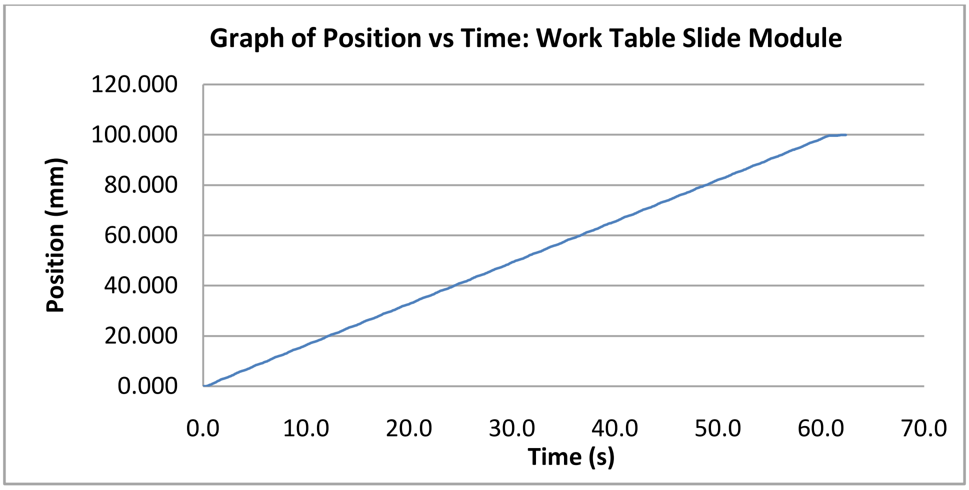


Figure F.1.7: Graph of Measured Position vs Time: Work Table Slide Module (-Y Direction)

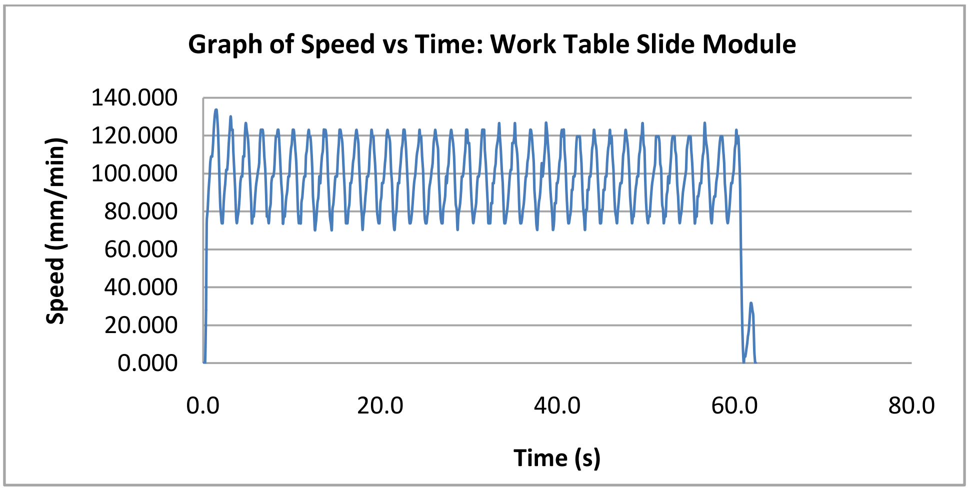


Figure F.1.8: Graph of Measured Speed vs Time: Work Table Slide Module (-Y Direction)

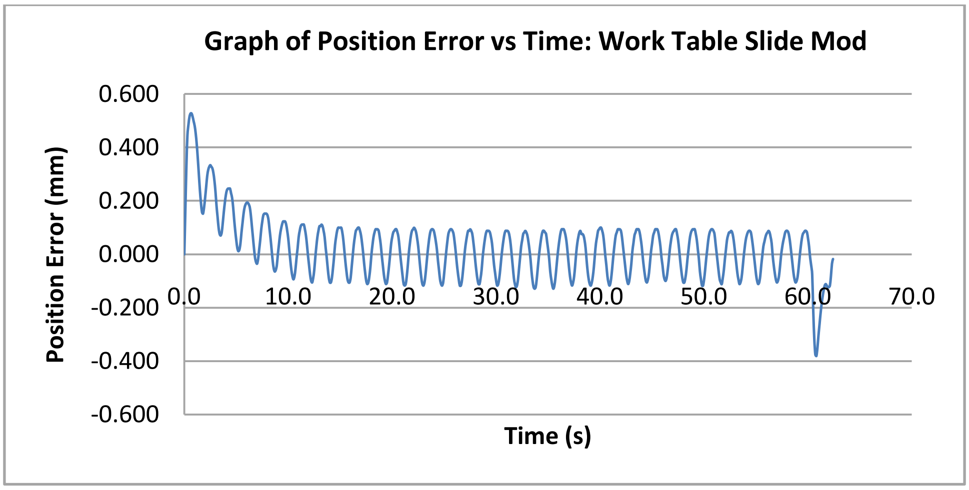


Figure F.1.9: Graph of Position Error vs Time: Work Table Slide Module (-Y Direction)

Column Module (+Z Direction)

Linear interpolation performed for a distance of 100 mm at a feed rate of 100 mm/min.

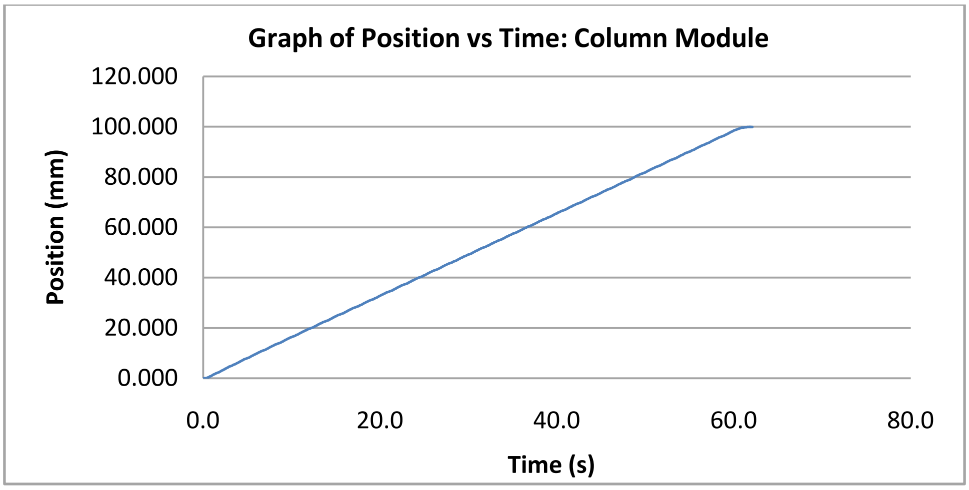


Figure F.1.10: Graph of Measured Position vs Time: Column Module (+Z Direction)

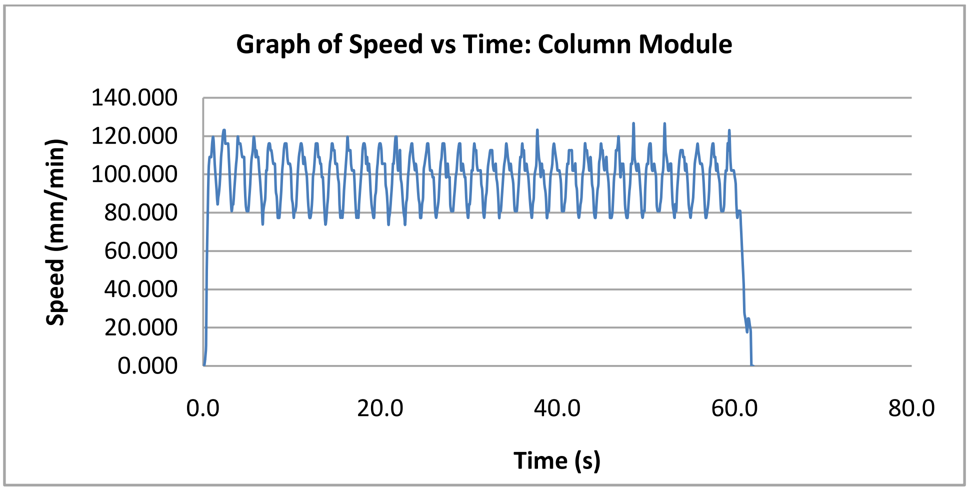


Figure F.1.11: Graph of Measured Speed vs Time: Column Module (+Z Direction)

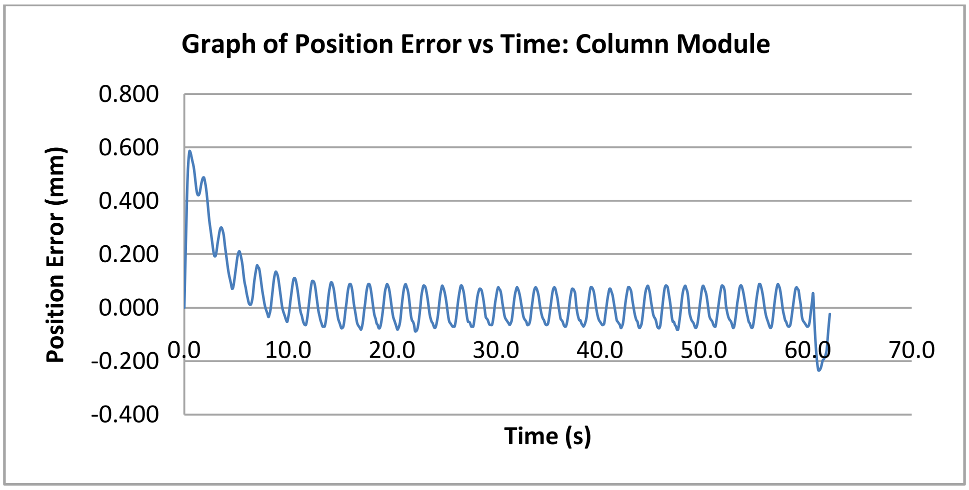


Figure F.1.12: Graph of Position Error vs Time: Column Module (+Z Direction)

Column Module (-Z Direction)

Linear interpolation performed for a distance of 100 mm at a feed rate of 100 mm/min.

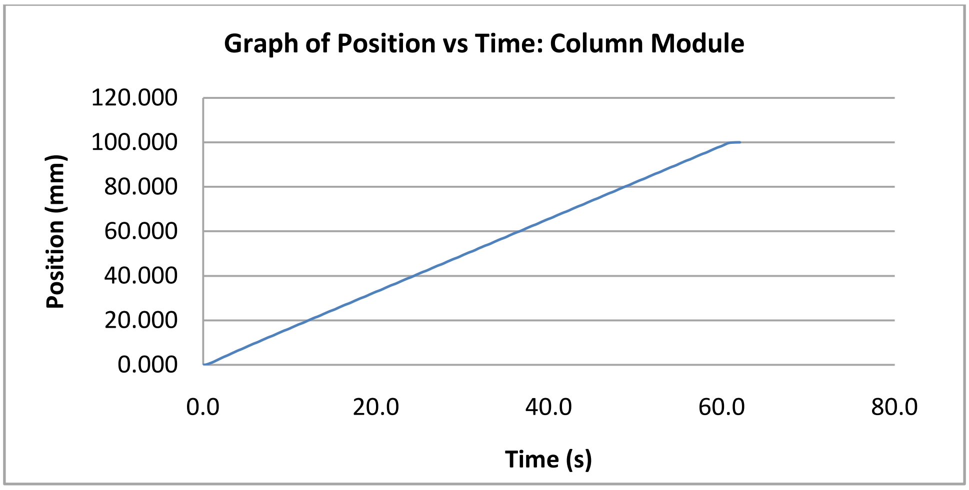


Figure F.1.13: Graph of Measured Position vs Time: Column Module (-Z Direction)

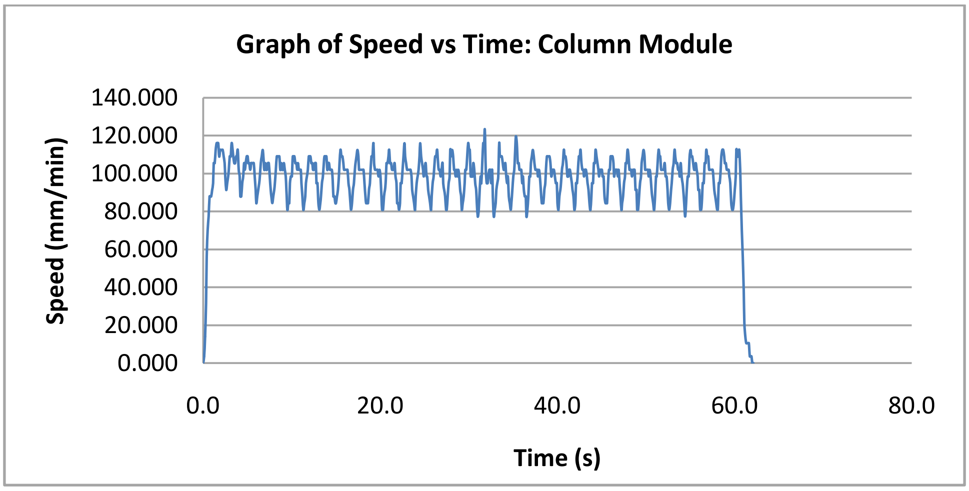


Figure F.1.14: Graph of Measured Speed vs Time: Column Module (-Z Direction)

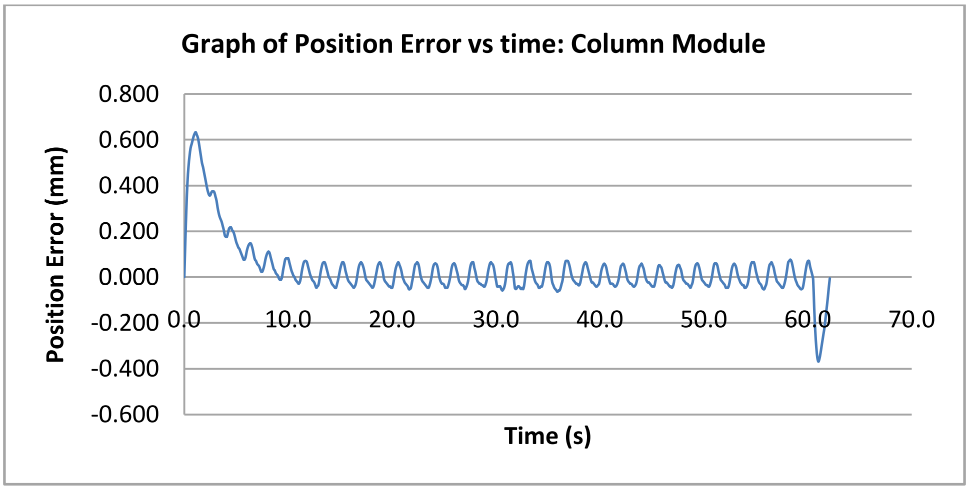


Figure F.1.15: Graph of Position Error vs Time: Column Module (-Z Direction)

Cross Slide Module (+Y Direction)

Linear interpolation performed for a distance of 50 mm at a feed rate of 100 mm/min.

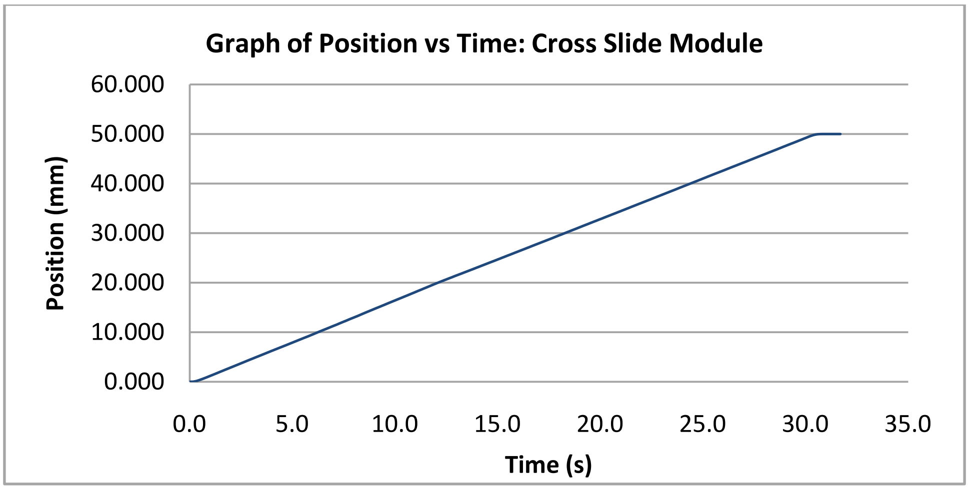


Figure F.1.16: Graph of Measured Position vs Time: Cross Slide Module (+Y Direction)

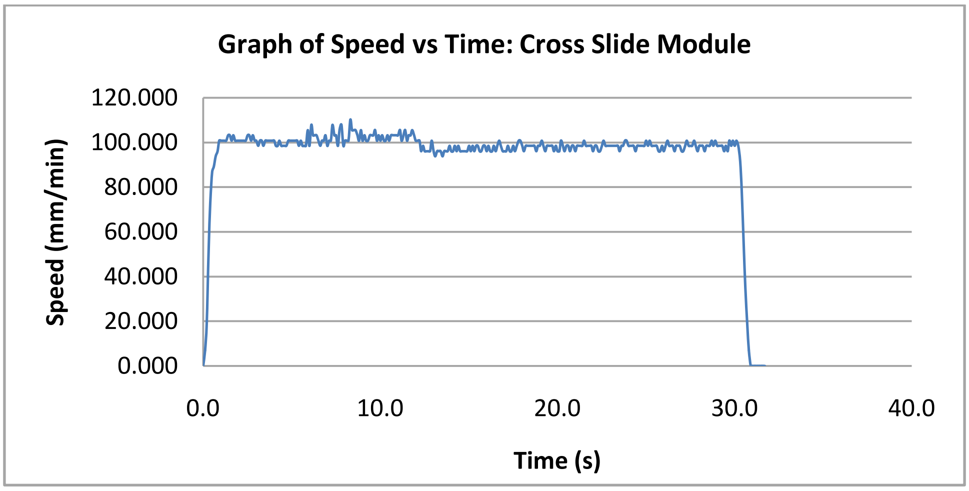


Figure F.1.17: Graph of Measured Speed vs Time: Cross Slide Module (+Y Direction)

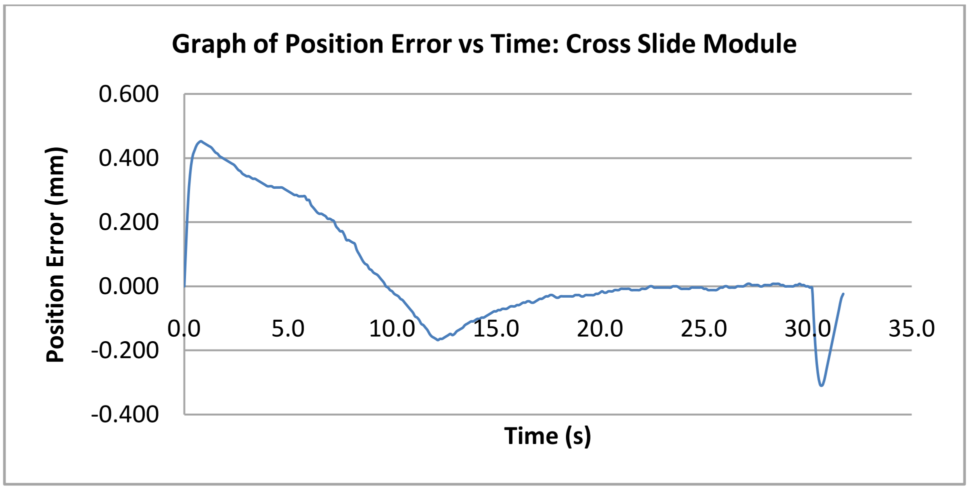


Figure F.1.18: Graph of Position Error vs Time: Cross Slide Module (+Y Direction)

Cross Slide Module (-Y Direction)

Linear interpolation performed for a distance of 50 mm at a feed rate of 100 mm/min.

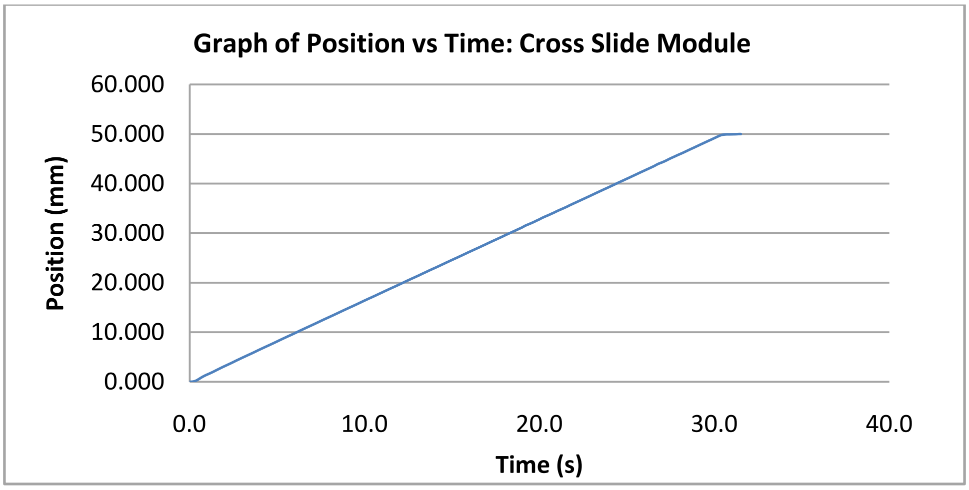


Figure F.1.19: Graph of Measured Position vs Time: Cross Slide Module (-Y Direction)

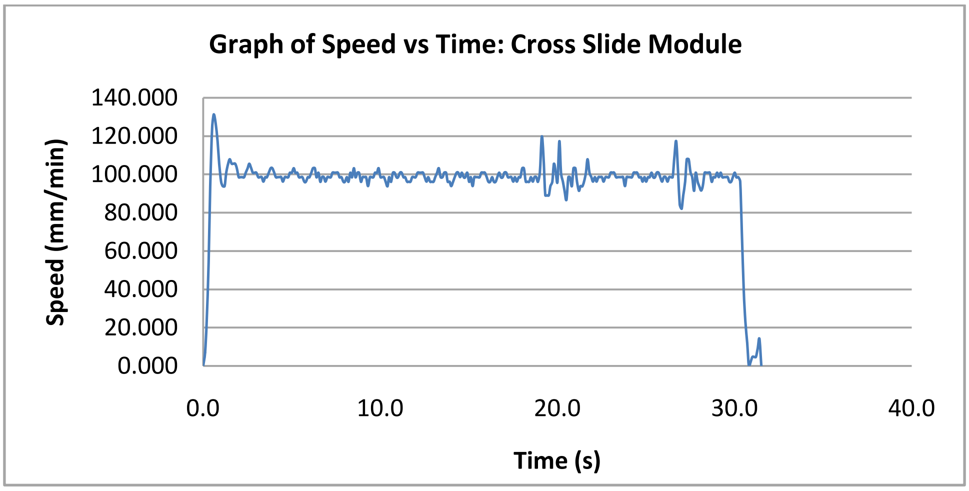


Figure F.1.20: Graph of Measured Speed vs Time: Cross Slide Module (-Y Direction)

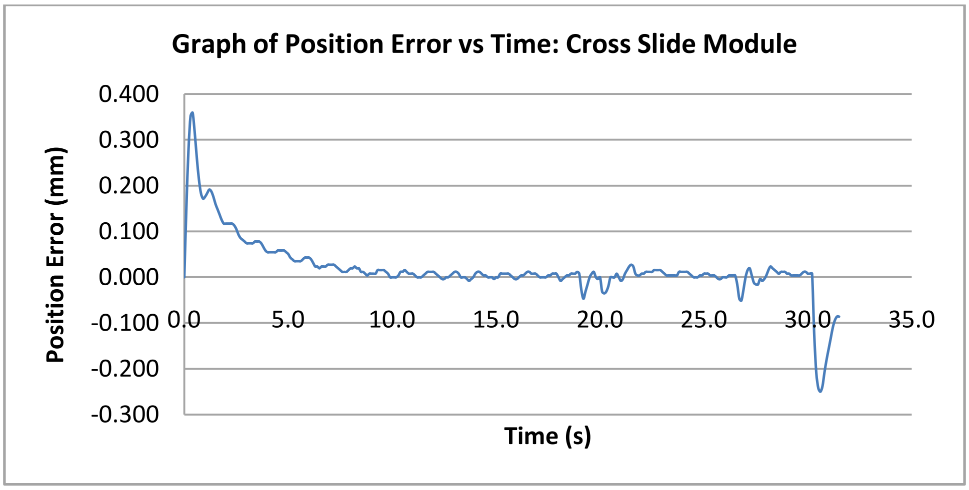


Figure F.1.21: Graph of Position Error vs Time: Cross Slide Module (-Y Direction)

F.2 Interpolation: Rotary Axes

Cutting Head Rotary Module (+ A/γ Direction)

Interpolation performed for an angle of 360° at a speed of 10 rev/min.

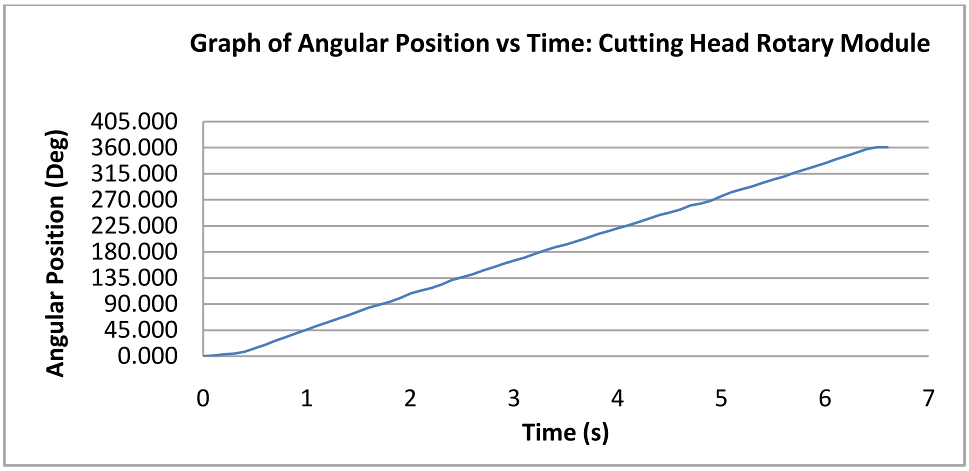


Figure F.2.1: Graph of Angular Position vs Time: Cutting Head Rotary Module (+A/γ Direction)

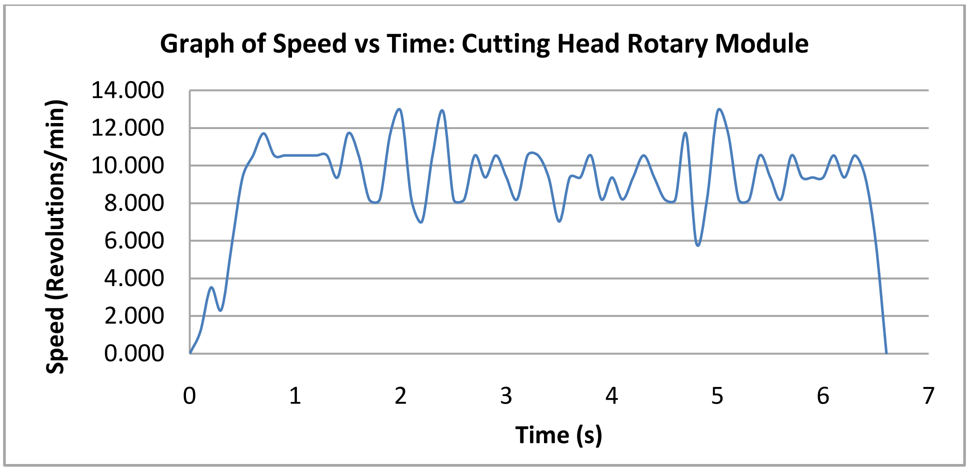


Figure F.2.2: Graph of Measured Speed vs Time: Cutting Head Rotary Module (+A/γ Direction)

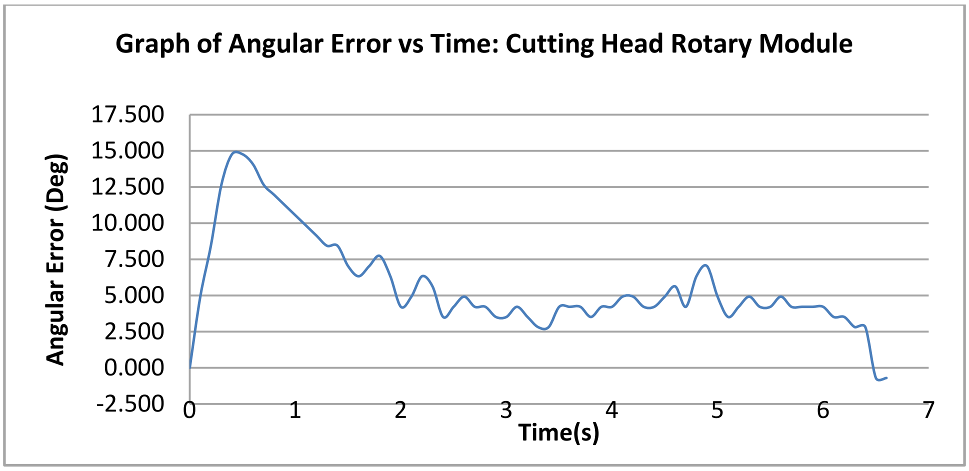


Figure F.2.3: Graph of Angular Position Error vs Time: Cutting Head Rotary Module (+A/γ Direction)

Cutting Head Rotary Module (- A/γ Direction)

Interpolation performed for an angle of 360° at a speed of 10 rev/min.

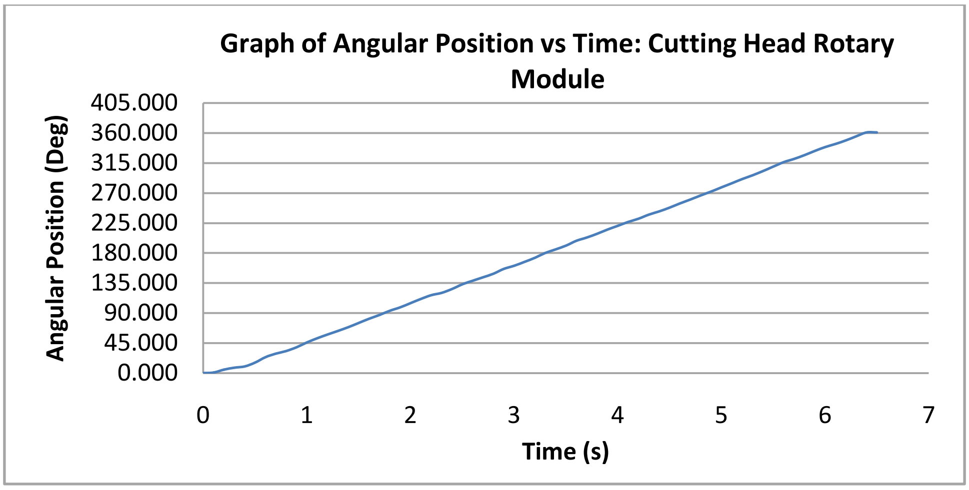


Figure F.2.4: Graph of Angular Position vs Time: Cutting Head Rotary Module (-A/γ Direction)

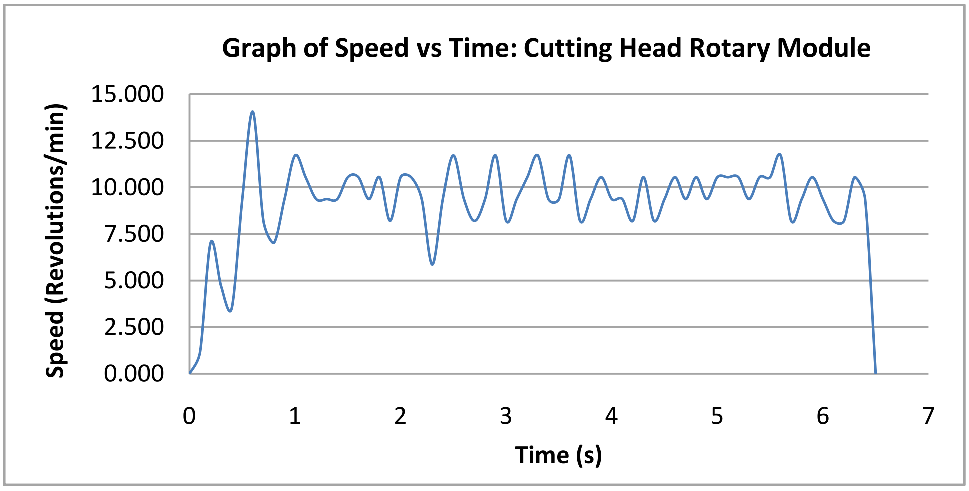


Figure F.2.5: Graph of Measured Speed vs Time: Cutting Head Rotary Module (-A/γ Direction)

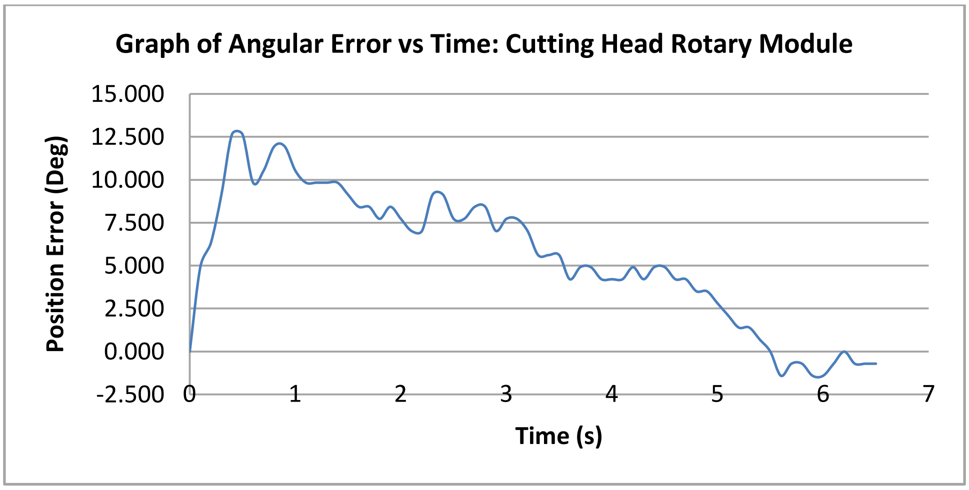


Figure F.2.6: Graph of Angular Position Error vs Time: Cutting Head Rotary Module (-A/γ Direction)

Tilt Table Module (+B/β Direction)

Interpolation performed for an angle of 90° at a speed of 15 rev/min.

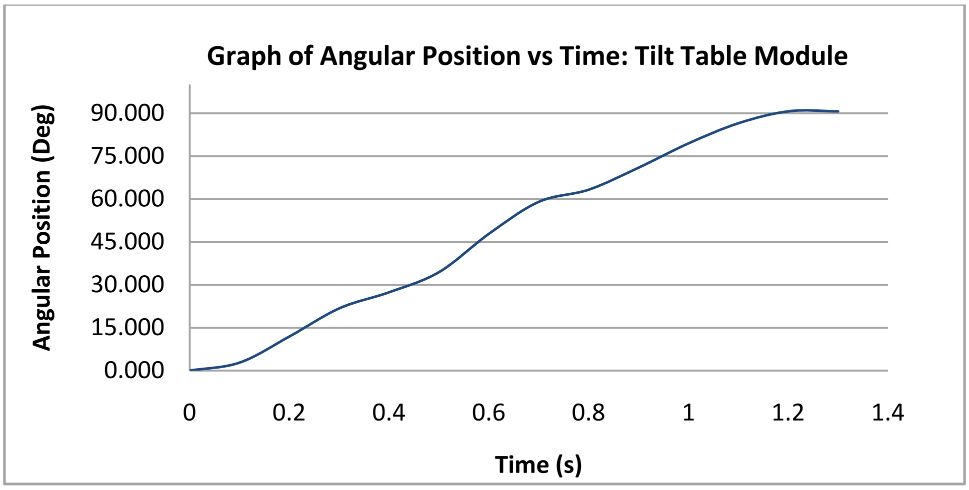


Figure F.2.7: Graph of Angular Position vs Time: Tilt Table Module (+B/β Direction)

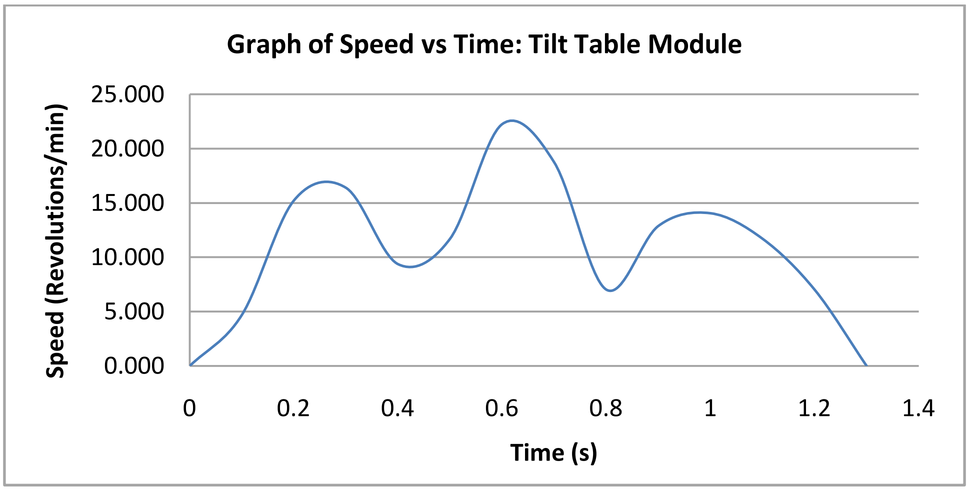


Figure F.2.8: Graph of Measured Speed vs Time: Tilt Table Module (+B/β Direction)

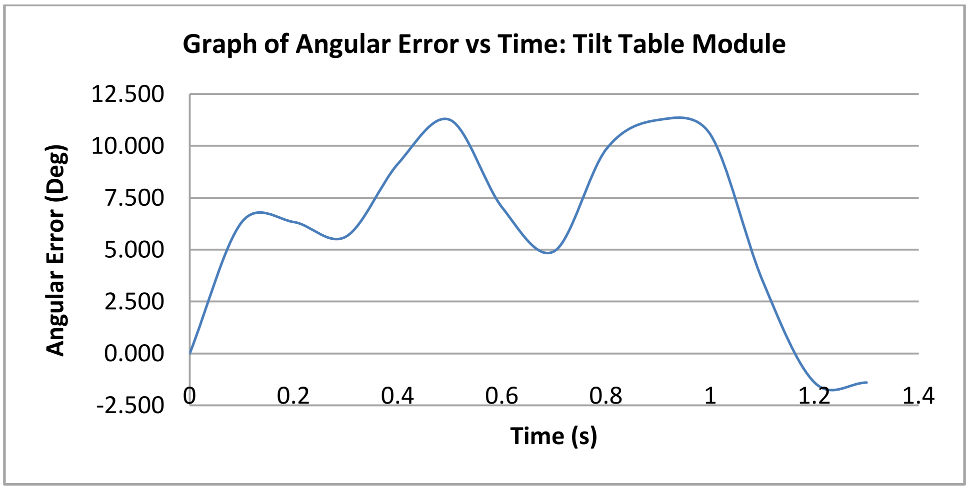


Figure F.2.9: Graph of Angular Position Error vs Time: Tilt Table Module (+B/β Direction)

Tilt Table Module (-B/β Direction)

Interpolation performed for an angle of 90° at a speed of 15 rev/min

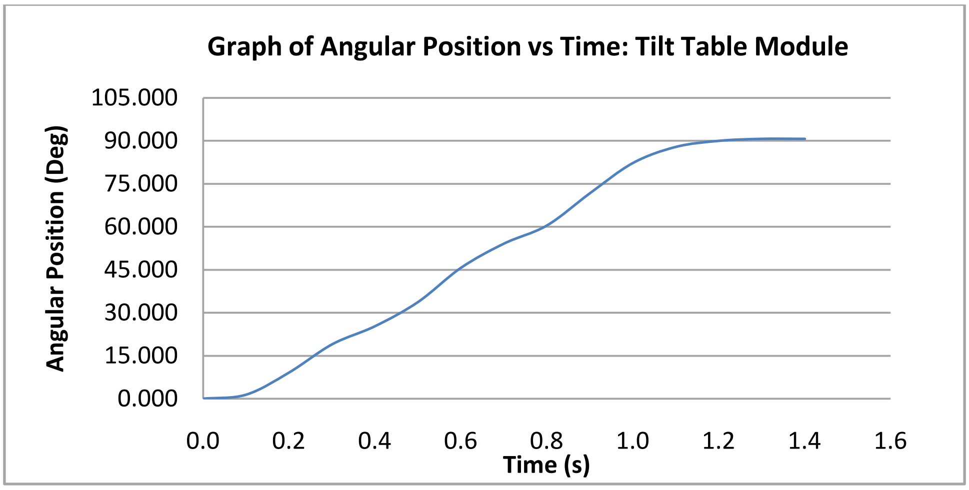


Figure F.2.10: Graph of Angular Position vs Time: Tilt Table Module (-B/β Direction)

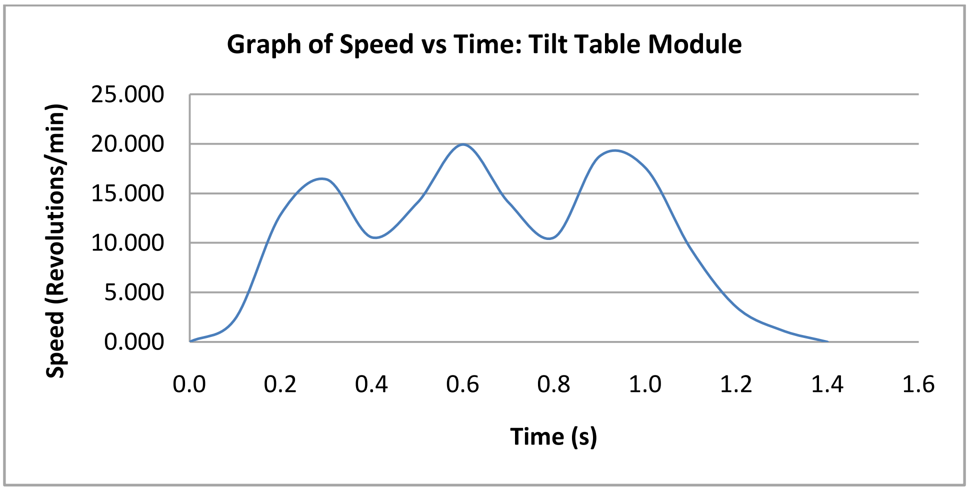


Figure F.2.11: Graph of Measured Speed vs Time: Tilt Table Module (-B/β Direction)

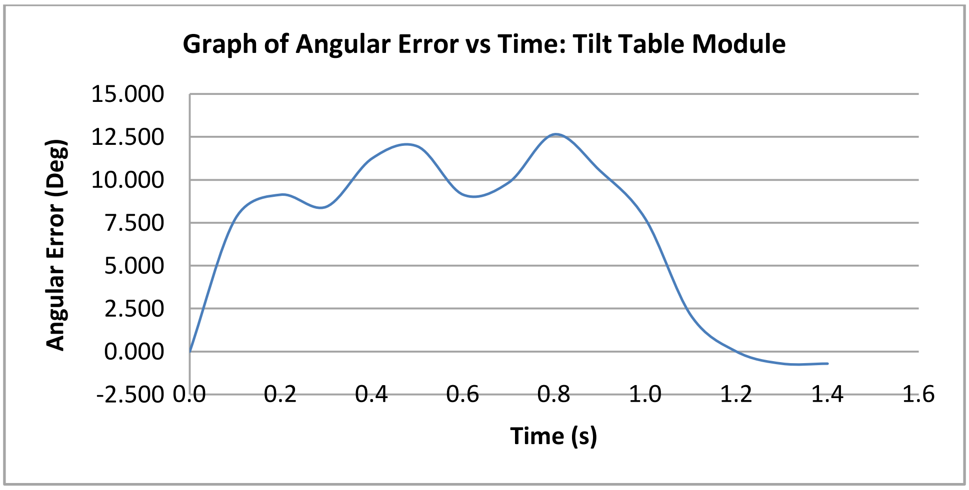


Figure F.2.12: Graph of Angular Position Error vs Time: Tilt Table Module (-B/β Direction)

Rotary Table Module (- C/α Direction)

Interpolation performed for an angle of 360° at a speed of 15 rev/min.

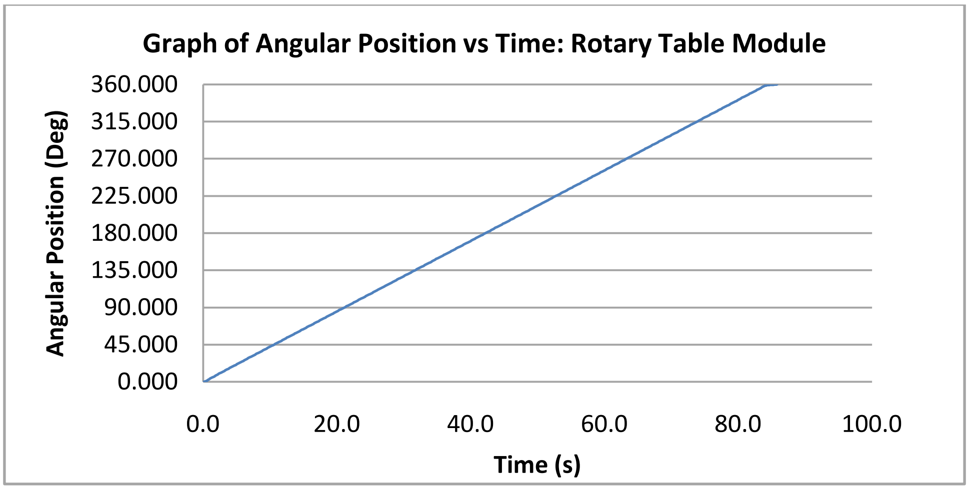


Figure F.2.13: Graph of Angular Position vs Time: Rotary Table Module (-C/α Direction)

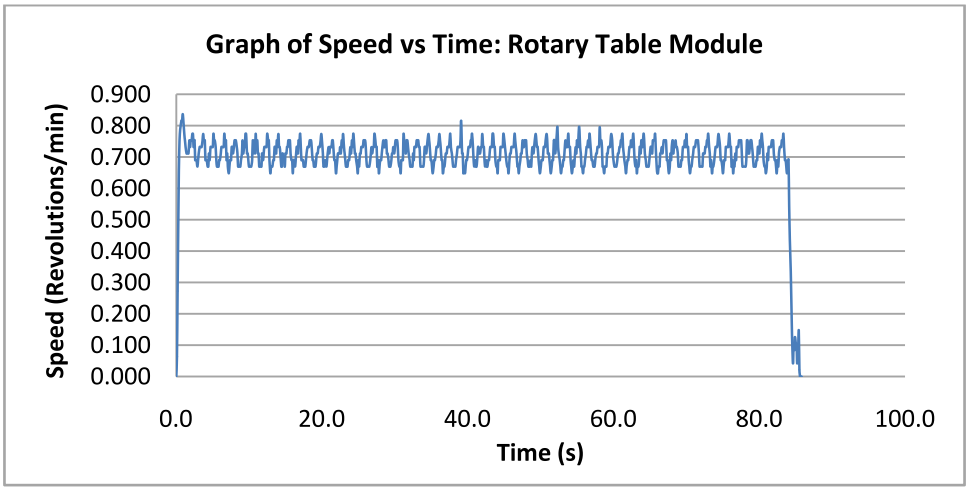


Figure F.2.14: Graph of Measured Speed vs Time: Rotary Table Module (-C/α Direction)

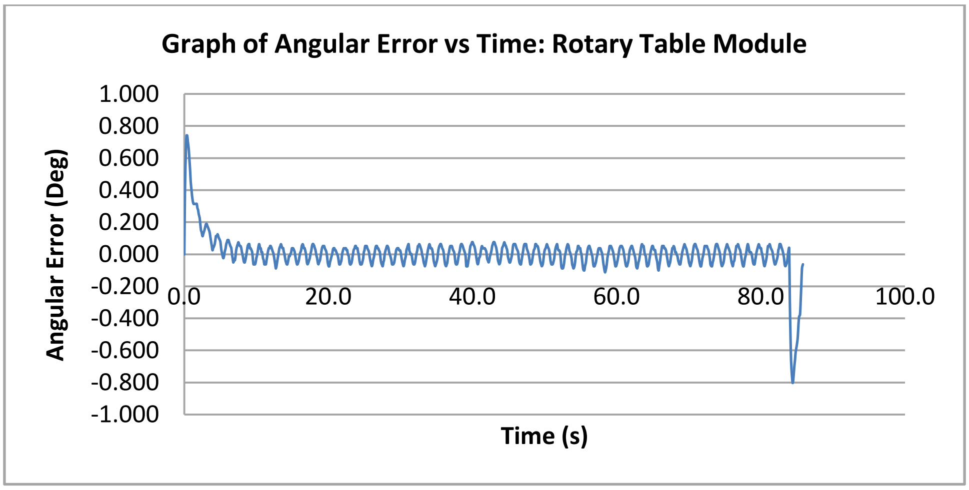


Figure F.2.15: Graph of Angular Position Error vs Time: Rotary Table Module (-C/α Direction)

F.3 Point to Point Motion Control

Table F.3.1: Test Results, Point to Point Motion Control of Linear Axes

	Base Module	Work Table Slide Module	Column Module	Cross Slide Module
Target Distance (mm)	**Overshoot (mm)**	**Overshoot (mm)**	**Overshoot (mm)**	**Overshoot (mm)**
25	0.029	0.001	0.001	0.000
-25	0.020	0.001	0.007	0.004
50	0.000	0.026	0.026	0.000
-50	0.034	0.015	0.059	0.000
75	-	-	-	0.000
-75	-	-	-	0.004
100	0.010	0.023	0.000	-
-100	0.015	0.018	0.018	-
Average	**0.018**	**0.014**	**0.019**	**0.001**
Maximum	**0.034**	**0.026**	**0.059**	**0.004**

Table F.3.2: Test Results, Point to Point Motion Control of Rotary Axes

	Cutting Head Rotary Module	Tilt Table Module	Rotary Table Module
Target Angle (Deg)	**Overshoot (Deg)**	**Overshoot (Deg)**	**Overshoot (Deg)**
45	0.000	0.000	0.013
-45	0.703	0.000	0.025
90	0.000	0.703	0.113
-90	0.000	0.703	0.100
180	0.703	-	0.113
-180	0.000	-	0.088
360	0.703	-	0.100
-360	1.406	-	0.138
Average	**0.439**	**0.352**	**0.086**
Maximum	**1.406**	**0.703**	**0.138**

F.4 Accuracy and Repeatability Test Data

Table F.4.1: Control Accuracy and Repeatability, Test Data for Linear Modules

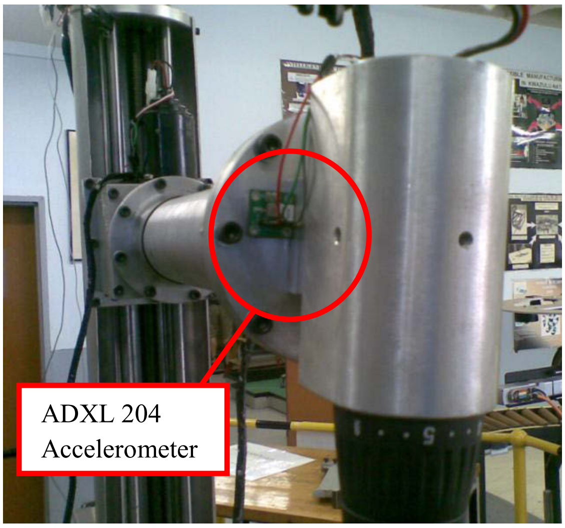
	Base Module		Work Table Slide Module		Column Module		Cross Slide Module	
Conditions	X+	X-	Y+	Y-	Z+	Z-	Y+	Y-
Target (mm)	100	-100	100	-100	100	-100	50	-50
Speed (mm/s)	100	100	100	100	100	100	100	100
Test No	Error (mm)		Error (mm)		Error (mm)		Error (mm)	
Test 1	0.015	0.000	0.012	0.012	0.018	0.012	0.008	0.000
Test 2	0.015	0.005	0.012	0.018	0.012	0.012	0.012	0.004
Test 3	0.015	0.010	0.018	0.023	0.012	0.006	0.008	0.008
Test 4	0.010	0.005	0.018	0.006	0.018	0.006	0.004	0.008
Test 5	0.020	0.010	0.023	0.012	0.029	0.023	0.008	0.008
Test 6	0.020	0.015	0.018	0.012	0.029	0.006	0.012	0.012
Statistics								
Mean Error	0.015	0.007	0.017	0.014	0.020	0.011	0.008	0.007
Std Dev	0.004	0.005	0.004	0.006	0.008	0.007	0.003	0.004
Max Error	0.020	0.015	0.023	0.023	0.029	0.023	0.012	0.012

Table F.4.2: Control Accuracy and Repeatability, Test Data for Rotary Modules

	Cutting Head Rotary Module		Tilt Table Module		Rotary Table Module	
Conditions	A+	A-	B+	B-	C+	C-
Target (Deg)	360	-360	90	-90	360	-360
Speed (rev/min)	40	40	30	30	0.75	0.75
Test No	Error (Deg)		Error (Deg)		Error (Deg)	
Test 1	0.000	1.406	0.000	0.000	0.063	0.038
Test 2	0.703	0.703	1.406	0.703	0.100	0.038
Test 3	1.406	2.109	0.703	0.000	0.151	0.038
Test 4	0.703	0.703	1.406	0.703	0.075	0.000
Test 5	0.703	0.000	0.703	1.406	0.088	0.113
Test 6	1.406	1.406	1.406	0.000	0.075	0.050
Statistics						
Mean Error	0.820	1.055	0.938	0.469	0.092	0.046
Std Dev	0.529	0.737	0.574	0.574	0.031	0.037
Max Error	1.406	2.109	1.406	1.406	0.151	0.113

F.5 Sample Output from Accelerometer

a. **b.**



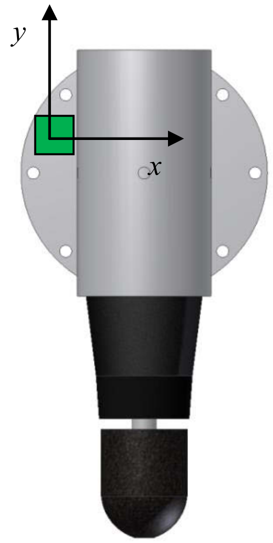


Figure F.5.1: Mounting of ADXL 204 Accelerometer

a. Mounting of ADXL 204 accelerometer on drilling head
b. Axes of ADXL 204 accelerometer in relation to drilling head

Table F.5.1: Conditions for Sampling of Accelerometer Signal

Test Conditions	
Spindle Speed	approximately 580 rev/min
Spindle Loading	Unloaded
Spindle Orientation	Vertical
Test Axis	X-axis
Signal Sampling Rate	100 Hz

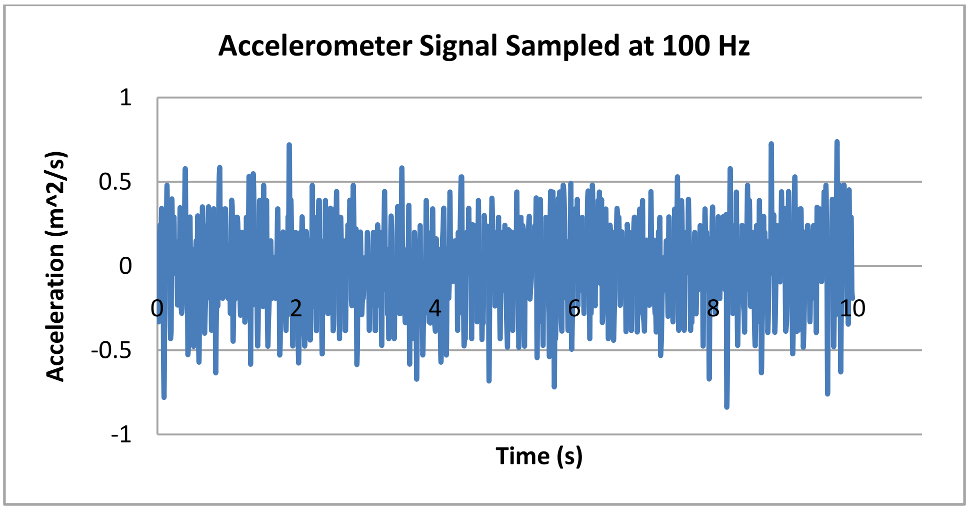


Figure F.5.2: Accelerometer Signal Sampled at 100 Hz for a Spindle Speed of 580 rev/min

F.6 Test Data - Samples

Note: only a sample of the data collected during performance testing is presented in this appendix. This is due to the extensive number of readings that are generated in a position control performance test (100 lines of readings for every 10 seconds). The data used in the preparation of ALL performance tables and graphs is located on the supplementary DVD disk.

Performance Test on Base Module (Figures 9.1-3)

Linear interpolation performed on the base module for a distance of 100 mm at a feed rate of 100 mm/min. The following data was used in the preparation of Figures 9.1-3.

Table F.6.1: Test Data, Performance Test on Base Module

Speed (pulses/s)	Ref Position (pulses)	Measured Position (pulses)	Speed (mm/min)	Ref Position (mm)	Measured Position (mm)	Error (mm)	Time (s)
0	0	0	0.000	0.000	0.000	0.000	0.0
1	34	1	2.930	0.166	0.005	0.161	0.1
1	68	2	2.930	0.332	0.010	0.322	0.2
6	102	8	17.578	0.498	0.039	0.459	0.3
17	136	25	49.805	0.664	0.122	0.542	0.4
27	170	52	79.102	0.830	0.254	0.576	0.5
33	204	85	96.680	0.996	0.415	0.581	0.6
36	238	121	105.469	1.162	0.591	0.571	0.7
40	272	161	117.188	1.328	0.786	0.542	0.8
41	306	202	120.117	1.494	0.986	0.508	0.9
42	340	244	123.047	1.660	1.191	0.469	1.0
44	374	288	128.906	1.826	1.406	0.420	1.1
44	408	332	128.906	1.992	1.621	0.371	1.2
42	442	374	123.047	2.158	1.826	0.332	1.3
41	476	415	120.117	2.324	2.026	0.298	1.4
38	510	453	111.328	2.490	2.212	0.278	1.5
36	544	489	105.469	2.656	2.388	0.269	1.6
36	578	525	105.469	2.822	2.563	0.259	1.7
35	612	560	102.539	2.988	2.734	0.254	1.8
35	646	595	102.539	3.154	2.905	0.249	1.9
36	680	631	105.469	3.320	3.081	0.239	2.0
37	714	668	108.398	3.486	3.262	0.225	2.1
38	748	706	111.328	3.652	3.447	0.205	2.2
40	782	746	117.188	3.818	3.643	0.176	2.3
41	816	787	120.117	3.984	3.843	0.142	2.4
41	850	828	120.117	4.150	4.043	0.107	2.5
39	884	867	114.258	4.316	4.233	0.083	2.6
37	918	904	108.398	4.482	4.414	0.068	2.7
35	952	939	102.539	4.648	4.585	0.063	2.8
33	986	972	96.680	4.814	4.746	0.068	2.9
32	1020	1004	93.750	4.980	4.902	0.078	3.0
31	1054	1035	90.820	5.146	5.054	0.093	3.1

31	1088	1066	90.820	5.313	5.205	0.107	3.2
33	1122	1099	96.680	5.479	5.366	0.112	3.3
33	1156	1132	96.680	5.645	5.527	0.117	3.4
35	1190	1167	102.539	5.811	5.698	0.112	3.5
37	1224	1204	108.398	5.977	5.879	0.098	3.6
38	1258	1242	111.328	6.143	6.064	0.078	3.7
41	1292	1283	120.117	6.309	6.265	0.044	3.8
38	1326	1321	111.328	6.475	6.450	0.024	3.9
38	1360	1359	111.328	6.641	6.636	0.005	4.0
37	1394	1396	108.398	6.807	6.816	-0.010	4.1
36	1428	1432	105.469	6.973	6.992	-0.020	4.2
33	1462	1465	96.680	7.139	7.153	-0.015	4.3
29	1496	1494	84.961	7.305	7.295	0.010	4.4
29	1530	1523	84.961	7.471	7.437	0.034	4.5
30	1564	1553	87.891	7.637	7.583	0.054	4.6
31	1598	1584	90.820	7.803	7.734	0.068	4.7
32	1632	1616	93.750	7.969	7.891	0.078	4.8
33	1666	1649	96.680	8.135	8.052	0.083	4.9
36	1700	1685	105.469	8.301	8.228	0.073	5.0
37	1734	1722	108.398	8.467	8.408	0.059	5.1
37	1768	1759	108.398	8.633	8.589	0.044	5.2
39	1802	1798	114.258	8.799	8.779	0.020	5.3
39	1836	1837	114.258	8.965	8.970	-0.005	5.4
37	1870	1874	108.398	9.131	9.150	-0.020	5.5
36	1904	1910	105.469	9.297	9.326	-0.029	5.6
34	1938	1944	99.609	9.463	9.492	-0.029	5.7
32	1972	1976	93.750	9.629	9.648	-0.020	5.8
30	2006	2006	87.891	9.795	9.795	0.000	5.9
30	2040	2036	87.891	9.961	9.941	0.020	6.0
30	2074	2066	87.891	10.127	10.088	0.039	6.1
31	2108	2097	90.820	10.293	10.239	0.054	6.2
33	2142	2130	96.680	10.459	10.400	0.059	6.3
34	2176	2164	99.609	10.625	10.566	0.059	6.4
36	2210	2200	105.469	10.791	10.742	0.049	6.5
39	2244	2239	114.258	10.957	10.933	0.024	6.6
38	2278	2277	111.328	11.123	11.118	0.005	6.7
40	2312	2317	117.188	11.289	11.313	-0.024	6.8
38	2346	2355	111.328	11.455	11.499	-0.044	6.9
37	2380	2392	108.398	11.621	11.680	-0.059	7.0
35	2414	2427	102.539	11.787	11.851	-0.063	7.1
31	2448	2458	90.820	11.953	12.002	-0.049	7.2
31	2482	2489	90.820	12.119	12.153	-0.034	7.3
29	2516	2518	84.961	12.285	12.295	-0.010	7.4
29	2550	2547	84.961	12.451	12.437	0.015	7.5
30	2584	2577	87.891	12.617	12.583	0.034	7.6
32	2618	2609	93.750	12.783	12.739	0.044	7.7
32	2652	2641	93.750	12.949	12.896	0.054	7.8
35	2686	2676	102.539	13.115	13.066	0.049	7.9
37	2720	2713	108.398	13.281	13.247	0.034	8.0
36	2754	2749	105.469	13.447	13.423	0.024	8.1
39	2788	2788	114.258	13.613	13.613	0.000	8.2
38	2822	2826	111.328	13.779	13.799	-0.020	8.3
38	2856	2864	111.328	13.945	13.984	-0.039	8.4

36	2890	2900	105.469	14.111	14.160	-0.049	8.5
34	2924	2934	99.609	14.277	14.326	-0.049	8.6
33	2958	2967	96.680	14.443	14.487	-0.044	8.7
32	2992	2999	93.750	14.609	14.644	-0.034	8.8
30	3026	3029	87.891	14.775	14.790	-0.015	8.9
30	3060	3059	87.891	14.941	14.937	0.005	9.0
30	3094	3089	87.891	15.107	15.083	0.024	9.1
31	3128	3120	90.820	15.273	15.234	0.039	9.2
33	3162	3153	96.680	15.439	15.396	0.044	9.3
36	3196	3189	105.469	15.605	15.571	0.034	9.4
38	3230	3227	111.328	15.771	15.757	0.015	9.5
37	3264	3264	108.398	15.938	15.938	0.000	9.6
37	3298	3301	108.398	16.104	16.118	-0.015	9.7
38	3332	3339	111.328	16.270	16.304	-0.034	9.8
39	3366	3378	114.258	16.436	16.494	-0.059	9.9
36	3400	3414	105.469	16.602	16.670	-0.068	10.0
35	3434	3449	102.539	16.768	16.841	-0.073	10.1
30	3468	3479	87.891	16.934	16.987	-0.054	10.2
28	3502	3507	82.031	17.100	17.124	-0.024	10.3
29	3536	3536	84.961	17.266	17.266	0.000	10.4
30	3570	3566	87.891	17.432	17.412	0.020	10.5
31	3604	3597	90.820	17.598	17.563	0.034	10.6
34	3638	3631	99.609	17.764	17.729	0.034	10.7
34	3672	3665	99.609	17.930	17.896	0.034	10.8
36	3706	3701	105.469	18.096	18.071	0.024	10.9
37	3740	3738	108.398	18.262	18.252	0.010	11.0
37	3774	3775	108.398	18.428	18.433	-0.005	11.1
37	3808	3812	108.398	18.594	18.613	-0.020	11.2
36	3842	3848	105.469	18.760	18.789	-0.029	11.3
36	3876	3884	105.469	18.926	18.965	-0.039	11.4
38	3910	3922	111.328	19.092	19.150	-0.059	11.5
33	3944	3955	96.680	19.258	19.312	-0.054	11.6
30	3978	3985	87.891	19.424	19.458	-0.034	11.7
29	4012	4014	84.961	19.590	19.600	-0.010	11.8
29	4046	4043	84.961	19.756	19.741	0.015	11.9
30	4080	4073	87.891	19.922	19.888	0.034	12.0
32	4114	4105	93.750	20.088	20.044	0.044	12.1
33	4148	4138	96.680	20.254	20.205	0.049	12.2
35	4182	4173	102.539	20.420	20.376	0.044	12.3
38	4216	4211	111.328	20.586	20.562	0.024	12.4
37	4250	4248	108.398	20.752	20.742	0.010	12.5
37	4284	4285	108.398	20.918	20.923	-0.005	12.6
37	4318	4322	108.398	21.084	21.104	-0.020	12.7
38	4352	4360	111.328	21.250	21.289	-0.039	12.8
35	4386	4395	102.539	21.416	21.460	-0.044	12.9
36	4420	4431	105.469	21.582	21.636	-0.054	13.0
32	4454	4463	93.750	21.748	21.792	-0.044	13.1
31	4488	4494	90.820	21.914	21.943	-0.029	13.2
28	4522	4522	82.031	22.080	22.080	0.000	13.3
29	4556	4551	84.961	22.246	22.222	0.024	13.4
30	4590	4581	87.891	22.412	22.368	0.044	13.5
31	4624	4612	90.820	22.578	22.520	0.059	13.6
34	4658	4646	99.609	22.744	22.686	0.059	13.7

37	4692	4683	108.398	22.910	22.866	0.044	13.8
38	4726	4721	111.328	23.076	23.052	0.024	13.9
39	4760	4760	114.258	23.242	23.242	0.000	14.0
37	4794	4797	108.398	23.408	23.423	-0.015	14.1
37	4828	4834	108.398	23.574	23.604	-0.029	14.2
37	4862	4871	108.398	23.740	23.784	-0.044	14.3
36	4896	4907	105.469	23.906	23.960	-0.054	14.4
34	4930	4941	99.609	24.072	24.126	-0.054	14.5
33	4964	4974	96.680	24.238	24.287	-0.049	14.6
29	4998	5003	84.961	24.404	24.429	-0.024	14.7
29	5032	5032	84.961	24.570	24.570	0.000	14.8
29	5066	5061	84.961	24.736	24.712	0.024	14.9
30	5100	5091	87.891	24.902	24.858	0.044	15.0
31	5134	5122	90.820	25.068	25.010	0.059	15.1
34	5168	5156	99.609	25.234	25.176	0.059	15.2
35	5202	5191	102.539	25.400	25.347	0.054	15.3
39	5236	5230	114.258	25.566	25.537	0.029	15.4
38	5270	5268	111.328	25.732	25.723	0.010	15.5
37	5304	5305	108.398	25.898	25.903	-0.005	15.6
38	5338	5343	111.328	26.064	26.089	-0.024	15.7
37	5372	5380	108.398	26.230	26.270	-0.039	15.8
35	5406	5415	102.539	26.396	26.440	-0.044	15.9
35	5440	5450	102.539	26.563	26.611	-0.049	16.0
32	5474	5482	93.750	26.729	26.768	-0.039	16.1
30	5508	5512	87.891	26.895	26.914	-0.020	16.2
28	5542	5540	82.031	27.061	27.051	0.010	16.3
30	5576	5570	87.891	27.227	27.197	0.029	16.4
31	5610	5601	90.820	27.393	27.349	0.044	16.5
32	5644	5633	93.750	27.559	27.505	0.054	16.6
34	5678	5667	99.609	27.725	27.671	0.054	16.7
36	5712	5703	105.469	27.891	27.847	0.044	16.8
37	5746	5740	108.398	28.057	28.027	0.029	16.9
38	5780	5778	111.328	28.223	28.213	0.010	17.0
38	5814	5816	111.328	28.389	28.398	-0.010	17.1
38	5848	5854	111.328	28.555	28.584	-0.029	17.2
37	5882	5891	108.398	28.721	28.765	-0.044	17.3
36	5916	5927	105.469	28.887	28.940	-0.054	17.4
34	5950	5961	99.609	29.053	29.106	-0.054	17.5
31	5984	5992	90.820	29.219	29.258	-0.039	17.6
29	6018	6021	84.961	29.385	29.399	-0.015	17.7
29	6052	6050	84.961	29.551	29.541	0.010	17.8
29	6086	6079	84.961	29.717	29.683	0.034	17.9
30	6120	6109	87.891	29.883	29.829	0.054	18.0
32	6154	6141	93.750	30.049	29.985	0.063	18.1
34	6188	6175	99.609	30.215	30.151	0.063	18.2
37	6222	6212	108.398	30.381	30.332	0.049	18.3
37	6256	6249	108.398	30.547	30.513	0.034	18.4
37	6290	6286	108.398	30.713	30.693	0.020	18.5
38	6324	6324	111.328	30.879	30.879	0.000	18.6
38	6358	6362	111.328	31.045	31.064	-0.020	18.7
38	6392	6400	111.328	31.211	31.250	-0.039	18.8
36	6426	6436	105.469	31.377	31.426	-0.049	18.9
33	6460	6469	96.680	31.543	31.587	-0.044	19.0

32	6494	6501	93.750	31.709	31.743	-0.034	19.1
29	6528	6530	84.961	31.875	31.885	-0.010	19.2
28	6562	6558	82.031	32.041	32.021	0.020	19.3
30	6596	6588	87.891	32.207	32.168	0.039	19.4
31	6630	6619	90.820	32.373	32.319	0.054	19.5
33	6664	6652	96.680	32.539	32.480	0.059	19.6
34	6698	6686	99.609	32.705	32.646	0.059	19.7
37	6732	6723	108.398	32.871	32.827	0.044	19.8
37	6766	6760	108.398	33.037	33.008	0.029	19.9
38	6800	6798	111.328	33.203	33.193	0.010	20.0
38	6834	6836	111.328	33.369	33.379	-0.010	20.1
38	6868	6874	111.328	33.535	33.564	-0.029	20.2
37	6902	6911	108.398	33.701	33.745	-0.044	20.3
35	6936	6946	102.539	33.867	33.916	-0.049	20.4
35	6970	6981	102.539	34.033	34.087	-0.054	20.5
30	7004	7011	87.891	34.199	34.233	-0.034	20.6
29	7038	7040	84.961	34.365	34.375	-0.010	20.7
28	7072	7068	82.031	34.531	34.512	0.020	20.8
30	7106	7098	87.891	34.697	34.658	0.039	20.9
32	7140	7130	93.750	34.863	34.814	0.049	21.0
34	7174	7164	99.609	35.029	34.980	0.049	21.1
35	7208	7199	102.539	35.195	35.151	0.044	21.2
38	7242	7237	111.328	35.361	35.337	0.024	21.3
37	7276	7274	108.398	35.527	35.518	0.010	21.4
38	7310	7312	111.328	35.693	35.703	-0.010	21.5
37	7344	7349	108.398	35.859	35.884	-0.024	21.6
38	7378	7387	111.328	36.025	36.069	-0.044	21.7
36	7412	7423	105.469	36.191	36.245	-0.054	21.8
35	7446	7458	102.539	36.357	36.416	-0.059	21.9
32	7480	7490	93.750	36.523	36.572	-0.049	22.0
30	7514	7520	87.891	36.689	36.719	-0.029	22.1
28	7548	7548	82.031	36.855	36.855	0.000	22.2
30	7582	7578	87.891	37.021	37.002	0.020	22.3
31	7616	7609	90.820	37.188	37.153	0.034	22.4
32	7650	7641	93.750	37.354	37.310	0.044	22.5
34	7684	7675	99.609	37.520	37.476	0.044	22.6
35	7718	7710	102.539	37.686	37.646	0.039	22.7
38	7752	7748	111.328	37.852	37.832	0.020	22.8
37	7786	7785	108.398	38.018	38.013	0.005	22.9
38	7820	7823	111.328	38.184	38.198	-0.015	23.0
37	7854	7860	108.398	38.350	38.379	-0.029	23.1
38	7888	7898	111.328	38.516	38.564	-0.049	23.2
36	7922	7934	105.469	38.682	38.740	-0.059	23.3
34	7956	7968	99.609	38.848	38.906	-0.059	23.4
31	7990	7999	90.820	39.014	39.058	-0.044	23.5
29	8024	8028	84.961	39.180	39.199	-0.020	23.6
29	8058	8057	84.961	39.346	39.341	0.005	23.7
29	8092	8086	84.961	39.512	39.482	0.029	23.8
31	8126	8117	90.820	39.678	39.634	0.044	23.9
32	8160	8149	93.750	39.844	39.790	0.054	24.0
35	8194	8184	102.539	40.010	39.961	0.049	24.1
37	8228	8221	108.398	40.176	40.142	0.034	24.2
38	8262	8259	111.328	40.342	40.327	0.015	24.3

37	8296	8296	108.398	40.508	40.508	0.000	24.4
38	8330	8334	111.328	40.674	40.693	-0.020	24.5
37	8364	8371	108.398	40.840	40.874	-0.034	24.6
37	8398	8408	108.398	41.006	41.055	-0.049	24.7
35	8432	8443	102.539	41.172	41.226	-0.054	24.8
33	8466	8476	96.680	41.338	41.387	-0.049	24.9
31	8500	8507	90.820	41.504	41.538	-0.034	25.0
29	8534	8536	84.961	41.670	41.680	-0.010	25.1
28	8568	8564	82.031	41.836	41.816	0.020	25.2
30	8602	8594	87.891	42.002	41.963	0.039	25.3
31	8636	8625	90.820	42.168	42.114	0.054	25.4
34	8670	8659	99.609	42.334	42.280	0.054	25.5
35	8704	8694	102.539	42.500	42.451	0.049	25.6
37	8738	8731	108.398	42.666	42.632	0.034	25.7
38	8772	8769	111.328	42.832	42.817	0.015	25.8
38	8806	8807	111.328	42.998	43.003	-0.005	25.9
37	8840	8844	108.398	43.164	43.184	-0.020	26.0
37	8874	8881	108.398	43.330	43.364	-0.034	26.1
37	8908	8918	108.398	43.496	43.545	-0.049	26.2
34	8942	8952	99.609	43.662	43.711	-0.049	26.3
33	8976	8985	96.680	43.828	43.872	-0.044	26.4
31	9010	9016	90.820	43.994	44.023	-0.029	26.5
28	9044	9044	82.031	44.160	44.160	0.000	26.6
29	9078	9073	84.961	44.326	44.302	0.024	26.7
30	9112	9103	87.891	44.492	44.448	0.044	26.8
33	9146	9136	96.680	44.658	44.609	0.049	26.9
33	9180	9169	96.680	44.824	44.771	0.054	27.0
37	9214	9206	108.398	44.990	44.951	0.039	27.1
37	9248	9243	108.398	45.156	45.132	0.024	27.2
37	9282	9280	108.398	45.322	45.313	0.010	27.3
40	9316	9320	117.188	45.488	45.508	-0.020	27.4
37	9350	9357	108.398	45.654	45.688	-0.034	27.5
37	9384	9394	108.398	45.820	45.869	-0.049	27.6
37	9418	9431	108.398	45.986	46.050	-0.063	27.7
33	9452	9464	96.680	46.152	46.211	-0.059	27.8
32	9486	9496	93.750	46.318	46.367	-0.049	27.9
29	9520	9525	84.961	46.484	46.509	-0.024	28.0
28	9554	9553	82.031	46.650	46.646	0.005	28.1
29	9588	9582	84.961	46.816	46.787	0.029	28.2
30	9622	9612	87.891	46.982	46.934	0.049	28.3
33	9656	9645	96.680	47.148	47.095	0.054	28.4
34	9690	9679	99.609	47.314	47.261	0.054	28.5
37	9724	9716	108.398	47.480	47.441	0.039	28.6
38	9758	9754	111.328	47.646	47.627	0.020	28.7
39	9792	9793	114.258	47.813	47.817	-0.005	28.8
38	9826	9831	111.328	47.979	48.003	-0.024	28.9
37	9860	9868	108.398	48.145	48.184	-0.039	29.0
37	9894	9905	108.398	48.311	48.364	-0.054	29.1
34	9928	9939	99.609	48.477	48.530	-0.054	29.2
34	9962	9973	99.609	48.643	48.696	-0.054	29.3
31	9996	10004	90.820	48.809	48.848	-0.039	29.4
28	10030	10032	82.031	48.975	48.984	-0.010	29.5
29	10064	10061	84.961	49.141	49.126	0.015	29.6

29	10098	10090	84.961	49.307	49.268	0.039	29.7
31	10132	10121	90.820	49.473	49.419	0.054	29.8
32	10166	10153	93.750	49.639	49.575	0.063	29.9
36	10200	10189	105.469	49.805	49.751	0.054	30.0
37	10234	10226	108.398	49.971	49.932	0.039	30.1
37	10268	10263	108.398	50.137	50.112	0.024	30.2
38	10302	10301	111.328	50.303	50.298	0.005	30.3
39	10336	10340	114.258	50.469	50.488	-0.020	30.4
38	10370	10378	111.328	50.635	50.674	-0.039	30.5
36	10404	10414	105.469	50.801	50.850	-0.049	30.6
35	10438	10449	102.539	50.967	51.021	-0.054	30.7
33	10472	10482	96.680	51.133	51.182	-0.049	30.8
30	10506	10512	87.891	51.299	51.328	-0.029	30.9
29	10540	10541	84.961	51.465	51.470	-0.005	31.0
28	10574	10569	82.031	51.631	51.606	0.024	31.1
30	10608	10599	87.891	51.797	51.753	0.044	31.2
33	10642	10632	96.680	51.963	51.914	0.049	31.3
34	10676	10666	99.609	52.129	52.080	0.049	31.4
36	10710	10702	105.469	52.295	52.256	0.039	31.5
37	10744	10739	108.398	52.461	52.437	0.024	31.6
37	10778	10776	108.398	52.627	52.617	0.010	31.7
37	10812	10813	108.398	52.793	52.798	-0.005	31.8
38	10846	10851	111.328	52.959	52.983	-0.024	31.9
37	10880	10888	108.398	53.125	53.164	-0.039	32.0
36	10914	10924	105.469	53.291	53.340	-0.049	32.1
35	10948	10959	102.539	53.457	53.511	-0.054	32.2
33	10982	10992	96.680	53.623	53.672	-0.049	32.3
30	11016	11022	87.891	53.789	53.818	-0.029	32.4
28	11050	11050	82.031	53.955	53.955	0.000	32.5
29	11084	11079	84.961	54.121	54.097	0.024	32.6
29	11118	11108	84.961	54.287	54.238	0.049	32.7
32	11152	11140	93.750	54.453	54.395	0.059	32.8
34	11186	11174	99.609	54.619	54.561	0.059	32.9
36	11220	11210	105.469	54.785	54.736	0.049	33.0
38	11254	11248	111.328	54.951	54.922	0.029	33.1
37	11288	11285	108.398	55.117	55.103	0.015	33.2
38	11322	11323	111.328	55.283	55.288	-0.005	33.3
38	11356	11361	111.328	55.449	55.474	-0.024	33.4
36	11390	11397	105.469	55.615	55.649	-0.034	33.5
36	11424	11433	105.469	55.781	55.825	-0.044	33.6
35	11458	11468	102.539	55.947	55.996	-0.049	33.7
32	11492	11500	93.750	56.113	56.152	-0.039	33.8
30	11526	11530	87.891	56.279	56.299	-0.020	33.9
28	11560	11558	82.031	56.445	56.436	0.010	34.0
30	11594	11588	87.891	56.611	56.582	0.029	34.1
30	11628	11618	87.891	56.777	56.729	0.049	34.2
32	11662	11650	93.750	56.943	56.885	0.059	34.3
34	11696	11684	99.609	57.109	57.051	0.059	34.4
37	11730	11721	108.398	57.275	57.231	0.044	34.5
37	11764	11758	108.398	57.441	57.412	0.029	34.6
39	11798	11797	114.258	57.607	57.603	0.005	34.7
37	11832	11834	108.398	57.773	57.783	-0.010	34.8
37	11866	11871	108.398	57.939	57.964	-0.024	34.9

37	11900	11908	108.398	58.105	58.145	-0.039	35.0
35	11934	11943	102.539	58.271	58.315	-0.044	35.1
34	11968	11977	99.609	58.438	58.481	-0.044	35.2
32	12002	12009	93.750	58.604	58.638	-0.034	35.3
29	12036	12038	84.961	58.770	58.779	-0.010	35.4
29	12070	12067	84.961	58.936	58.921	0.015	35.5
30	12104	12097	87.891	59.102	59.067	0.034	35.6
31	12138	12128	90.820	59.268	59.219	0.049	35.7
32	12172	12160	93.750	59.434	59.375	0.059	35.8
35	12206	12195	102.539	59.600	59.546	0.054	35.9
37	12240	12232	108.398	59.766	59.727	0.039	36.0
38	12274	12270	111.328	59.932	59.912	0.020	36.1
38	12308	12308	111.328	60.098	60.098	0.000	36.2
39	12342	12347	114.258	60.264	60.288	-0.024	36.3
37	12376	12384	108.398	60.430	60.469	-0.039	36.4
36	12410	12420	105.469	60.596	60.645	-0.049	36.5
35	12444	12455	102.539	60.762	60.815	-0.054	36.6
34	12478	12489	99.609	60.928	60.981	-0.054	36.7
31	12512	12520	90.820	61.094	61.133	-0.039	36.8
28	12546	12548	82.031	61.260	61.270	-0.010	36.9
29	12580	12577	84.961	61.426	61.411	0.015	37.0
30	12614	12607	87.891	61.592	61.558	0.034	37.1
31	12648	12638	90.820	61.758	61.709	0.049	37.2
33	12682	12671	96.680	61.924	61.870	0.054	37.3
35	12716	12706	102.539	62.090	62.041	0.049	37.4
38	12750	12744	111.328	62.256	62.227	0.029	37.5
37	12784	12781	108.398	62.422	62.407	0.015	37.6
38	12818	12819	111.328	62.588	62.593	-0.005	37.7
38	12852	12857	111.328	62.754	62.778	-0.024	37.8
37	12886	12894	108.398	62.920	62.959	-0.039	37.9
36	12920	12930	105.469	63.086	63.135	-0.049	38.0
35	12954	12965	102.539	63.252	63.306	-0.054	38.1
33	12988	12998	96.680	63.418	63.467	-0.049	38.2
30	13022	13028	87.891	63.584	63.613	-0.029	38.3
29	13056	13057	84.961	63.750	63.755	-0.005	38.4
29	13090	13086	84.961	63.916	63.896	0.020	38.5
30	13124	13116	87.891	64.082	64.043	0.039	38.6
32	13158	13148	93.750	64.248	64.199	0.049	38.7
34	13192	13182	99.609	64.414	64.365	0.049	38.8
36	13226	13218	105.469	64.580	64.541	0.039	38.9
37	13260	13255	108.398	64.746	64.722	0.024	39.0
37	13294	13292	108.398	64.912	64.902	0.010	39.1
38	13328	13330	111.328	65.078	65.088	-0.010	39.2
38	13362	13368	111.328	65.244	65.273	-0.029	39.3
36	13396	13404	105.469	65.410	65.449	-0.039	39.4
36	13430	13440	105.469	65.576	65.625	-0.049	39.5
34	13464	13474	99.609	65.742	65.791	-0.049	39.6
32	13498	13506	93.750	65.908	65.947	-0.039	39.7
30	13532	13536	87.891	66.074	66.094	-0.020	39.8
29	13566	13565	84.961	66.240	66.235	0.005	39.9
29	13600	13594	84.961	66.406	66.377	0.029	40.0
30	13634	13624	87.891	66.572	66.523	0.049	40.1
32	13668	13656	93.750	66.738	66.680	0.059	40.2

35	13702	13691	102.539	66.904	66.851	0.054	40.3
37	13736	13728	108.398	67.070	67.031	0.039	40.4
38	13770	13766	111.328	67.236	67.217	0.020	40.5
37	13804	13803	108.398	67.402	67.397	0.005	40.6
38	13838	13841	111.328	67.568	67.583	-0.015	40.7
38	13872	13879	111.328	67.734	67.769	-0.034	40.8
37	13906	13916	108.398	67.900	67.949	-0.049	40.9
36	13940	13952	105.469	68.066	68.125	-0.059	41.0
33	13974	13985	96.680	68.232	68.286	-0.054	41.1
32	14008	14017	93.750	68.398	68.442	-0.044	41.2
29	14042	14046	84.961	68.564	68.584	-0.020	41.3
28	14076	14074	82.031	68.730	68.721	0.010	41.4
31	14110	14105	90.820	68.896	68.872	0.024	41.5
31	14144	14136	90.820	69.063	69.023	0.039	41.6
33	14178	14169	96.680	69.229	69.185	0.044	41.7
35	14212	14204	102.539	69.395	69.355	0.039	41.8
37	14246	14241	108.398	69.561	69.536	0.024	41.9
38	14280	14279	111.328	69.727	69.722	0.005	42.0
37	14314	14316	108.398	69.893	69.902	-0.010	42.1
37	14348	14353	108.398	70.059	70.083	-0.024	42.2
37	14382	14390	108.398	70.225	70.264	-0.039	42.3
35	14416	14425	102.539	70.391	70.435	-0.044	42.4
35	14450	14460	102.539	70.557	70.605	-0.049	42.5
33	14484	14493	96.680	70.723	70.767	-0.044	42.6
30	14518	14523	87.891	70.889	70.913	-0.024	42.7
29	14552	14552	84.961	71.055	71.055	0.000	42.8
29	14586	14581	84.961	71.221	71.196	0.024	42.9
30	14620	14611	87.891	71.387	71.343	0.044	43.0
31	14654	14642	90.820	71.553	71.494	0.059	43.1
34	14688	14676	99.609	71.719	71.660	0.059	43.2
36	14722	14712	105.469	71.885	71.836	0.049	43.3
37	14756	14749	108.398	72.051	72.017	0.034	43.4
38	14790	14787	111.328	72.217	72.202	0.015	43.5
38	14824	14825	111.328	72.383	72.388	-0.005	43.6
38	14858	14863	111.328	72.549	72.573	-0.024	43.7
37	14892	14900	108.398	72.715	72.754	-0.039	43.8
36	14926	14936	105.469	72.881	72.930	-0.049	43.9
37	14960	14973	108.398	73.047	73.110	-0.063	44.0
32	14994	15005	93.750	73.213	73.267	-0.054	44.1
29	15028	15034	84.961	73.379	73.408	-0.029	44.2
29	15062	15063	84.961	73.545	73.550	-0.005	44.3
28	15096	15091	82.031	73.711	73.687	0.024	44.4
30	15130	15121	87.891	73.877	73.833	0.044	44.5
32	15164	15153	93.750	74.043	73.989	0.054	44.6
34	15198	15187	99.609	74.209	74.155	0.054	44.7
37	15232	15224	108.398	74.375	74.336	0.039	44.8
38	15266	15262	111.328	74.541	74.521	0.020	44.9
37	15300	15299	108.398	74.707	74.702	0.005	45.0
38	15334	15337	111.328	74.873	74.888	-0.015	45.1
37	15368	15374	108.398	75.039	75.068	-0.029	45.2
37	15402	15411	108.398	75.205	75.249	-0.044	45.3
36	15436	15447	105.469	75.371	75.425	-0.054	45.4
34	15470	15481	99.609	75.537	75.591	-0.054	45.5

31	15504	15512	90.820	75.703	75.742	-0.039	45.6
30	15538	15542	87.891	75.869	75.889	-0.020	45.7
28	15572	15570	82.031	76.035	76.025	0.010	45.8
29	15606	15599	84.961	76.201	76.167	0.034	45.9
31	15640	15630	90.820	76.367	76.318	0.049	46.0
32	15674	15662	93.750	76.533	76.475	0.059	46.1
36	15708	15698	105.469	76.699	76.650	0.049	46.2
37	15742	15735	108.398	76.865	76.831	0.034	46.3
38	15776	15773	111.328	77.031	77.017	0.015	46.4
38	15810	15811	111.328	77.197	77.202	-0.005	46.5
39	15844	15850	114.258	77.363	77.393	-0.029	46.6
37	15878	15887	108.398	77.529	77.573	-0.044	46.7
37	15912	15924	108.398	77.695	77.754	-0.059	46.8
35	15946	15959	102.539	77.861	77.925	-0.063	46.9
33	15980	15992	96.680	78.027	78.086	-0.059	47.0
30	16014	16022	87.891	78.193	78.232	-0.039	47.1
29	16048	16051	84.961	78.359	78.374	-0.015	47.2
28	16082	16079	82.031	78.525	78.511	0.015	47.3
29	16116	16108	84.961	78.691	78.652	0.039	47.4
32	16150	16140	93.750	78.857	78.809	0.049	47.5
33	16184	16173	96.680	79.023	78.970	0.054	47.6
35	16218	16208	102.539	79.189	79.141	0.049	47.7
38	16252	16246	111.328	79.355	79.326	0.029	47.8
38	16286	16284	111.328	79.521	79.512	0.010	47.9
37	16320	16321	108.398	79.688	79.692	-0.005	48.0
38	16354	16359	111.328	79.854	79.878	-0.024	48.1
37	16388	16396	108.398	80.020	80.059	-0.039	48.2
36	16422	16432	105.469	80.186	80.234	-0.049	48.3
35	16456	16467	102.539	80.352	80.405	-0.054	48.4
33	16490	16500	96.680	80.518	80.566	-0.049	48.5
30	16524	16530	87.891	80.684	80.713	-0.029	48.6
29	16558	16559	84.961	80.850	80.854	-0.005	48.7
28	16592	16587	82.031	81.016	80.991	0.024	48.8
30	16626	16617	87.891	81.182	81.138	0.044	48.9
31	16660	16648	90.820	81.348	81.289	0.059	49.0
34	16694	16682	99.609	81.514	81.455	0.059	49.1
36	16728	16718	105.469	81.680	81.631	0.049	49.2
37	16762	16755	108.398	81.846	81.812	0.034	49.3
38	16796	16793	111.328	82.012	81.997	0.015	49.4
38	16830	16831	111.328	82.178	82.183	-0.005	49.5
38	16864	16869	111.328	82.344	82.368	-0.024	49.6
37	16898	16906	108.398	82.510	82.549	-0.039	49.7
36	16932	16942	105.469	82.676	82.725	-0.049	49.8
35	16966	16977	102.539	82.842	82.896	-0.054	49.9
32	17000	17009	93.750	83.008	83.052	-0.044	50.0
30	17034	17039	87.891	83.174	83.198	-0.024	50.1
28	17068	17067	82.031	83.340	83.335	0.005	50.2
29	17102	17096	84.961	83.506	83.477	0.029	50.3
31	17136	17127	90.820	83.672	83.628	0.044	50.4
32	17170	17159	93.750	83.838	83.784	0.054	50.5
35	17204	17194	102.539	84.004	83.955	0.049	50.6
37	17238	17231	108.398	84.170	84.136	0.034	50.7
38	17272	17269	111.328	84.336	84.321	0.015	50.8

38	17306	17307	111.328	84.502	84.507	-0.005	50.9
38	17340	17345	111.328	84.668	84.692	-0.024	51.0
37	17374	17382	108.398	84.834	84.873	-0.039	51.1
37	17408	17419	108.398	85.000	85.054	-0.054	51.2
35	17442	17454	102.539	85.166	85.225	-0.059	51.3
34	17476	17488	99.609	85.332	85.391	-0.059	51.4
31	17510	17519	90.820	85.498	85.542	-0.044	51.5
28	17544	17547	82.031	85.664	85.679	-0.015	51.6
27	17578	17574	79.102	85.830	85.811	0.020	51.7
29	17612	17603	84.961	85.996	85.952	0.044	51.8
30	17646	17633	87.891	86.162	86.099	0.063	51.9
33	17680	17666	96.680	86.328	86.260	0.068	52.0
35	17714	17701	102.539	86.494	86.431	0.063	52.1
38	17748	17739	111.328	86.660	86.616	0.044	52.2
38	17782	17777	111.328	86.826	86.802	0.024	52.3
38	17816	17815	111.328	86.992	86.987	0.005	52.4
38	17850	17853	111.328	87.158	87.173	-0.015	52.5
38	17884	17891	111.328	87.324	87.358	-0.034	52.6
36	17918	17927	105.469	87.490	87.534	-0.044	52.7
36	17952	17963	105.469	87.656	87.710	-0.054	52.8
33	17986	17996	96.680	87.822	87.871	-0.049	52.9
31	18020	18027	90.820	87.988	88.022	-0.034	53.0
29	18054	18056	84.961	88.154	88.164	-0.010	53.1
28	18088	18084	82.031	88.320	88.301	0.020	53.2
29	18122	18113	84.961	88.486	88.442	0.044	53.3
31	18156	18144	90.820	88.652	88.594	0.059	53.4
34	18190	18178	99.609	88.818	88.760	0.059	53.5
36	18224	18214	105.469	88.984	88.936	0.049	53.6
37	18258	18251	108.398	89.150	89.116	0.034	53.7
38	18292	18289	111.328	89.316	89.302	0.015	53.8
38	18326	18327	111.328	89.482	89.487	-0.005	53.9
38	18360	18365	111.328	89.648	89.673	-0.024	54.0
37	18394	18402	108.398	89.814	89.854	-0.039	54.1
36	18428	18438	105.469	89.980	90.029	-0.049	54.2
36	18462	18474	105.469	90.146	90.205	-0.059	54.3
32	18496	18506	93.750	90.313	90.361	-0.049	54.4
29	18530	18535	84.961	90.479	90.503	-0.024	54.5
28	18564	18563	82.031	90.645	90.640	0.005	54.6
29	18598	18592	84.961	90.811	90.781	0.029	54.7
30	18632	18622	87.891	90.977	90.928	0.049	54.8
33	18666	18655	96.680	91.143	91.089	0.054	54.9
34	18700	18689	99.609	91.309	91.255	0.054	55.0
37	18734	18726	108.398	91.475	91.436	0.039	55.1
38	18768	18764	111.328	91.641	91.621	0.020	55.2
37	18802	18801	108.398	91.807	91.802	0.005	55.3
38	18836	18839	111.328	91.973	91.987	-0.015	55.4
38	18870	18877	111.328	92.139	92.173	-0.034	55.5
37	18904	18914	108.398	92.305	92.354	-0.049	55.6
36	18938	18950	105.469	92.471	92.529	-0.059	55.7
34	18972	18984	99.609	92.637	92.695	-0.059	55.8
31	19006	19015	90.820	92.803	92.847	-0.044	55.9
28	19040	19043	82.031	92.969	92.983	-0.015	56.0
27	19074	19070	79.102	93.135	93.115	0.020	56.1

29	19108	19099	84.961	93.301	93.257	0.044	56.2
30	19142	19129	87.891	93.467	93.403	0.063	56.3
33	19176	19162	96.680	93.633	93.564	0.068	56.4
35	19210	19197	102.539	93.799	93.735	0.063	56.5
38	19244	19235	111.328	93.965	93.921	0.044	56.6
38	19278	19273	111.328	94.131	94.106	0.024	56.7
38	19312	19311	111.328	94.297	94.292	0.005	56.8
38	19346	19349	111.328	94.463	94.478	-0.015	56.9
37	19380	19386	108.398	94.629	94.658	-0.029	57.0
37	19414	19423	108.398	94.795	94.839	-0.044	57.1
35	19448	19458	102.539	94.961	95.010	-0.049	57.2
34	19482	19492	99.609	95.127	95.176	-0.049	57.3
31	19516	19523	90.820	95.293	95.327	-0.034	57.4
28	19550	19551	82.031	95.459	95.464	-0.005	57.5
28	19584	19579	82.031	95.625	95.601	0.024	57.6
30	19618	19609	87.891	95.791	95.747	0.044	57.7
31	19652	19640	90.820	95.957	95.898	0.059	57.8
33	19686	19673	96.680	96.123	96.060	0.063	57.9
36	19720	19709	105.469	96.289	96.235	0.054	58.0
37	19754	19746	108.398	96.455	96.416	0.039	58.1
38	19788	19784	111.328	96.621	96.602	0.020	58.2
38	19822	19822	111.328	96.787	96.787	0.000	58.3
39	19856	19861	114.258	96.953	96.978	-0.024	58.4
37	19890	19898	108.398	97.119	97.158	-0.039	58.5
37	19924	19935	108.398	97.285	97.339	-0.054	58.6
35	19958	19970	102.539	97.451	97.510	-0.059	58.7
33	19992	20003	96.680	97.617	97.671	-0.054	58.8
30	20026	20033	87.891	97.783	97.817	-0.034	58.9
28	20060	20061	82.031	97.949	97.954	-0.005	59.0
29	20094	20090	84.961	98.115	98.096	0.020	59.1
30	20128	20120	87.891	98.281	98.242	0.039	59.2
31	20162	20151	90.820	98.447	98.394	0.054	59.3
35	20196	20186	102.539	98.613	98.564	0.049	59.4
36	20230	20222	105.469	98.779	98.740	0.039	59.5
38	20264	20260	111.328	98.945	98.926	0.020	59.6
37	20298	20297	108.398	99.111	99.106	0.005	59.7
39	20332	20336	114.258	99.277	99.297	-0.020	59.8
36	20340	20372	105.469	99.316	99.473	-0.156	59.9
33	20348	20405	96.680	99.355	99.634	-0.278	60.0
24	20356	20429	70.313	99.395	99.751	-0.356	60.1
17	20364	20446	49.805	99.434	99.834	-0.400	60.2
11	20372	20457	32.227	99.473	99.888	-0.415	60.3
5	20380	20462	14.648	99.512	99.912	-0.400	60.4
0	20388	20462	0.000	99.551	99.912	-0.361	60.5
0	20396	20462	0.000	99.590	99.912	-0.322	60.6
1	20404	20463	2.930	99.629	99.917	-0.288	60.7
0	20412	20463	0.000	99.668	99.917	-0.249	60.8
0	20420	20463	0.000	99.707	99.917	-0.210	60.9
1	20428	20464	2.930	99.746	99.922	-0.176	61.0
1	20436	20465	2.930	99.785	99.927	-0.142	61.1
1	20444	20466	2.930	99.824	99.932	-0.107	61.2
1	20452	20467	2.930	99.863	99.937	-0.073	61.3
3	20460	20470	8.789	99.902	99.951	-0.049	61.4

2	20468	20472	5.859	99.941	99.961	-0.020	61.5
4	20476	20476	11.719	99.980	99.980	0.000	61.6
4	20480	20480	11.719	100.000	100.000	0.000	61.7
3	20480	20483	8.789	100.000	100.015	-0.015	61.8
0	20480	20483	0.000	100.000	100.015	-0.015	61.9

Performance Test on Rotary Table Module (Figures 9.4-6)

Interpolation performed on the rotary table module for a 360° rotation at a speed of 0.75 rev/min. The following data was used in the preparation of Figures 9.4-6.

Table F.6.2: Test Data, Performance Test on Rotary Table Module

Speed (pulses/s)	Ref Position (pulses)	Measured Position (pulses)	Speed (rev/min)	Ref Position (deg)	Measured Position (deg)	Error (deg)	Time (s)
0	0	0	0.000	0.000	0.000	0.000	0.0
3	34	3	0.063	0.427	0.038	0.389	0.1
14	68	17	0.293	0.854	0.213	0.640	0.2
27	102	44	0.565	1.281	0.552	0.728	0.3
35	136	79	0.732	1.708	0.992	0.716	0.4
39	170	118	0.816	2.134	1.482	0.653	0.5
42	204	160	0.879	2.561	2.009	0.552	0.6
41	238	201	0.858	2.988	2.524	0.465	0.7
41	272	242	0.858	3.415	3.039	0.377	0.8
41	306	283	0.858	3.842	3.553	0.289	0.9
39	340	322	0.816	4.269	4.043	0.226	1.0
39	374	361	0.816	4.696	4.533	0.163	1.1
35	408	396	0.732	5.123	4.972	0.151	1.2
35	442	431	0.732	5.550	5.412	0.138	1.3
32	476	463	0.670	5.977	5.813	0.163	1.4
31	510	494	0.649	6.403	6.203	0.201	1.5
31	544	525	0.649	6.830	6.592	0.239	1.6
33	578	558	0.691	7.257	7.006	0.251	1.7
33	612	591	0.691	7.684	7.420	0.264	1.8
34	646	625	0.711	8.111	7.847	0.264	1.9
36	680	661	0.753	8.538	8.299	0.239	2.0
35	714	696	0.732	8.965	8.739	0.226	2.1
36	748	732	0.753	9.392	9.191	0.201	2.2
36	782	768	0.753	9.819	9.643	0.176	2.3
37	816	805	0.774	10.246	10.107	0.138	2.4
37	850	842	0.774	10.672	10.572	0.100	2.5
36	884	878	0.753	11.099	11.024	0.075	2.6
34	918	912	0.711	11.526	11.451	0.075	2.7
34	952	946	0.711	11.953	11.878	0.075	2.8
32	986	978	0.670	12.380	12.280	0.100	2.9
33	1020	1011	0.691	12.807	12.694	0.113	3.0
32	1054	1043	0.670	13.234	13.096	0.138	3.1
33	1088	1076	0.691	13.661	13.510	0.151	3.2
34	1122	1110	0.711	14.088	13.937	0.151	3.3
34	1156	1144	0.711	14.515	14.364	0.151	3.4
35	1190	1179	0.732	14.941	14.803	0.138	3.5
35	1224	1214	0.732	15.368	15.243	0.126	3.6
35	1258	1249	0.732	15.795	15.682	0.113	3.7
37	1292	1286	0.774	16.222	16.147	0.075	3.8
36	1326	1322	0.753	16.649	16.599	0.050	3.9
36	1360	1358	0.753	17.076	17.051	0.025	4.0
35	1394	1393	0.732	17.503	17.490	0.013	4.1
33	1428	1426	0.691	17.930	17.905	0.025	4.2

33	1462	1459	0.691	18.357	18.319	0.038	4.3
32	1496	1491	0.670	18.783	18.721	0.063	4.4
33	1530	1524	0.691	19.210	19.135	0.075	4.5
33	1564	1557	0.691	19.637	19.549	0.088	4.6
32	1598	1589	0.670	20.064	19.951	0.113	4.7
35	1632	1624	0.732	20.491	20.391	0.100	4.8
34	1666	1658	0.711	20.918	20.818	0.100	4.9
35	1700	1693	0.732	21.345	21.257	0.088	5.0
35	1734	1728	0.732	21.772	21.696	0.075	5.1
37	1768	1765	0.774	22.199	22.161	0.038	5.2
36	1802	1801	0.753	22.626	22.613	0.013	5.3
37	1836	1838	0.774	23.052	23.078	-0.025	5.4
37	1870	1875	0.774	23.479	23.542	-0.063	5.5
34	1904	1909	0.711	23.906	23.969	-0.063	5.6
32	1938	1941	0.670	24.333	24.371	-0.038	5.7
30	1972	1971	0.628	24.760	24.747	0.013	5.8
31	2006	2002	0.649	25.187	25.137	0.050	5.9
31	2040	2033	0.649	25.614	25.526	0.088	6.0
33	2074	2066	0.691	26.041	25.940	0.100	6.1
33	2108	2099	0.691	26.468	26.355	0.113	6.2
35	2142	2134	0.732	26.895	26.794	0.100	6.3
35	2176	2169	0.732	27.321	27.234	0.088	6.4
36	2210	2205	0.753	27.748	27.686	0.063	6.5
36	2244	2241	0.753	28.175	28.138	0.038	6.6
36	2278	2277	0.753	28.602	28.590	0.013	6.7
36	2312	2313	0.753	29.029	29.042	-0.013	6.8
37	2346	2350	0.774	29.456	29.506	-0.050	6.9
35	2380	2385	0.732	29.883	29.946	-0.063	7.0
34	2414	2419	0.711	30.310	30.372	-0.063	7.1
32	2448	2451	0.670	30.737	30.774	-0.038	7.2
31	2482	2482	0.649	31.164	31.164	0.000	7.3
32	2516	2514	0.670	31.590	31.565	0.025	7.4
32	2550	2546	0.670	32.017	31.967	0.050	7.5
33	2584	2579	0.691	32.444	32.381	0.063	7.6
34	2618	2613	0.711	32.871	32.808	0.063	7.7
34	2652	2647	0.711	33.298	33.235	0.063	7.8
35	2686	2682	0.732	33.725	33.675	0.050	7.9
35	2720	2717	0.732	34.152	34.114	0.038	8.0
36	2754	2753	0.753	34.579	34.566	0.013	8.1
36	2788	2789	0.753	35.006	35.018	-0.013	8.2
35	2822	2824	0.732	35.432	35.458	-0.025	8.3
36	2856	2860	0.753	35.859	35.910	-0.050	8.4
34	2890	2894	0.711	36.286	36.336	-0.050	8.5
33	2924	2927	0.691	36.713	36.751	-0.038	8.6
33	2958	2960	0.691	37.140	37.165	-0.025	8.7
32	2992	2992	0.670	37.567	37.567	0.000	8.8
33	3026	3025	0.691	37.994	37.981	0.013	8.9
32	3060	3057	0.670	38.421	38.383	0.038	9.0
33	3094	3090	0.691	38.848	38.797	0.050	9.1
34	3128	3124	0.711	39.275	39.224	0.050	9.2
34	3162	3158	0.711	39.701	39.651	0.050	9.3
35	3196	3193	0.732	40.128	40.091	0.038	9.4
35	3230	3228	0.732	40.555	40.530	0.025	9.5

35	3264	3263	0.732	40.982	40.970	0.013	9.6
36	3298	3299	0.753	41.409	41.422	-0.013	9.7
36	3332	3335	0.753	41.836	41.874	-0.038	9.8
35	3366	3370	0.732	42.263	42.313	-0.050	9.9
35	3400	3405	0.732	42.690	42.753	-0.063	10.0
33	3434	3438	0.691	43.117	43.167	-0.050	10.1
32	3468	3470	0.670	43.544	43.569	-0.025	10.2
32	3502	3502	0.670	43.970	43.970	0.000	10.3
32	3536	3534	0.670	44.397	44.372	0.025	10.4
32	3570	3566	0.670	44.824	44.774	0.050	10.5
34	3604	3600	0.711	45.251	45.201	0.050	10.6
34	3638	3634	0.711	45.678	45.628	0.050	10.7
35	3672	3669	0.732	46.105	46.067	0.038	10.8
34	3706	3703	0.711	46.532	46.494	0.038	10.9
35	3740	3738	0.732	46.959	46.934	0.025	11.0
36	3774	3774	0.753	47.386	47.386	0.000	11.1
35	3808	3809	0.732	47.813	47.825	-0.013	11.2
36	3842	3845	0.753	48.239	48.277	-0.038	11.3
36	3876	3881	0.753	48.666	48.729	-0.063	11.4
34	3910	3915	0.711	49.093	49.156	-0.063	11.5
33	3944	3948	0.691	49.520	49.570	-0.050	11.6
32	3978	3980	0.670	49.947	49.972	-0.025	11.7
32	4012	4012	0.670	50.374	50.374	0.000	11.8
32	4046	4044	0.670	50.801	50.776	0.025	11.9
32	4080	4076	0.670	51.228	51.177	0.050	12.0
34	4114	4110	0.711	51.655	51.604	0.050	12.1
34	4148	4144	0.711	52.081	52.031	0.050	12.2
35	4182	4179	0.732	52.508	52.471	0.038	12.3
35	4216	4214	0.732	52.935	52.910	0.025	12.4
35	4250	4249	0.732	53.362	53.350	0.013	12.5
36	4284	4285	0.753	53.789	53.802	-0.013	12.6
36	4318	4321	0.753	54.216	54.254	-0.038	12.7
36	4352	4357	0.753	54.643	54.706	-0.063	12.8
34	4386	4391	0.711	55.070	55.133	-0.063	12.9
34	4420	4425	0.711	55.497	55.559	-0.063	13.0
33	4454	4458	0.691	55.924	55.974	-0.050	13.1
31	4488	4489	0.649	56.350	56.363	-0.013	13.2
32	4522	4521	0.670	56.777	56.765	0.013	13.3
33	4556	4554	0.691	57.204	57.179	0.025	13.4
32	4590	4586	0.670	57.631	57.581	0.050	13.5
33	4624	4619	0.691	58.058	57.995	0.063	13.6
35	4658	4654	0.732	58.485	58.435	0.050	13.7
35	4692	4689	0.732	58.912	58.874	0.038	13.8
35	4726	4724	0.732	59.339	59.314	0.025	13.9
35	4760	4759	0.732	59.766	59.753	0.013	14.0
36	4794	4795	0.753	60.193	60.205	-0.013	14.1
36	4828	4831	0.753	60.619	60.657	-0.038	14.2
36	4862	4867	0.753	61.046	61.109	-0.063	14.3
34	4896	4901	0.711	61.473	61.536	-0.063	14.4
33	4930	4934	0.691	61.900	61.950	-0.050	14.5
33	4964	4967	0.691	62.327	62.365	-0.038	14.6
32	4998	4999	0.670	62.754	62.766	-0.013	14.7
32	5032	5031	0.670	63.181	63.168	0.013	14.8

32	5066	5063	0.670	63.608	63.570	0.038	14.9
33	5100	5096	0.691	64.035	63.984	0.050	15.0
34	5134	5130	0.711	64.461	64.411	0.050	15.1
35	5168	5165	0.732	64.888	64.851	0.038	15.2
34	5202	5199	0.711	65.315	65.278	0.038	15.3
35	5236	5234	0.732	65.742	65.717	0.025	15.4
35	5270	5269	0.732	66.169	66.157	0.013	15.5
36	5304	5305	0.753	66.596	66.609	-0.013	15.6
36	5338	5341	0.753	67.023	67.061	-0.038	15.7
36	5372	5377	0.753	67.450	67.513	-0.063	15.8
35	5406	5412	0.732	67.877	67.952	-0.075	15.9
33	5440	5445	0.691	68.304	68.366	-0.063	16.0
32	5474	5477	0.670	68.730	68.768	-0.038	16.1
32	5508	5509	0.670	69.157	69.170	-0.013	16.2
32	5542	5541	0.670	69.584	69.572	0.013	16.3
32	5576	5573	0.670	70.011	69.973	0.038	16.4
33	5610	5606	0.691	70.438	70.388	0.050	16.5
34	5644	5640	0.711	70.865	70.815	0.050	16.6
35	5678	5675	0.732	71.292	71.254	0.038	16.7
34	5712	5709	0.711	71.719	71.681	0.038	16.8
35	5746	5744	0.732	72.146	72.121	0.025	16.9
37	5780	5781	0.774	72.573	72.585	-0.013	17.0
36	5814	5817	0.753	72.999	73.037	-0.038	17.1
35	5848	5852	0.732	73.426	73.477	-0.050	17.2
35	5882	5887	0.732	73.853	73.916	-0.063	17.3
34	5916	5921	0.711	74.280	74.343	-0.063	17.4
33	5950	5954	0.691	74.707	74.757	-0.050	17.5
33	5984	5987	0.691	75.134	75.172	-0.038	17.6
32	6018	6019	0.670	75.561	75.573	-0.013	17.7
32	6052	6051	0.670	75.988	75.975	0.013	17.8
32	6086	6083	0.670	76.415	76.377	0.038	17.9
33	6120	6116	0.691	76.842	76.791	0.050	18.0
35	6154	6151	0.732	77.268	77.231	0.038	18.1
35	6188	6186	0.732	77.695	77.670	0.025	18.2
34	6222	6220	0.711	78.122	78.097	0.025	18.3
34	6256	6254	0.711	78.549	78.524	0.025	18.4
36	6290	6290	0.753	78.976	78.976	0.000	18.5
36	6324	6326	0.753	79.403	79.428	-0.025	18.6
36	6358	6362	0.753	79.830	79.880	-0.050	18.7
34	6392	6396	0.711	80.257	80.307	-0.050	18.8
35	6426	6431	0.732	80.684	80.746	-0.063	18.9
33	6460	6464	0.691	81.110	81.161	-0.050	19.0
32	6494	6496	0.670	81.537	81.563	-0.025	19.1
32	6528	6528	0.670	81.964	81.964	0.000	19.2
32	6562	6560	0.670	82.391	82.366	0.025	19.3
32	6596	6592	0.670	82.818	82.768	0.050	19.4
34	6630	6626	0.711	83.245	83.195	0.050	19.5
35	6664	6661	0.732	83.672	83.634	0.038	19.6
34	6698	6695	0.711	84.099	84.061	0.038	19.7
34	6732	6729	0.711	84.526	84.488	0.038	19.8
36	6766	6765	0.753	84.953	84.940	0.013	19.9
36	6800	6801	0.753	85.379	85.392	-0.013	20.0
36	6834	6837	0.753	85.806	85.844	-0.038	20.1

36	6868	6873	0.753	86.233	86.296	-0.063	20.2
34	6902	6907	0.711	86.660	86.723	-0.063	20.3
33	6936	6940	0.691	87.087	87.137	-0.050	20.4
33	6970	6973	0.691	87.514	87.552	-0.038	20.5
32	7004	7005	0.670	87.941	87.953	-0.013	20.6
32	7038	7037	0.670	88.368	88.355	0.013	20.7
32	7072	7069	0.670	88.795	88.757	0.038	20.8
33	7106	7102	0.691	89.222	89.171	0.050	20.9
34	7140	7136	0.711	89.648	89.598	0.050	21.0
34	7174	7170	0.711	90.075	90.025	0.050	21.1
35	7208	7205	0.732	90.502	90.465	0.038	21.2
34	7242	7239	0.711	90.929	90.891	0.038	21.3
36	7276	7275	0.753	91.356	91.343	0.013	21.4
36	7310	7311	0.753	91.783	91.795	-0.013	21.5
37	7344	7348	0.774	92.210	92.260	-0.050	21.6
35	7378	7383	0.732	92.637	92.699	-0.063	21.7
34	7412	7417	0.711	93.064	93.126	-0.063	21.8
34	7446	7451	0.711	93.491	93.553	-0.063	21.9
32	7480	7483	0.670	93.917	93.955	-0.038	22.0
32	7514	7515	0.670	94.344	94.357	-0.013	22.1
32	7548	7547	0.670	94.771	94.759	0.013	22.2
31	7582	7578	0.649	95.198	95.148	0.050	22.3
33	7616	7611	0.691	95.625	95.562	0.063	22.4
34	7650	7645	0.711	96.052	95.989	0.063	22.5
35	7684	7680	0.732	96.479	96.429	0.050	22.6
35	7718	7715	0.732	96.906	96.868	0.038	22.7
35	7752	7750	0.732	97.333	97.307	0.025	22.8
35	7786	7785	0.732	97.759	97.747	0.013	22.9
36	7820	7821	0.753	98.186	98.199	-0.013	23.0
36	7854	7857	0.753	98.613	98.651	-0.038	23.1
36	7888	7893	0.753	99.040	99.103	-0.063	23.2
34	7922	7927	0.711	99.467	99.530	-0.063	23.3
33	7956	7960	0.691	99.894	99.944	-0.050	23.4
32	7990	7992	0.670	100.321	100.346	-0.025	23.5
32	8024	8024	0.670	100.748	100.748	0.000	23.6
32	8058	8056	0.670	101.175	101.150	0.025	23.7
32	8092	8088	0.670	101.602	101.551	0.050	23.8
33	8126	8121	0.691	102.028	101.966	0.063	23.9
34	8160	8155	0.711	102.455	102.393	0.063	24.0
36	8194	8191	0.753	102.882	102.845	0.038	24.1
35	8228	8226	0.732	103.309	103.284	0.025	24.2
35	8262	8261	0.732	103.736	103.723	0.013	24.3
36	8296	8297	0.753	104.163	104.176	-0.013	24.4
36	8330	8333	0.753	104.590	104.628	-0.038	24.5
36	8364	8369	0.753	105.017	105.080	-0.063	24.6
35	8398	8404	0.732	105.444	105.519	-0.075	24.7
33	8432	8437	0.691	105.871	105.933	-0.063	24.8
32	8466	8469	0.670	106.297	106.335	-0.038	24.9
32	8500	8501	0.670	106.724	106.737	-0.013	25.0
31	8534	8532	0.649	107.151	107.126	0.025	25.1
33	8568	8565	0.691	107.578	107.540	0.038	25.2
32	8602	8597	0.670	108.005	107.942	0.063	25.3
34	8636	8631	0.711	108.432	108.369	0.063	25.4

35	8670	8666	0.732	108.859	108.809	0.050	25.5
34	8704	8700	0.711	109.286	109.235	0.050	25.6
35	8738	8735	0.732	109.713	109.675	0.038	25.7
37	8772	8772	0.774	110.140	110.140	0.000	25.8
36	8806	8808	0.753	110.566	110.592	-0.025	25.9
36	8840	8844	0.753	110.993	111.044	-0.050	26.0
35	8874	8879	0.732	111.420	111.483	-0.063	26.1
34	8908	8913	0.711	111.847	111.910	-0.063	26.2
34	8942	8947	0.711	112.274	112.337	-0.063	26.3
33	8976	8980	0.691	112.701	112.751	-0.050	26.4
31	9010	9011	0.649	113.128	113.140	-0.013	26.5
31	9044	9042	0.649	113.555	113.530	0.025	26.6
32	9078	9074	0.670	113.982	113.931	0.050	26.7
33	9112	9107	0.691	114.408	114.346	0.063	26.8
34	9146	9141	0.711	114.835	114.773	0.063	26.9
34	9180	9175	0.711	115.262	115.199	0.063	27.0
35	9214	9210	0.732	115.689	115.639	0.050	27.1
35	9248	9245	0.732	116.116	116.078	0.038	27.2
36	9282	9281	0.753	116.543	116.530	0.013	27.3
36	9316	9317	0.753	116.970	116.982	-0.013	27.4
36	9350	9353	0.753	117.397	117.434	-0.038	27.5
35	9384	9388	0.732	117.824	117.874	-0.050	27.6
34	9418	9422	0.711	118.251	118.301	-0.050	27.7
34	9452	9456	0.711	118.677	118.728	-0.050	27.8
32	9486	9488	0.670	119.104	119.129	-0.025	27.9
33	9520	9521	0.691	119.531	119.544	-0.013	28.0
32	9554	9553	0.670	119.958	119.946	0.013	28.1
32	9588	9585	0.670	120.385	120.347	0.038	28.2
34	9622	9619	0.711	120.812	120.774	0.038	28.3
33	9656	9652	0.691	121.239	121.189	0.050	28.4
34	9690	9686	0.711	121.666	121.616	0.050	28.5
35	9724	9721	0.732	122.093	122.055	0.038	28.6
34	9758	9755	0.711	122.520	122.482	0.038	28.7
36	9792	9791	0.753	122.946	122.934	0.013	28.8
36	9826	9827	0.753	123.373	123.386	-0.013	28.9
38	9860	9865	0.795	123.800	123.863	-0.063	29.0
39	9894	9904	0.816	124.227	124.353	-0.126	29.1
32	9928	9936	0.670	124.654	124.754	-0.100	29.2
31	9962	9967	0.649	125.081	125.144	-0.063	29.3
30	9996	9997	0.628	125.508	125.520	-0.013	29.4
30	10030	10027	0.628	125.935	125.897	0.038	29.5
31	10064	10058	0.649	126.362	126.286	0.075	29.6
33	10098	10091	0.691	126.789	126.701	0.088	29.7
34	10132	10125	0.711	127.215	127.128	0.088	29.8
35	10166	10160	0.732	127.642	127.567	0.075	29.9
35	10200	10195	0.732	128.069	128.006	0.063	30.0
35	10234	10230	0.732	128.496	128.446	0.050	30.1
36	10268	10266	0.753	128.923	128.898	0.025	30.2
36	10302	10302	0.753	129.350	129.350	0.000	30.3
36	10336	10338	0.753	129.777	129.802	-0.025	30.4
36	10370	10374	0.753	130.204	130.254	-0.050	30.5
34	10404	10408	0.711	130.631	130.681	-0.050	30.6
35	10438	10443	0.732	131.057	131.120	-0.063	30.7

32	10472	10475	0.670	131.484	131.522	-0.038	30.8
32	10506	10507	0.670	131.911	131.924	-0.013	30.9
32	10540	10539	0.670	132.338	132.326	0.013	31.0
32	10574	10571	0.670	132.765	132.727	0.038	31.1
32	10608	10603	0.670	133.192	133.129	0.063	31.2
33	10642	10636	0.691	133.619	133.544	0.075	31.3
34	10676	10670	0.711	134.046	133.970	0.075	31.4
35	10710	10705	0.732	134.473	134.410	0.063	31.5
36	10744	10741	0.753	134.900	134.862	0.038	31.6
35	10778	10776	0.732	135.326	135.301	0.025	31.7
36	10812	10812	0.753	135.753	135.753	0.000	31.8
36	10846	10848	0.753	136.180	136.205	-0.025	31.9
36	10880	10884	0.753	136.607	136.657	-0.050	32.0
36	10914	10920	0.753	137.034	137.109	-0.075	32.1
33	10948	10953	0.691	137.461	137.524	-0.063	32.2
32	10982	10985	0.670	137.888	137.926	-0.038	32.3
32	11016	11017	0.670	138.315	138.327	-0.013	32.4
32	11050	11049	0.670	138.742	138.729	0.013	32.5
32	11084	11081	0.670	139.169	139.131	0.038	32.6
32	11118	11113	0.670	139.595	139.533	0.063	32.7
33	11152	11146	0.691	140.022	139.947	0.075	32.8
35	11186	11181	0.732	140.449	140.386	0.063	32.9
34	11220	11215	0.711	140.876	140.813	0.063	33.0
36	11254	11251	0.753	141.303	141.265	0.038	33.1
36	11288	11287	0.753	141.730	141.717	0.013	33.2
37	11322	11324	0.774	142.157	142.182	-0.025	33.3
36	11356	11360	0.753	142.584	142.634	-0.050	33.4
35	11390	11395	0.732	143.011	143.073	-0.063	33.5
33	11424	11428	0.691	143.438	143.488	-0.050	33.6
34	11458	11462	0.711	143.864	143.915	-0.050	33.7
32	11492	11494	0.670	144.291	144.316	-0.025	33.8
32	11526	11526	0.670	144.718	144.718	0.000	33.9
33	11560	11559	0.691	145.145	145.133	0.013	34.0
32	11594	11591	0.670	145.572	145.534	0.038	34.1
33	11628	11624	0.691	145.999	145.949	0.050	34.2
33	11662	11657	0.691	146.426	146.363	0.063	34.3
35	11696	11692	0.732	146.853	146.802	0.050	34.4
34	11730	11726	0.711	147.280	147.229	0.050	34.5
35	11764	11761	0.732	147.706	147.669	0.038	34.6
37	11798	11798	0.774	148.133	148.133	0.000	34.7
35	11832	11833	0.732	148.560	148.573	-0.013	34.8
36	11866	11869	0.753	148.987	149.025	-0.038	34.9
35	11900	11904	0.732	149.414	149.464	-0.050	35.0
34	11934	11938	0.711	149.841	149.891	-0.050	35.1
33	11968	11971	0.691	150.268	150.306	-0.038	35.2
32	12002	12003	0.670	150.695	150.707	-0.013	35.3
35	12036	12038	0.732	151.122	151.147	-0.025	35.4
31	12070	12069	0.649	151.549	151.536	0.013	35.5
31	12104	12100	0.649	151.975	151.925	0.050	35.6
33	12138	12133	0.691	152.402	152.340	0.063	35.7
34	12172	12167	0.711	152.829	152.766	0.063	35.8
34	12206	12201	0.711	153.256	153.193	0.063	35.9
36	12240	12237	0.753	153.683	153.645	0.038	36.0

36	12274	12273	0.753	154.110	154.097	0.013	36.1
36	12308	12309	0.753	154.537	154.549	-0.013	36.2
36	12342	12345	0.753	154.964	155.001	-0.038	36.3
35	12376	12380	0.732	155.391	155.441	-0.050	36.4
35	12410	12415	0.732	155.818	155.880	-0.063	36.5
33	12444	12448	0.691	156.244	156.295	-0.050	36.6
33	12478	12481	0.691	156.671	156.709	-0.038	36.7
32	12512	12513	0.670	157.098	157.111	-0.013	36.8
31	12546	12544	0.649	157.525	157.500	0.025	36.9
32	12580	12576	0.670	157.952	157.902	0.050	37.0
33	12614	12609	0.691	158.379	158.316	0.063	37.1
33	12648	12642	0.691	158.806	158.730	0.075	37.2
34	12682	12676	0.711	159.233	159.157	0.075	37.3
35	12716	12711	0.732	159.660	159.597	0.063	37.4
36	12750	12747	0.753	160.086	160.049	0.038	37.5
35	12784	12782	0.732	160.513	160.488	0.025	37.6
37	12818	12819	0.774	160.940	160.953	-0.013	37.7
36	12852	12855	0.753	161.367	161.405	-0.038	37.8
35	12886	12890	0.732	161.794	161.844	-0.050	37.9
36	12920	12926	0.753	162.221	162.296	-0.075	38.0
33	12954	12959	0.691	162.648	162.711	-0.063	38.1
32	12988	12991	0.670	163.075	163.112	-0.038	38.2
32	13022	13023	0.670	163.502	163.514	-0.013	38.3
32	13056	13055	0.670	163.929	163.916	0.013	38.4
32	13090	13087	0.670	164.355	164.318	0.038	38.5
32	13124	13119	0.670	164.782	164.720	0.063	38.6
33	13158	13152	0.691	165.209	165.134	0.075	38.7
36	13192	13188	0.753	165.636	165.586	0.050	38.8
35	13226	13223	0.732	166.063	166.025	0.038	38.9
34	13260	13257	0.711	166.490	166.452	0.038	39.0
37	13294	13294	0.774	166.917	166.917	0.000	39.1
38	13328	13332	0.795	167.344	167.394	-0.050	39.2
35	13362	13367	0.732	167.771	167.833	-0.063	39.3
34	13396	13401	0.711	168.198	168.260	-0.063	39.4
35	13430	13436	0.732	168.624	168.700	-0.075	39.5
32	13464	13468	0.670	169.051	169.102	-0.050	39.6
32	13498	13500	0.670	169.478	169.503	-0.025	39.7
33	13532	13533	0.691	169.905	169.918	-0.013	39.8
32	13566	13565	0.670	170.332	170.319	0.013	39.9
32	13600	13597	0.670	170.759	170.721	0.038	40.0
32	13634	13629	0.670	171.186	171.123	0.063	40.1
33	13668	13662	0.691	171.613	171.537	0.075	40.2
35	13702	13697	0.732	172.040	171.977	0.063	40.3
35	13736	13732	0.732	172.467	172.416	0.050	40.4
36	13770	13768	0.753	172.893	172.868	0.025	40.5
37	13804	13805	0.774	173.320	173.333	-0.013	40.6
36	13838	13841	0.753	173.747	173.785	-0.038	40.7
36	13872	13877	0.753	174.174	174.237	-0.063	40.8
35	13906	13912	0.732	174.601	174.676	-0.075	40.9
33	13940	13945	0.691	175.028	175.091	-0.063	41.0
33	13974	13978	0.691	175.455	175.505	-0.050	41.1
33	14008	14011	0.691	175.882	175.919	-0.038	41.2
31	14042	14042	0.649	176.309	176.309	0.000	41.3

33	14076	14075	0.691	176.735	176.723	0.013	41.4
32	14110	14107	0.670	177.162	177.125	0.038	41.5
33	14144	14140	0.691	177.589	177.539	0.050	41.6
34	14178	14174	0.711	178.016	177.966	0.050	41.7
35	14212	14209	0.732	178.443	178.405	0.038	41.8
35	14246	14244	0.732	178.870	178.845	0.025	41.9
35	14280	14279	0.732	179.297	179.284	0.013	42.0
35	14314	14314	0.732	179.724	179.724	0.000	42.1
36	14348	14350	0.753	180.151	180.176	-0.025	42.2
37	14382	14387	0.774	180.578	180.640	-0.063	42.3
35	14416	14422	0.732	181.004	181.080	-0.075	42.4
34	14450	14456	0.711	181.431	181.507	-0.075	42.5
33	14484	14489	0.691	181.858	181.921	-0.063	42.6
33	14518	14522	0.691	182.285	182.335	-0.050	42.7
31	14552	14553	0.649	182.712	182.725	-0.013	42.8
32	14586	14585	0.670	183.139	183.126	0.013	42.9
32	14620	14617	0.670	183.566	183.528	0.038	43.0
34	14654	14651	0.711	183.993	183.955	0.038	43.1
34	14688	14685	0.711	184.420	184.382	0.038	43.2
35	14722	14720	0.732	184.847	184.821	0.025	43.3
34	14756	14754	0.711	185.273	185.248	0.025	43.4
35	14790	14789	0.732	185.700	185.688	0.013	43.5
37	14824	14826	0.774	186.127	186.152	-0.025	43.6
36	14858	14862	0.753	186.554	186.604	-0.050	43.7
36	14892	14898	0.753	186.981	187.056	-0.075	43.8
35	14926	14933	0.732	187.408	187.496	-0.088	43.9
33	14960	14966	0.691	187.835	187.910	-0.075	44.0
33	14994	14999	0.691	188.262	188.324	-0.063	44.1
32	15028	15031	0.670	188.689	188.726	-0.038	44.2
31	15062	15062	0.649	189.116	189.116	0.000	44.3
32	15096	15094	0.670	189.542	189.517	0.025	44.4
33	15130	15127	0.691	189.969	189.932	0.038	44.5
34	15164	15161	0.711	190.396	190.359	0.038	44.6
34	15198	15195	0.711	190.823	190.785	0.038	44.7
35	15232	15230	0.732	191.250	191.225	0.025	44.8
35	15266	15265	0.732	191.677	191.664	0.013	44.9
35	15300	15300	0.732	192.104	192.104	0.000	45.0
37	15334	15337	0.774	192.531	192.568	-0.038	45.1
38	15368	15375	0.795	192.958	193.045	-0.088	45.2
35	15402	15410	0.732	193.384	193.485	-0.100	45.3
34	15436	15444	0.711	193.811	193.912	-0.100	45.4
32	15470	15476	0.670	194.238	194.314	-0.075	45.5
32	15504	15508	0.670	194.665	194.715	-0.050	45.6
32	15538	15540	0.670	195.092	195.117	-0.025	45.7
32	15572	15572	0.670	195.519	195.519	0.000	45.8
33	15606	15605	0.691	195.946	195.933	0.013	45.9
32	15640	15637	0.670	196.373	196.335	0.038	46.0
34	15674	15671	0.711	196.800	196.762	0.038	46.1
35	15708	15706	0.732	197.227	197.201	0.025	46.2
34	15742	15740	0.711	197.653	197.628	0.025	46.3
35	15776	15775	0.732	198.080	198.068	0.013	46.4
35	15810	15810	0.732	198.507	198.507	0.000	46.5
36	15844	15846	0.753	198.934	198.959	-0.025	46.6

37	15878	15883	0.774	199.361	199.424	-0.063	46.7
36	15912	15919	0.753	199.788	199.876	-0.088	46.8
34	15946	15953	0.711	200.215	200.303	-0.088	46.9
34	15980	15987	0.711	200.642	200.730	-0.088	47.0
32	16014	16019	0.670	201.069	201.131	-0.063	47.1
31	16048	16050	0.649	201.496	201.521	-0.025	47.2
32	16082	16082	0.670	201.922	201.922	0.000	47.3
32	16116	16114	0.670	202.349	202.324	0.025	47.4
34	16150	16148	0.711	202.776	202.751	0.025	47.5
33	16184	16181	0.691	203.203	203.165	0.038	47.6
35	16218	16216	0.732	203.630	203.605	0.025	47.7
35	16252	16251	0.732	204.057	204.044	0.013	47.8
34	16286	16285	0.711	204.484	204.471	0.013	47.9
37	16320	16322	0.774	204.911	204.936	-0.025	48.0
36	16354	16358	0.753	205.338	205.388	-0.050	48.1
36	16388	16394	0.753	205.765	205.840	-0.075	48.2
35	16422	16429	0.732	206.191	206.279	-0.088	48.3
34	16456	16463	0.711	206.618	206.706	-0.088	48.4
32	16490	16495	0.670	207.045	207.108	-0.063	48.5
33	16524	16528	0.691	207.472	207.522	-0.050	48.6
32	16558	16560	0.670	207.899	207.924	-0.025	48.7
31	16592	16591	0.649	208.326	208.313	0.013	48.8
33	16626	16624	0.691	208.753	208.728	0.025	48.9
33	16660	16657	0.691	209.180	209.142	0.038	49.0
34	16694	16691	0.711	209.607	209.569	0.038	49.1
34	16728	16725	0.711	210.033	209.996	0.038	49.2
35	16762	16760	0.732	210.460	210.435	0.025	49.3
35	16796	16795	0.732	210.887	210.875	0.013	49.4
36	16830	16831	0.753	211.314	211.327	-0.013	49.5
37	16864	16868	0.774	211.741	211.791	-0.050	49.6
36	16898	16904	0.753	212.168	212.243	-0.075	49.7
36	16932	16940	0.753	212.595	212.695	-0.100	49.8
35	16966	16975	0.732	213.022	213.135	-0.113	49.9
31	17000	17006	0.649	213.449	213.524	-0.075	50.0
31	17034	17037	0.649	213.876	213.913	-0.038	50.1
32	17068	17069	0.670	214.302	214.315	-0.013	50.2
32	17102	17101	0.670	214.729	214.717	0.013	50.3
32	17136	17133	0.670	215.156	215.119	0.038	50.4
33	17170	17166	0.691	215.583	215.533	0.050	50.5
34	17204	17200	0.711	216.010	215.960	0.050	50.6
35	17238	17235	0.732	216.437	216.399	0.038	50.7
37	17272	17272	0.774	216.864	216.864	0.000	50.8
35	17306	17307	0.732	217.291	217.303	-0.013	50.9
36	17340	17343	0.753	217.718	217.755	-0.038	51.0
36	17374	17379	0.753	218.145	218.207	-0.063	51.1
36	17408	17415	0.753	218.571	218.659	-0.088	51.2
35	17442	17450	0.732	218.998	219.099	-0.100	51.3
32	17476	17482	0.670	219.425	219.501	-0.075	51.4
31	17510	17513	0.649	219.852	219.890	-0.038	51.5
31	17544	17544	0.649	220.279	220.279	0.000	51.6
31	17578	17575	0.649	220.706	220.668	0.038	51.7
33	17612	17608	0.691	221.133	221.083	0.050	51.8
33	17646	17641	0.691	221.560	221.497	0.063	51.9

34	17680	17675	0.711	221.987	221.924	0.063	52.0
36	17714	17711	0.753	222.414	222.376	0.038	52.1
35	17748	17746	0.732	222.840	222.815	0.025	52.2
35	17782	17781	0.732	223.267	223.255	0.013	52.3
35	17816	17816	0.732	223.694	223.694	0.000	52.4
35	17850	17851	0.732	224.121	224.134	-0.013	52.5
36	17884	17887	0.753	224.548	224.586	-0.038	52.6
36	17918	17923	0.753	224.975	225.038	-0.063	52.7
34	17952	17957	0.711	225.402	225.465	-0.063	52.8
33	17986	17990	0.691	225.829	225.879	-0.050	52.9
33	18020	18023	0.691	226.256	226.293	-0.038	53.0
32	18054	18055	0.670	226.682	226.695	-0.013	53.1
32	18088	18087	0.670	227.109	227.097	0.013	53.2
33	18122	18120	0.691	227.536	227.511	0.025	53.3
33	18156	18153	0.691	227.963	227.926	0.038	53.4
34	18190	18187	0.711	228.390	228.352	0.038	53.5
34	18224	18221	0.711	228.817	228.779	0.038	53.6
34	18258	18255	0.711	229.244	229.206	0.038	53.7
35	18292	18290	0.732	229.671	229.646	0.025	53.8
35	18326	18325	0.732	230.098	230.085	0.013	53.9
36	18360	18361	0.753	230.525	230.537	-0.013	54.0
36	18394	18397	0.753	230.951	230.989	-0.038	54.1
35	18428	18432	0.732	231.378	231.429	-0.050	54.2
35	18462	18467	0.732	231.805	231.868	-0.063	54.3
33	18496	18500	0.691	232.232	232.282	-0.050	54.4
33	18530	18533	0.691	232.659	232.697	-0.038	54.5
32	18564	18565	0.670	233.086	233.098	-0.013	54.6
32	18598	18597	0.670	233.513	233.500	0.013	54.7
33	18632	18630	0.691	233.940	233.915	0.025	54.8
33	18666	18663	0.691	234.367	234.329	0.038	54.9
33	18700	18696	0.691	234.794	234.743	0.050	55.0
35	18734	18731	0.732	235.220	235.183	0.038	55.1
34	18768	18765	0.711	235.647	235.610	0.038	55.2
35	18802	18800	0.732	236.074	236.049	0.025	55.3
36	18836	18836	0.753	236.501	236.501	0.000	55.4
36	18870	18872	0.753	236.928	236.953	-0.025	55.5
36	18904	18908	0.753	237.355	237.405	-0.050	55.6
35	18938	18943	0.732	237.782	237.845	-0.063	55.7
34	18972	18977	0.711	238.209	238.271	-0.063	55.8
33	19006	19010	0.691	238.636	238.686	-0.050	55.9
32	19040	19042	0.670	239.063	239.088	-0.025	56.0
32	19074	19074	0.670	239.489	239.489	0.000	56.1
32	19108	19106	0.670	239.916	239.891	0.025	56.2
33	19142	19139	0.691	240.343	240.306	0.038	56.3
33	19176	19172	0.691	240.770	240.720	0.050	56.4
34	19210	19206	0.711	241.197	241.147	0.050	56.5
35	19244	19241	0.732	241.624	241.586	0.038	56.6
35	19278	19276	0.732	242.051	242.026	0.025	56.7
35	19312	19311	0.732	242.478	242.465	0.013	56.8
35	19346	19346	0.732	242.905	242.905	0.000	56.9
36	19380	19382	0.753	243.331	243.357	-0.025	57.0
36	19414	19418	0.753	243.758	243.809	-0.050	57.1
35	19448	19453	0.732	244.185	244.248	-0.063	57.2

34	19482	19487	0.711	244.612	244.675	-0.063	57.3
33	19516	19520	0.691	245.039	245.089	-0.050	57.4
31	19550	19551	0.649	245.466	245.479	-0.013	57.5
32	19584	19583	0.670	245.893	245.880	0.013	57.6
33	19618	19616	0.691	246.320	246.295	0.025	57.7
32	19652	19648	0.670	246.747	246.696	0.050	57.8
34	19686	19682	0.711	247.174	247.123	0.050	57.9
34	19720	19716	0.711	247.600	247.550	0.050	58.0
35	19754	19751	0.732	248.027	247.990	0.038	58.1
35	19788	19786	0.732	248.454	248.429	0.025	58.2
35	19822	19821	0.732	248.881	248.869	0.013	58.3
36	19856	19857	0.753	249.308	249.321	-0.013	58.4
35	19890	19892	0.732	249.735	249.760	-0.025	58.5
36	19924	19928	0.753	250.162	250.212	-0.050	58.6
36	19958	19964	0.753	250.589	250.664	-0.075	58.7
33	19992	19997	0.691	251.016	251.078	-0.063	58.8
33	20026	20030	0.691	251.443	251.493	-0.050	58.9
31	20060	20061	0.649	251.869	251.882	-0.013	59.0
31	20094	20092	0.649	252.296	252.271	0.025	59.1
32	20128	20124	0.670	252.723	252.673	0.050	59.2
33	20162	20157	0.691	253.150	253.087	0.063	59.3
34	20196	20191	0.711	253.577	253.514	0.063	59.4
35	20230	20226	0.732	254.004	253.954	0.050	59.5
35	20264	20261	0.732	254.431	254.393	0.038	59.6
34	20298	20295	0.711	254.858	254.820	0.038	59.7
36	20332	20331	0.753	255.285	255.272	0.013	59.8
36	20366	20367	0.753	255.711	255.724	-0.013	59.9
36	20400	20403	0.753	256.138	256.176	-0.038	60.0
37	20434	20440	0.774	256.565	256.641	-0.075	60.1
35	20468	20475	0.732	256.992	257.080	-0.088	60.2
33	20502	20508	0.691	257.419	257.494	-0.075	60.3
31	20536	20539	0.649	257.846	257.884	-0.038	60.4
31	20570	20570	0.649	258.273	258.273	0.000	60.5
31	20604	20601	0.649	258.700	258.662	0.038	60.6
32	20638	20633	0.670	259.127	259.064	0.063	60.7
33	20672	20666	0.691	259.554	259.478	0.075	60.8
34	20706	20700	0.711	259.980	259.905	0.075	60.9
35	20740	20735	0.732	260.407	260.345	0.063	61.0
36	20774	20771	0.753	260.834	260.797	0.038	61.1
36	20808	20807	0.753	261.261	261.249	0.013	61.2
35	20842	20842	0.732	261.688	261.688	0.000	61.3
36	20876	20878	0.753	262.115	262.140	-0.025	61.4
35	20910	20913	0.732	262.542	262.580	-0.038	61.5
35	20944	20948	0.732	262.969	263.019	-0.050	61.6
35	20978	20983	0.732	263.396	263.458	-0.063	61.7
32	21012	21015	0.670	263.823	263.860	-0.038	61.8
33	21046	21048	0.691	264.249	264.275	-0.025	61.9
32	21080	21080	0.670	264.676	264.676	0.000	62.0
32	21114	21112	0.670	265.103	265.078	0.025	62.1
32	21148	21144	0.670	265.530	265.480	0.050	62.2
33	21182	21177	0.691	265.957	265.894	0.063	62.3
35	21216	21212	0.732	266.384	266.334	0.050	62.4
35	21250	21247	0.732	266.811	266.773	0.038	62.5

34	21284	21281	0.711	267.238	267.200	0.038	62.6
35	21318	21316	0.732	267.665	267.640	0.025	62.7
36	21352	21352	0.753	268.092	268.092	0.000	62.8
36	21386	21388	0.753	268.518	268.544	-0.025	62.9
36	21420	21424	0.753	268.945	268.996	-0.050	63.0
34	21454	21458	0.711	269.372	269.422	-0.050	63.1
34	21488	21492	0.711	269.799	269.849	-0.050	63.2
33	21522	21525	0.691	270.226	270.264	-0.038	63.3
32	21556	21557	0.670	270.653	270.665	-0.013	63.4
32	21590	21589	0.670	271.080	271.067	0.013	63.5
33	21624	21622	0.691	271.507	271.482	0.025	63.6
32	21658	21654	0.670	271.934	271.883	0.050	63.7
34	21692	21688	0.711	272.360	272.310	0.050	63.8
34	21726	21722	0.711	272.787	272.737	0.050	63.9
34	21760	21756	0.711	273.214	273.164	0.050	64.0
35	21794	21791	0.732	273.641	273.604	0.038	64.1
35	21828	21826	0.732	274.068	274.043	0.025	64.2
38	21862	21864	0.795	274.495	274.520	-0.025	64.3
36	21896	21900	0.753	274.922	274.972	-0.050	64.4
36	21930	21936	0.753	275.349	275.424	-0.075	64.5
33	21964	21969	0.691	275.776	275.838	-0.063	64.6
33	21998	22002	0.691	276.203	276.253	-0.050	64.7
33	22032	22035	0.691	276.629	276.667	-0.038	64.8
32	22066	22067	0.670	277.056	277.069	-0.013	64.9
31	22100	22098	0.649	277.483	277.458	0.025	65.0
33	22134	22131	0.691	277.910	277.872	0.038	65.1
33	22168	22164	0.691	278.337	278.287	0.050	65.2
34	22202	22198	0.711	278.764	278.714	0.050	65.3
35	22236	22233	0.732	279.191	279.153	0.038	65.4
35	22270	22268	0.732	279.618	279.593	0.025	65.5
34	22304	22302	0.711	280.045	280.020	0.025	65.6
35	22338	22337	0.732	280.472	280.459	0.013	65.7
35	22372	22372	0.732	280.898	280.898	0.000	65.8
37	22406	22409	0.774	281.325	281.363	-0.038	65.9
36	22440	22445	0.753	281.752	281.815	-0.063	66.0
35	22474	22480	0.732	282.179	282.254	-0.075	66.1
33	22508	22513	0.691	282.606	282.669	-0.063	66.2
32	22542	22545	0.670	283.033	283.071	-0.038	66.3
32	22576	22577	0.670	283.460	283.472	-0.013	66.4
31	22610	22608	0.649	283.887	283.862	0.025	66.5
32	22644	22640	0.670	284.314	284.263	0.050	66.6
33	22678	22673	0.691	284.741	284.678	0.063	66.7
34	22712	22707	0.711	285.167	285.105	0.063	66.8
35	22746	22742	0.732	285.594	285.544	0.050	66.9
35	22780	22777	0.732	286.021	285.984	0.038	67.0
35	22814	22812	0.732	286.448	286.423	0.025	67.1
35	22848	22847	0.732	286.875	286.862	0.013	67.2
36	22882	22883	0.753	287.302	287.314	-0.013	67.3
37	22916	22920	0.774	287.729	287.779	-0.050	67.4
39	22950	22959	0.816	288.156	288.269	-0.113	67.5
34	22984	22993	0.711	288.583	288.696	-0.113	67.6
30	23018	23023	0.628	289.009	289.072	-0.063	67.7
31	23052	23054	0.649	289.436	289.461	-0.025	67.8

31	23086	23085	0.649	289.863	289.851	0.013	67.9
31	23120	23116	0.649	290.290	290.240	0.050	68.0
32	23154	23148	0.670	290.717	290.642	0.075	68.1
34	23188	23182	0.711	291.144	291.069	0.075	68.2
35	23222	23217	0.732	291.571	291.508	0.063	68.3
35	23256	23252	0.732	291.998	291.948	0.050	68.4
35	23290	23287	0.732	292.425	292.387	0.038	68.5
36	23324	23323	0.753	292.852	292.839	0.013	68.6
36	23358	23359	0.753	293.278	293.291	-0.013	68.7
35	23392	23394	0.732	293.705	293.730	-0.025	68.8
36	23426	23430	0.753	294.132	294.182	-0.050	68.9
35	23460	23465	0.732	294.559	294.622	-0.063	69.0
34	23494	23499	0.711	294.986	295.049	-0.063	69.1
34	23528	23533	0.711	295.413	295.476	-0.063	69.2
32	23562	23565	0.670	295.840	295.878	-0.038	69.3
31	23596	23596	0.649	296.267	296.267	0.000	69.4
32	23630	23628	0.670	296.694	296.669	0.025	69.5
32	23664	23660	0.670	297.121	297.070	0.050	69.6
33	23698	23693	0.691	297.547	297.485	0.063	69.7
34	23732	23727	0.711	297.974	297.912	0.063	69.8
34	23766	23761	0.711	298.401	298.338	0.063	69.9
36	23800	23797	0.753	298.828	298.790	0.038	70.0
35	23834	23832	0.732	299.255	299.230	0.025	70.1
36	23868	23868	0.753	299.682	299.682	0.000	70.2
36	23902	23904	0.753	300.109	300.134	-0.025	70.3
37	23936	23941	0.774	300.536	300.598	-0.063	70.4
35	23970	23976	0.732	300.963	301.038	-0.075	70.5
33	24004	24009	0.691	301.390	301.452	-0.063	70.6
33	24038	24042	0.691	301.816	301.867	-0.050	70.7
32	24072	24074	0.670	302.243	302.268	-0.025	70.8
32	24106	24106	0.670	302.670	302.670	0.000	70.9
31	24140	24137	0.649	303.097	303.059	0.038	71.0
32	24174	24169	0.670	303.524	303.461	0.063	71.1
35	24208	24204	0.732	303.951	303.901	0.050	71.2
34	24242	24238	0.711	304.378	304.328	0.050	71.3
35	24276	24273	0.732	304.805	304.767	0.038	71.4
36	24310	24309	0.753	305.232	305.219	0.013	71.5
36	24344	24345	0.753	305.658	305.671	-0.013	71.6
36	24378	24381	0.753	306.085	306.123	-0.038	71.7
35	24412	24416	0.732	306.512	306.563	-0.050	71.8
36	24446	24452	0.753	306.939	307.015	-0.075	71.9
35	24480	24487	0.732	307.366	307.454	-0.088	72.0
32	24514	24519	0.670	307.793	307.856	-0.063	72.1
31	24548	24550	0.649	308.220	308.245	-0.025	72.2
32	24582	24582	0.670	308.647	308.647	0.000	72.3
31	24616	24613	0.649	309.074	309.036	0.038	72.4
33	24650	24646	0.691	309.501	309.450	0.050	72.5
33	24684	24679	0.691	309.927	309.865	0.063	72.6
34	24718	24713	0.711	310.354	310.292	0.063	72.7
35	24752	24748	0.732	310.781	310.731	0.050	72.8
35	24786	24783	0.732	311.208	311.170	0.038	72.9
34	24820	24817	0.711	311.635	311.597	0.038	73.0
36	24854	24853	0.753	312.062	312.049	0.013	73.1

35	24888	24888	0.732	312.489	312.489	0.000	73.2
36	24922	24924	0.753	312.916	312.941	-0.025	73.3
37	24956	24961	0.774	313.343	313.405	-0.063	73.4
34	24990	24995	0.711	313.770	313.832	-0.063	73.5
33	25024	25028	0.691	314.196	314.247	-0.050	73.6
33	25058	25061	0.691	314.623	314.661	-0.038	73.7
33	25092	25094	0.691	315.050	315.075	-0.025	73.8
32	25126	25126	0.670	315.477	315.477	0.000	73.9
32	25160	25158	0.670	315.904	315.879	0.025	74.0
32	25194	25190	0.670	316.331	316.281	0.050	74.1
35	25228	25225	0.732	316.758	316.720	0.038	74.2
34	25262	25259	0.711	317.185	317.147	0.038	74.3
33	25296	25292	0.691	317.612	317.561	0.050	74.4
35	25330	25327	0.732	318.039	318.001	0.038	74.5
37	25364	25364	0.774	318.465	318.465	0.000	74.6
36	25398	25400	0.753	318.892	318.917	-0.025	74.7
35	25432	25435	0.732	319.319	319.357	-0.038	74.8
36	25466	25471	0.753	319.746	319.809	-0.063	74.9
34	25500	25505	0.711	320.173	320.236	-0.063	75.0
33	25534	25538	0.691	320.600	320.650	-0.050	75.1
32	25568	25570	0.670	321.027	321.052	-0.025	75.2
32	25602	25602	0.670	321.454	321.454	0.000	75.3
32	25636	25634	0.670	321.881	321.855	0.025	75.4
32	25670	25666	0.670	322.307	322.257	0.050	75.5
33	25704	25699	0.691	322.734	322.672	0.063	75.6
34	25738	25733	0.711	323.161	323.098	0.063	75.7
35	25772	25768	0.732	323.588	323.538	0.050	75.8
35	25806	25803	0.732	324.015	323.977	0.038	75.9
36	25840	25839	0.753	324.442	324.429	0.013	76.0
36	25874	25875	0.753	324.869	324.881	-0.013	76.1
36	25908	25911	0.753	325.296	325.333	-0.038	76.2
35	25942	25946	0.732	325.723	325.773	-0.050	76.3
35	25976	25981	0.732	326.150	326.212	-0.063	76.4
34	26010	26015	0.711	326.576	326.639	-0.063	76.5
33	26044	26048	0.691	327.003	327.054	-0.050	76.6
32	26078	26080	0.670	327.430	327.455	-0.025	76.7
31	26112	26111	0.649	327.857	327.845	0.013	76.8
32	26146	26143	0.670	328.284	328.246	0.038	76.9
33	26180	26176	0.691	328.711	328.661	0.050	77.0
33	26214	26209	0.691	329.138	329.075	0.063	77.1
35	26248	26244	0.732	329.565	329.515	0.050	77.2
34	26282	26278	0.711	329.992	329.941	0.050	77.3
36	26316	26314	0.753	330.419	330.393	0.025	77.4
36	26350	26350	0.753	330.845	330.845	0.000	77.5
37	26384	26387	0.774	331.272	331.310	-0.038	77.6
37	26418	26424	0.774	331.699	331.775	-0.075	77.7
35	26452	26459	0.732	332.126	332.214	-0.088	77.8
33	26486	26492	0.691	332.553	332.628	-0.075	77.9
33	26520	26525	0.691	332.980	333.043	-0.063	78.0
32	26554	26557	0.670	333.407	333.444	-0.038	78.1
31	26588	26588	0.649	333.834	333.834	0.000	78.2
31	26622	26619	0.649	334.261	334.223	0.038	78.3
33	26656	26652	0.691	334.688	334.637	0.050	78.4

32	26690	26684	0.670	335.114	335.039	0.075	78.5
34	26724	26718	0.711	335.541	335.466	0.075	78.6
35	26758	26753	0.732	335.968	335.905	0.063	78.7
36	26792	26789	0.753	336.395	336.357	0.038	78.8
34	26826	26823	0.711	336.822	336.784	0.038	78.9
36	26860	26859	0.753	337.249	337.236	0.013	79.0
39	26894	26898	0.816	337.676	337.726	-0.050	79.1
35	26928	26933	0.732	338.103	338.165	-0.063	79.2
34	26962	26967	0.711	338.530	338.592	-0.063	79.3
34	26996	27001	0.711	338.956	339.019	-0.063	79.4
34	27030	27035	0.711	339.383	339.446	-0.063	79.5
32	27064	27067	0.670	339.810	339.848	-0.038	79.6
31	27098	27098	0.649	340.237	340.237	0.000	79.7
32	27132	27130	0.670	340.664	340.639	0.025	79.8
32	27166	27162	0.670	341.091	341.041	0.050	79.9
32	27200	27194	0.670	341.518	341.443	0.075	80.0
34	27234	27228	0.711	341.945	341.869	0.075	80.1
35	27268	27263	0.732	342.372	342.309	0.063	80.2
36	27302	27299	0.753	342.799	342.761	0.038	80.3
34	27336	27333	0.711	343.225	343.188	0.038	80.4
36	27370	27369	0.753	343.652	343.640	0.013	80.5
36	27404	27405	0.753	344.079	344.092	-0.013	80.6
36	27438	27441	0.753	344.506	344.544	-0.038	80.7
37	27472	27478	0.774	344.933	345.008	-0.075	80.8
34	27506	27512	0.711	345.360	345.435	-0.075	80.9
33	27540	27545	0.691	345.787	345.850	-0.063	81.0
32	27574	27577	0.670	346.214	346.251	-0.038	81.1
31	27608	27608	0.649	346.641	346.641	0.000	81.2
32	27642	27640	0.670	347.068	347.042	0.025	81.3
31	27676	27671	0.649	347.494	347.432	0.063	81.4
33	27710	27704	0.691	347.921	347.846	0.075	81.5
34	27744	27738	0.711	348.348	348.273	0.075	81.6
35	27778	27773	0.732	348.775	348.712	0.063	81.7
35	27812	27808	0.732	349.202	349.152	0.050	81.8
35	27846	27843	0.732	349.629	349.591	0.038	81.9
36	27880	27879	0.753	350.056	350.043	0.013	82.0
35	27914	27914	0.732	350.483	350.483	0.000	82.1
37	27948	27951	0.774	350.910	350.947	-0.038	82.2
36	27982	27987	0.753	351.336	351.399	-0.063	82.3
34	28016	28021	0.711	351.763	351.826	-0.063	82.4
33	28050	28054	0.691	352.190	352.241	-0.050	82.5
34	28084	28088	0.711	352.617	352.667	-0.050	82.6
31	28118	28119	0.649	353.044	353.057	-0.013	82.7
31	28152	28150	0.649	353.471	353.446	0.025	82.8
34	28186	28184	0.711	353.898	353.873	0.025	82.9
32	28220	28216	0.670	354.325	354.275	0.050	83.0
33	28254	28249	0.691	354.752	354.689	0.063	83.1
33	28288	28282	0.691	355.179	355.103	0.075	83.2
35	28322	28317	0.732	355.605	355.543	0.063	83.3
35	28356	28352	0.732	356.032	355.982	0.050	83.4
38	28390	28390	0.795	356.459	356.459	0.000	83.5
37	28424	28427	0.774	356.886	356.924	-0.038	83.6
36	28458	28463	0.753	357.313	357.376	-0.063	83.7

35	28492	28498	0.732	357.740	357.815	-0.075	83.8
33	28526	28531	0.691	358.167	358.230	-0.063	83.9
32	28534	28563	0.670	358.267	358.631	-0.364	84.0
28	28542	28591	0.586	358.368	358.983	-0.615	84.1
23	28550	28614	0.481	358.468	359.272	-0.804	84.2
16	28558	28630	0.335	358.569	359.473	-0.904	84.3
11	28566	28641	0.230	358.669	359.611	-0.942	84.4
6	28574	28647	0.126	358.770	359.686	-0.917	84.5
1	28582	28648	0.021	358.870	359.699	-0.829	84.6
4	28590	28652	0.084	358.970	359.749	-0.778	84.7
5	28598	28657	0.105	359.071	359.812	-0.741	84.8
6	28606	28663	0.126	359.171	359.887	-0.716	84.9
6	28614	28669	0.126	359.272	359.962	-0.691	85.0
5	28622	28674	0.105	359.372	360.025	-0.653	85.1
1	28630	28675	0.021	359.473	360.038	-0.565	85.2
0	28638	28675	0.000	359.573	360.038	-0.465	85.3
0	28646	28675	0.000	359.674	360.038	-0.364	85.4
0	28654	28675	0.000	359.774	360.038	-0.264	85.5
0	28662	28675	0.000	359.874	360.038	-0.163	85.6
0	28670	28675	0.000	359.975	360.038	-0.063	85.7
0	28672	28675	0.000	360.000	360.038	-0.038	85.8

Appendix G

Note: only a sample of the engineering drawings created during this research are located in this appendix. This is due to the extensive number of drawings that were necessary for the fabrication of the library of modules (+80 drawings). The drawings used in the manufacturing of ALL MRM modules are located on the supplementary DVD disk.

Mechanical Drawings for Base Module

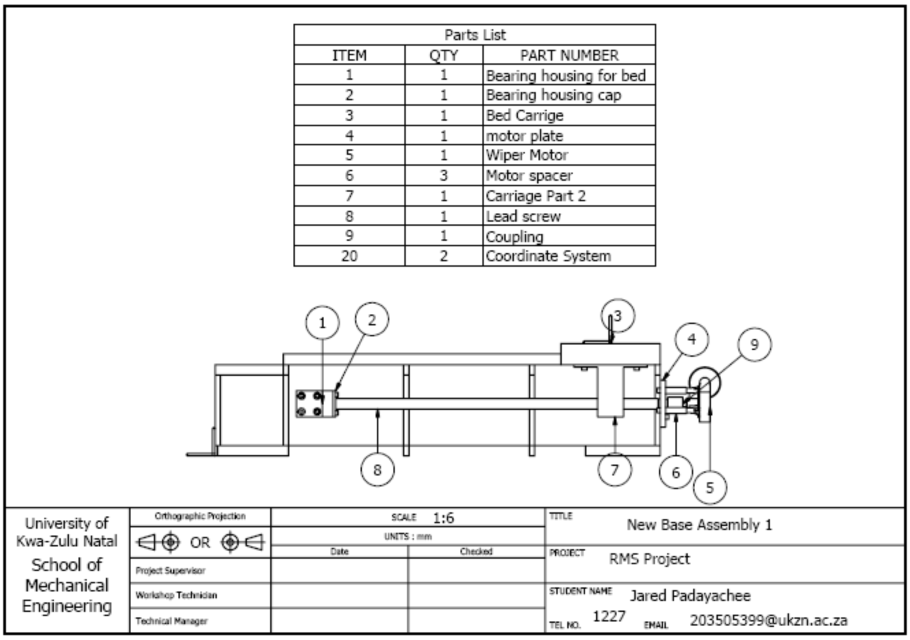


Figure G.1: Assembly of Base Module (View One)

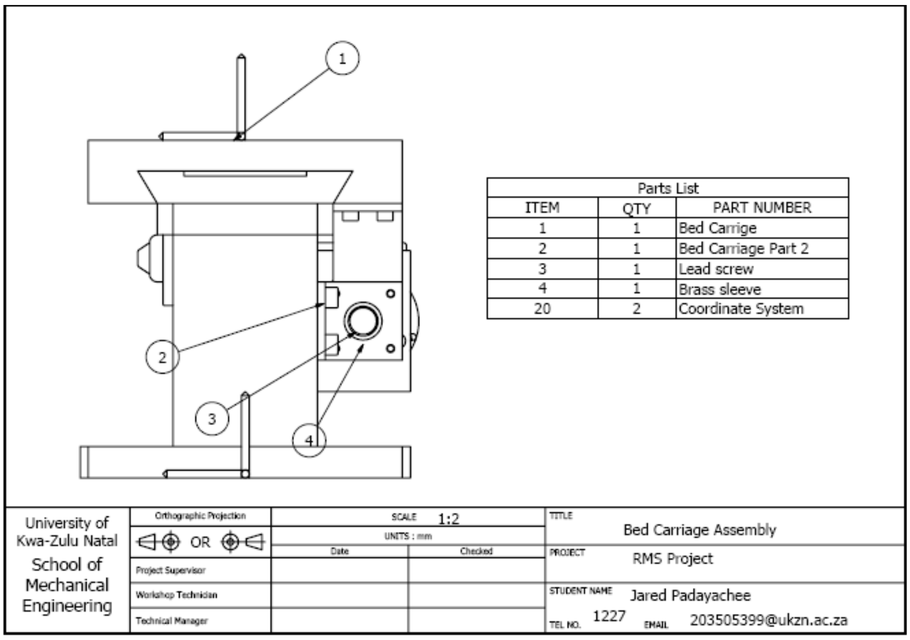


Figure G.2: Assembly of Base Module (View Two)

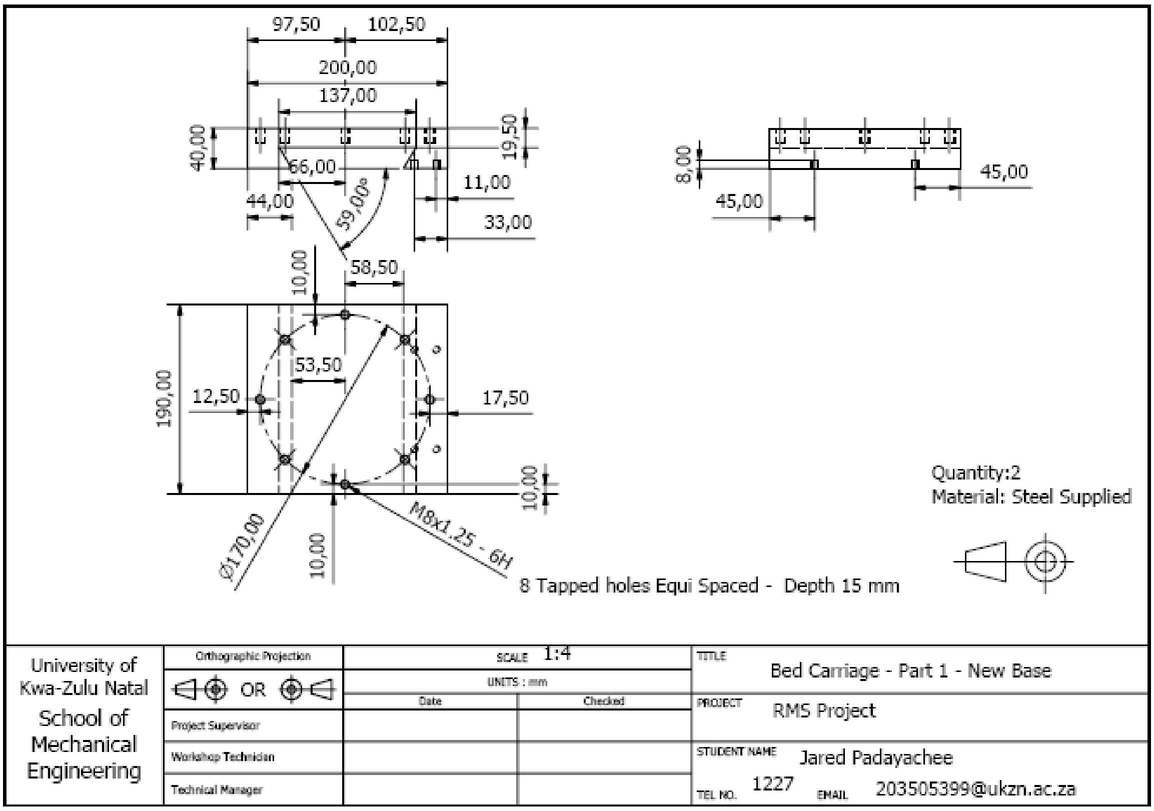


Figure G.3: Bed Carriage – Part One

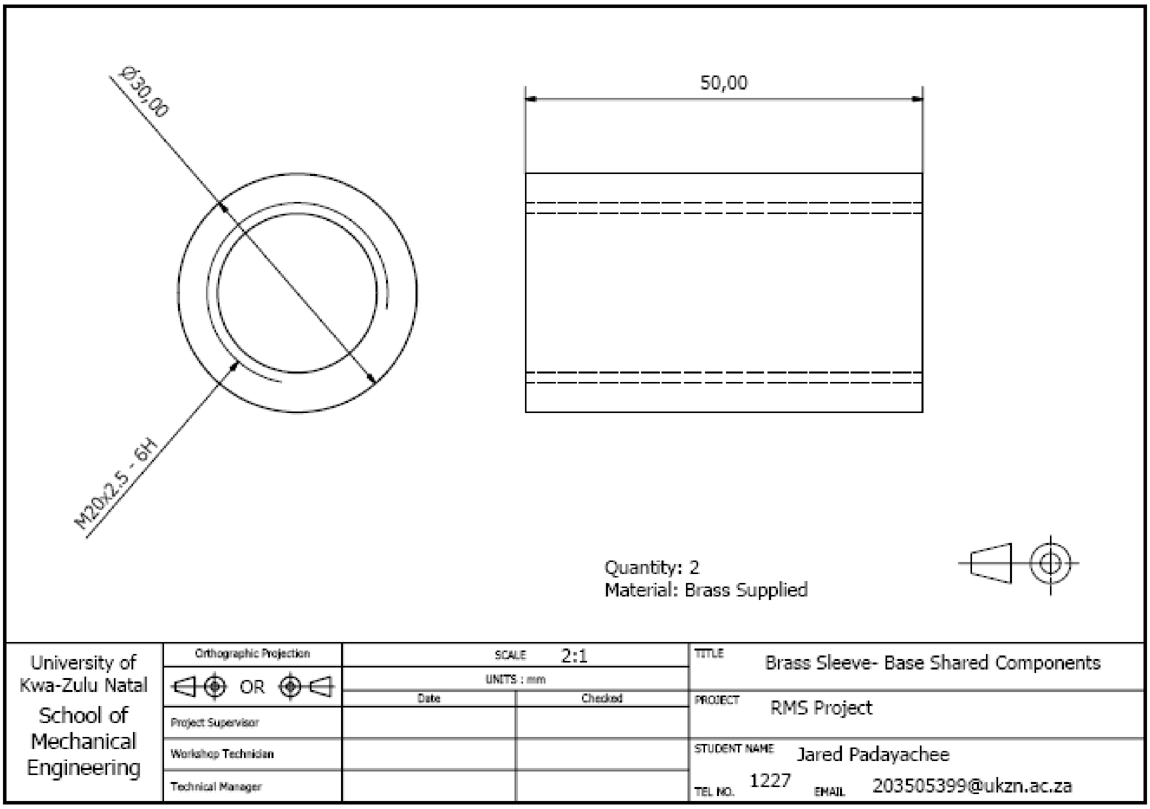


Figure G.4: Brass Collar

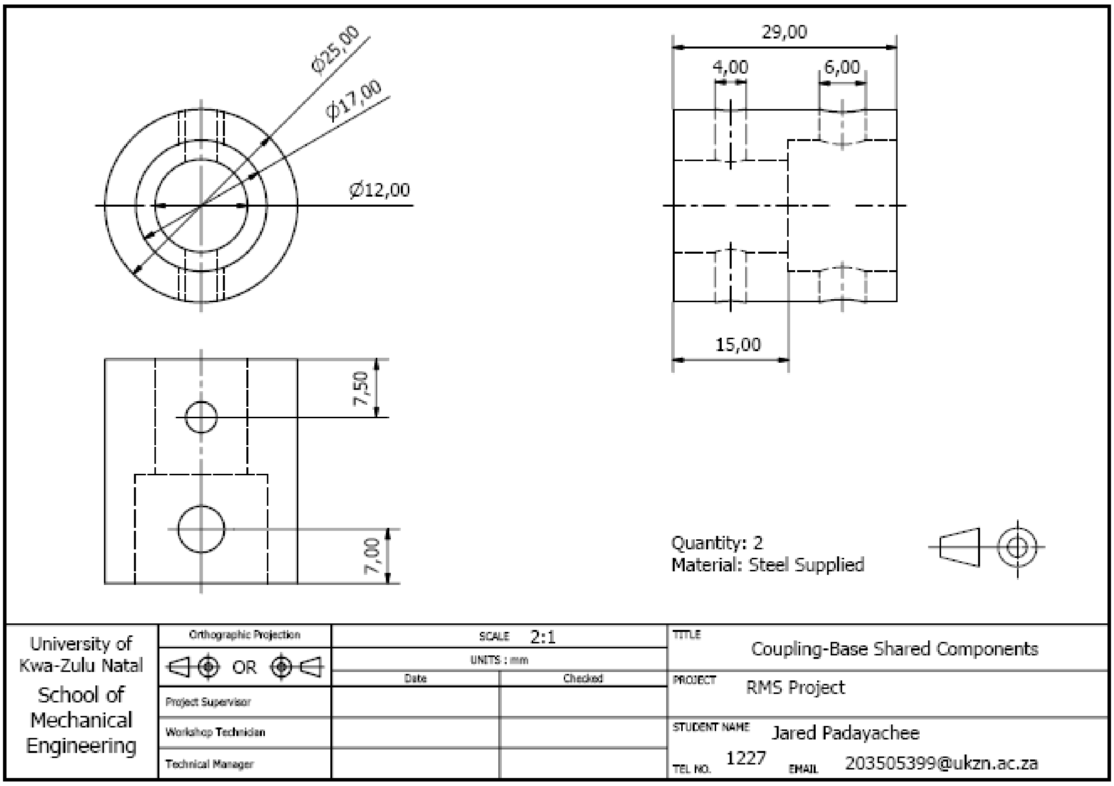


Figure G.5: Motor Coupling

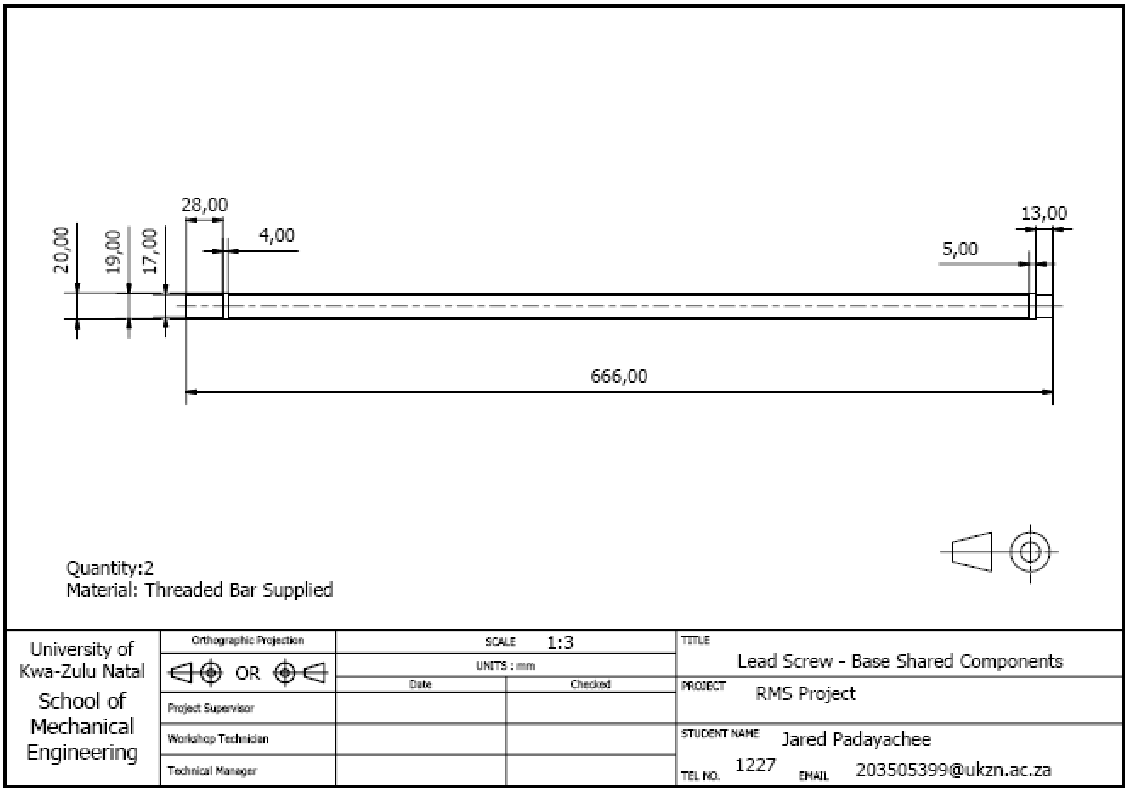


Figure G.6: Lead Screw

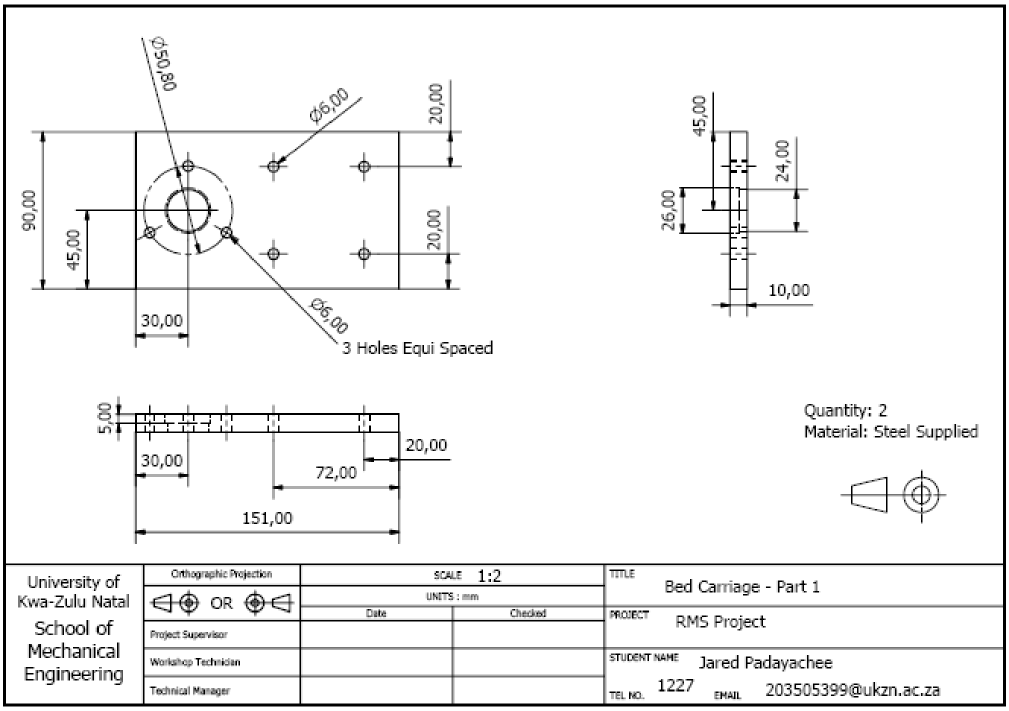


Figure G.7: Supporting Plate for Slide/Carriage Mechanism

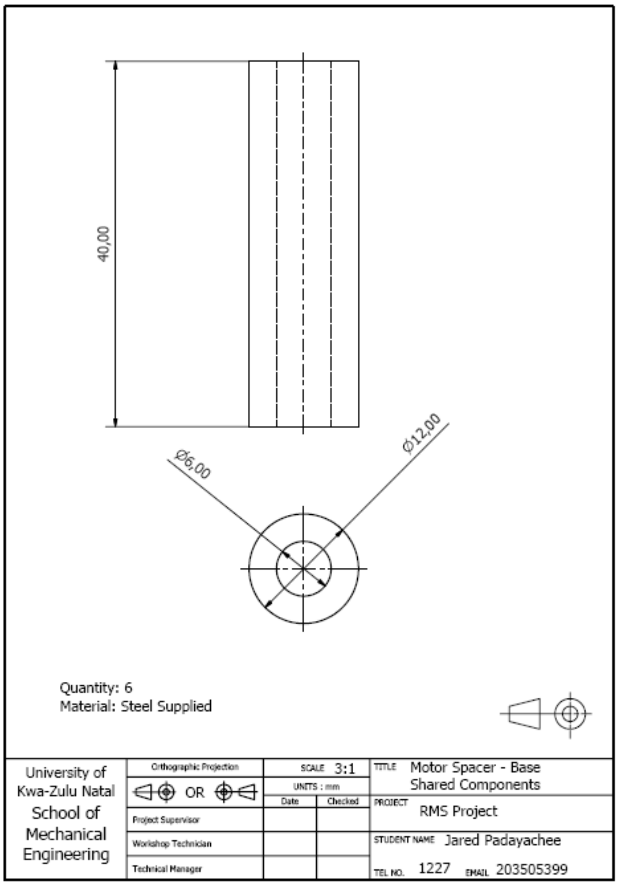


Figure G.8: Motor Spacer

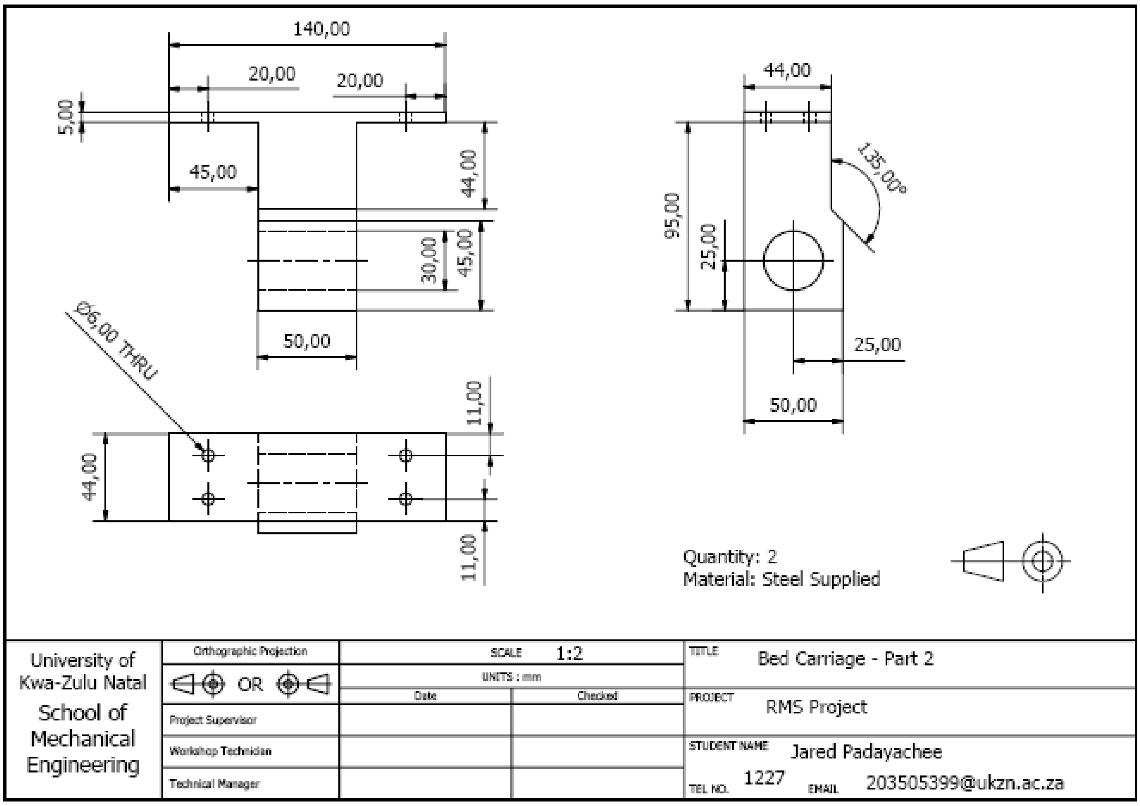


Figure G.9: Bed Carriage – Part Two

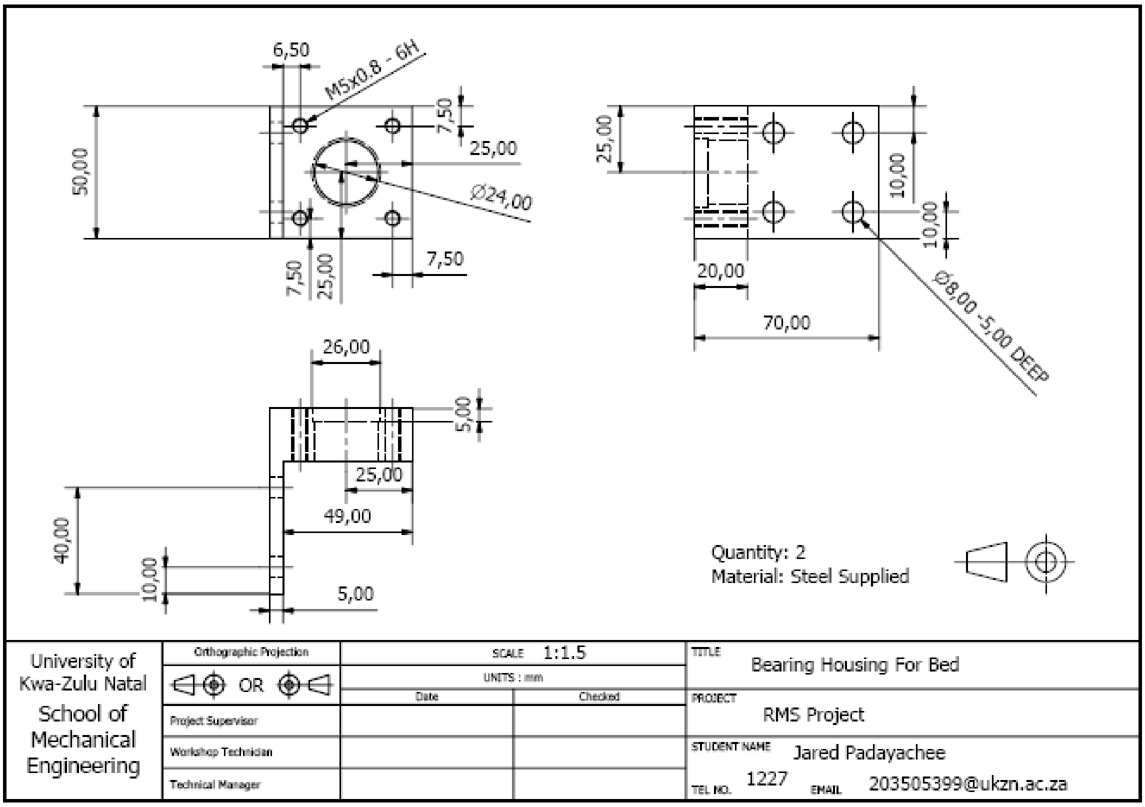


Figure G.10: Bearing Housing

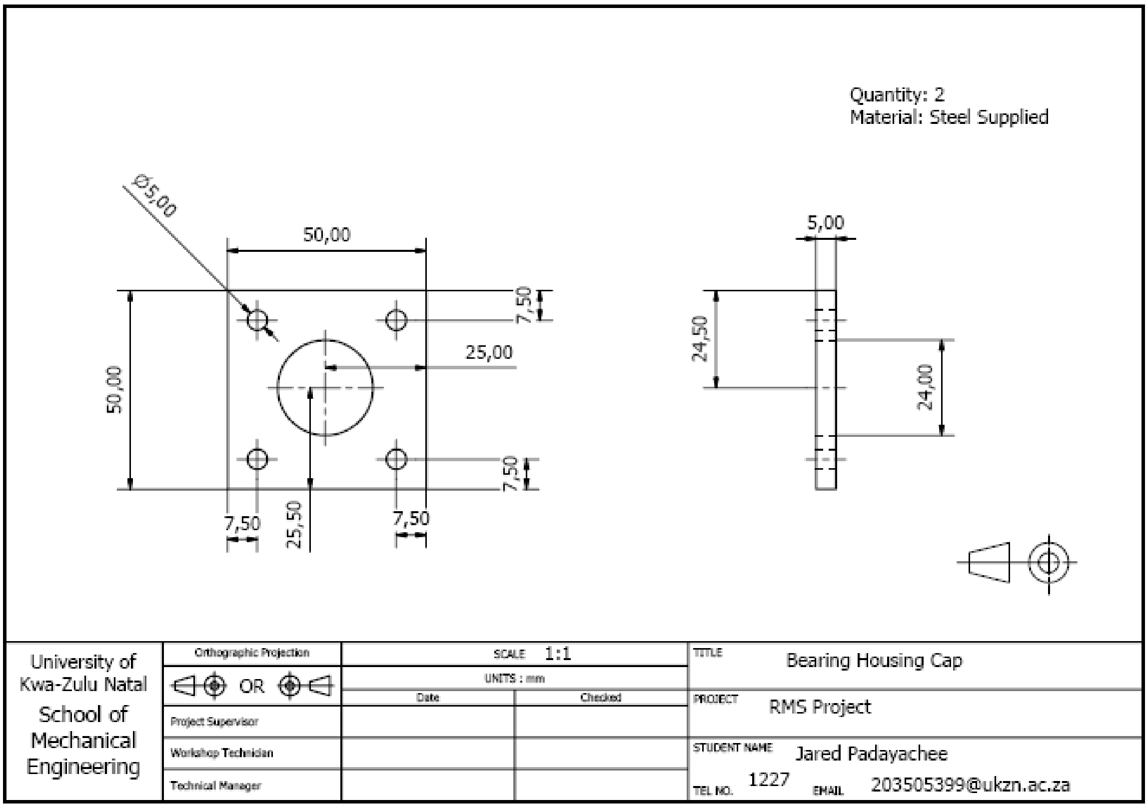


Figure G.11: Bearing Housing Cap

Appendix H

Final Specifications for MRM Modules and Assemblies

Table H.1: Specifications for MRM Modules and Assemblies

Specifications	Prescribed	Final
General		
Processing functions	Drilling and Turning	Drilling and Turning
Machinable Materials	Wax and Plastic	Wax and Plastic
Drilling - degrees of freedom	3-6	3-6
Turning - degrees of freedom	2-3	2-3
Motion Modules (Modular Axes)		
Linear Axes		
Maximum speed of at least	100 mm/min	116 mm/min
Worst Accuracy	1 mm	0.038 mm
Worst Repeatability	0.5 mm	0.035 mm
Rotary Axes		
Maximum speed of at least	1 rev/min	1 rev/min
Worst Accuracy	1.5^o	3.164^o
Worst Repeatability	1^o	2.812^o
Process Modules (Modular Cutting Heads)		
Drilling capacity	1 mm – 10 mm	0.5 mm – 12 mm
Drilling speeds	Not Specified	700 rev/min (unloaded)
Drilling Motor Power	Not Specified	80 watts
Turning Capacity	100 mm	120 mm
Turning Spindle Hole	Not Specified	24 mm
Turning Speeds	Not Specified	315 to 1054 rev/min
Turning Motor Power	Not Specified	550 watts
Drilling Assemblies		
Work table size	100 mm by 100 mm	100 mm by 100 mm
Maximum part size	100 mm x 100 mm x100 mm	10 mm x 100 mm x 100 mm
Turning Assemblies		
Maximum part length of at least	400 mm	500 mm
Maximum swing over bed of at least	300 mm	420 mm
Electrical Specifications		
Operating voltage	220 volts, AC current	220 volts, AC current
Digital electronics power supply	12 volts, DC current	12 volts, DC current
Software Specifications		
Software programming languages	C/C++	C/C++
Machine operating system	Linux	Linux
Machine programming language	Simplified G-Code	Simplified G-Code

Appendix I

Sample C++ Code for Host PC

Note: only a seventeen page sample of the C++ code that was written for the host PC has been included in this appendix (not the entire host PC code). This is due to the lengthy amount of code that was written for the host PC, the servo communication module, servo control modules and spindle control modules. The C and C++ code that was written for the entire control system is located on the supplementary DVD disk.

//main.cpp (initializes machine GUI)

```
#include <qapplication.h>
#include "MRMmain.h"

int main( int argc, char ** argv )
{
    QApplication a( argc, argv );
    MRMmain w;
    w.show();
    a.connect( &a, SIGNAL( lastWindowClosed() ), &a, SLOT( quit() ) );
    return a.exec();
}
#include "codemanip.h"
#include "execute.h"
#include "Transmission_Control.h"
#include "mrm_error.h"
```

//MRMmain.ui(initializes functions that are called through GUI)

```
void MRMmain::sortAndSave()
{
    int lineNumber=0;
    int lines= codeEdit->lines();
    int error;
    int linear;
    int angular;
    int second;

 //create code storgae data object
    codeManip code;
    code.PWarninglineEdit=WarninglineEdit;
    code.PStatuslineEdit=StatuslineEdit;
    code.PcodeEdit=codeEdit;
    code.PprogressBar=progressBar;

 //initialize progress ber
    progressBar->setTotalSteps(lines);

//Store the MRMs current configuration
    linear=linear_axis_combo->currentItem();
    angular=angular_axis_combo->currentItem();
    second=second_axis_combo->currentItem();
    code.storeConfiguration(linear,angular,second);
```

```
// check and store lines of code one at a time
    while(lineNumber<lines)
    { error=code.codeGet(lineNumber);
      if(error>0) //N.B error reporting handled by other functions
      {break;}
      else{    progressBar->setProgress(lineNumber+1);
          ++lineNumber;}
    }

//report sucessful storage once all lines are done
    if(lineNumber==lines)
    {StatuslineEdit->setText("Code Storage Successful");
      WarninglineEdit->setText("No Warnings");
    }

}


void MRMmain::codeExecute()
{

LineExecute Line;

int SerialSpeed;
int box=0;

Line.PWarninglineEdit=WarninglineEdit;// grant access to warning line
Line.PStatuslineEdit=StatuslineEdit;//grant access to status line
Line.PSpindlePortlineEdit=USB1lineEdit;
Line.PServoPortlineEdit=USB2lineEdit;
Line.PTIPOlineEdit=TIPOlineEdit;
Line.PcodeEdit=codeEdit;// grant access to code editting box
Line.PprogressBar=progressBar;// grant access to progress bar

box=SpeedcomboBox->currentItem();

switch(box)
{
case 0:
    SerialSpeed=2400;
    break;
case 1:
    SerialSpeed=4800;
    break;
case 2:
    SerialSpeed=9600;
    break;
case 3:
    SerialSpeed=19200;
    break;
case 4:
    SerialSpeed=38400;
    break;
default:
    SerialSpeed=9600;
    break;
}

Line.Start(SerialSpeed);
}
```

```
void MRMmain::vibrationMonitor( bool state )
{
TransmissionControl readPort;
char sensorReading[2];
const char *PortName;
int SerialSpeed;
int acceleration=0;
int box=0;
int error=0;

PortName= new char[strlen(USB1lineEdit->text())];
PortName=USB1lineEdit->text();

vibrationBar->setTotalSteps(20);

switch(box)
{
case 0:
    SerialSpeed=2400;
    break;
case 1:
    SerialSpeed=4800;
    break;
case 2:
    SerialSpeed=9600;
    break;
case 3:
    SerialSpeed=19200;
    break;
case 4:
    SerialSpeed=38400;
    break;
default:
    SerialSpeed=9600;
    break;
}

box=SpeedcomboBox->currentItem();

if(state==TRUE)
    {

    //while(1)
    {
      error=readPort.serialReceive(PortName,SerialSpeed, sensorReading,
2);
      switch(error)
      {
      case PORT_OPEN_FAIL:
          WarninglineEdit->setText("Failed To Open Serial Port");
          break;
      case PORT_READ_FAIL:
          WarninglineEdit->setText("Failed To Read Serial Port");
          break;
      case PORT_CLOSE_FAIL:
          WarninglineEdit->setText("Failed To Close Serial Port");
          break;
      default:

  break;
      }
```

```
      vibrationBar->setProgress(10);
      vibration_LCD->display(9);
      //break;
    }

}
}
```

//Codemanip.h (text interpreter, error checking and code storage)

```
#ifndef CODEMANIP_H
#define CODEMANIP_H
#include <qlineedit.h>
#include <qtextedit.h>
#include <qprogressbar.h>
#include <qcombobox.h>

class codeManip{
public:
    codeManip();
    ~codeManip();
    void resetVariables();
    int codeGet(int);
    int codeSyntaxFilter();
    void storeConfiguration(int, int, int);
    int codeSort();
    int codeInterpret(int, const char*);// reads values into variables
    int check_G();
    int check_M();
    int check_R();
    int check_Arc();
    int codeSave();//writes to file
    QLineEdit *PWarninglineEdit; //pointer to warning line
    QLineEdit *PStatuslineEdit;//pointer to status line
    QTextEdit *PcodeEdit;//pointer to code edit box
    QProgressBar *PprogressBar;//pointer to progress bar


private:
    const char *codeLineHold;

    int N;//line number
    int M;// miscellanoues functions
    int G;// function

    float A; // rotation about x
    float B; // rotation about y
    float C;//rotation about z
    float X;
    float Y;
    float Z;
    float U;
    float V;
    float W;

    float S;// spindle speed
    float F;// feed rate
    float I;// arc about X
    float J;//are about Y
    float K;//arc about Z
    float R; // radius

    //Axis Activation Code
```

```
    unsigned char a;
    unsigned char b;
    unsigned char c;
    unsigned char x;
    unsigned char y;
    unsigned char z;
    unsigned char u;
    unsigned char v;
    unsigned char w;

};
#endif
```

<u>//Codemanip.cpp (text interpreter, error checking and code storage</u>

```
#include <string.h>
#include <stdlib.h>
#include <stdio.h>
#include "codemanip.h"
#include "mrm_error.h"

codeManip::codeManip()
{
// clear code.dat file
    FILE *fp;
    fp=fopen("code.dat","w");
    fclose(fp);

// reset kinematic configuration variables
   a=0;
   b=0;
   c=0;
   x=0;
   y=0;
   z=0;
   u=0;
   v=0;
   w=0;
//reset
   resetVariables();
}

codeManip::~codeManip()
{;}

void codeManip::resetVariables()
{
   N=0;//line number
   M=100;// miscellanoues functions N.B 100 is the default value if it
is not overwritten in code
   G=100;// function
   A=0; // rotation about x
   B=0; // rotation about y
   C=0;//rotation about z
   X=0;// linear x
   Y=0;//inear y
   Z=0;// linear z
   U=0;// 2nd x
   V=0;// 2nd y
   W=0;//2nd z
   S=0;// spindle speed
   F=0;// feed rate
```

```
    I=0;// arc about X
    J=0;//are about Y
    K=0;// arc about Z
    R=0;// radius

}


void codeManip::storeConfiguration(int linear_box, int angular_box ,int
second_box)
{
// store linear kinematic config
    switch(linear_box)
    {
    case 0:
      x=y=z=0;
      break;
    case 1:
      x=1;
      break;
    case 2:
      y=1;
      break;
    case 3:
      z=1;
      break;
    case 4:
      x=y=1;
      break;
    case 5:
      x=z=1;
      break;
    case 6:
      y=z=1;
      break;
    case 7:
      x=y=z=1;
      break;
    }

//store angular kinematic config
        switch(angular_box)
    {
    case 0:
      a=b=c=0;
      break;
    case 1:
      a=1;
      break;
    case 2:
      b=1;
      break;
    case 3:
      c=1;
      break;
    case 4:
      a=b=1;
    case 5:
      a=c=1;
      break;
    case 6:
      b=c=1;
      break;
```

```
    case 7:
      a=b=c=1;
      break;
    }

// store secondry axis config
        switch(second_box)
    {
    case 0:
      u=v=w=0;
      break;
    case 1:
      u=1;
      break;
    case 2:
      v=1;
      break;
    case 3:
      w=1;
      break;
    case 4:
      u=v=1;
    case 5:
      u=w=1;
      break;
    case 6:
      v=w=1;
      break;
    case 7:
      u=v=w=1;
      break;
    }
}

int codeManip::codeGet(int lineCounter)
{
    int error;

 //return 1 = syntax error; return 2 = inactive axis
 //return 3 = not supported by current configuration; return 4 = not
available on this machine

 //Obtain a line of code for processinf
    codeLineHold= new char[strlen(PcodeEdit->text(lineCounter))];

    if(codeLineHold==NULL)
    {PWarninglineEdit->setText("ERROR: Dynamic Memory Allocation
Failed");
      return 1;
    }

   codeLineHold=PcodeEdit->text(lineCounter);

//Filter line of code for syntax errors

   error=codeSyntaxFilter();

   if(error==1)
      {PWarninglineEdit->setText("ERROR: Code Syntax");
          PStatuslineEdit-
>setText(QString::number(lineCounter+1,'f',0));
          return 1;
      }
```

```
//sort text code and convert to numerical values
   error=codeSort();

   switch(error)
   {
   case CODE_SYNTAX_ERROR:
       PWarninglineEdit->setText("ERROR: Code Syntax Error");
       PStatuslineEdit->setText(QString::number(lineCounter+1,'f',0));
       return 1;
   case AXIS_INACTIVE:
        PWarninglineEdit->setText("ERROR: Axis Inactive In Current
Configuration");
       PStatuslineEdit->setText(QString::number(lineCounter+1,'f',0));
       return 1;
   case INVALID_IN_CONFIGURATION:
       PWarninglineEdit->setText("ERROR: Command Invalid In Current
Configuration");
       PStatuslineEdit->setText(QString::number(lineCounter+1,'f',0));
       return 1;
   case FUNCTION_NOT_AVAILABLE:
       PWarninglineEdit->setText("ERROR: Function Not Available On
Platform");
       PStatuslineEdit->setText(QString::number(lineCounter+1,'f',0));
       return 1;
      }
//store the line of processed code in code.dat file
   error=codeSave();

   if(error==1)
         { PWarninglineEdit->setText("ERROR: Code Storage Failed");
             PStatuslineEdit-
>setText(QString::number(lineCounter+1,'f',0));
        }

//reset g-code variables for next stage of sort and store
   resetVariables();

   return 0;
}

int codeManip::codeSyntaxFilter()
{
    int length=strlen(codeLineHold);
    int counter;

    for(counter=0; counter<length; counter++)
   {
       switch(codeLineHold[counter])
       {
       case 'N':
         break;
       case 'M':
         break;
       case 'G':
         break;
// axis word addresses
       case 'A':
         break;
       case 'B':
         break;
       case 'C':
         break;
```

```
        case 'X':
          break;
        case 'Y':
          break;
        case 'Z':
          break;
        case 'U':
          break;
        case 'V':
          break;
        case 'W':
          break;
// other word addresses

        case 'S':
          break;
        case 'F':
          break;
        case 'I':
          break;
        case 'J':
          break;
        case 'K':
          break;
        case 'R':
          break;
// numerical characters etc
        case ' ':
          break;
        case '-':
          break;
        case '.':
          break;
        case '0':
          break;
        case '1':
          break;
        case '2':
          break;
        case '3':
          break;
        case '4':
          break;
        case '5':
          break;
        case '6':
          break;
        case '7':
          break;
        case '8':
          break;
        case '9':
          break;
        default:
          return CODE_SYNTAX_ERROR;
        }// end of switch
    }//end of for check loop
return 0;
}

int codeManip::codeSort()
{
    int length=strlen(codeLineHold);
```

```
  int counter;
  int error=0;
  char holder[7];
  int variableNumber=0;
  int holderPlace=0;
  const char reset[]="xxxxxxx";
  strcpy(holder,reset);

for(counter=0; counter<length; counter++)
  {
    switch(codeLineHold[counter])
    {

    case 'N':
      if(variableNumber>0)
      {error=codeInterpret(variableNumber, holder);
      if(error>0)
          {return error;}
      holderPlace=0;
      strcpy(holder,reset);
                 }
      variableNumber=1;
     break;
    case 'M':
      if(variableNumber>0)
      {error=codeInterpret(variableNumber, holder);
          if(error>0)
          {return error;}
       holderPlace=0;
      strcpy(holder,reset);
                 }
      variableNumber=2;
      break;
    case 'G':
      if(variableNumber>0)
      {error=codeInterpret(variableNumber, holder);
        if(error>0)
          {return error;}
      holderPlace=0;
      strcpy(holder,reset);
                 }
      variableNumber=3;
      break;

    case 'A':
      if(variableNumber>0) // call store on  previous string item
      {error=codeInterpret(variableNumber, holder);
        if(error>0)
          {return error;}
      holderPlace=0;
      strcpy(holder,reset);
                 }
      variableNumber=4;
      break;
    case 'B':
      if(variableNumber>0)
      {error=codeInterpret(variableNumber, holder);
        if(error>0)
          {return error;}
      holderPlace=0;
      strcpy(holder,reset);
                 }
      variableNumber=5;
```

```
    break;
  case 'C':
    if(variableNumber>0)
    {error=codeInterpret(variableNumber, holder);
      if(error>0)
        {return error;}
    holderPlace=0;
    strcpy(holder,reset);
                }
    variableNumber=6;
    break;
  case 'X':
    if(variableNumber>0)
    {error=codeInterpret(variableNumber, holder);
       if(error>0)
        {return error;}
    holderPlace=0;
    strcpy(holder,reset);
                }
    variableNumber=7;
    break;
  case 'Y':
    if(variableNumber>0)
    {error=codeInterpret(variableNumber, holder);
        if(error>0)
        {return error;}
    holderPlace=0;
    strcpy(holder,reset);
                }
    variableNumber=8;
   break;
  case 'Z':
    if(variableNumber>0)
    {error=codeInterpret(variableNumber, holder);
      if(error>0)
        {return error;}
    holderPlace=0;
    strcpy(holder,reset);
                }
    variableNumber=9;
    break;
  case 'U':
    if(variableNumber>0)
    {error=codeInterpret(variableNumber, holder);
      if(error>0)
        {return error;}
    holderPlace=0;
    strcpy(holder,reset);
                }
    variableNumber=10;
    break;
  case 'V':
    if(variableNumber>0)
    {error=codeInterpret(variableNumber, holder);
      if(error>0)
        {return error;}
    holderPlace=0;
    strcpy(holder,reset);
                }
    variableNumber=11;
   break;
 case 'W':
    if(variableNumber>0)
```

```
  {error=codeInterpret(variableNumber, holder);
    if(error>0)
      {return error;}
  holderPlace=0;
  strcpy(holder,reset);
            }
  variableNumber=12;
  break;

case 'S':
    if(variableNumber>0)
  {error=codeInterpret(variableNumber, holder);
    if(error>0)
      {return error;}
  holderPlace=0;
  strcpy(holder,reset);
            }
  variableNumber=13;
  break;
case 'F':
      if(variableNumber>0)
  {error=codeInterpret(variableNumber, holder);
    if(error>0)
      {return error;}
  holderPlace=0;
  strcpy(holder,reset);
            }
  variableNumber=14;
  break;
case 'I':
   if(variableNumber>0)
  {error=codeInterpret(variableNumber, holder);
    if(error>0)
      {return error;}
  holderPlace=0;
  strcpy(holder,reset);
            }
  variableNumber=15;
  break;
case 'J':
   if(variableNumber>0)
  {error=codeInterpret(variableNumber, holder);
    if(error>0)
      {return error;}
  holderPlace=0;
  strcpy(holder,reset);
            }
  variableNumber=16;
  break;
case 'K':
 if(variableNumber>0)
  {error=codeInterpret(variableNumber, holder);
    if(error>0)
      {return error;}
  holderPlace=0;
  strcpy(holder,reset);
            }
  variableNumber=17;
  break;
case 'R':
  if(variableNumber>0)
  {error=codeInterpret(variableNumber, holder);
    if(error>0)
```

```
            {return error;}
        holderPlace=0;
        strcpy(holder,reset);
                   }
        variableNumber=18;
        break;

      case ' ':
        break;
      default:

        holder[holderPlace]=codeLineHold[counter];
        ++holderPlace;
        break;
                    } // end of switch
 }// end of for

 if (codeLineHold[counter]=='\0') //save last string item
      {
        if (variableNumber>0)
        {error=codeInterpret(variableNumber, holder);
            if(error>0)
            {return error;}
        holderPlace=0;}
      }// end of  final save

 return 0;
}//end function

int codeManip::codeInterpret(int variable, const char *string)
{
    int error=0;

       switch(variable)
 {
 case 1:
     N=atoi(string);
     break;
 case 2:
     M=atof(string);
     error=check_M();
     if(error>0)
     {M=0;
     return error;}
     break;
 case 3:
      G=atof(string);
      error=check_G();
      if(error>0)
      {G=0;
        return error;}
     break;
 case 4:
     if(a==0)
     {return AXIS_INACTIVE;}
     else A=atof(string);
     break;
 case 5:
     if(b==0)
     {return AXIS_INACTIVE;}
     else B=atof(string);
     break;
 case 6:
```

```
      if(c==0)
     {return AXIS_INACTIVE;}
      else C=atof(string);
     break;
case 7:
   if(x==0)
  {return AXIS_INACTIVE;}
    else X=atof(string);
    break;
case 8:
    if(y==0)
  {return AXIS_INACTIVE;}
    else Y=atof(string);
    break;
case 9:
    if(z==0)
  {return AXIS_INACTIVE;}
    else Z=atof(string);
    break;
case 10:
     if(u==0)
  {return AXIS_INACTIVE;}
    else U=atof(string);
    break;
case 11:
     if(v==0)
    {return AXIS_INACTIVE;}
    else V=atof(string);
    break;
case 12:
     if(w==0)
    {return AXIS_INACTIVE;}
    else W=atof(string);
         break;
 case 13:
     S=atof(string);
    break;
 case 14:
     F=atof(string);
     break;
 case 15:
     if(x==0)
     {return INVALID_IN_CONFIGURATION;}
     else I=atof(string);
     break;
 case 16:
     if(y==0)
     {return INVALID_IN_CONFIGURATION;}
     else J=atof(string);
     break;
 case 17:
    if(z==0)
     {return INVALID_IN_CONFIGURATION;}
     else K=atof(string);
     break;
 case 18:
     error=check_Arc();
     if(error>0)
     {return error;}
     else R=atof(string);
     break;
default:
    return 1;
```

```
}//end switch
 return 0;
}

int codeManip::codeSave()
{
FILE *fp;

fp=fopen("code.dat","a+");


if(fp==NULL)
{return 1;}
else {
fprintf(fp,"%7d%7d%7d%7.2f%7.2f%7.2f%7.2f%7.2f%7.2f",N,M,G,A,B,C,X,Y,Z);
fprintf(fp,"%7.2f%7.2f%7.2f%7.2f%7.2f%7.2f%7.2f%7.2f%7.2f\n",U,V,W,S,F,I
,J,K,R);
}

fclose(fp);
return 0;
}

int codeManip::check_G()
{
    int error=0;

    switch(G)
    {
    case  0:
      break;
     case 1:
       break;
     case 2:
       error=check_Arc();
       break;
     case 3:
       error=check_Arc();
       break;
     case 10:
       break;
     case 90:
       break;
     case 91:
       break;
     default:
       return FUNCTION_NOT_AVAILABLE;
    }
    return error;}

int codeManip::check_M()
{

    switch(M)
    {
    case 0:
      break;
    case 2:
      break;
    case 3:
      break;
    case 4:
      break;
```

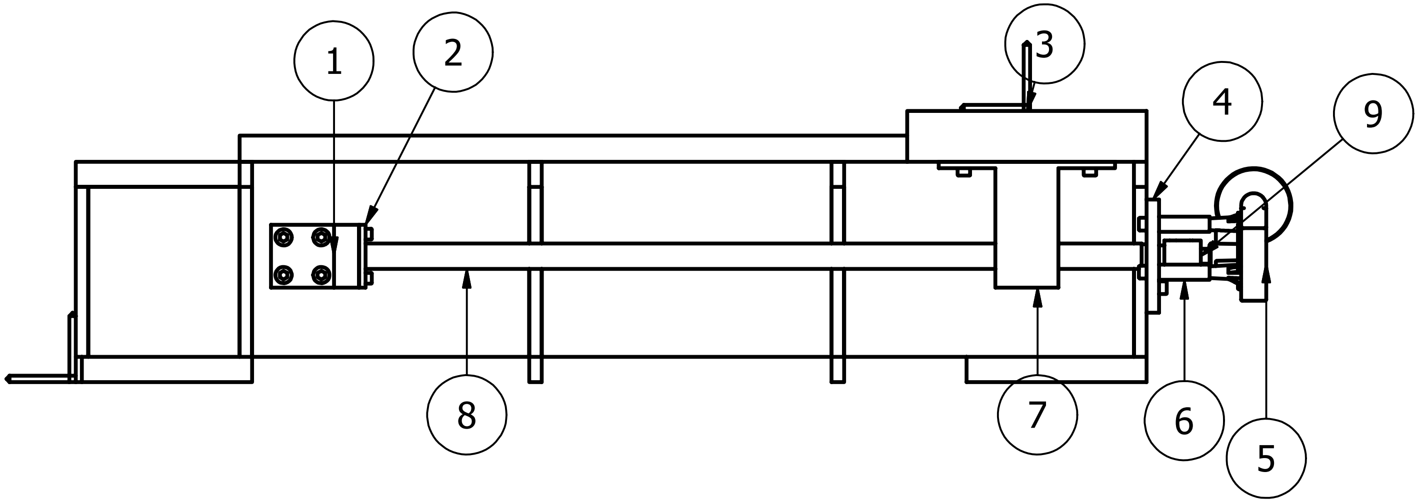
```
    case 5:
      break;
    default:
      return FUNCTION_NOT_AVAILABLE;
    }

    return 0;}


int codeManip::check_Arc()
{
 if(x*y)
    {return 0;}
 else if(x*z)
            {return 0;}
            else  if(y*z)
                          {return 0;}
return INVALID_IN_CONFIGURATION; //return error code if none of the
pairs of axes are active
}
```

<u>//Execute.h (header file for functions associated with the execution of user instructions)</u>

```
#ifndef EXECUTE_H
#define EXECUTE_H
#include <qlineedit.h>
#include <qtextedit.h>
#include <qprogressbar.h>

class LineExecute{
public:
    LineExecute();
    ~LineExecute();
    void resetVariables();
    int Start(int SerialPortSpeed);
    int NumberOfLines();
    int loadFunction(int SerialPortSpeed);
    void DistanceCalculator();
    void setGlobal_Position();
    void getGlobal_Position();
    void ProgramStop();
    void ProgramEnd();
    void goToOrigin(int TIPO);

    QLineEdit *PWarninglineEdit; //pointer to warning line
    QLineEdit *PStatuslineEdit;//pointer to status line
    QLineEdit *PServoPortlineEdit;
    QLineEdit *PSpindlePortlineEdit;
    QLineEdit *PTIPOlineEdit;
    QTextEdit *PcodeEdit;//pointer to code edit box
    QProgressBar *PprogressBar;//pointer to progress bar

    const char *ServoPortName;
    const char *SpindlePortName;
    const char *InterpolationCycleTime;

private:

    int N;
    int M;
    int G;
    float A;
```

```
    float B;
    float C;
    float X;
    float Y;
    float Z;
    float U;
    float V;
    float W;
    float S;
    float F;
    float I;
    float J;
    float K;
    float R;

    //Variables for transmission in float

    int Mp;
    int Gp;
    int Sp;
    float Ap;
    float Bp;
    float Cp;
    float Xp;
    float Yp;
    float Zp;
    float Up;
    float Vp;
    float Wp;
    float Fp;
    float Ip;
    float Jp;
    float Kp;
    float Rp;

    //absoute Programming
    int ABS; //Absolute Programming Flag
    float absA;
    float absB;
    float absC;
    float absX;
    float absY;
    float absZ;
    float absU;
    float absV;
    float absW;

};
#endif
```

Parts List		
ITEM	QTY	PART NUMBER
1	1	Bearing housing for bed
2	1	Bearing housing cap
3	1	Bed Carrige
4	1	motor plate
5	1	Wiper Motor
6	3	Motor spacer
7	1	Carriage Part 2
8	1	Lead screw
9	1	Coupling
20	2	Coordinate System



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:6 UNITS : mm	TITLE New Base Assembly 1
		Date | Checked	PROJECT RMS Project
	Project Supervisor		
	Workshop Technician		STUDENT NAME Jared Padayachee
	Technical Manager		TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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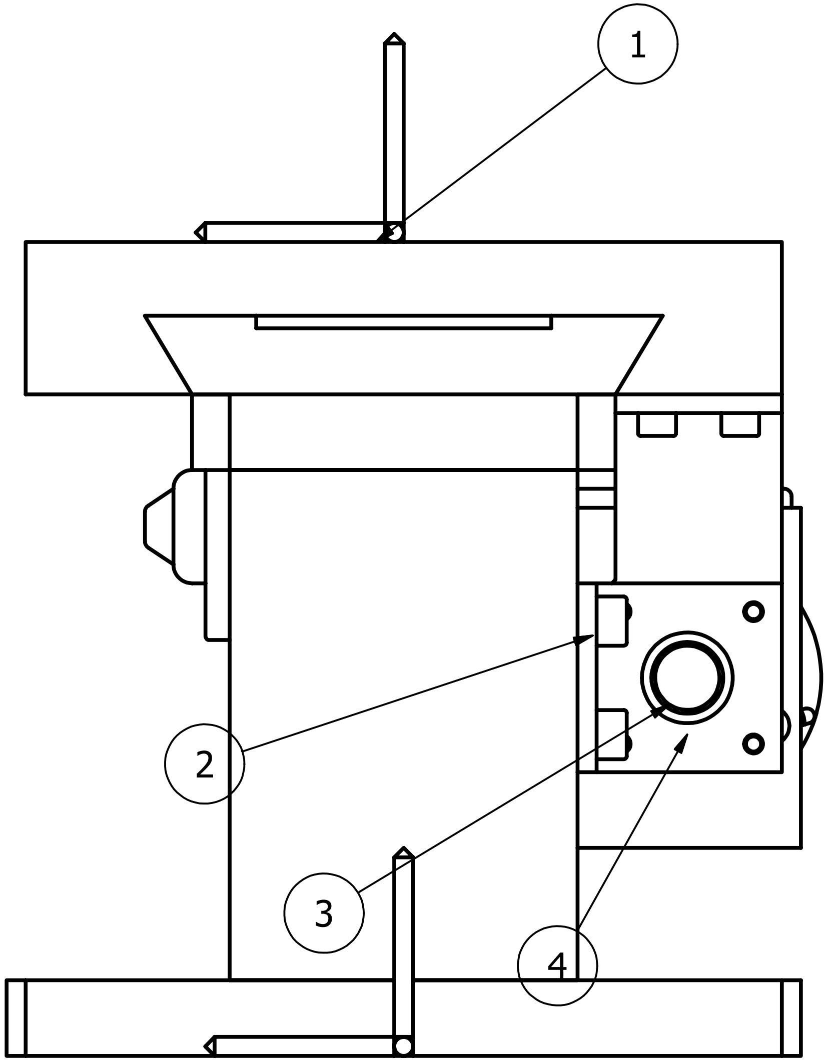

Parts List		
ITEM	QTY	PART NUMBER
1	1	Bed Carrige
2	1	Bed Carriage Part 2
3	1	Lead screw
4	1	Brass sleeve
20	2	Coordinate System

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:2 UNITS : mm	TITLE Bed Carriage Assembly
		Date / Checked	PROJECT RMS Project
	Project Supervisor		
	Workshop Technician		STUDENT NAME Jared Padayachee
	Technical Manager		TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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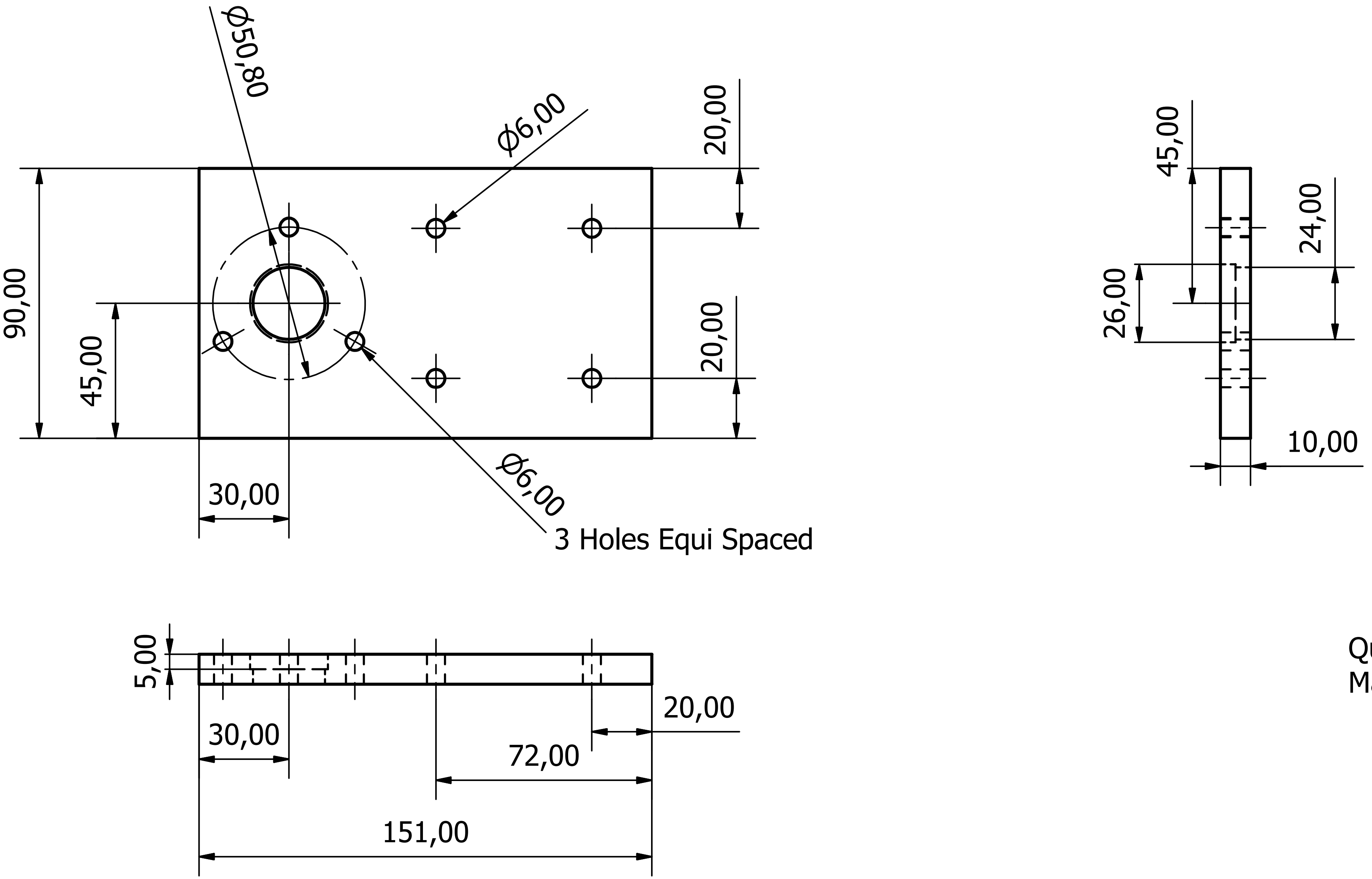
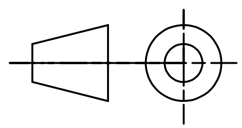
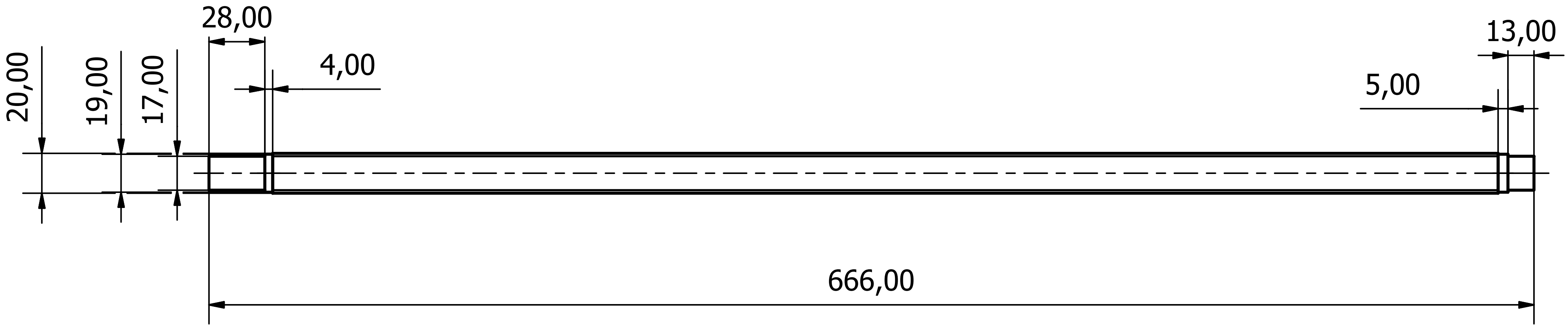
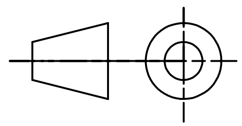


Quantity: 2
Material: Steel Supplied



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:2 UNITS : mm		TITLE Bed Carriage - Part 1
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za





Quantity:2
Material: Threaded Bar Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:3		TITLE Lead Screw - Base Shared Components
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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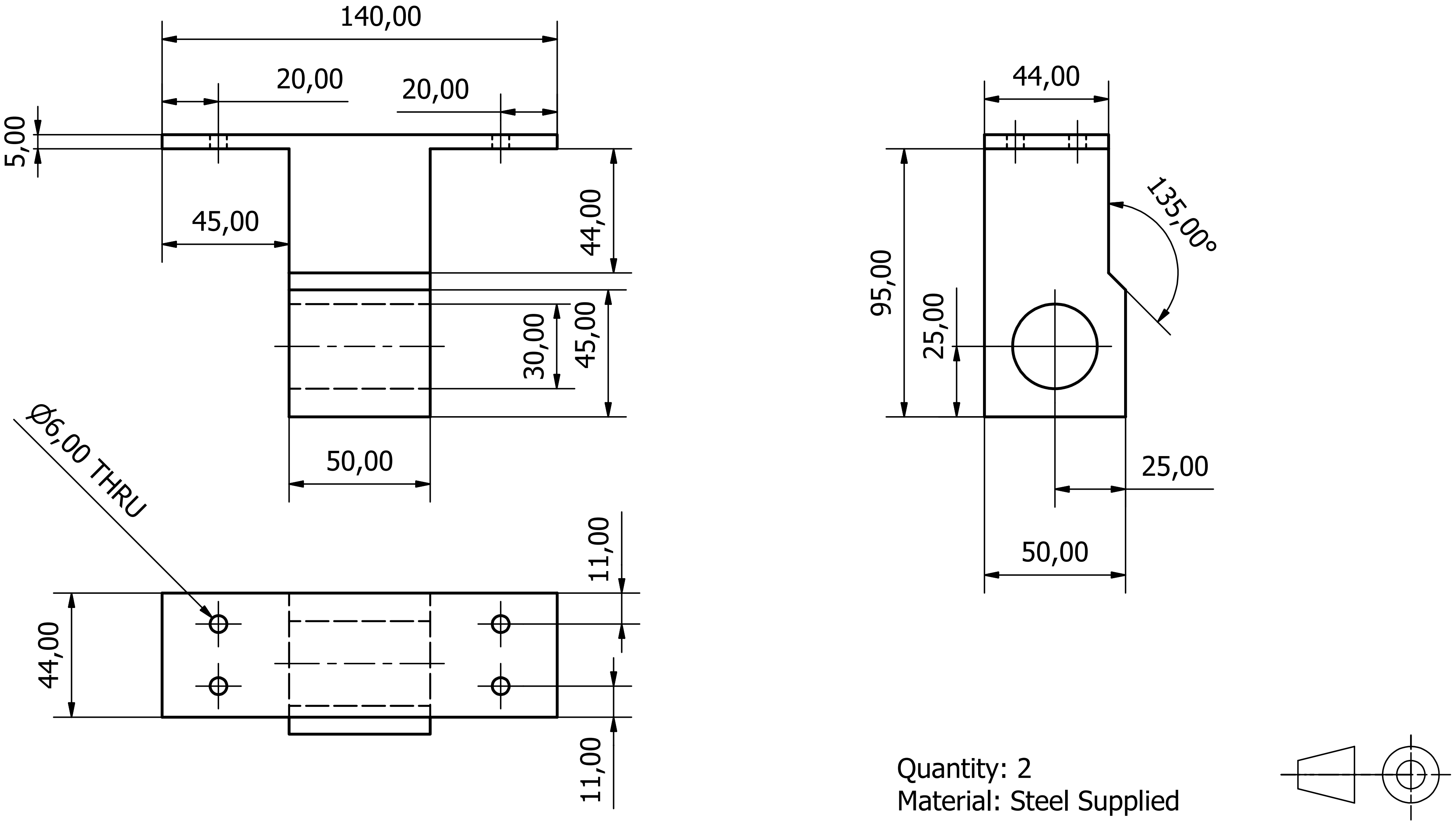

Quantity: 2
Material: Steel Supplied

University of Kwa-Zulu Natal
School of Mechanical Engineering

Orthographic Projection	SCALE 1:2		TITLE Bed Carriage - Part 2
OR	UNITS : mm		PROJECT RMS Project
	Date	Checked	
Project Supervisor			
Workshop Technician			STUDENT NAME Jared Padayachee
Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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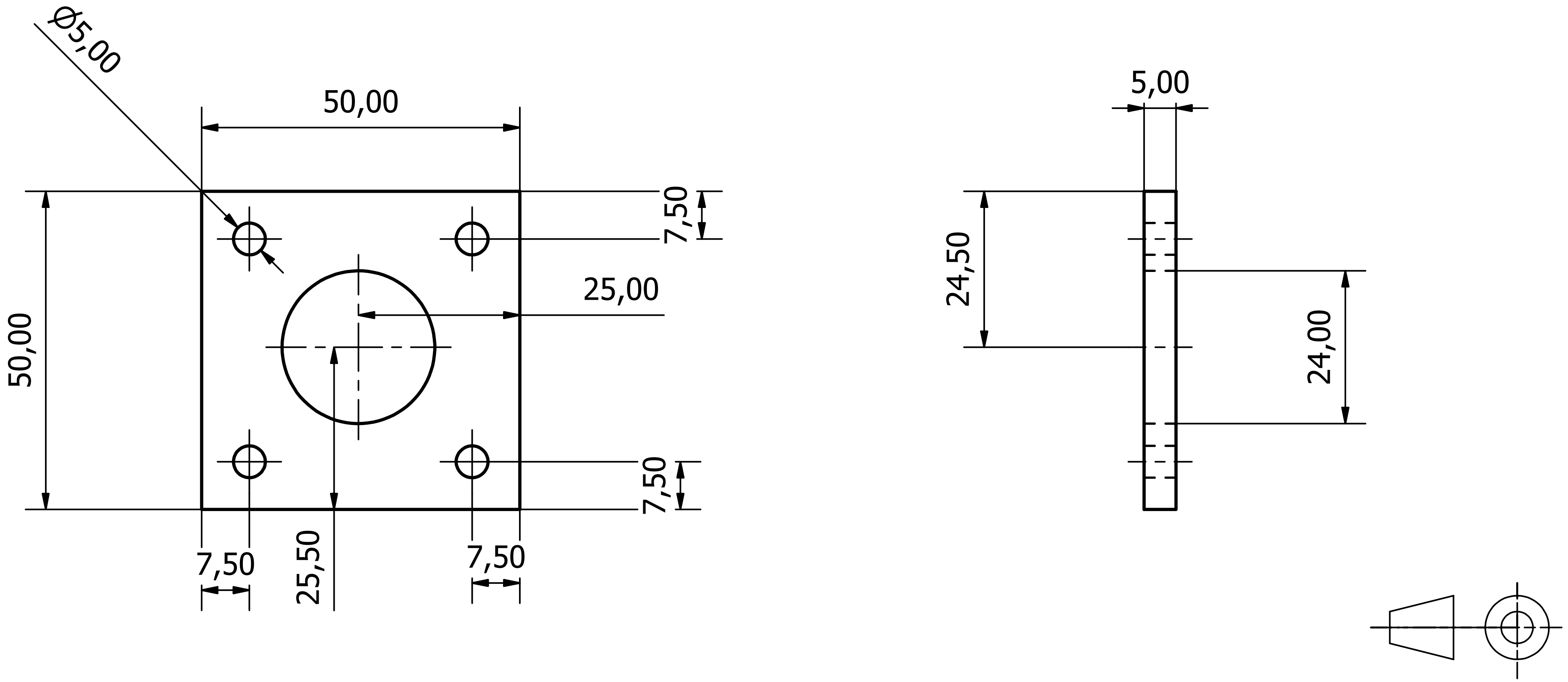
Quantity: 2
Material: Steel Supplied



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Bearing Housing Cap
	OR	UNITS : mm		PROJECT RMS Project
		Date	Checked	
	Project Supervisor			STUDENT NAME Jared Padayachee
	Workshop Technician			
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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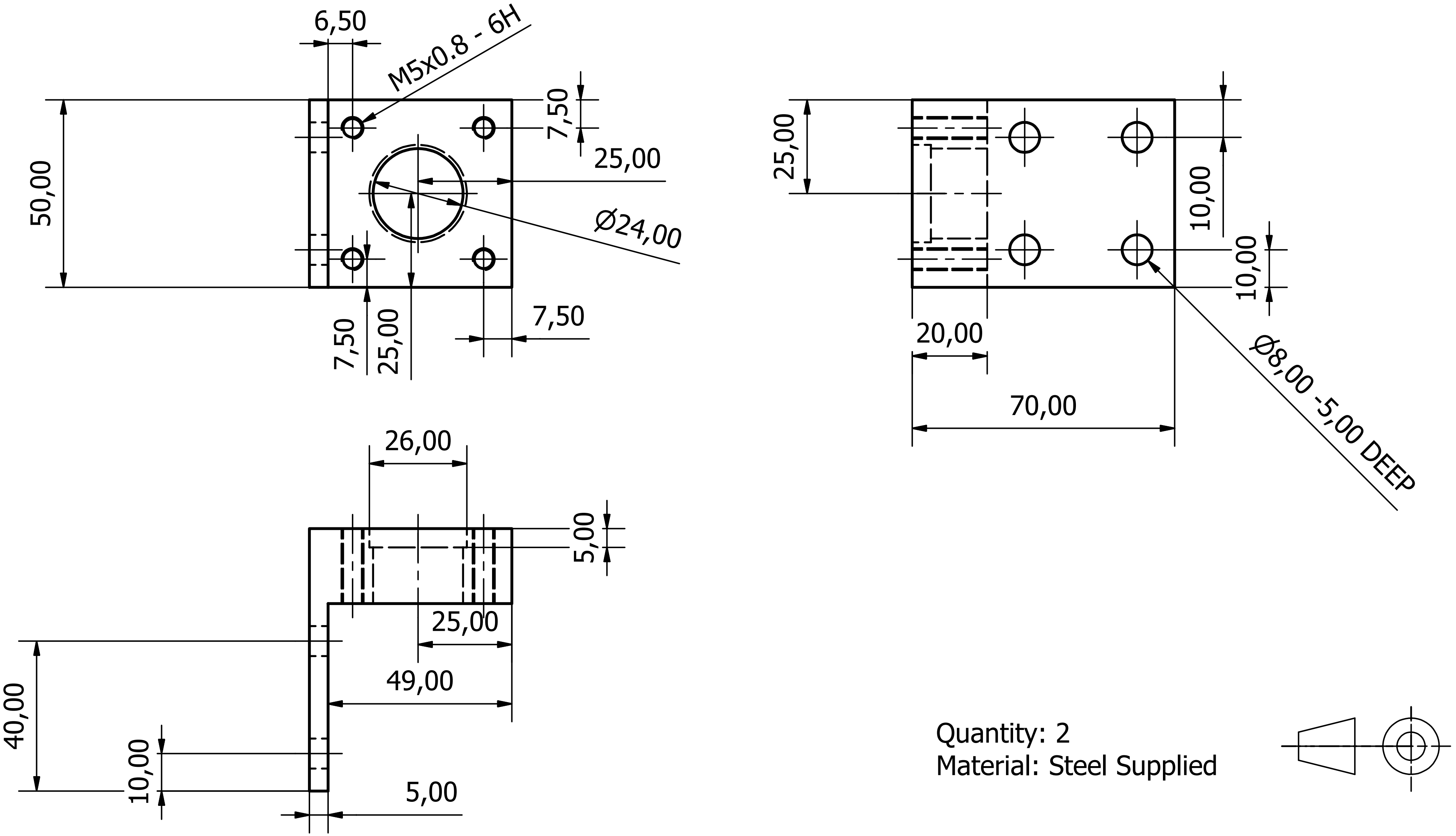

Quantity: 2
Material: Steel Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1.5	TITLE Bearing Housing For Bed
	OR	UNITS : mm	
		Date | Checked	PROJECT RMS Project
	Project Supervisor		
	Workshop Technician		STUDENT NAME Jared Padayachee
	Technical Manager		TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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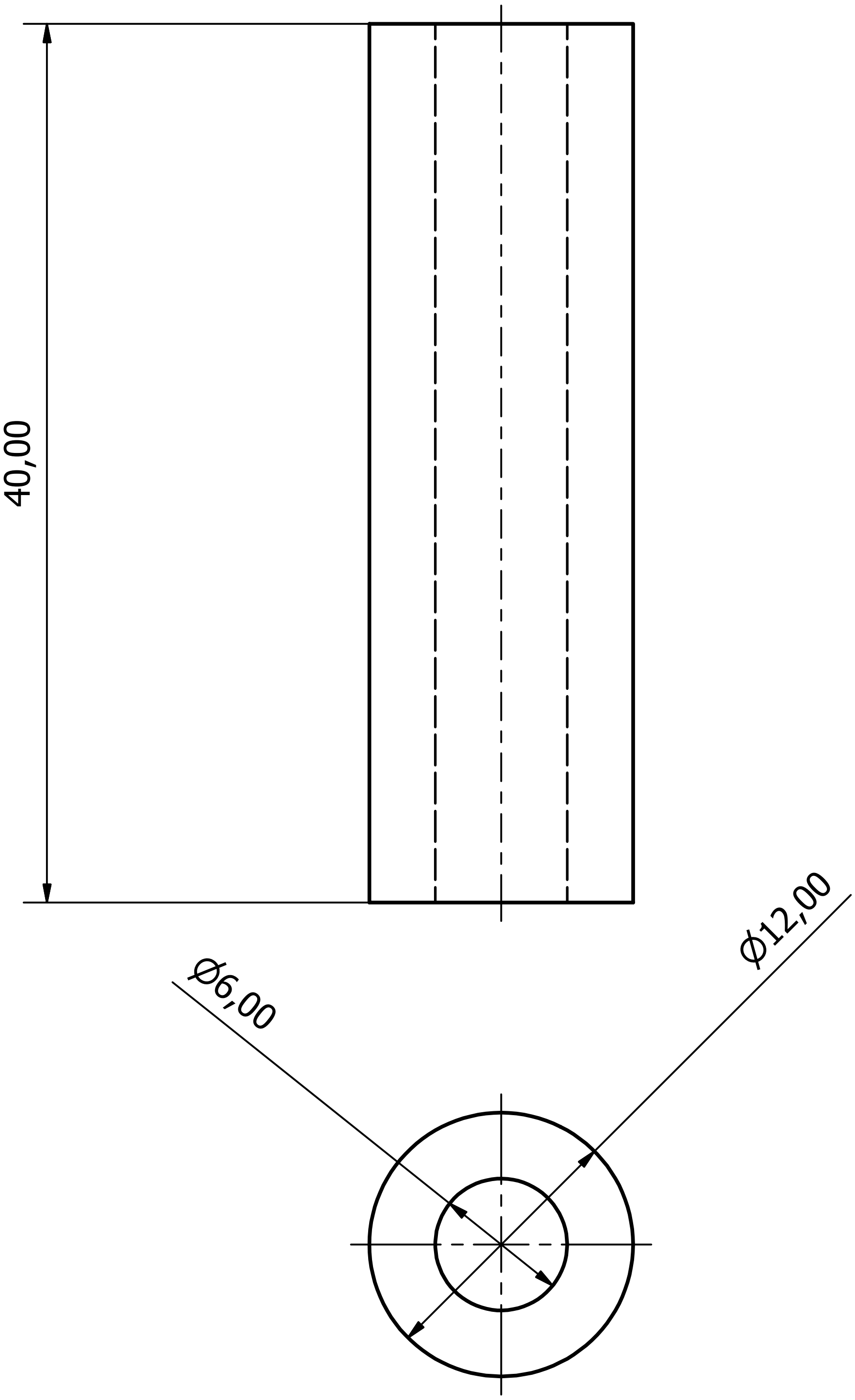
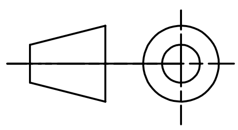


Quantity: 6
Material: Steel Supplied



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 3:1		TITLE Motor Spacer - Base Shared Components
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399

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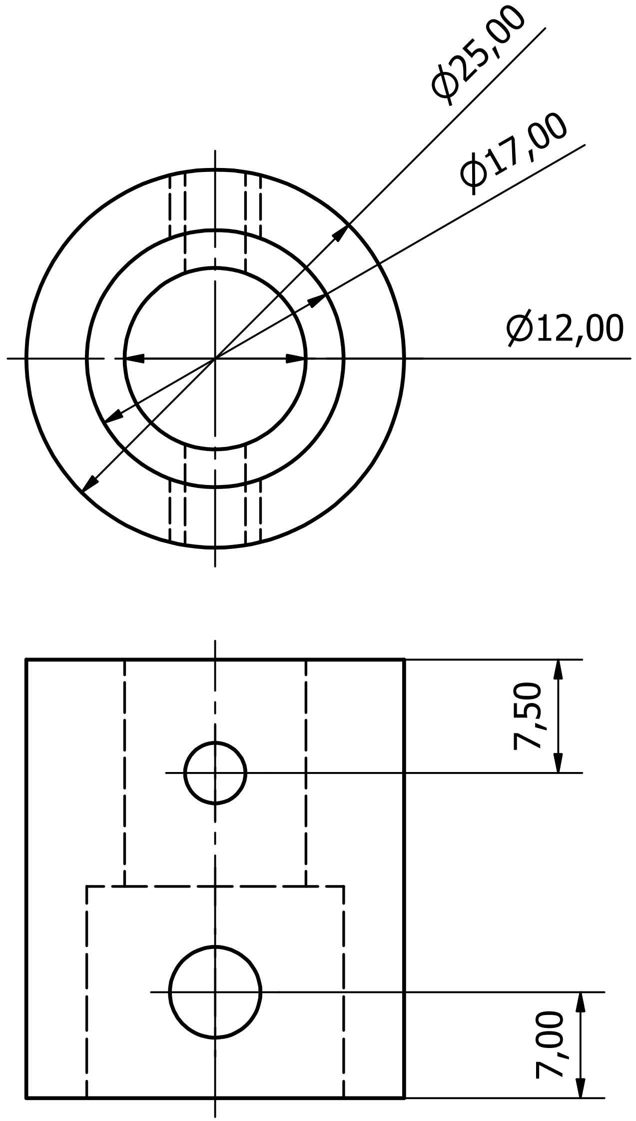

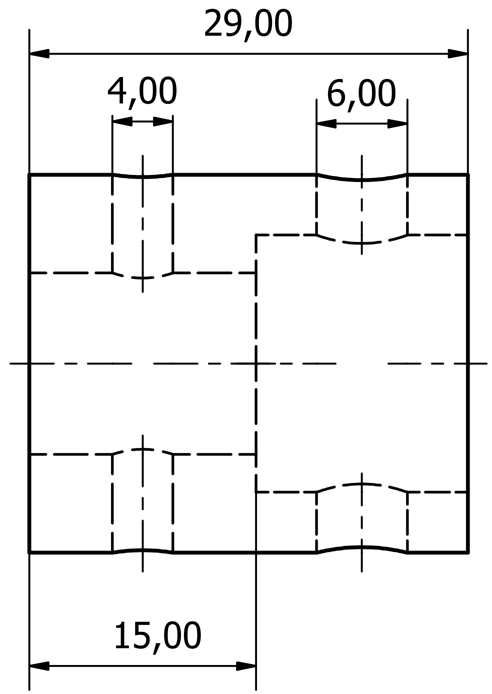

Quantity: 2
Material: Steel Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 2:1		TITLE Coupling-Base Shared Components
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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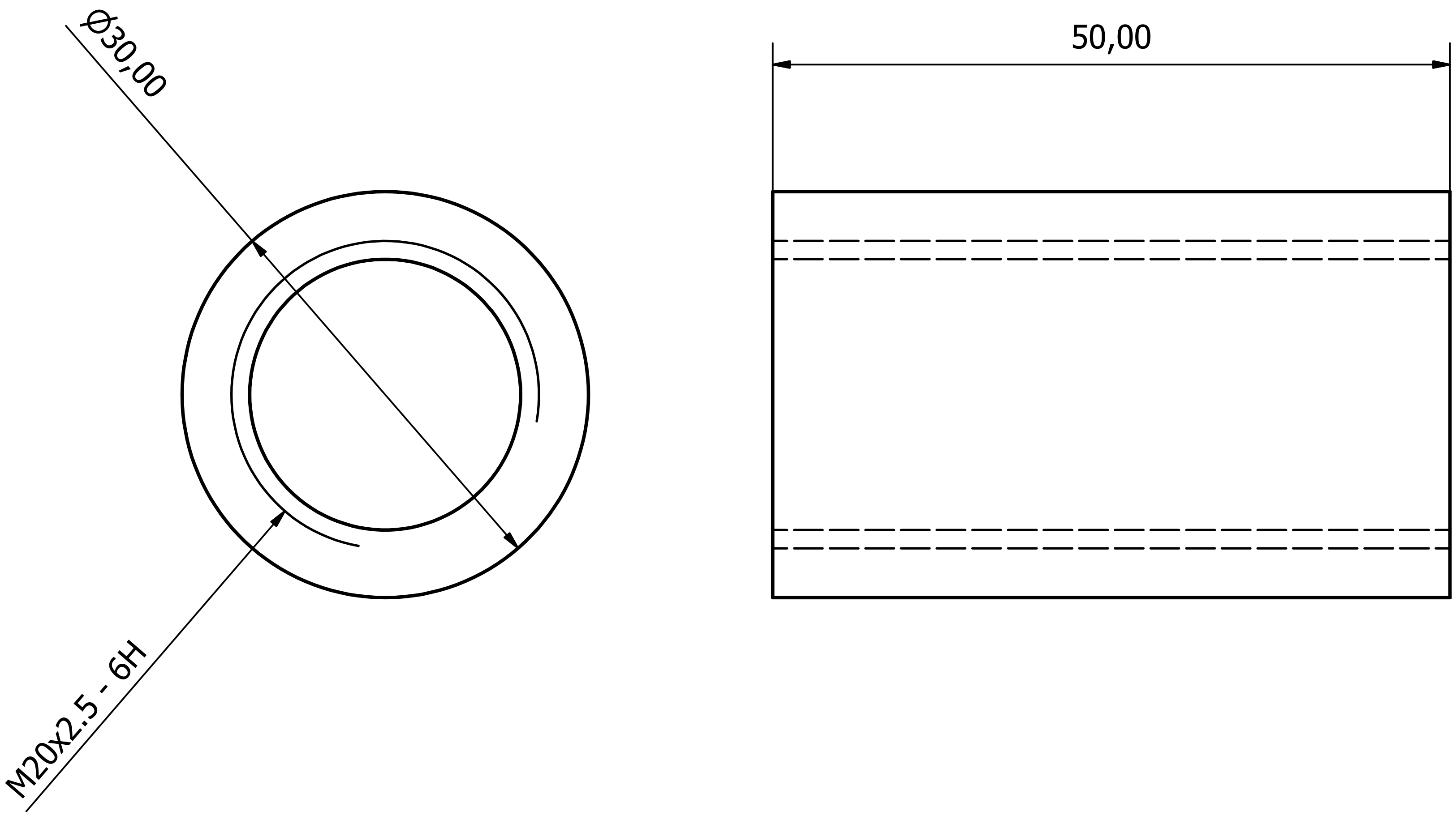
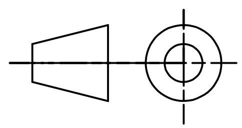
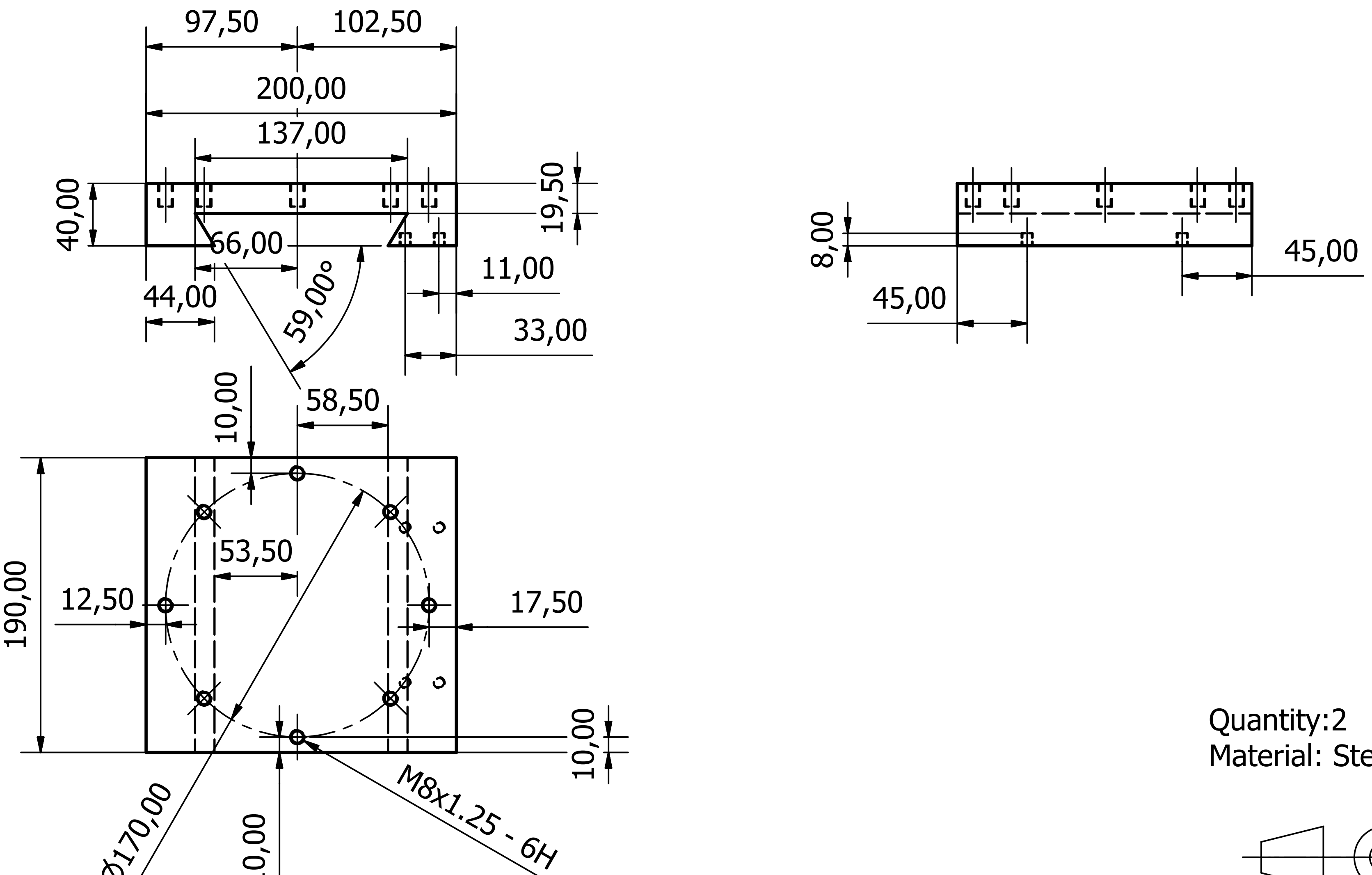


Quantity: 2
Material: Brass Supplied

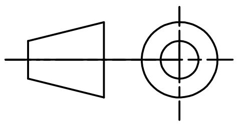


University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 2:1		TITLE Brass Sleeve- Base Shared Components
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

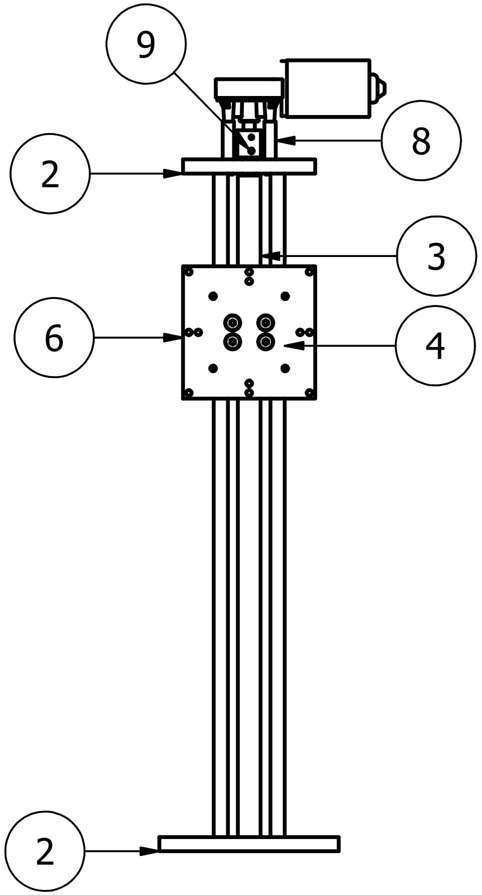


8 Tapped holes Equi Spaced - Depth 15 mm

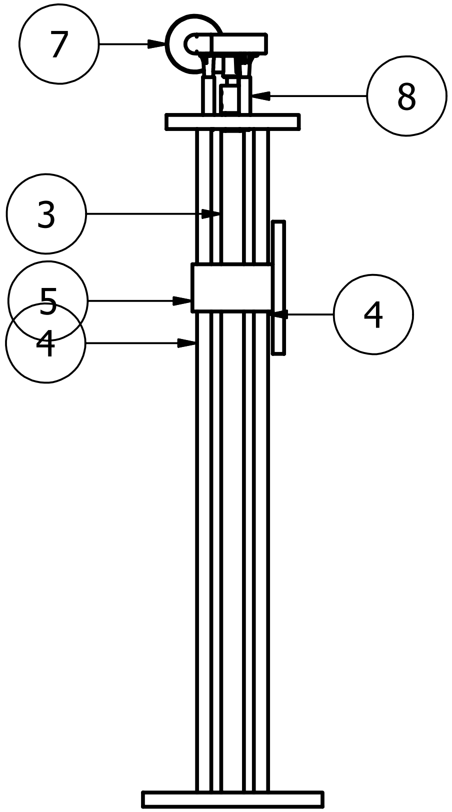
Quantity:2
Material: Steel Supplied



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:4		TITLE Bed Carriage - Part 1 - New Base
	OR	UNITS : mm		PROJECT RMS Project
		Date	Checked	
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



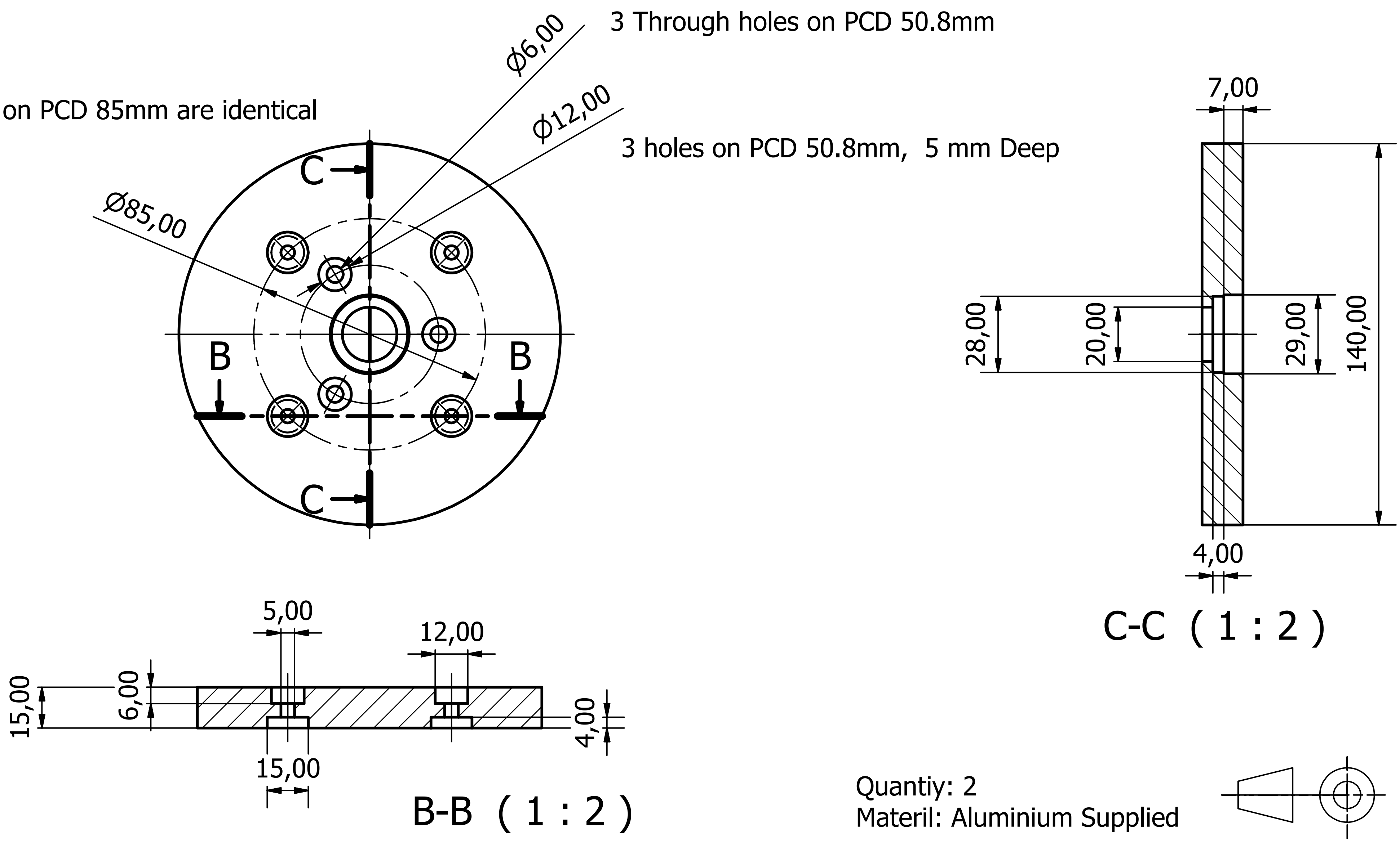
Front



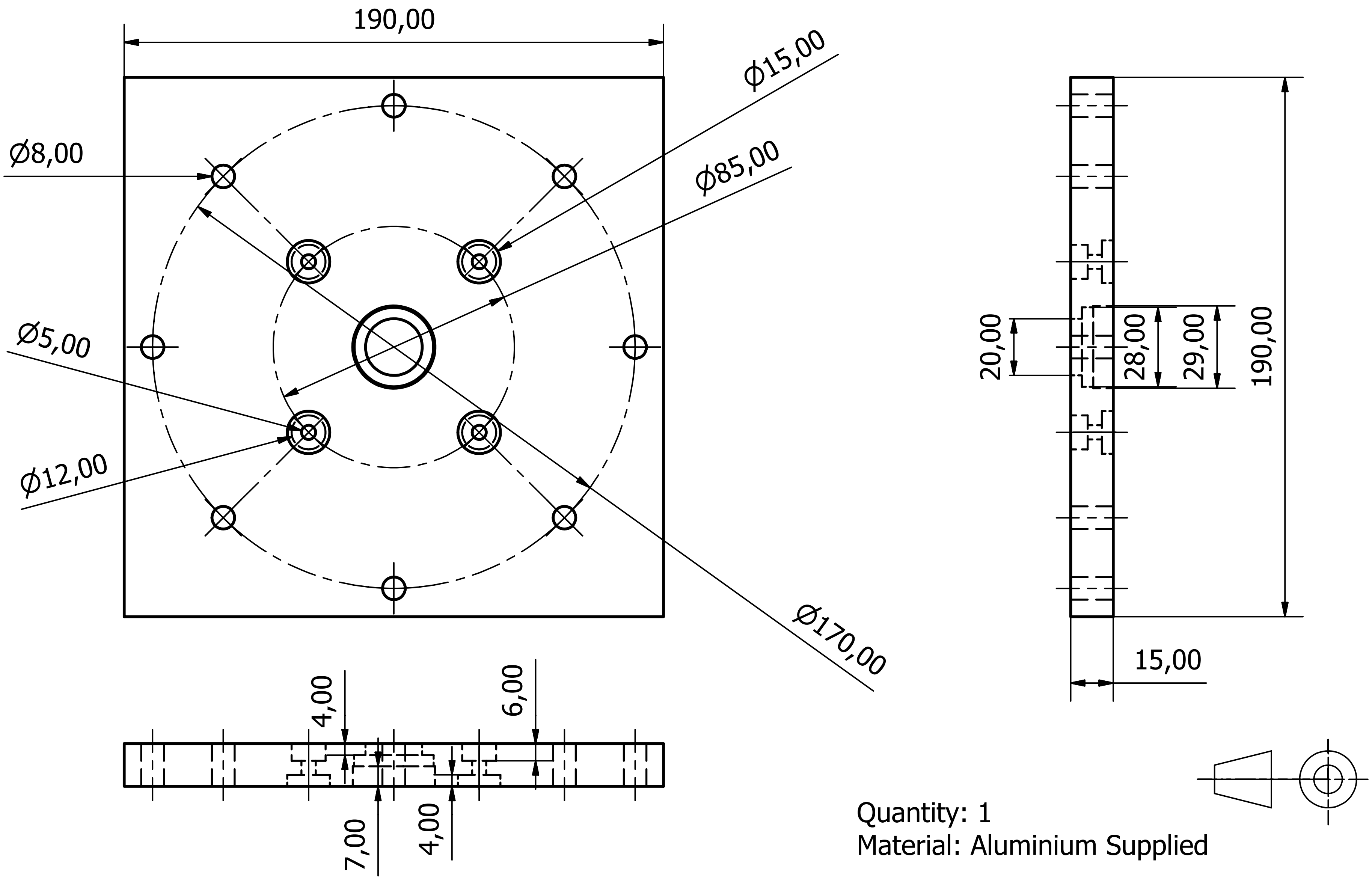
Left View

Parts List		
ITEM	QTY	PART NUMBER
1	1	Column Cap
2	1	Column Base
3	1	Lead screw
4	4	Guide Rod
5	1	Carriage
6	1	Carriage adaptor plate
7	1	Wiper Motor
8	3	Motor spacer
9	1	Coupling

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:8 UNITS : mm		TITLE Column Assembly 1
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Column Cap
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Quantity: 1
Material: Aluminium Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Column Base- Column
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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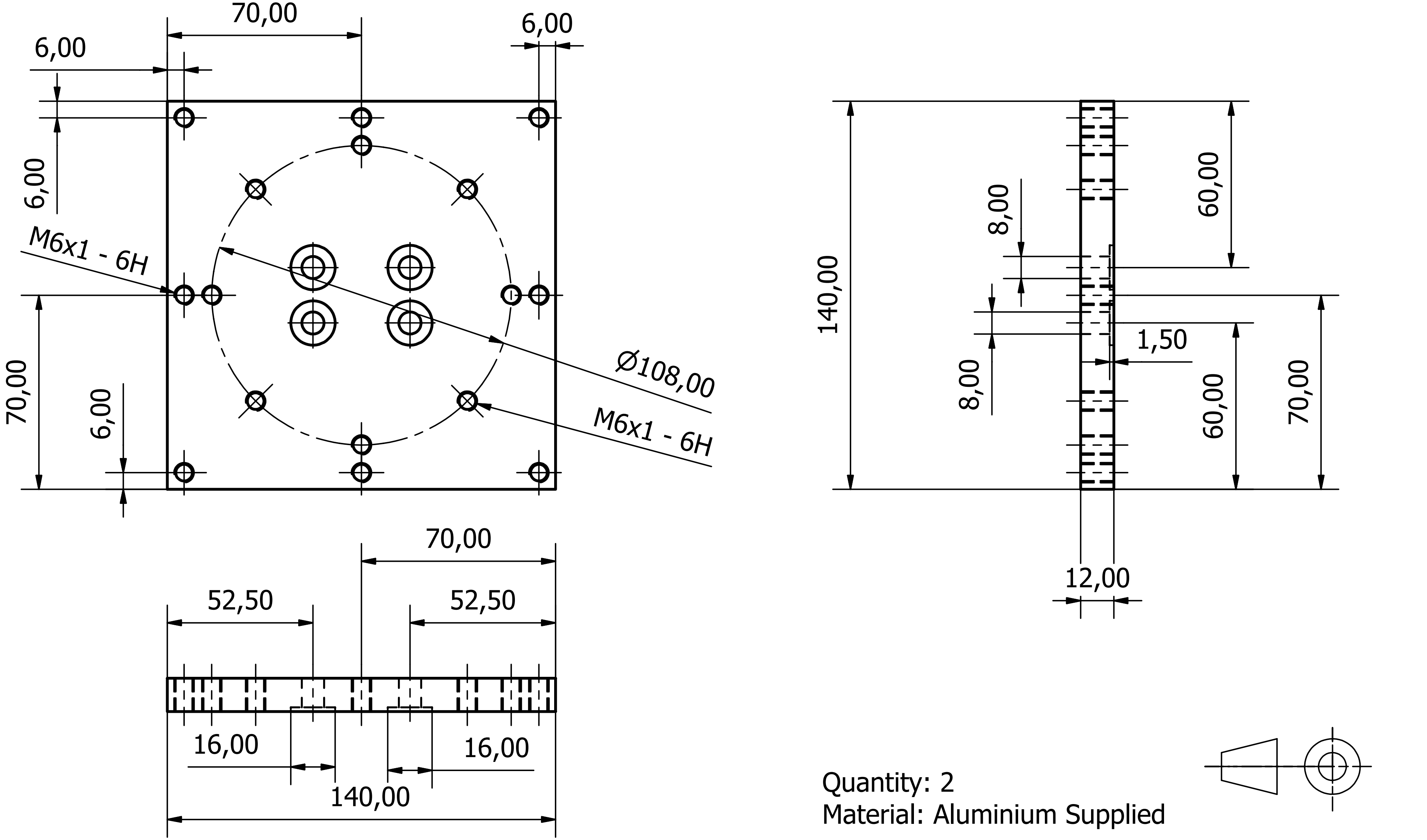

Quantity: 2
Material: Aluminium Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:2 UNITS : mm		TITLE Carriage Adaptor Plate - Column
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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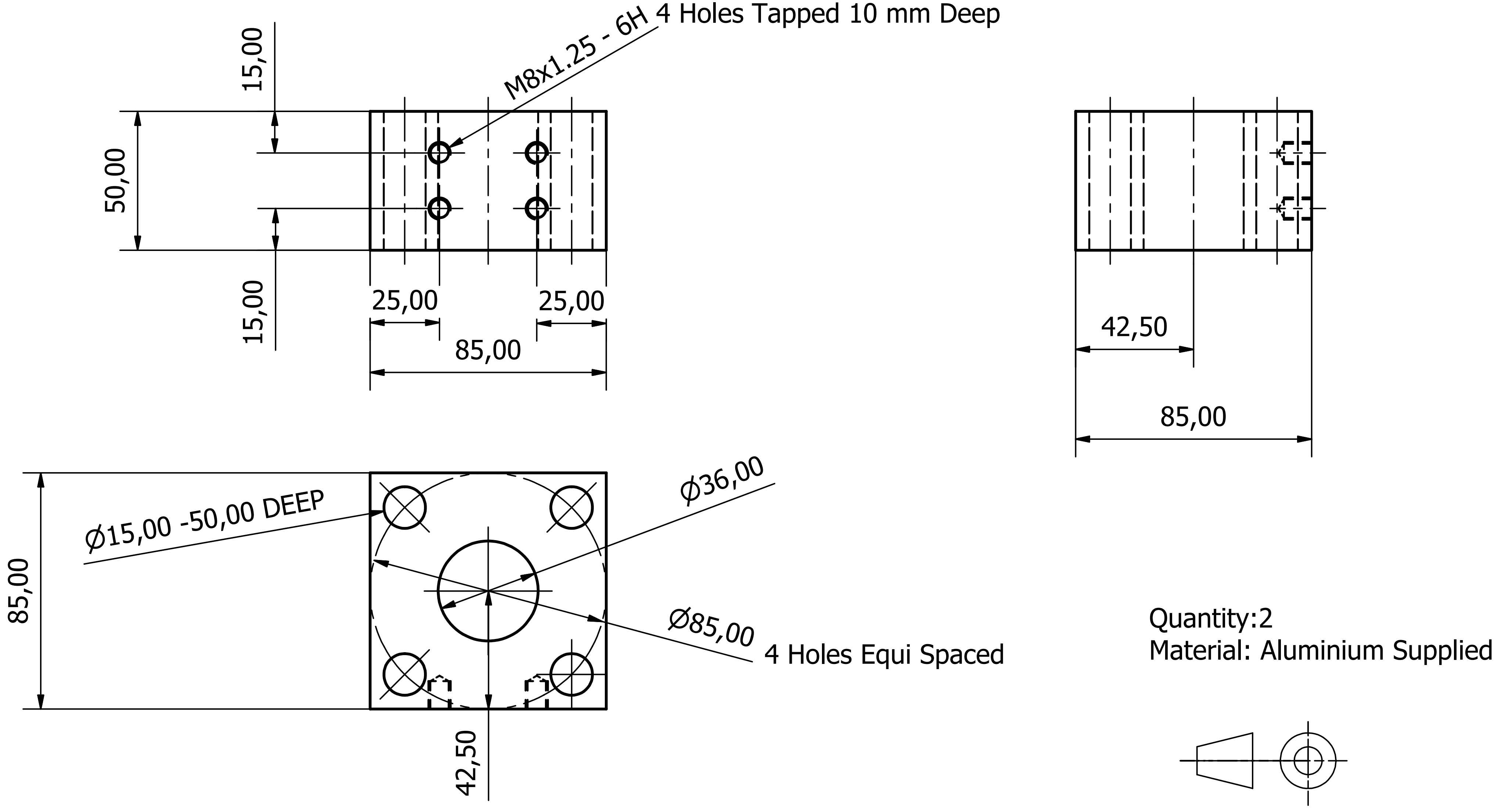
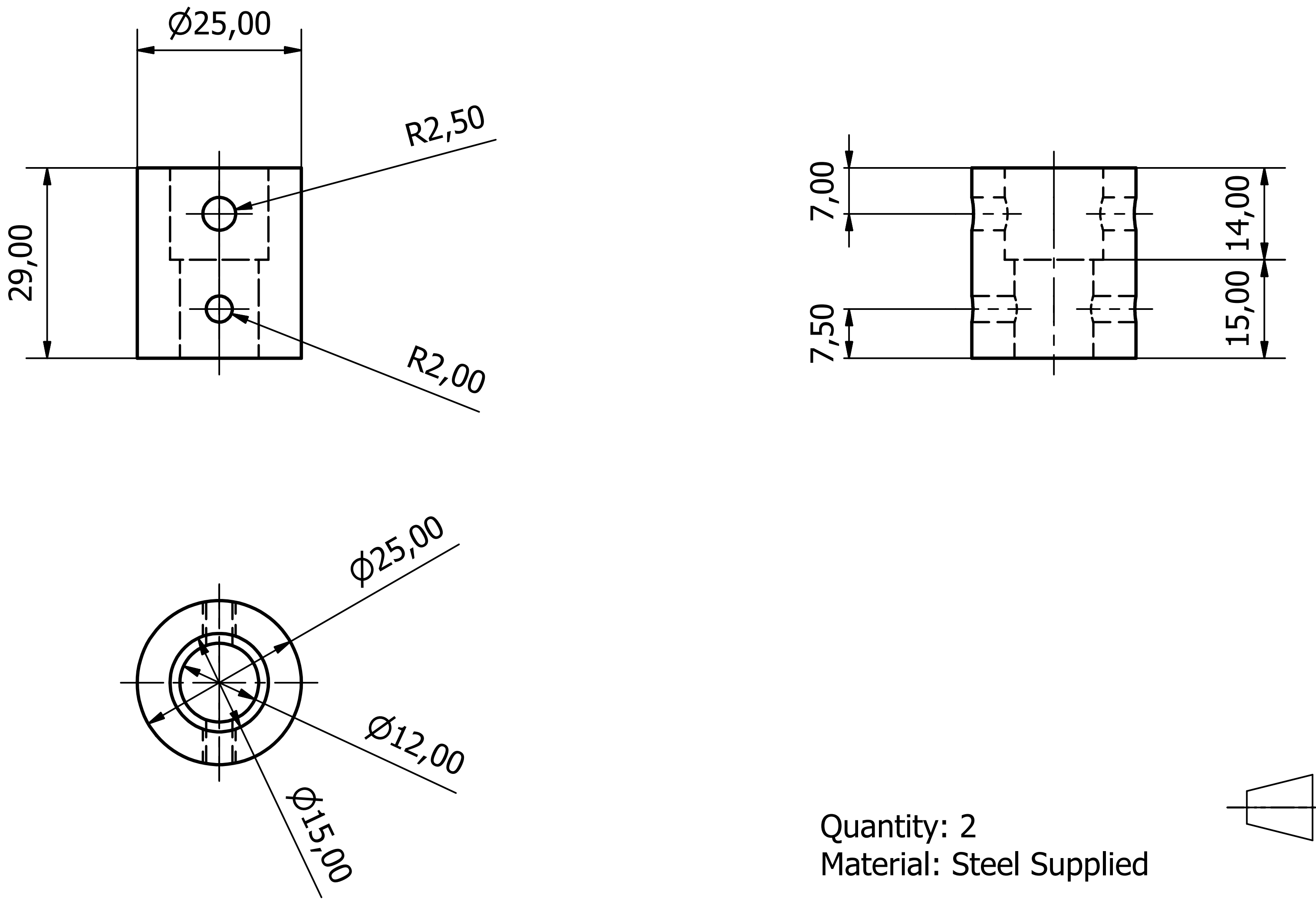


University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Carriage - Column
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Quantity: 2
Material: Steel Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Coupling for Column
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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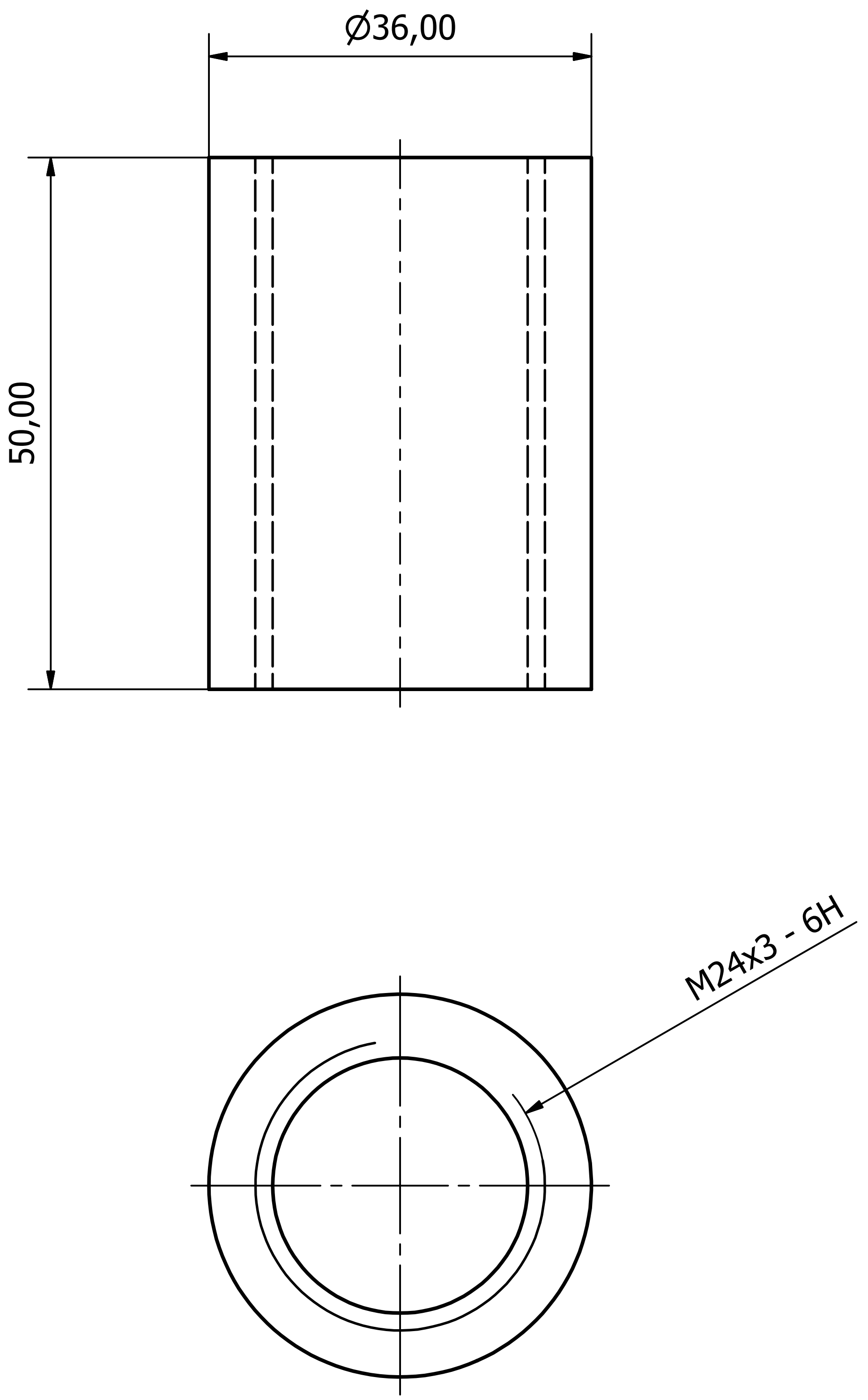

Quantity: 2
Material: Brass Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1.5:1		TITLE collar for column
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399

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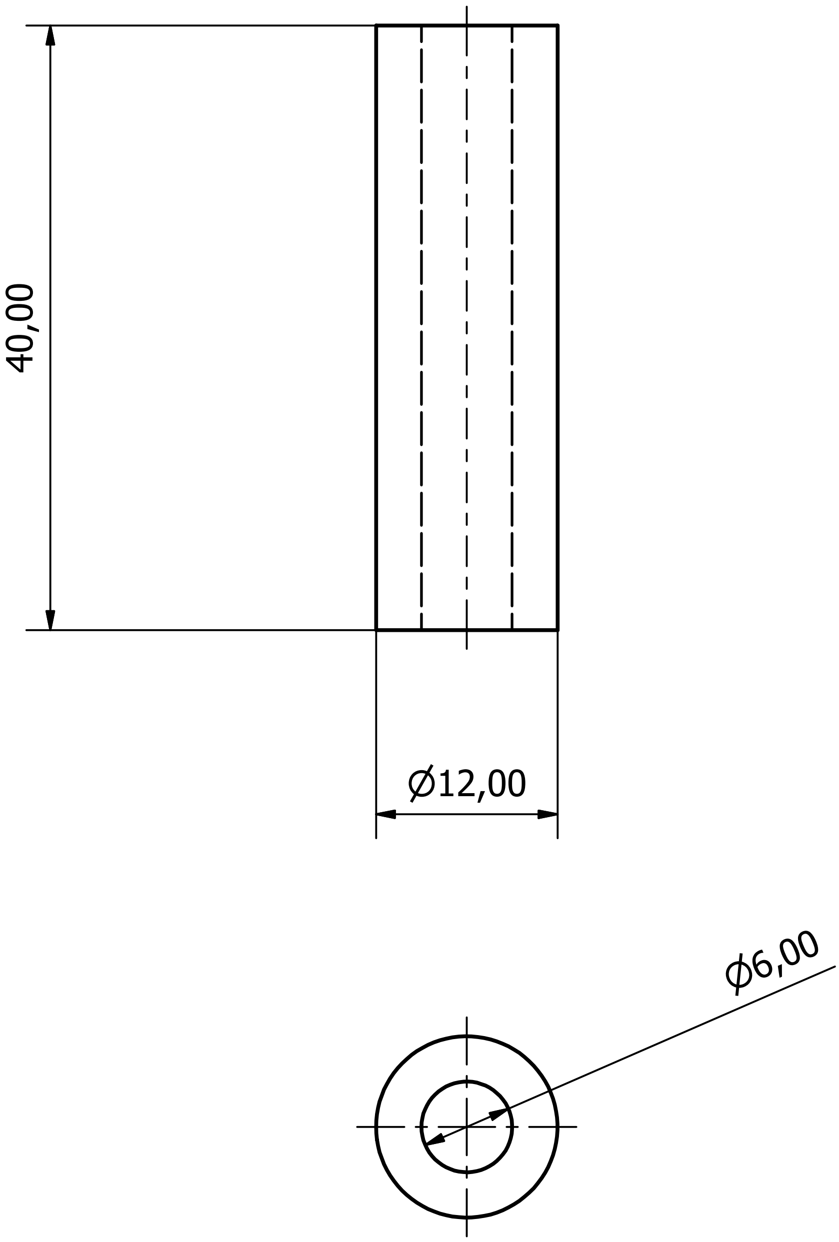
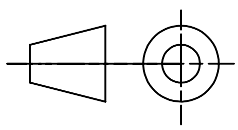
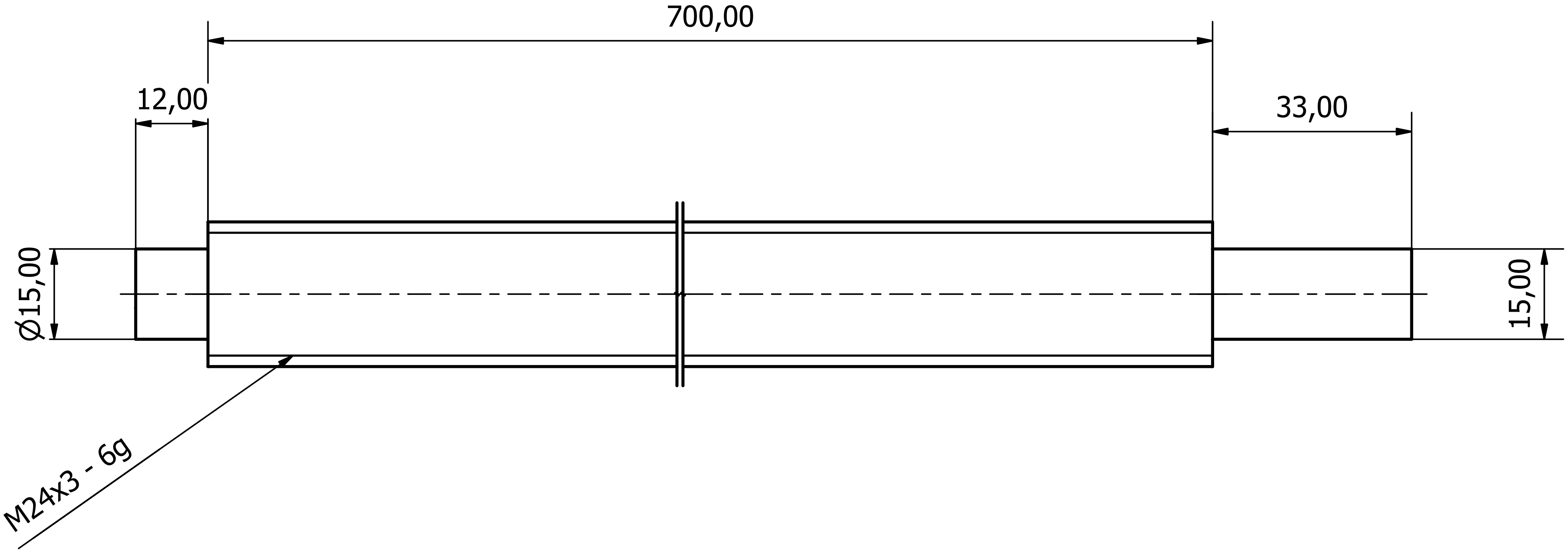


Quantity: 6
Material: Steel Supplied



University of Kwa-Zulu Natal	Orthographic Projection	SCALE 2:1		TITLE Motor Spacer
	OR	UNITS : mm		
School of Mechanical Engineering		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399



Quantity:2
Material: Threaded Bar Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Lead Screw - Column
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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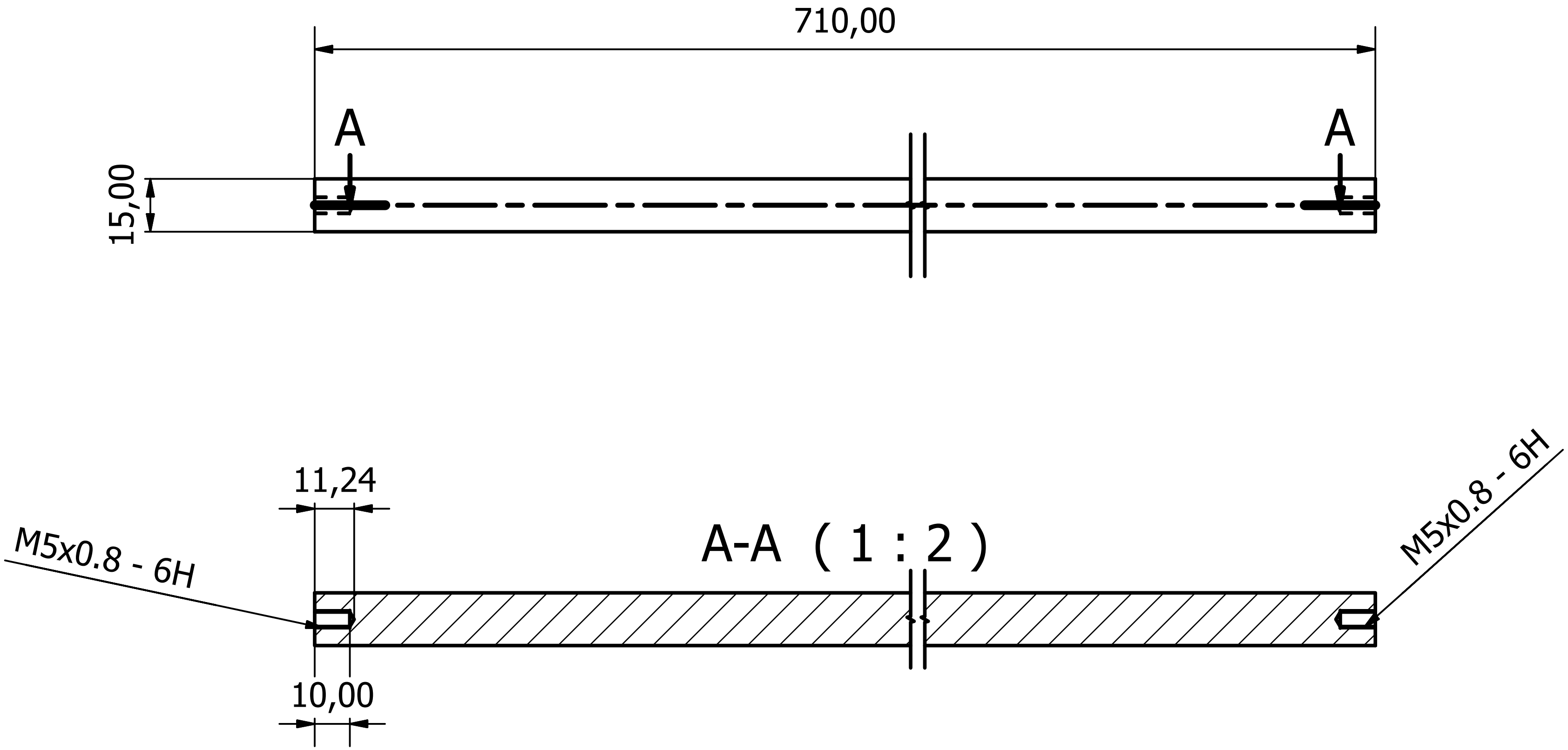
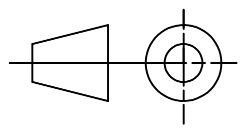
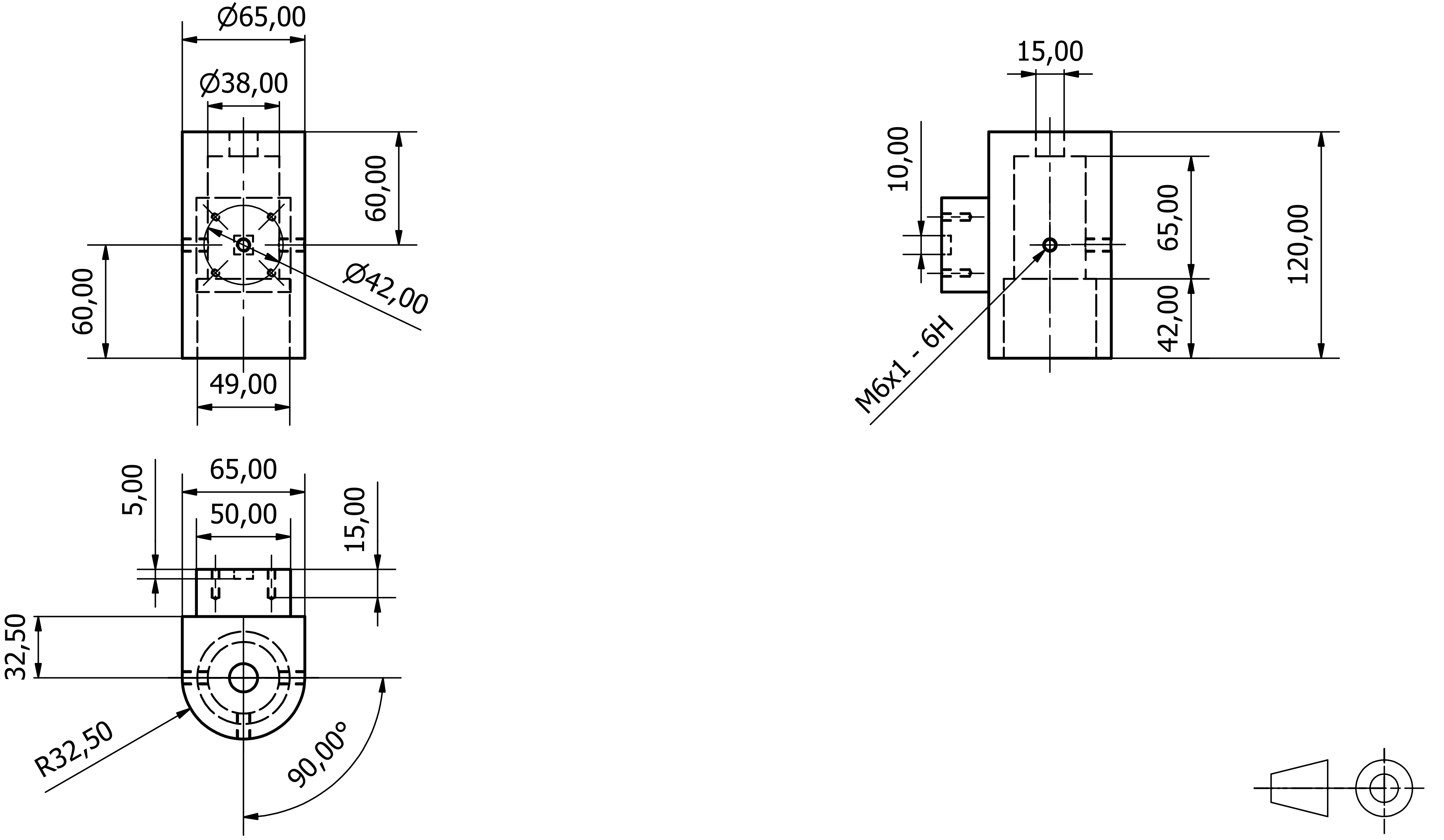


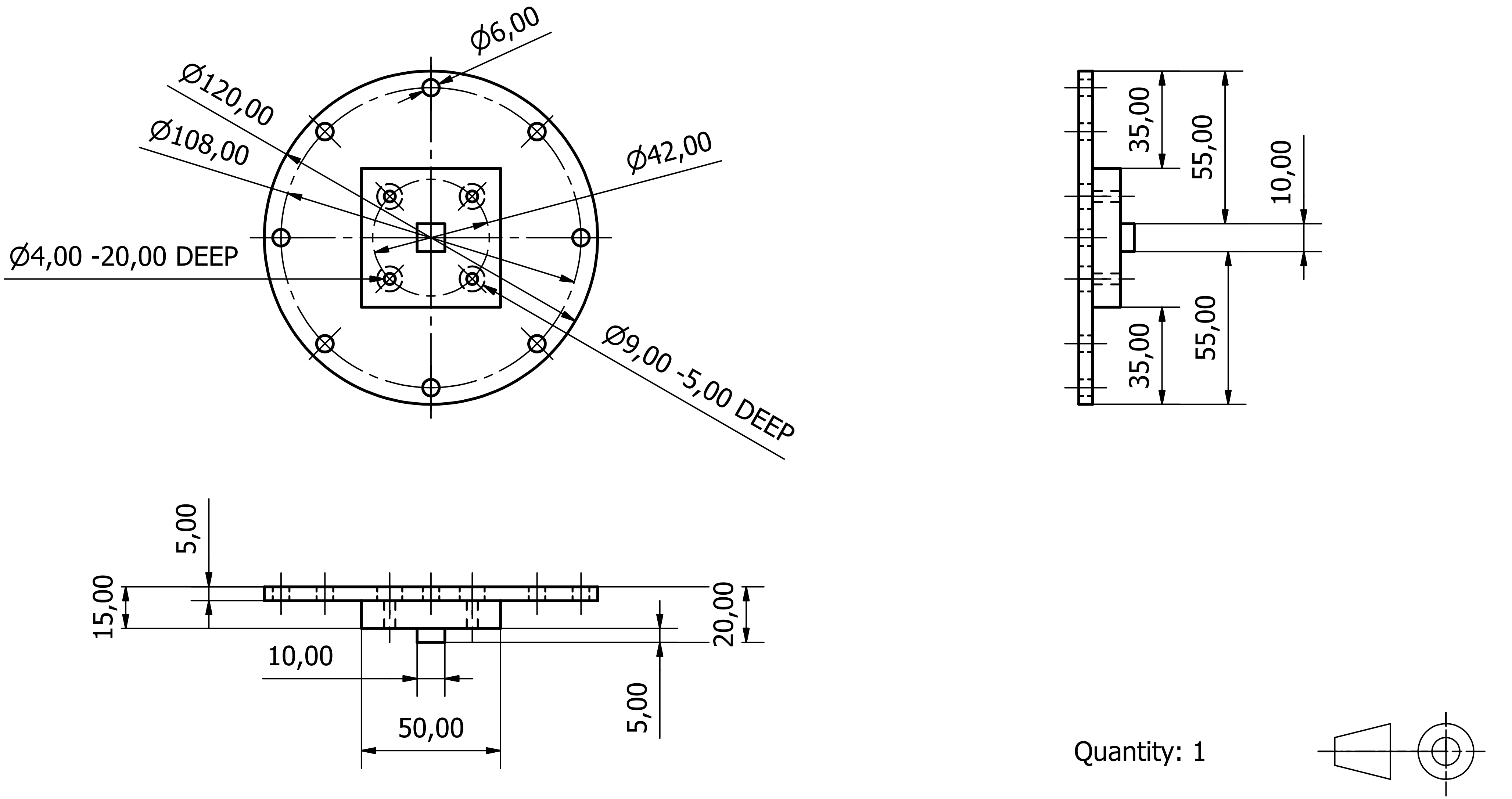
Quantity: 8
Material: Rod Supplied



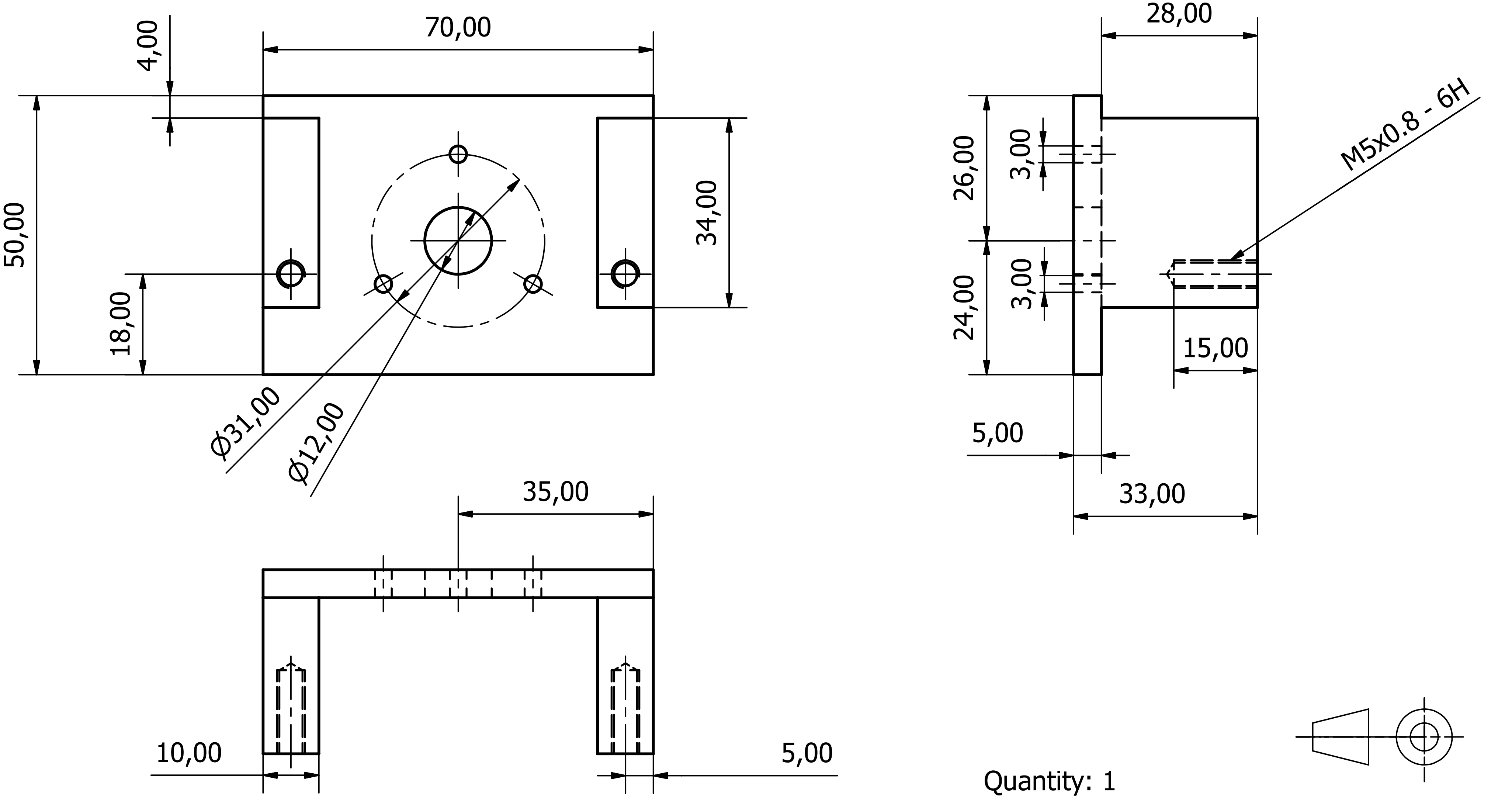
University of Kwa-Zulu Natal	Orthographic Projection	SCALE 1:2		TITLE Guide rod - Column
	OR	UNITS : mm		
School of Mechanical Engineering		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:3		TITLE Drill Cutter housing
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

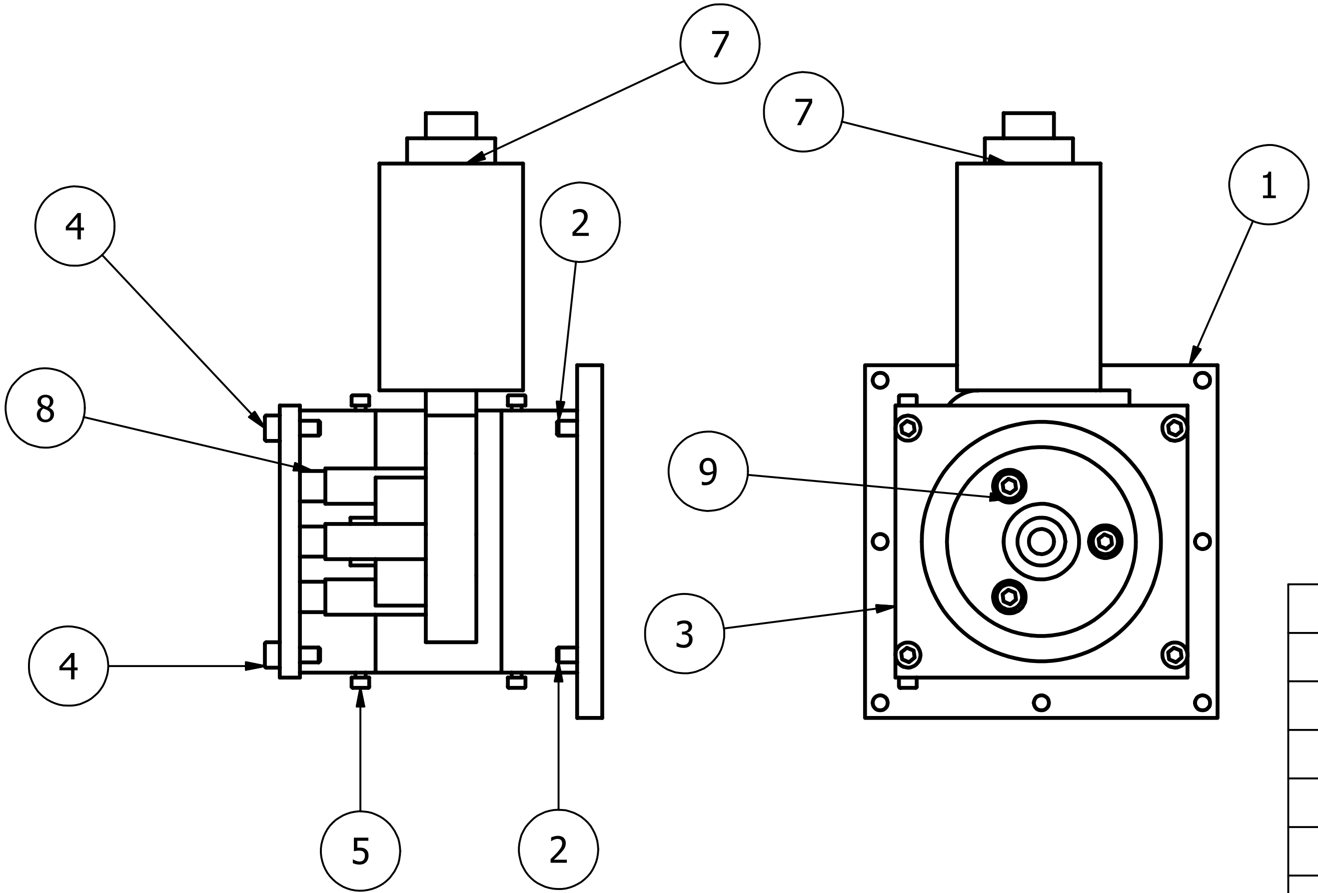


University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Drill cutter - base
	OR	UNITS : mm		PROJECT RMS Project
		Date	Checked	
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



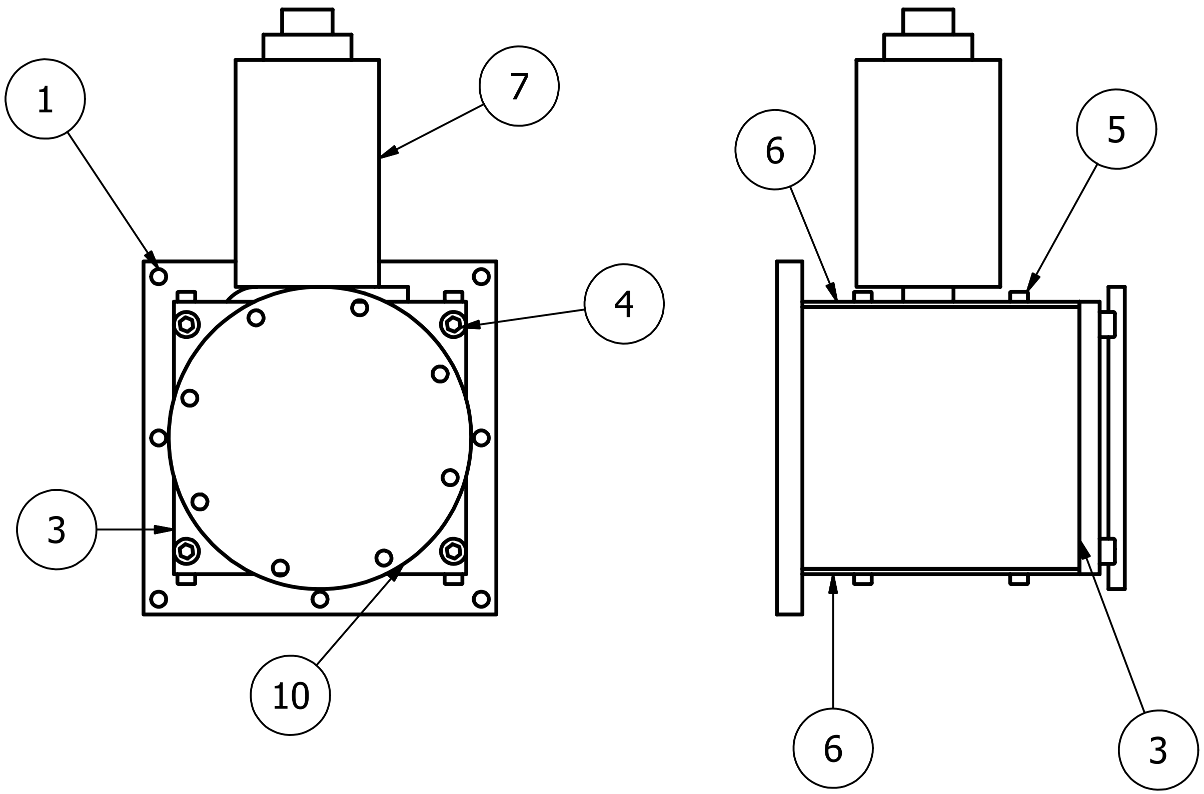
Quantity: 1
Material : Steel supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Motor Mounting - tool post
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Parts List		
ITEM	QTY	PART NUMBER
1	1	Rotary lower plate
2	4	ISO 4762 - M6 x 12
3	2	Rotary-Side plates
4	4	ISO 4762 - M6 x 16
5	8	ISO 4762 - M4 x 8
6	2	Cover
7	1	Small motor
8	3	Motor spacer
9	3	ISO 4762 - M6 x 20
10	1	Interface coupling

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:3 UNITS : mm	TITLE Rotary Assembly 2
		Date	Checked	PROJECT RMS Project
	Project Supervisor			STUDENT NAME Jared Padayachee
	Workshop Technician			TEL NO. 1227
	Technical Manager			EMAIL 203505399@ukzn.ac.za



Parts List		
ITEM	QTY	PART NUMBER
1	1	Rotary lower plate
2	4	ISO 4762 - M6 x 12
3	2	Rotary-Side plates
4	4	ISO 4762 - M6 x 16
5	8	ISO 4762 - M4 x 8
6	2	Cover
7	1	Small motor
8	3	Motor spacer
9	3	ISO 4762 - M6 x 20
10	1	Interface coupling

University of Kwa-Zulu Natal

School of Mechanical Engineering

Orthographic Projection

OR

SCALE 1:3

UNITS : mm

	Date	Checked
Project Supervisor		
Workshop Technician		
Technical Manager		

TITLE Rotary Assembly 1

PROJECT RMS Project

STUDENT NAME Jared Padayachee

TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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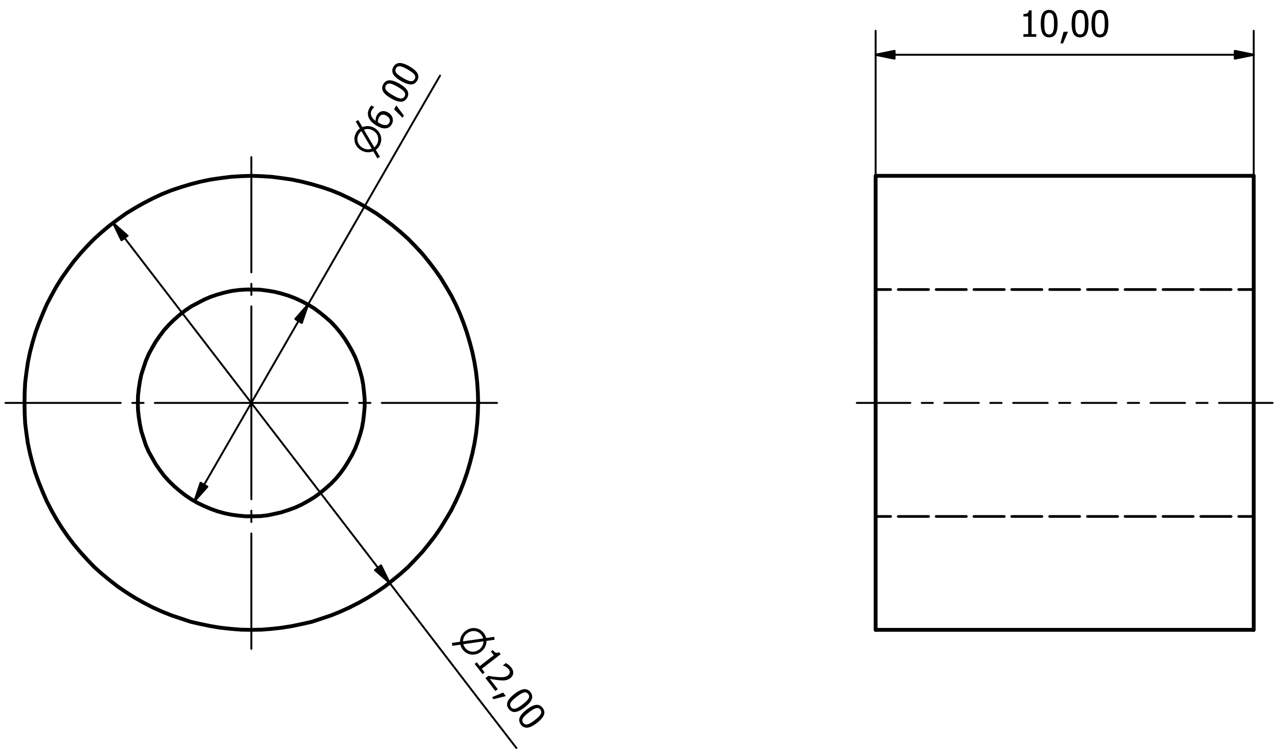
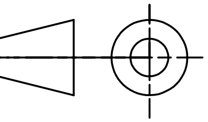


Quantity: 3
Material: Steel Supplied



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 5:1		TITLE Motor Spacer
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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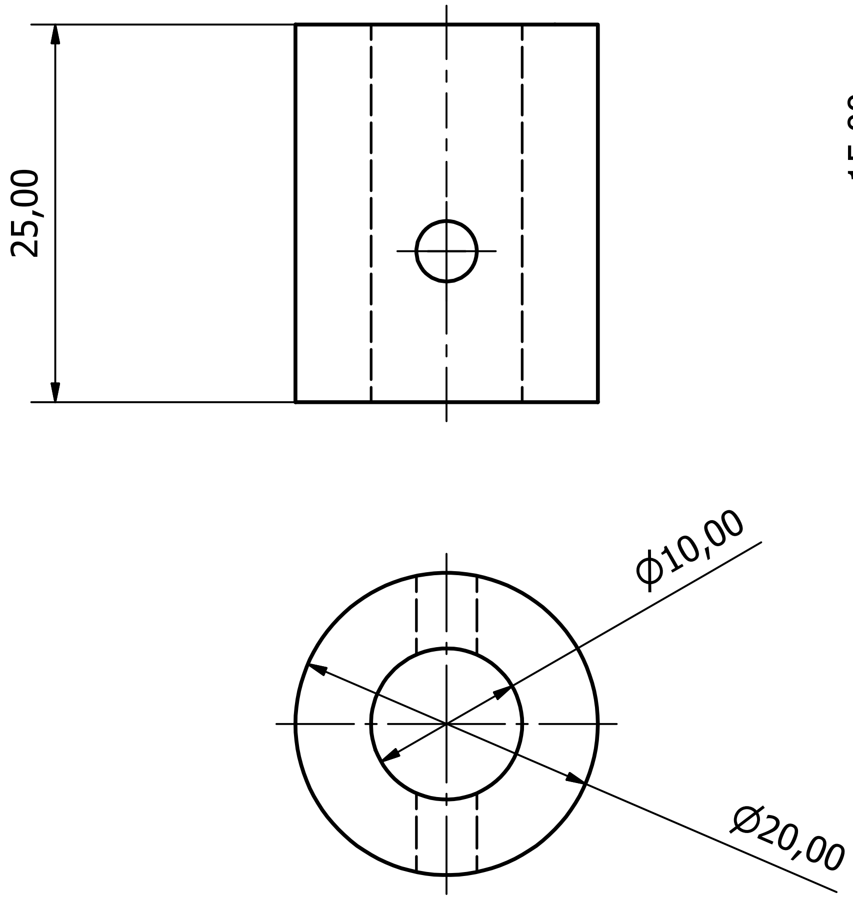

Quantity:1
Material: Aluminium Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 2:1		TITLE Coupling - Rotary unit
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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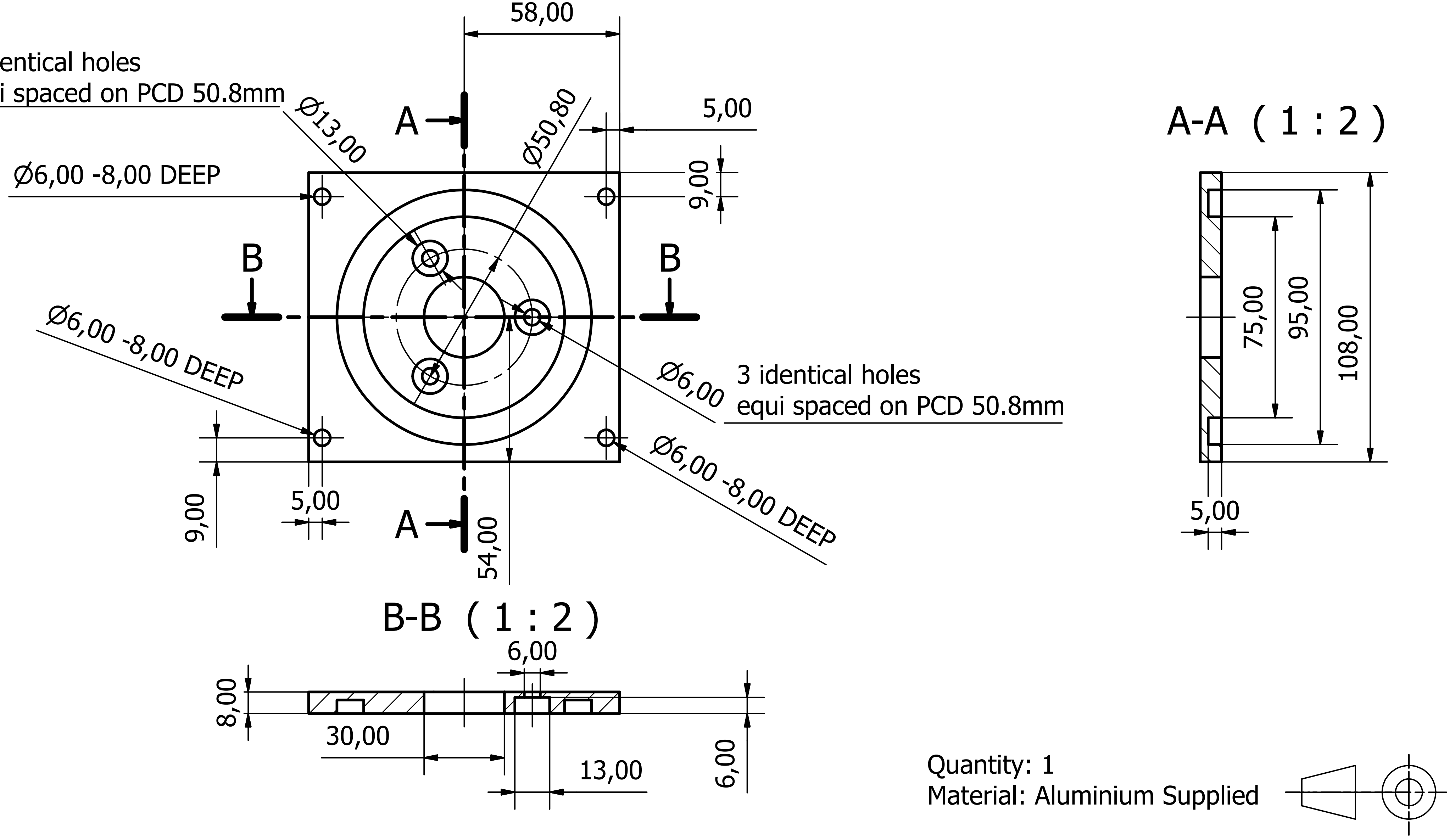

Quantity: 1
Material: Aluminium Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:2 UNITS : mm		TITLE Front Plate - Rotary
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

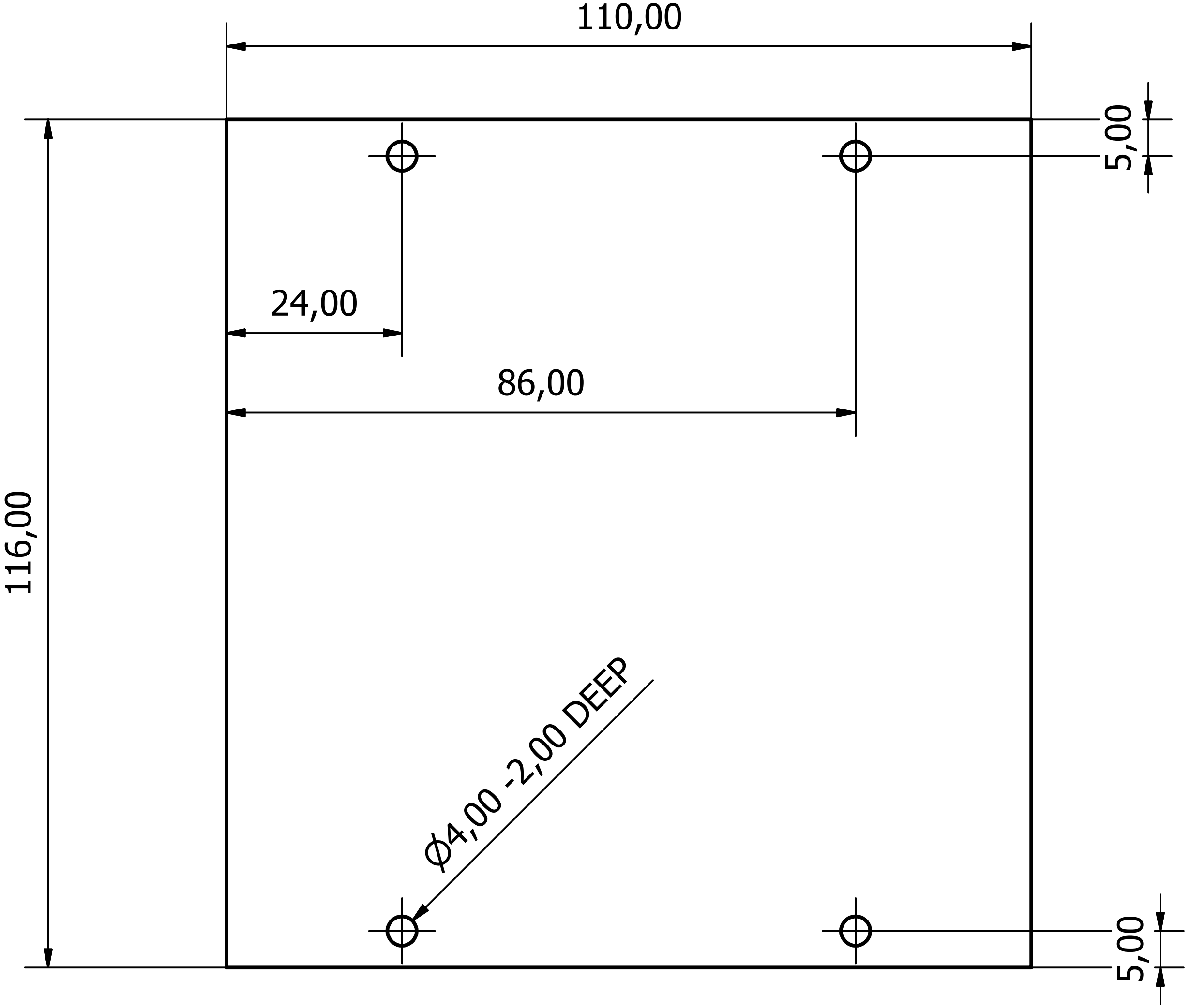

Plate Thickness: 2mm

Quantity: 2
Material: Stainless Steel Sheet Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Cover - Rotary Unit
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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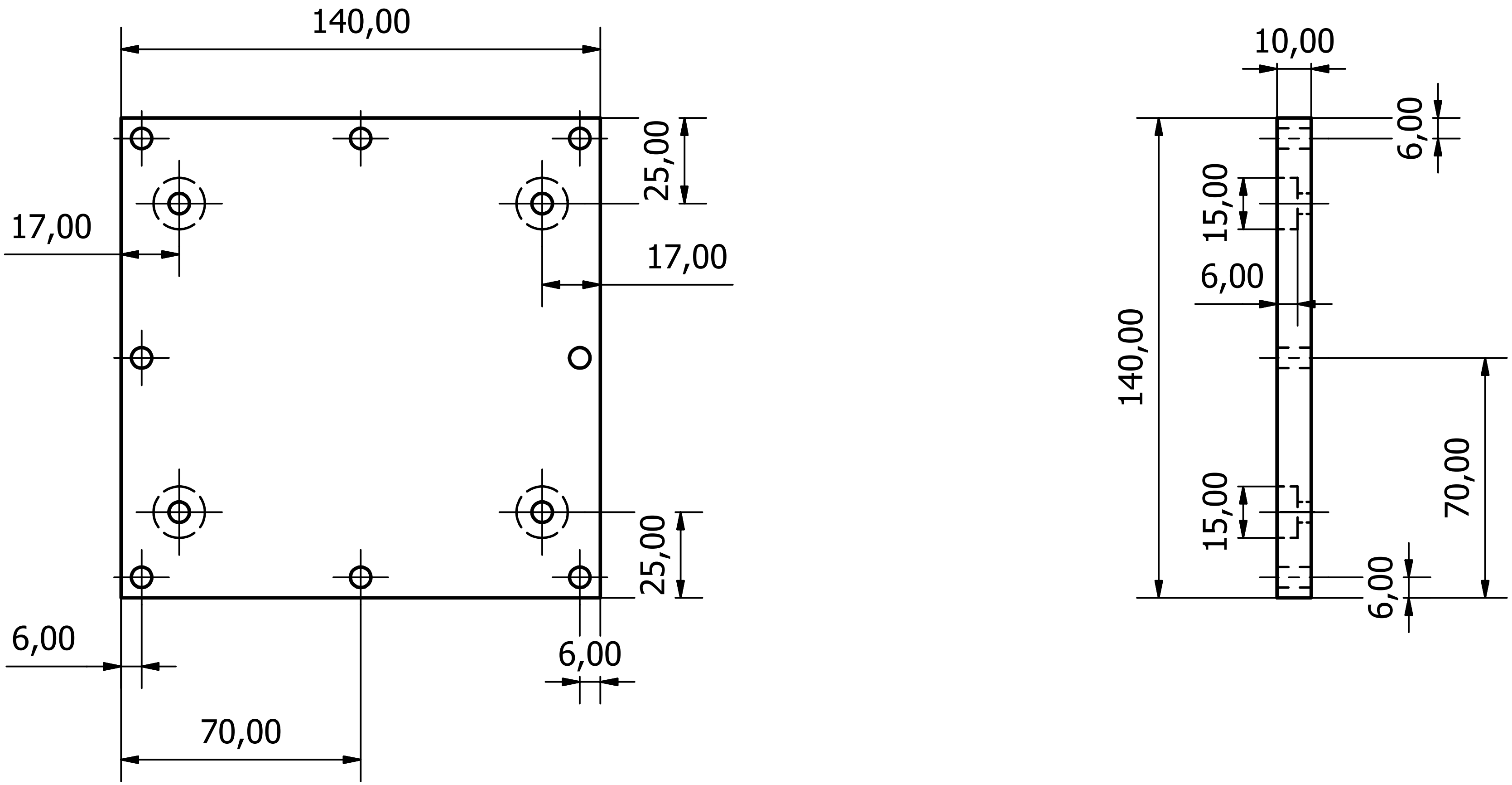
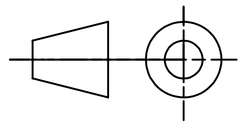


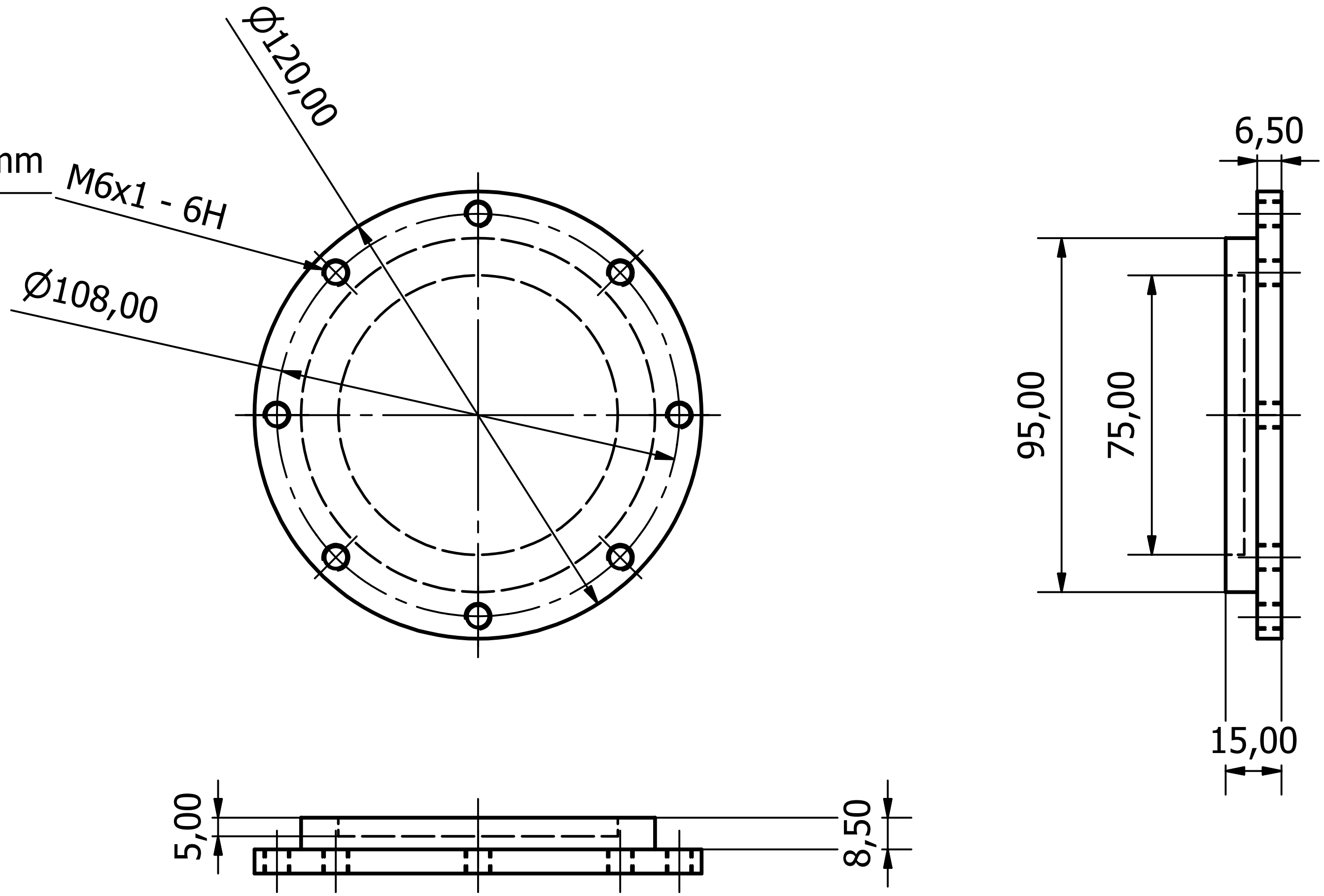
ALL THROUGH HOLES 6 mm DIAMETER
UNLESS OTHERWISE STATED

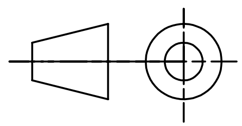
Quantity:1
Material: Aluminium Supplied



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Base Plate - Rotary Unit
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

8 identical tapped holes
equi spaced on PCD 108mm





Quantity: 1
Material: Aluminium Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Rotating Interface - Rotary Unit
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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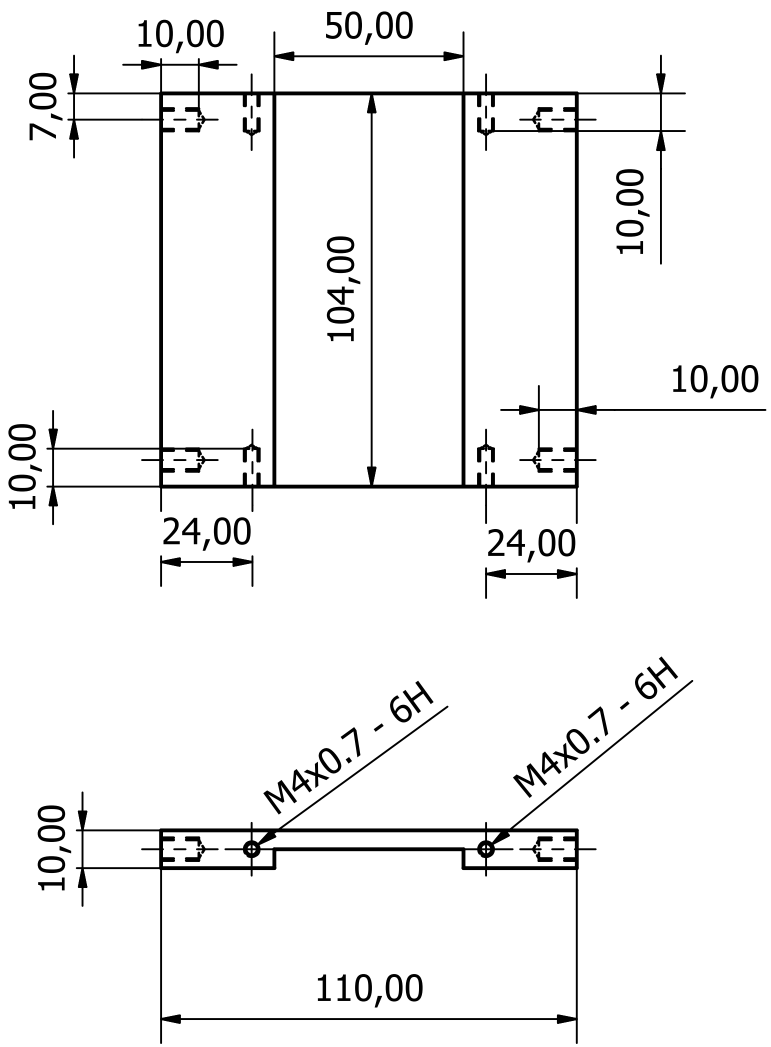
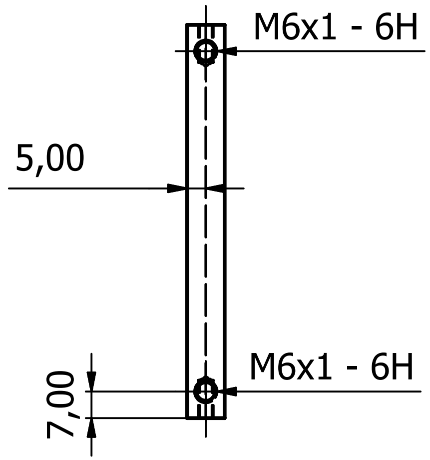
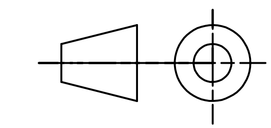




Quantity: 2
Material: Aluminium supplied



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Side Plate : Rotary unit
	⊲◎ OR ◎⊳	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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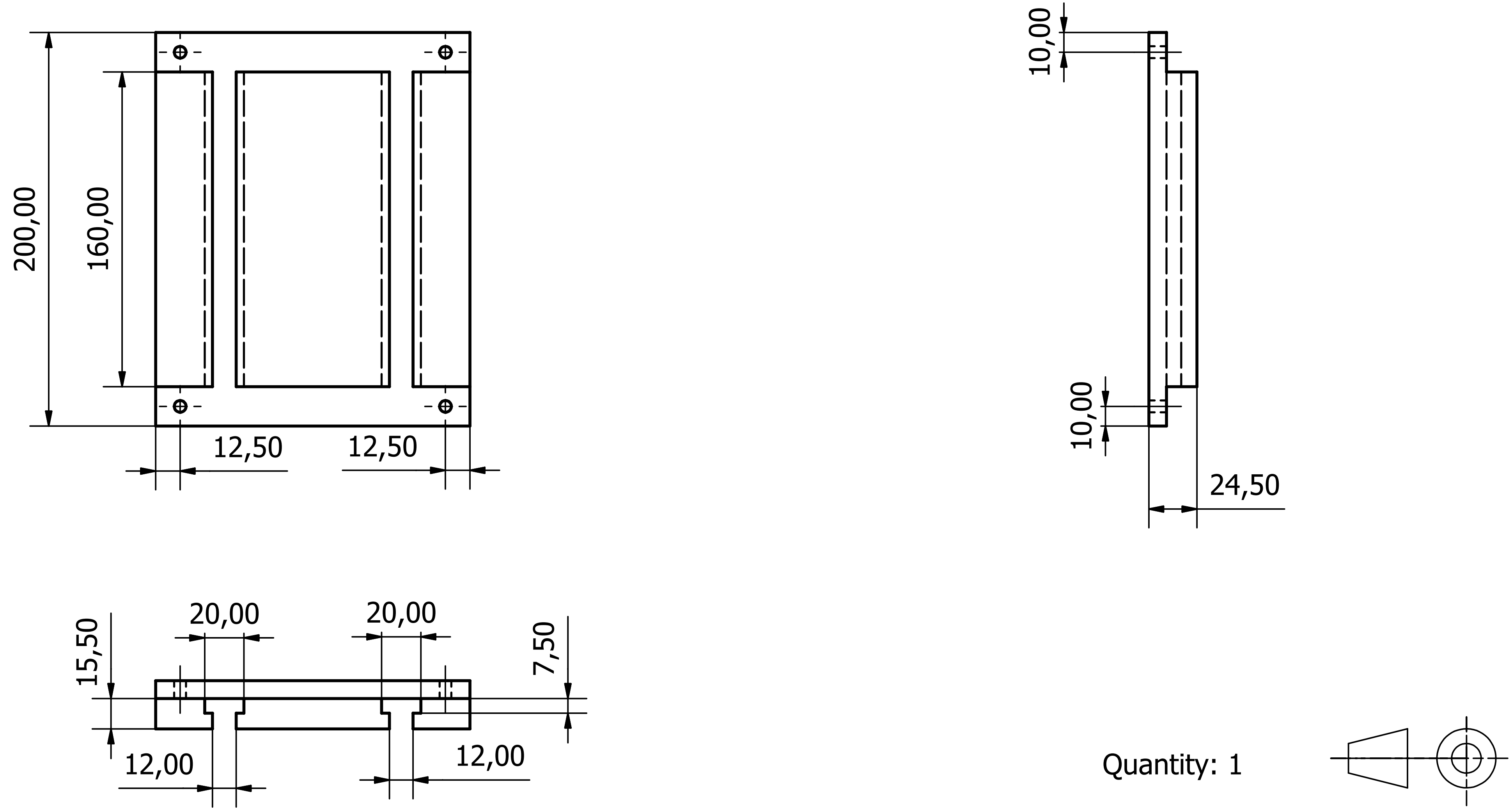

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:3		TITLE Work Table
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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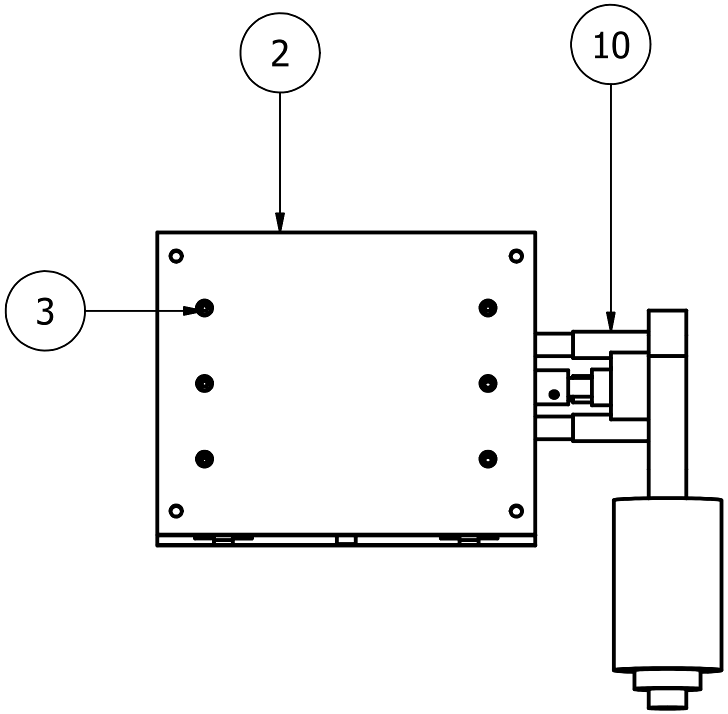

Parts List		
ITEM	QTY	PART NUMBER
1	1	Arch side one
2	1	Interface one
3	7	ISO 4762 - M4 x 16
4	2	Arch two
5	6	ISO 4762 - M4 x 30
6	2	SKF 61800-RZ
7	2	Arch one
8	1	Connecting rod
9	3	Motor spacer
10	1	Small motor
11	1	coupling
12	2	ISO 4762 - M4 x 20
13	1	Interface two
14	1	shaft
15	3	ISO 4762 - M6 x 55
16	1	Arch side two

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:4	
	OR	UNITS : mm	
		Date	Checked
	Project Supervisor		
	Workshop Technician		
	Technical Manager		

TITLE Work Table - pivot - two

PROJECT RMS Project

STUDENT NAME Jared Padayachee

TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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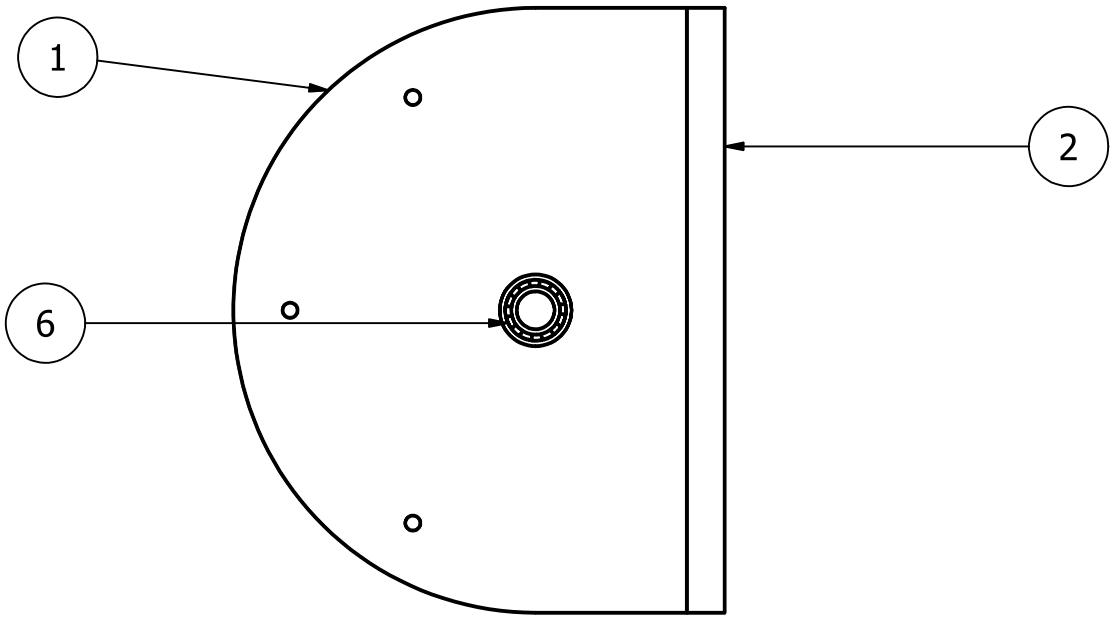

Parts List		
ITEM	QTY	PART NUMBER
1	1	Arch side one
2	1	Interface one
3	7	ISO 4762 - M4 x 16
4	2	Arch two
5	6	ISO 4762 - M4 x 30
6	2	SKF 61800-RZ
7	2	Arch one
8	1	Connecting rod
9	3	Motor spacer
10	1	Small motor
11	1	coupling
12	2	ISO 4762 - M4 x 20
13	1	Interface two
14	1	shaft
15	3	ISO 4762 - M6 x 55
16	1	Arch side two

University of Kwa-Zulu Natal
School of Mechanical Engineering

Orthographic Projection OR

SCALE 1:2

UNITS : mm

	Date	Checked
Project Supervisor		
Workshop Technician		
Technical Manager		

TITLE Work Table - pivot - bearing assembly

PROJECT RMS Project

STUDENT NAME Jared Padayachee

TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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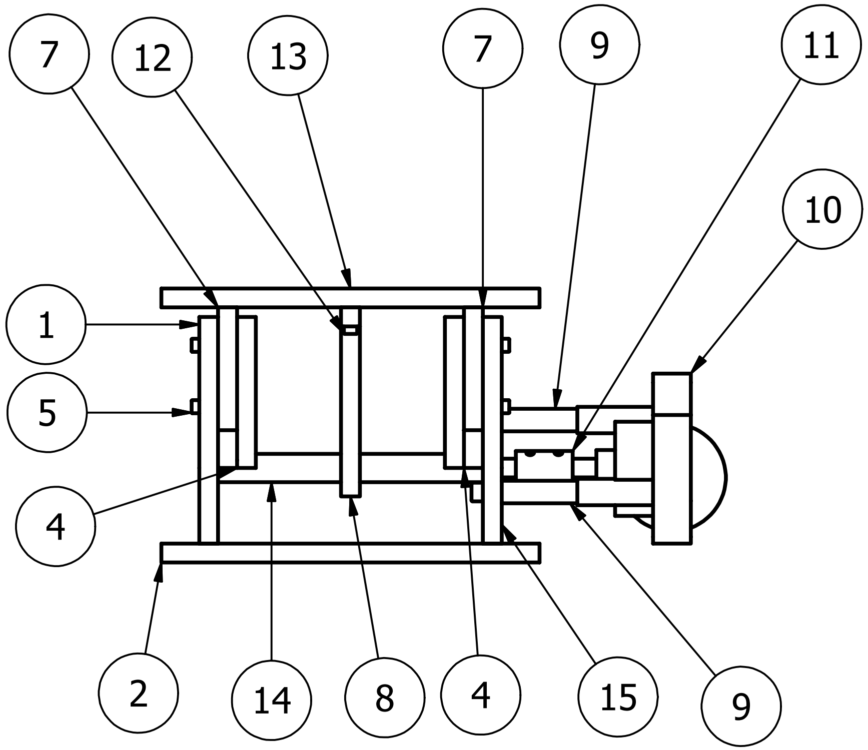
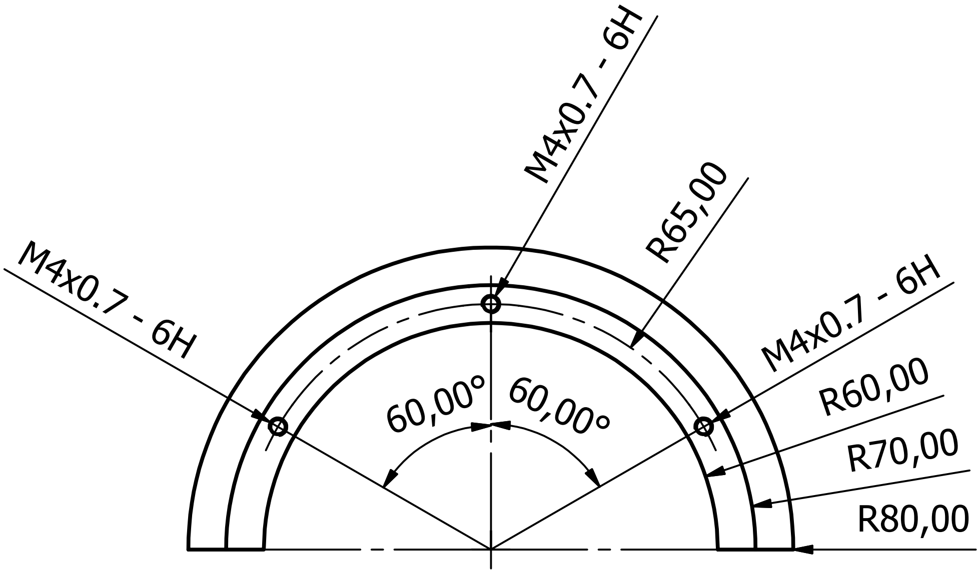
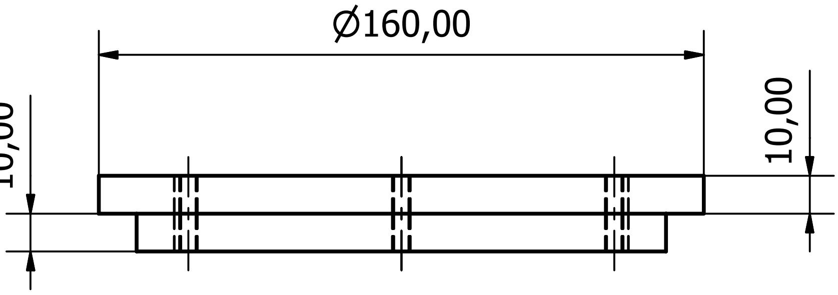
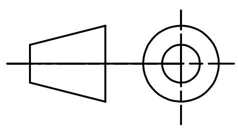


Parts List		
ITEM	QTY	PART NUMBER
1	1	Arch side one
2	1	Interface one
3	7	ISO 4762 - M4 x 16
4	2	Arch two
5	6	ISO 4762 - M4 x 30
6	2	SKF 61800-RZ
7	2	Arch one
8	1	Connecting rod
9	3	Motor spacer
10	1	Small motor
11	1	coupling
12	2	ISO 4762 - M4 x 20
13	1	Interface two
14	1	shaft
15	3	ISO 4762 - M6 x 55
16	1	Arch side two

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:4		TITLE Work Table - pivot - one
	OR	UNITS : mm		PROJECT RMS Project
		Date	Checked	
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za







Quantity:2
Material: Aluminium

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:2 UNITS : mm		TITLE Arch two - work table - pivot
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399

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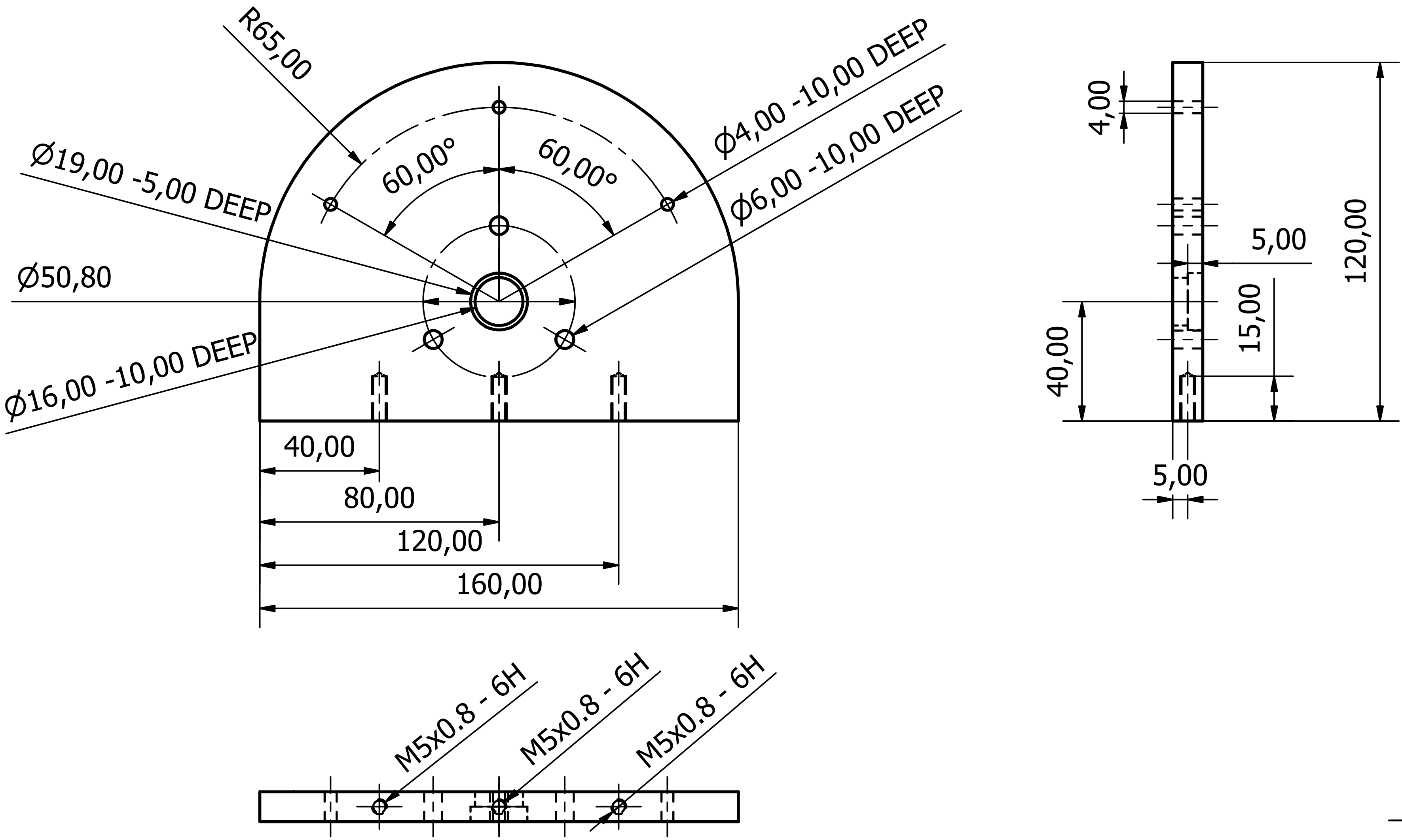
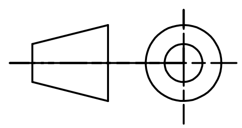
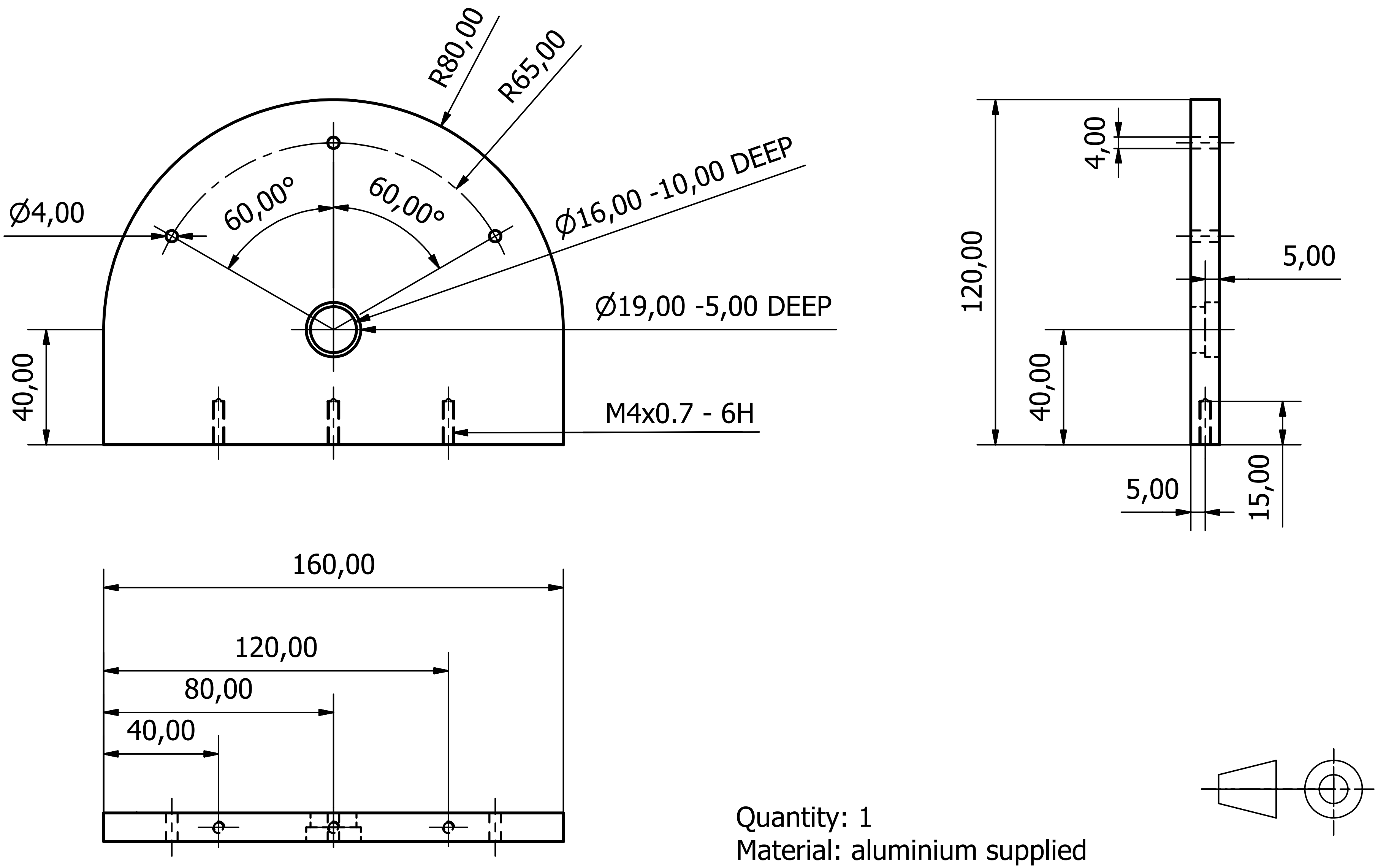




Quantity:1
Material: aluminium

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Arch side two - work table - pivot
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Quantity: 1
Material: aluminium supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Arch side one - work table - pivot
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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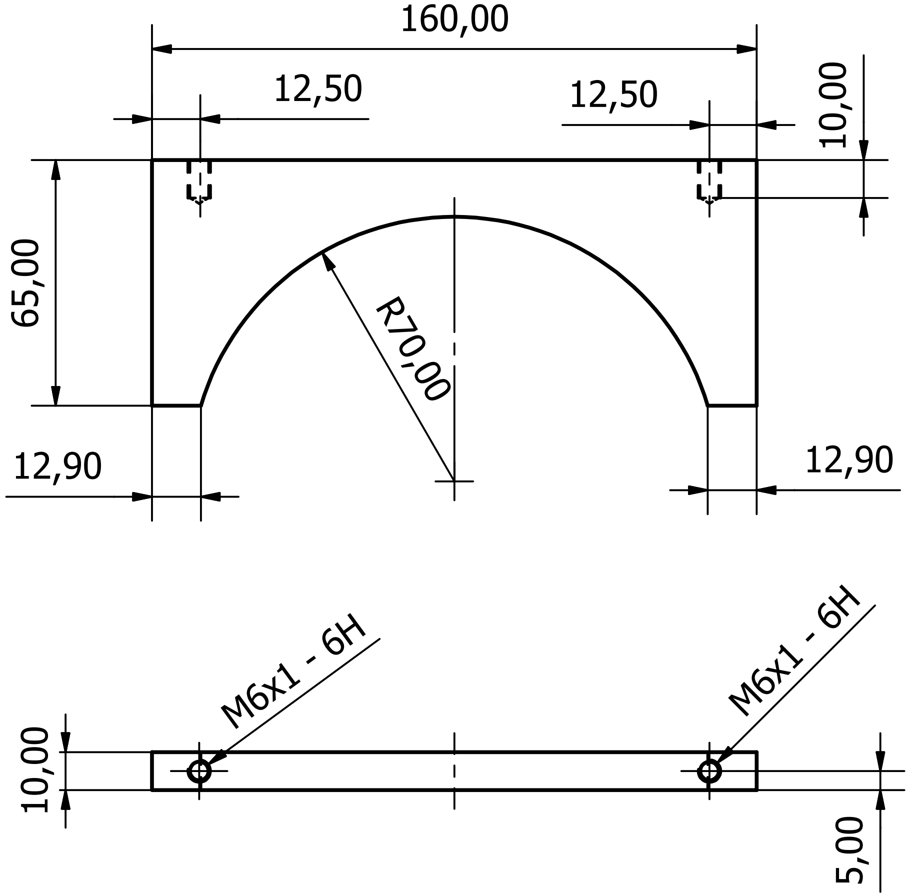

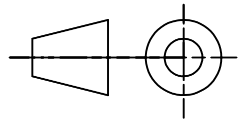

Quantity: 2
Material: aluminium supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Arch one - work table - pivot
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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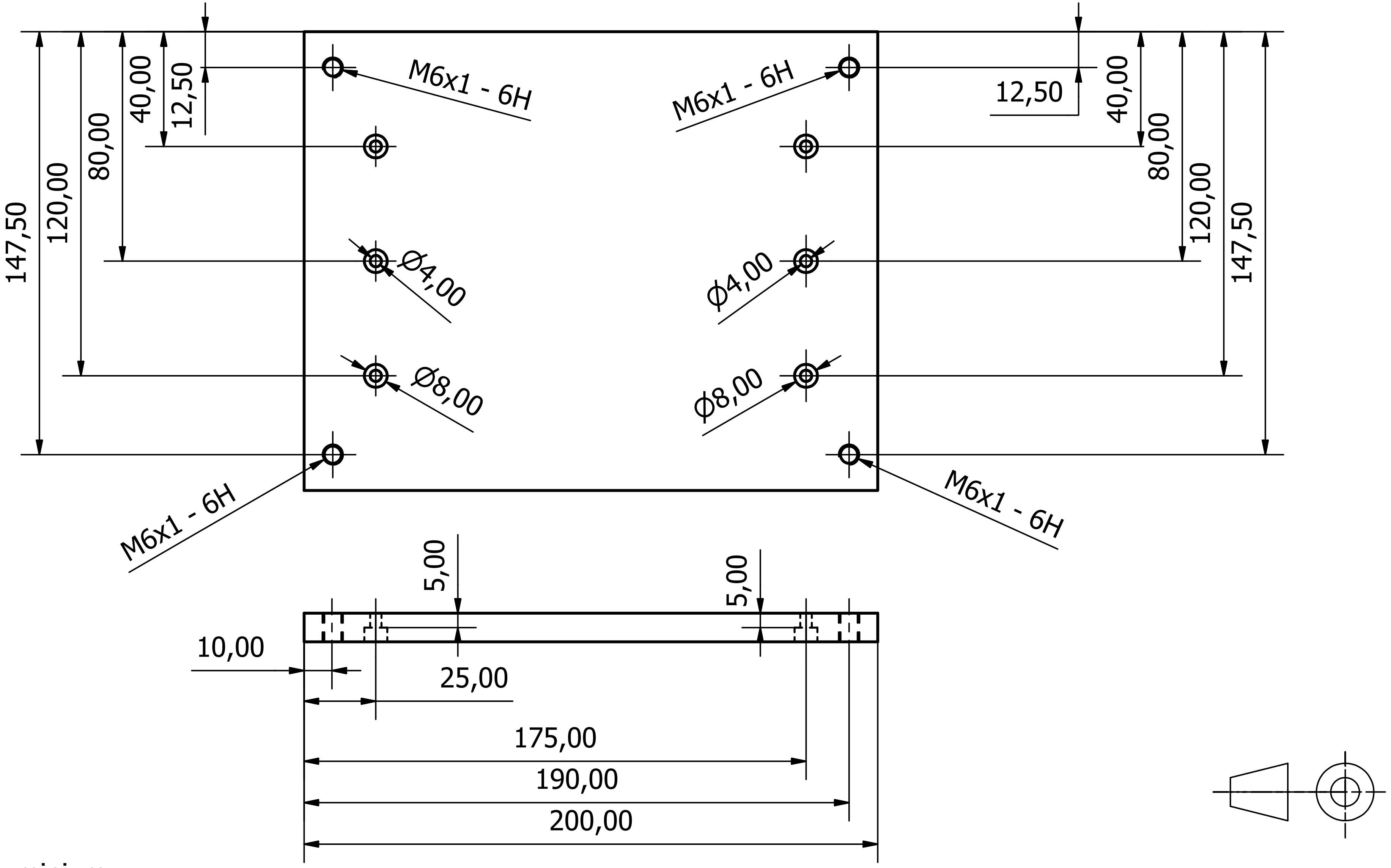
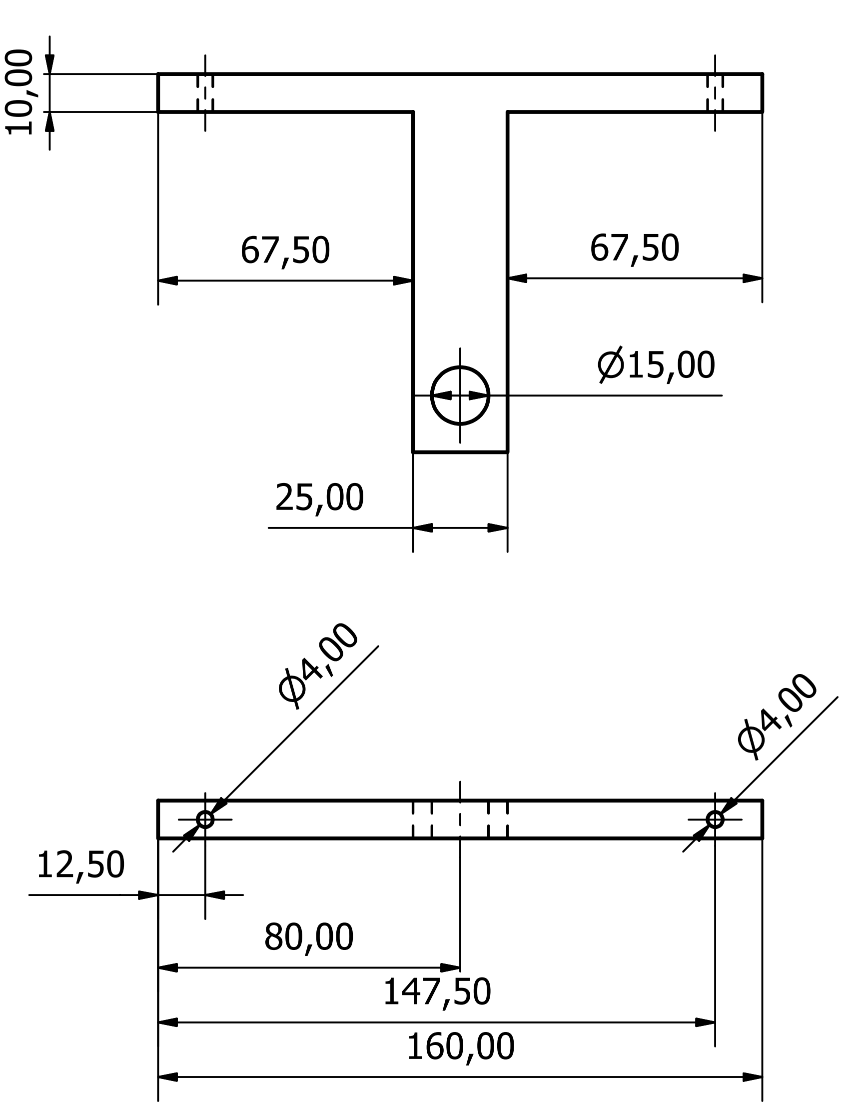
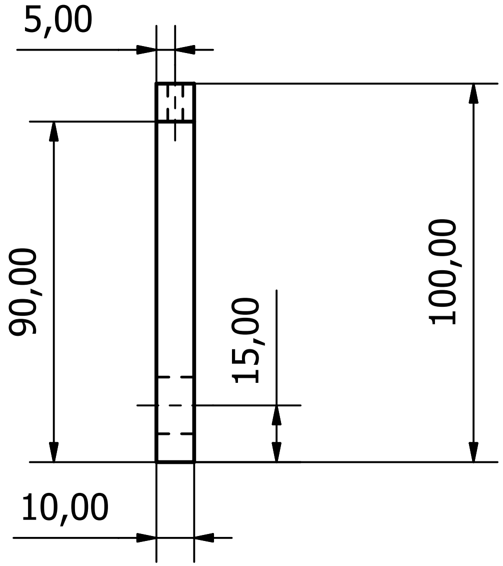


Quantity: 1
Material: Aluminium

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Interface one- work table - pivot
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za





Quantity: 1
Material: Aluminium

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Connecting Rod - Work Table - pivot
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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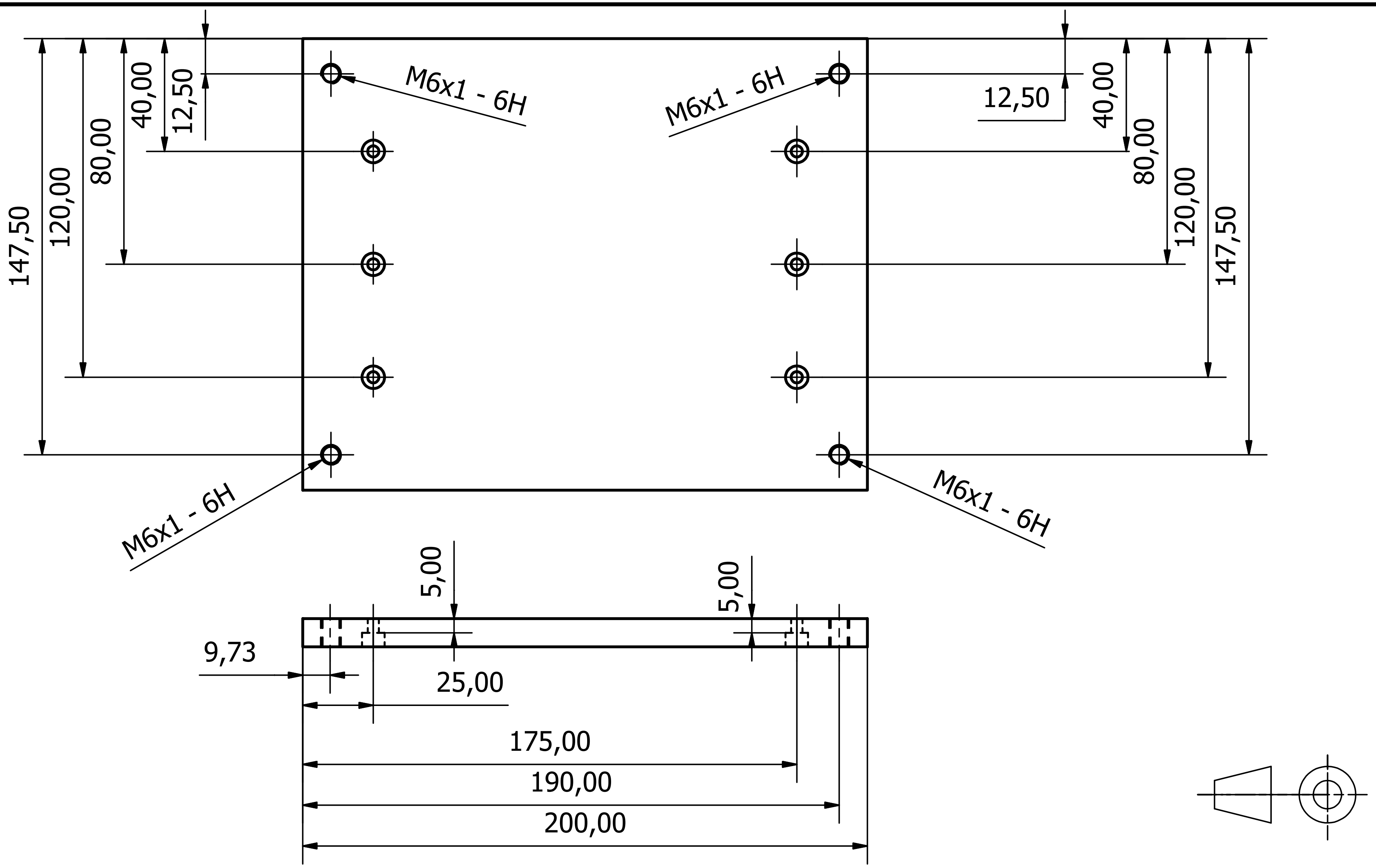

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE		TITLE
	OR	UNITS : mm		PROJECT RMS Project
		Date	Checked	
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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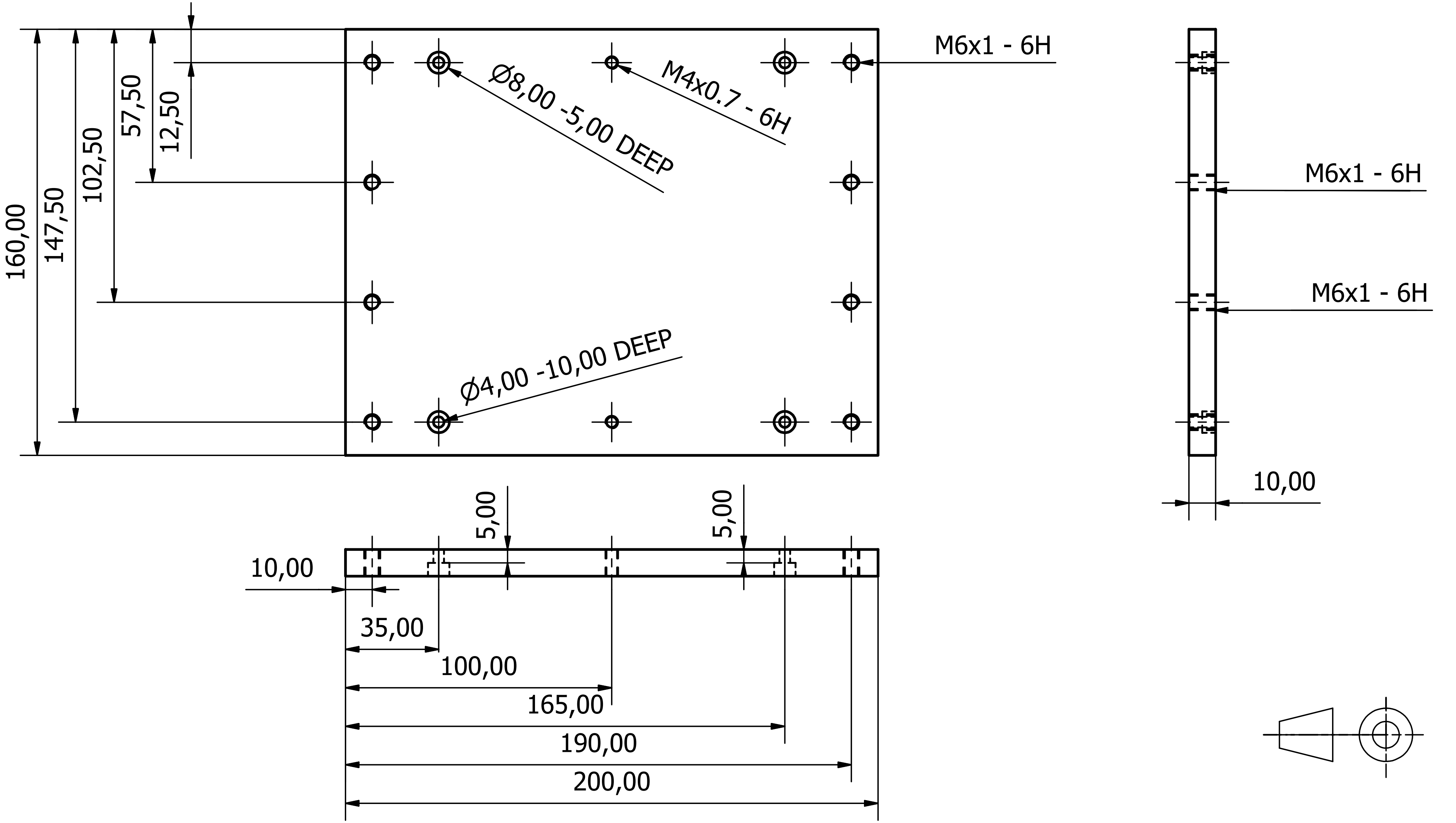
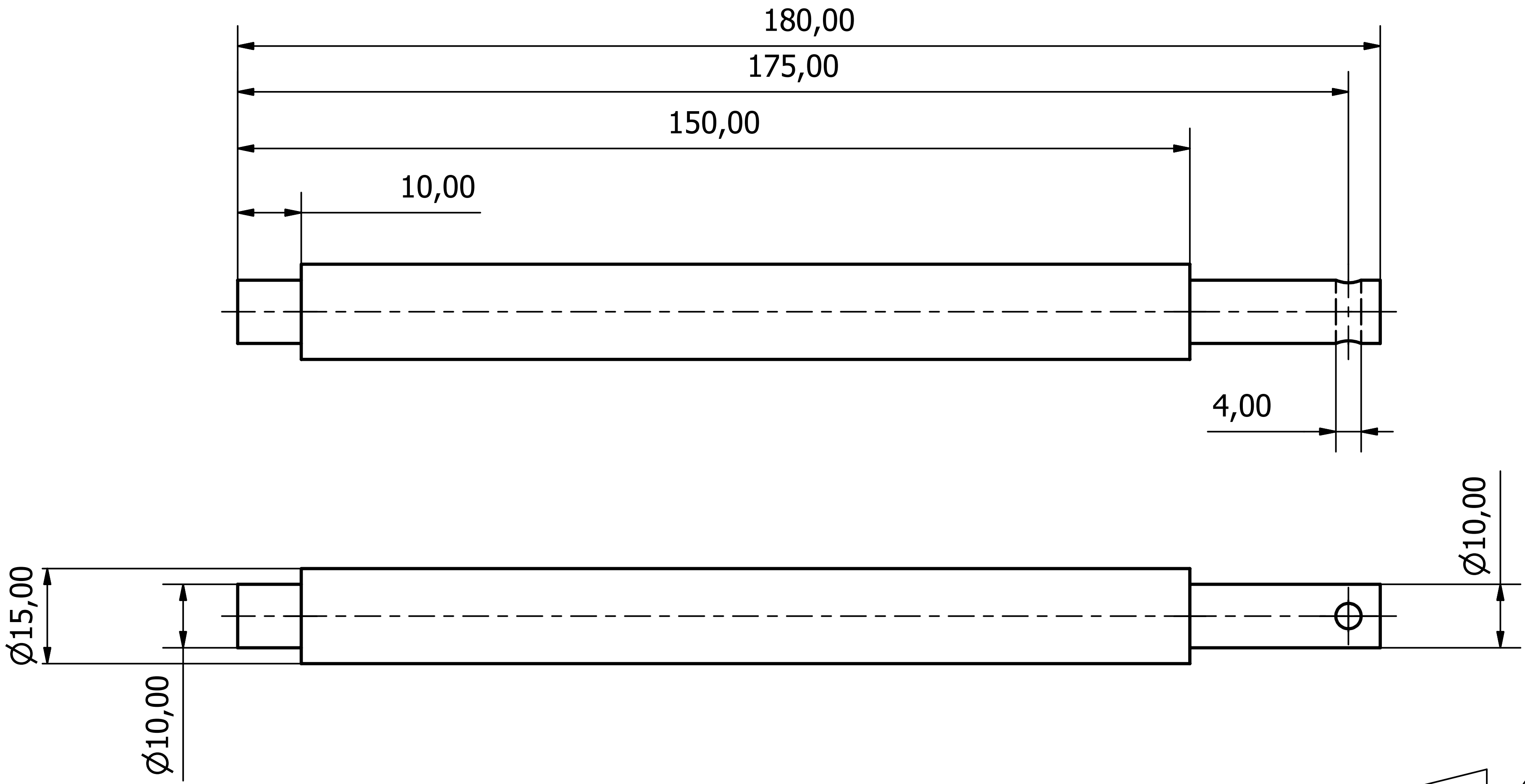
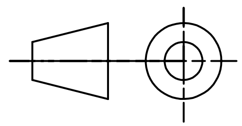


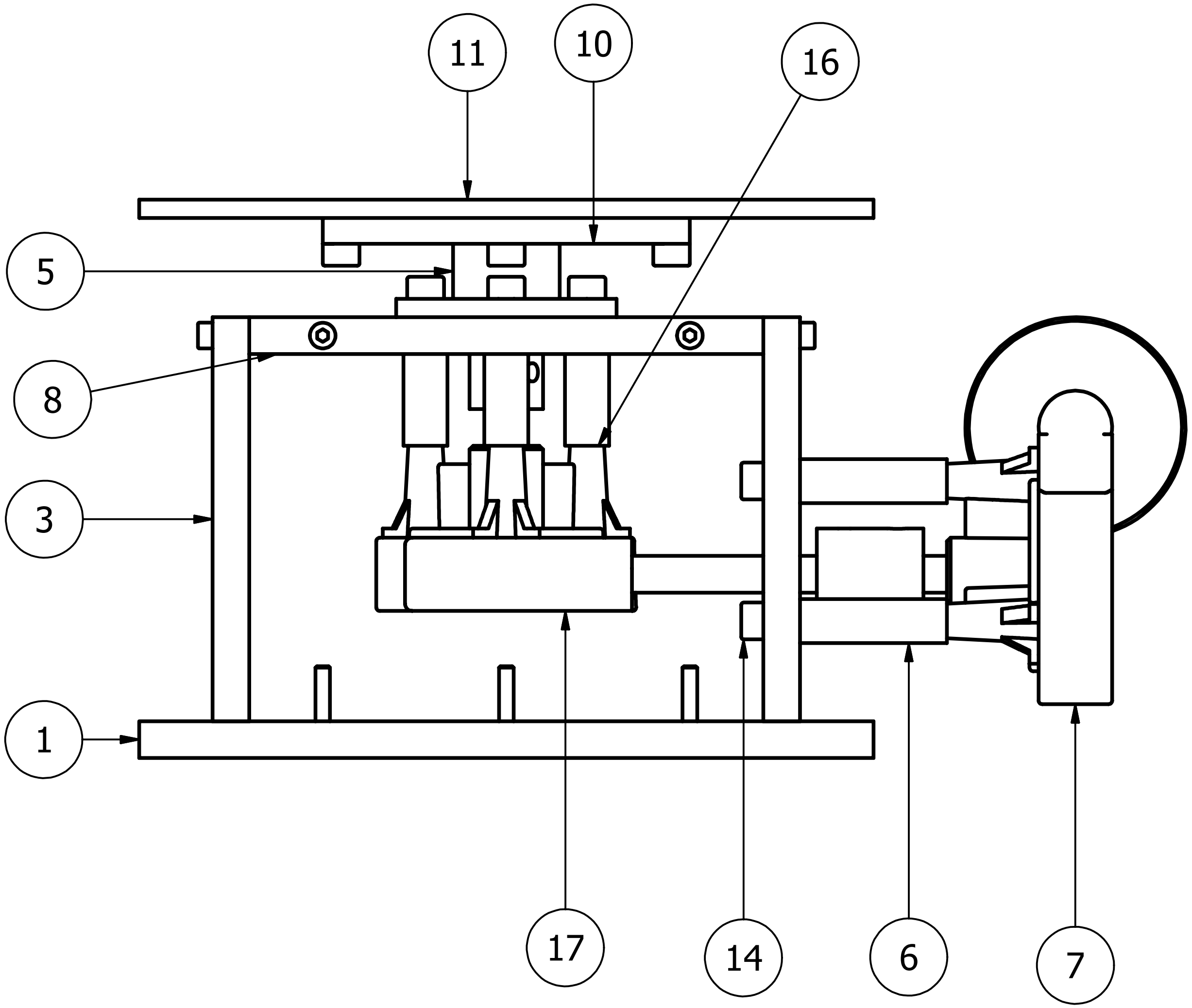
University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE		TITLE
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za





Quantity:1
Material: Steel rod supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Shaft - work table - pivot
	⊲⊕ OR ⊕⊳	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Parts List		
ITEM	QTY	PART NUMBER
1	1	Bottom interface
2	1	Side plate.
3	1	Side plate 2
4	2	Side Plate 3
5	1	Connecting rod
6	3	Motor spacer - long
7	2	Wiper Motor
8	1	Top plate
9	3	ISO 4762 - M6 x 55
10	1	Interface connector plate
11	1	Interface
12	4	ISO 4762 - M6 x 12
13	20	ISO 4762 - M4 x 20
14	3	ISO 4762 - M6 x 60
15	1	SKF 51104
16	1	Motor Spacer
17	1	Worm gear set
17	1	Coupling

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:2 UNITS : mm	TITLE Work table - rotary assembly two
		Date | Checked	PROJECT RMS Project
	Project Supervisor		
	Workshop Technician		STUDENT NAME Jared Padayachee
	Technical Manager		TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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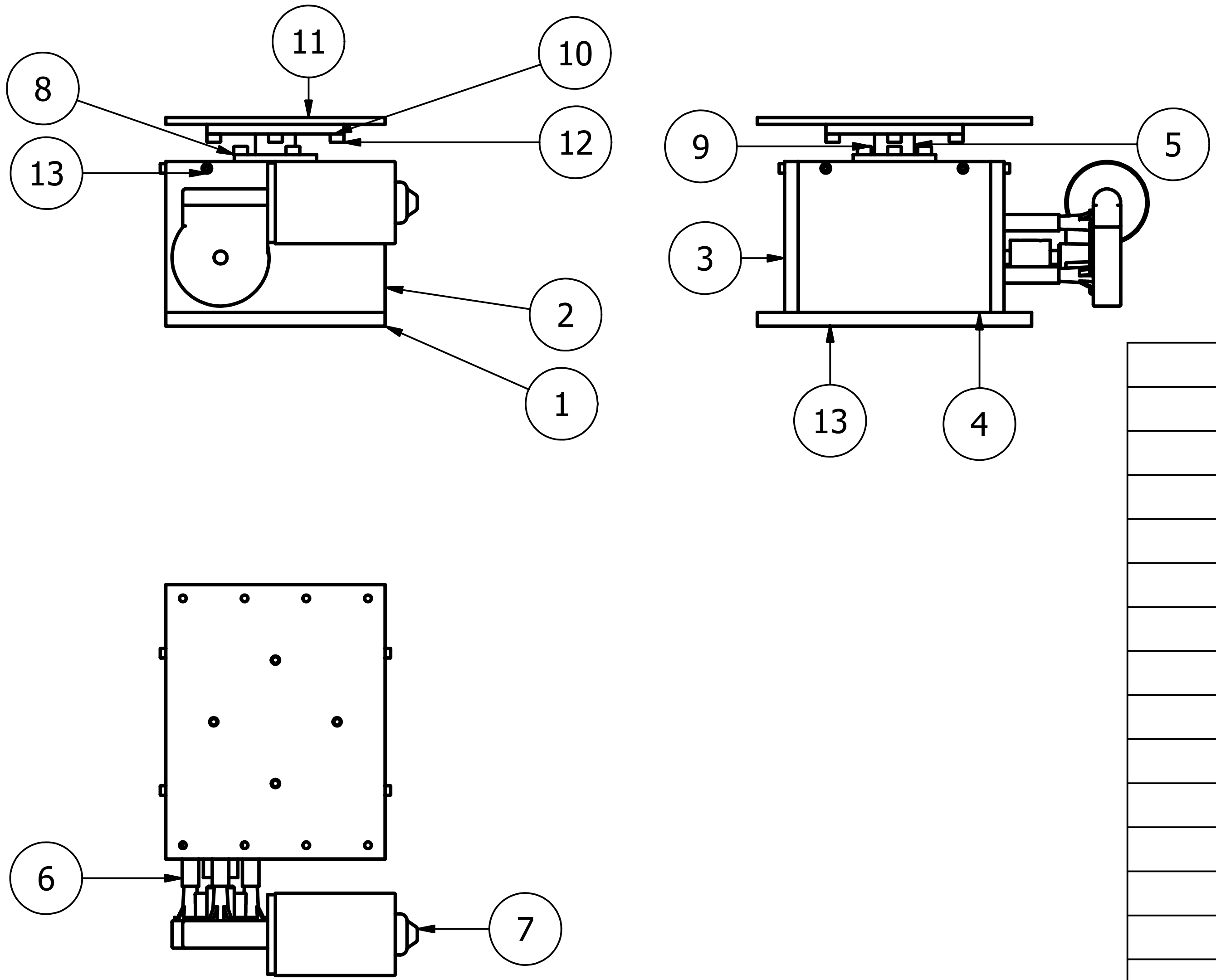

Parts List		
ITEM	QTY	PART NUMBER
1	1	Bottom interface
2	1	Side plate 1
3	1	Side plate 2
4	2	Side plate 3
5	1	Connecting rod
6	6	Motor spacer - long
7	2	Wiper motor
8	1	Top plate
9	3	ISO 4762 - M6 x 55
10	1	interface connector plate
11	1	Interface
12	4	ISO 4762 - M6 x 12
13	20	ISO 4762 - M4 x 20
14	3	ISO 4762 - M6 x 60
15	1	SKF 51104
17	1	Coupling

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:5	TITLE Work table - rotary assembly one
		UNITS : mm	
		Date	Checked	
	Project Supervisor			PROJECT RMS Project
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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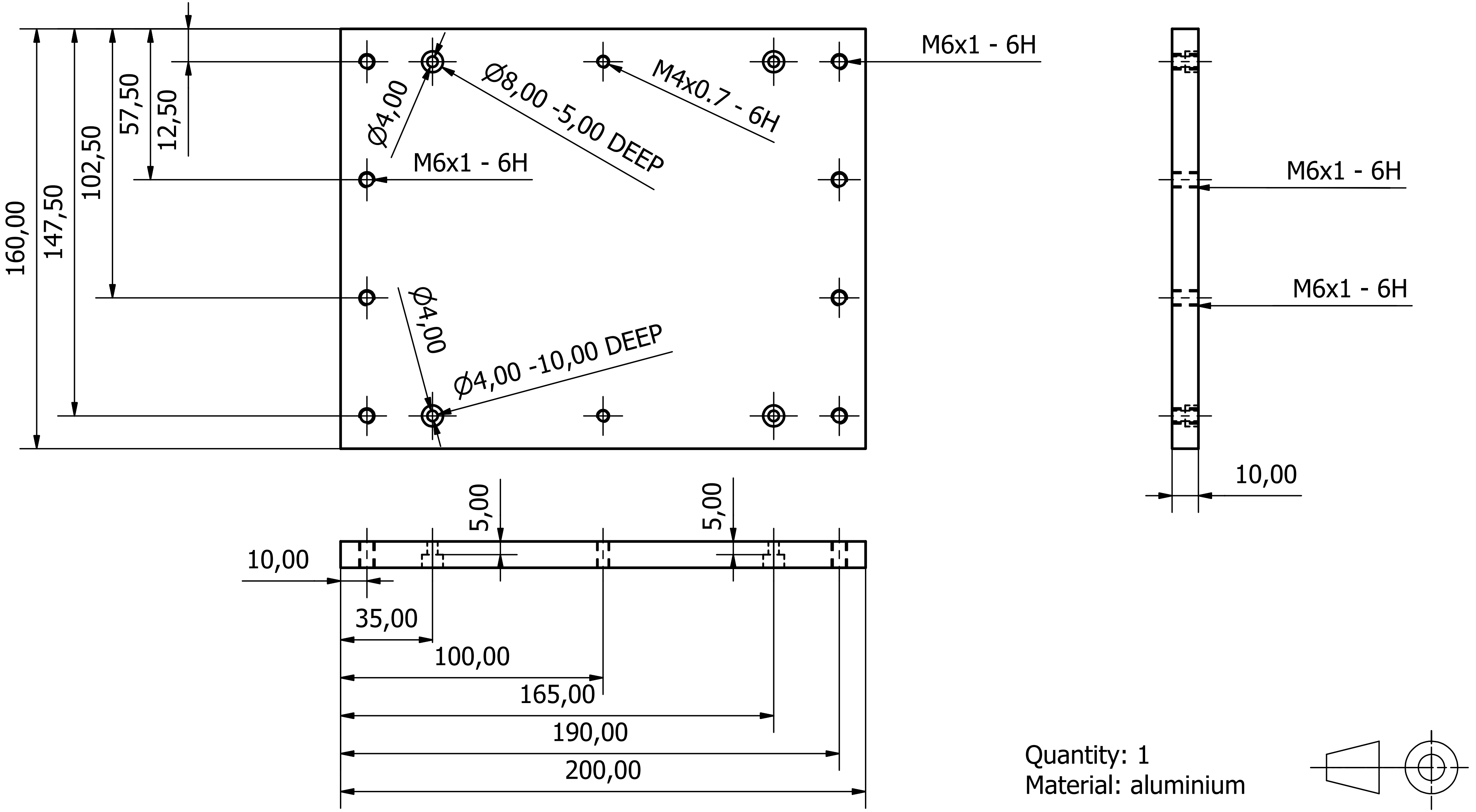
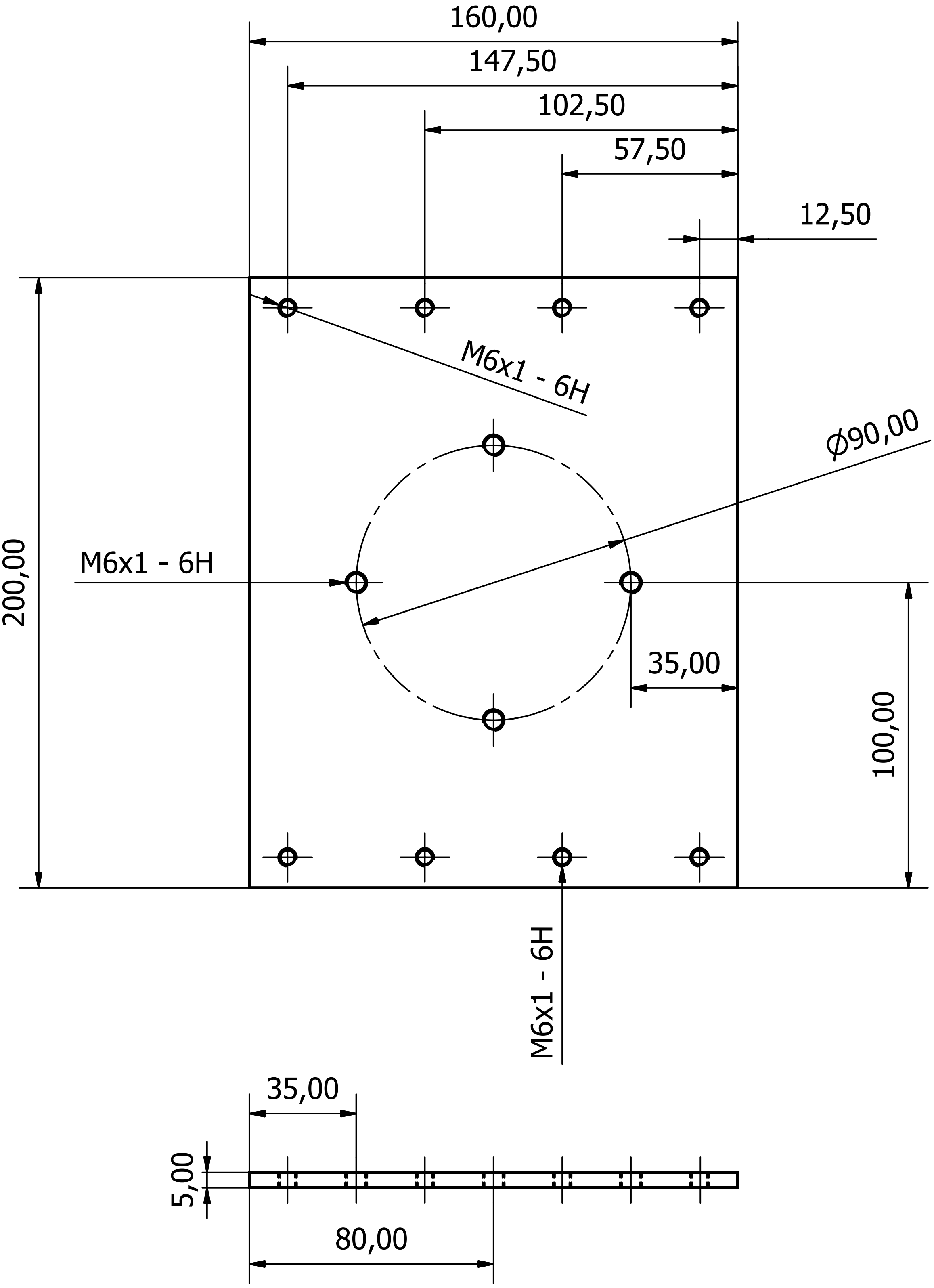
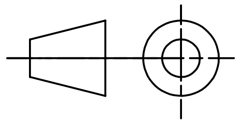


Quantity: 1
Material: aluminium

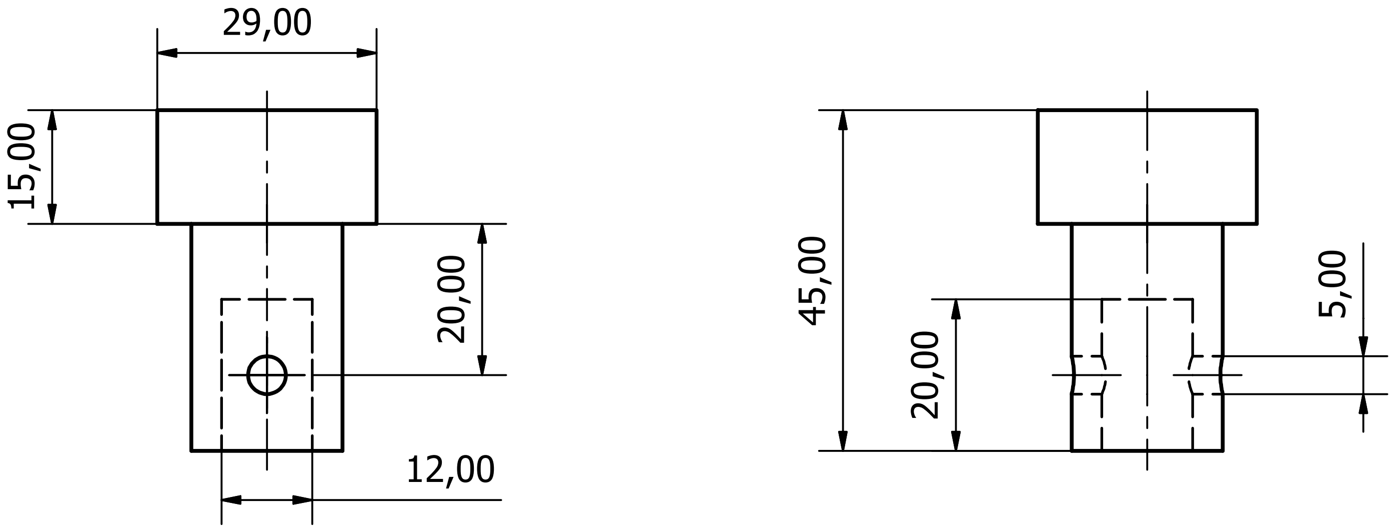
University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Interface two - work table - pivot
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

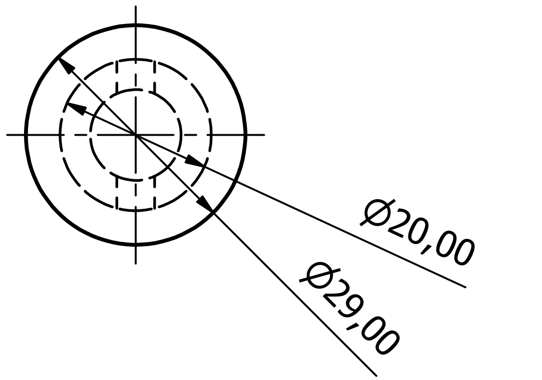




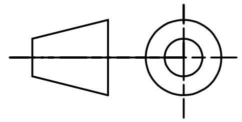
Quantity:1
Material: Aluminium

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:2 UNITS : mm		TITLE Interface - wort table - rotary
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399

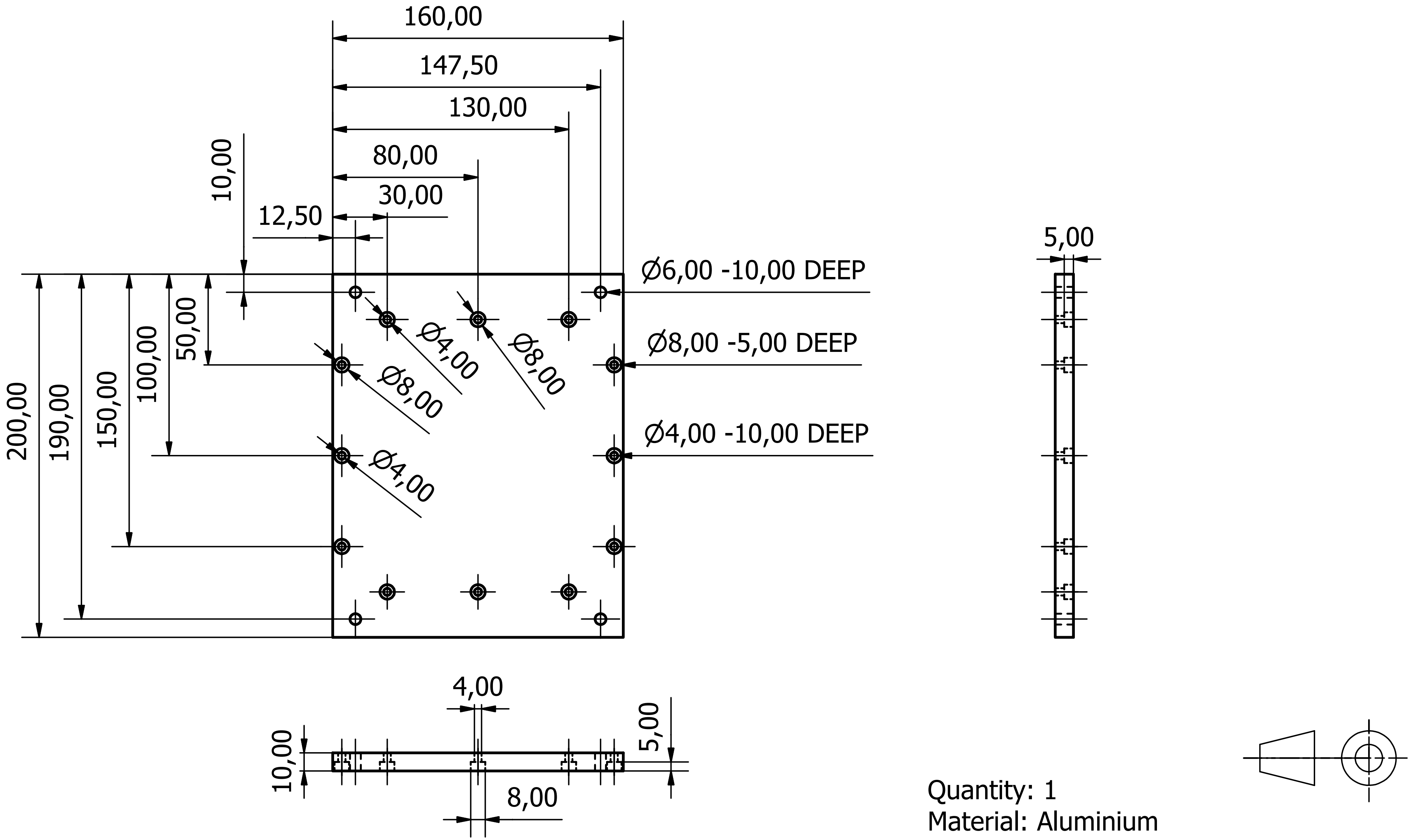




Quantity: 1
Material: Supplied



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Connecting rod - work table - rotary
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Quantity: 1
Material: Aluminium

University of Kwa-Zulu Natal
School of Mechanical Engineering

Orthographic Projection

OR

SCALE 1:3

UNITS : mm

	Date	Checked
Project Supervisor		
Workshop Technician		
Technical Manager		

TITLE Bottom interface - work table - rotary

PROJECT RMS Project

STUDENT NAME Jared Padayachee
TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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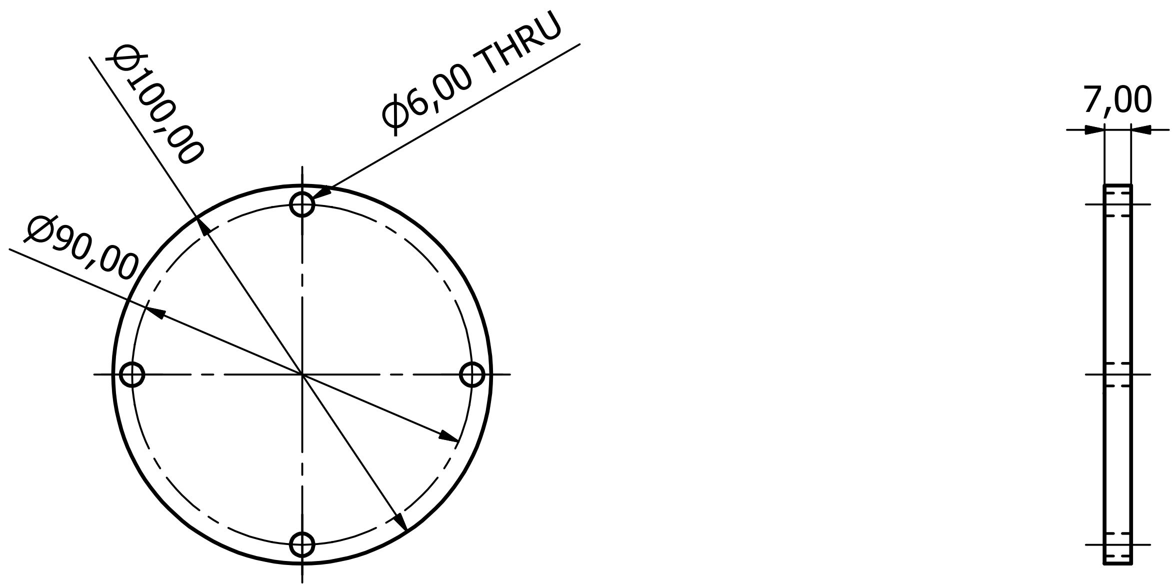
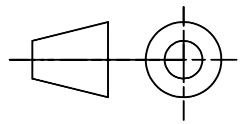


Quantity: 1
Material: Aluminium



University of Kwa-Zulu Natal	Orthographic Projection	SCALE 1:2		TITLE Interface Connector
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
School of Mechanical Engineering	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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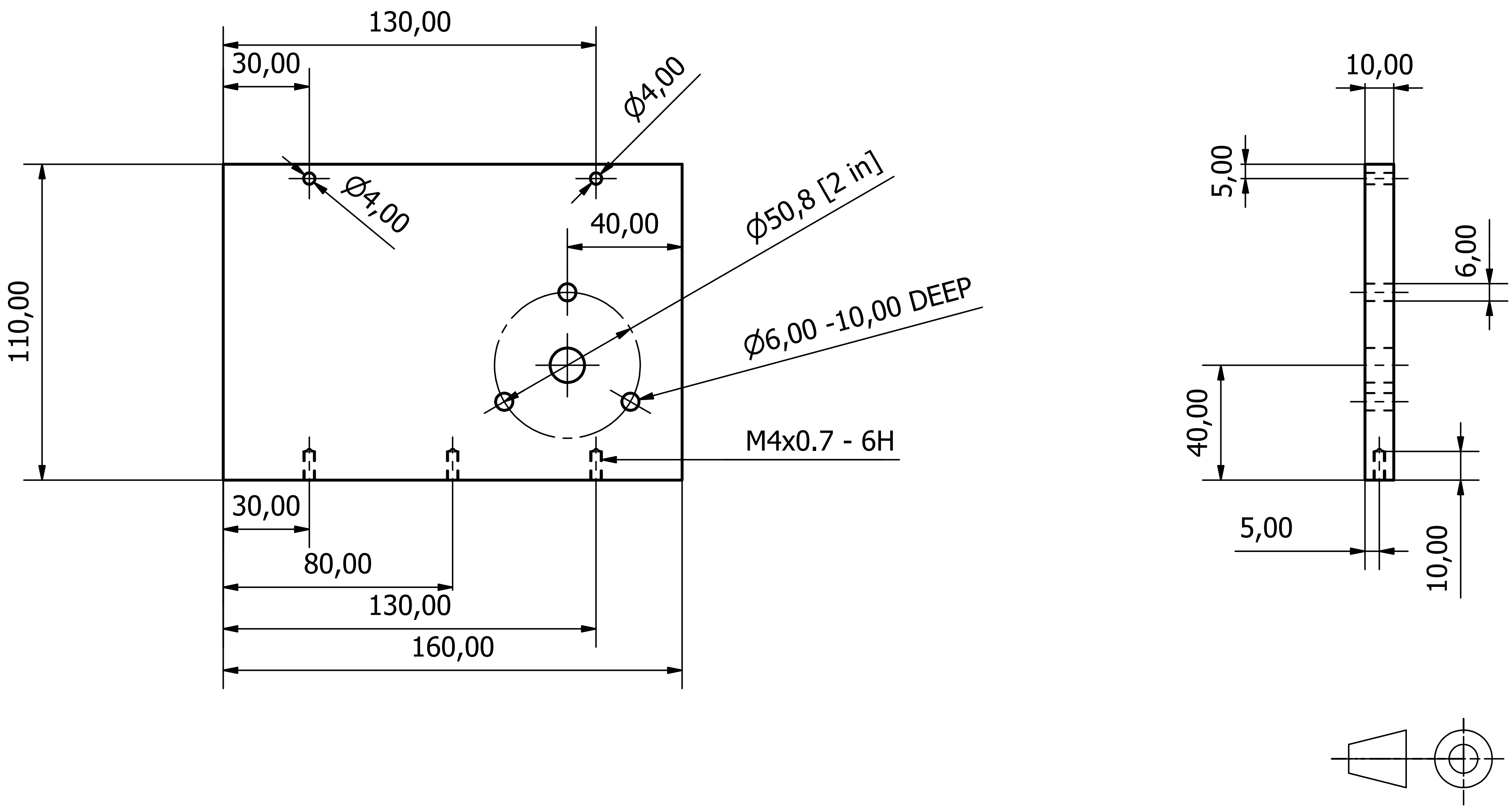
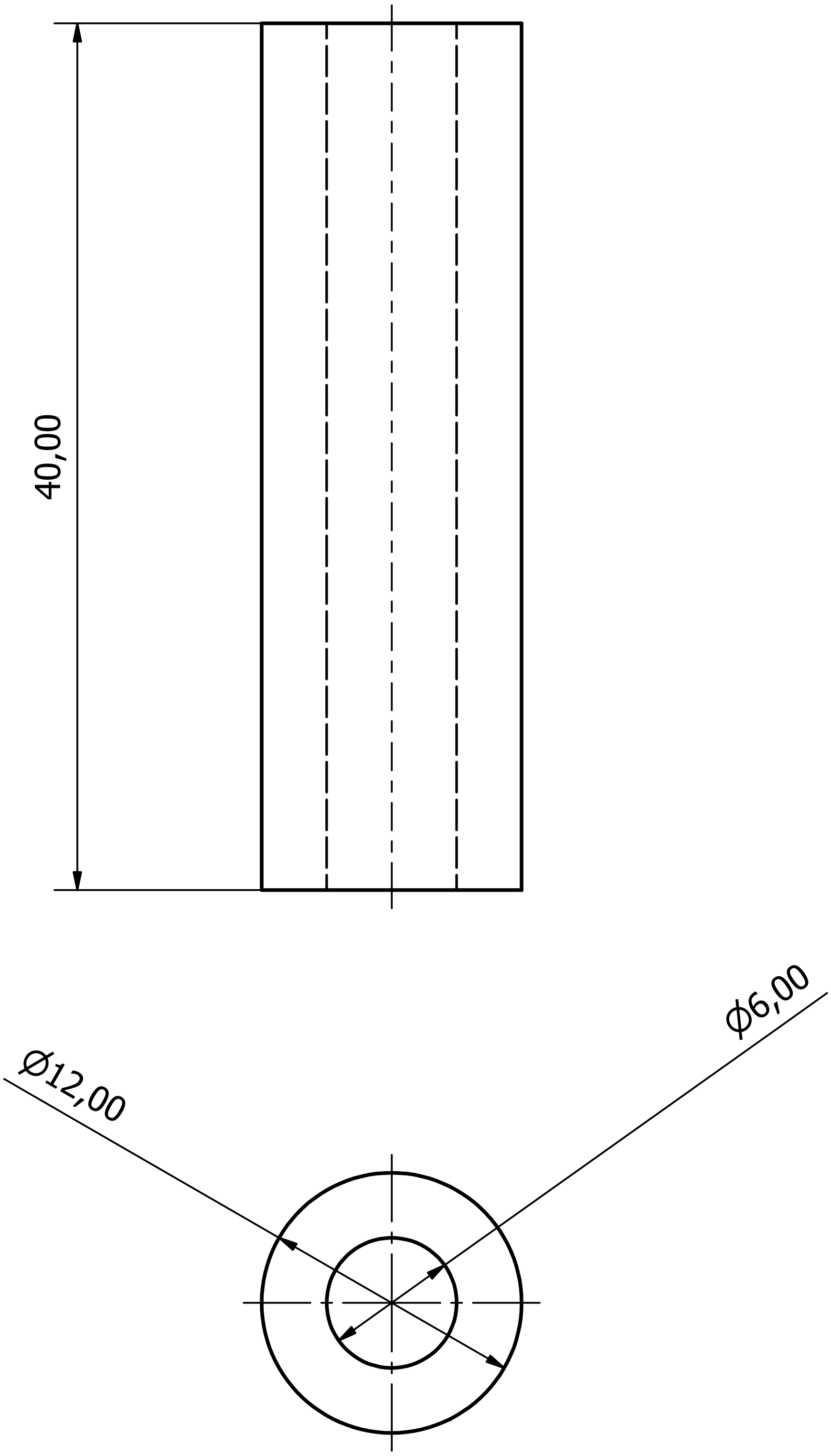
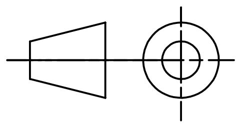
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE		TITLE
	OR	UNITS : mm		PROJECT RMS Project
		Date	Checked	
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za





Quantity: 3
Material: Steel Supplied

University of Kwa-Zulu Natal
School of Mechanical Engineering

Orthographic Projection
OR

SCALE 3:1
UNITS : mm

	Date	Checked
Project Supervisor		
Workshop Technician		
Technical Manager		

TITLE Motor Spacer - long -work table -rotary

PROJECT RMS Project

STUDENT NAME Jared Padayachee

TEL NO. 1227 EMAIL 203505399

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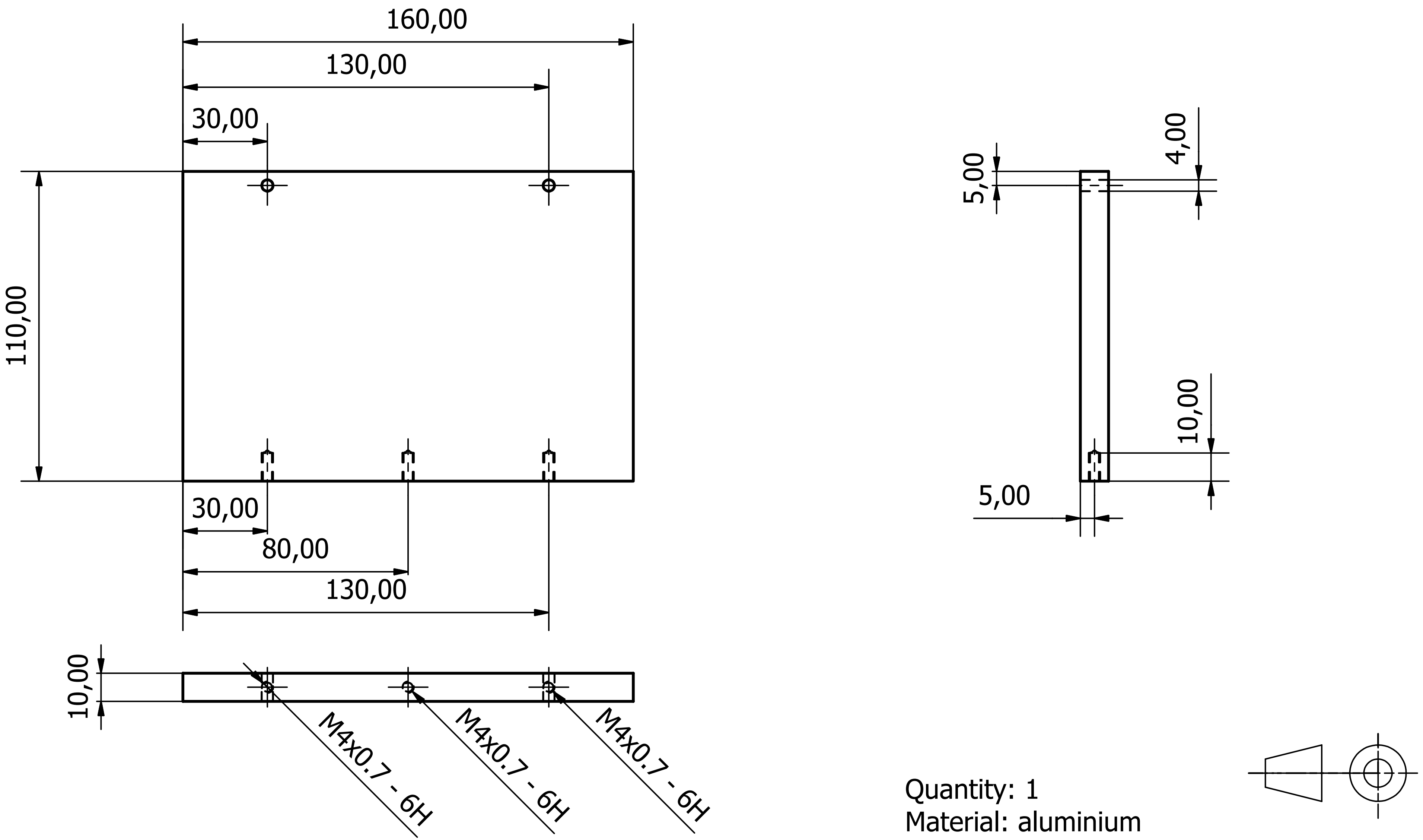
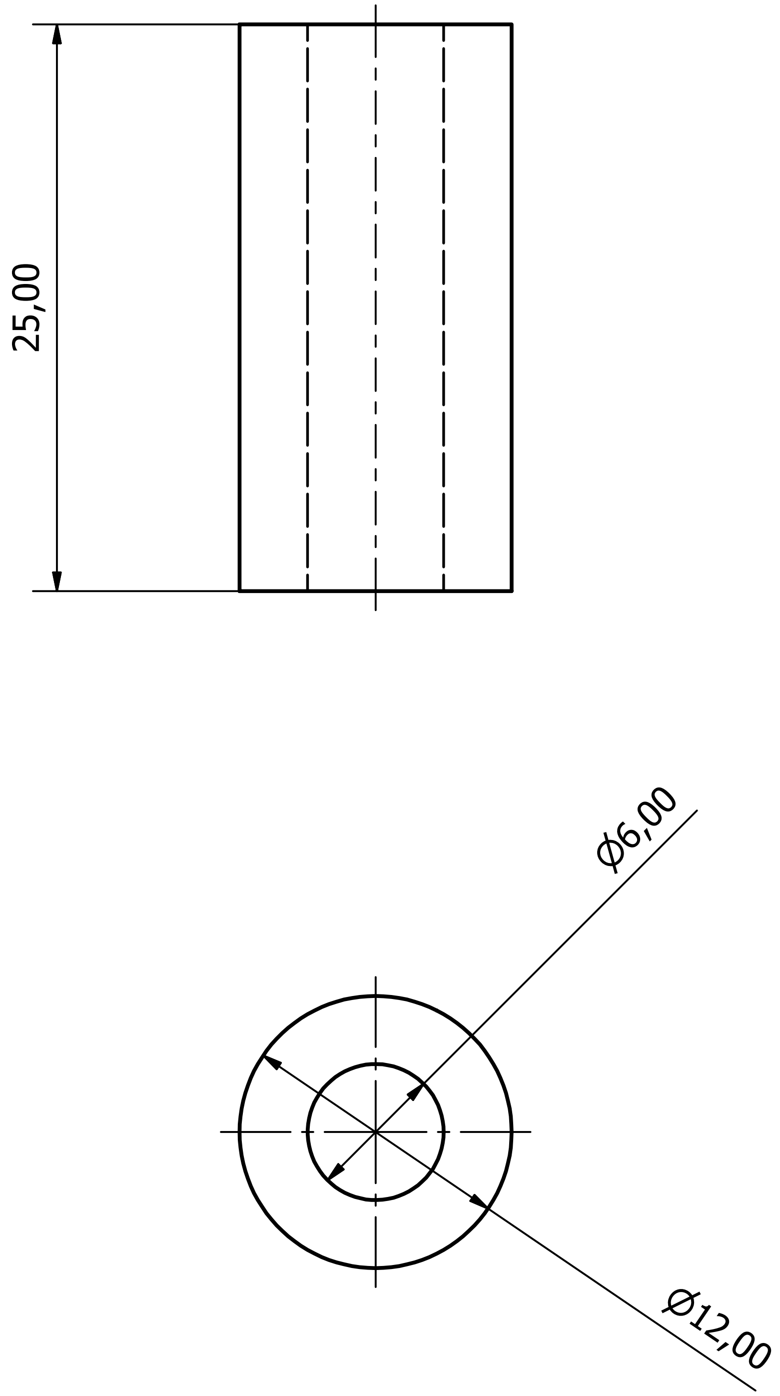
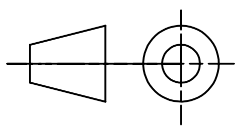


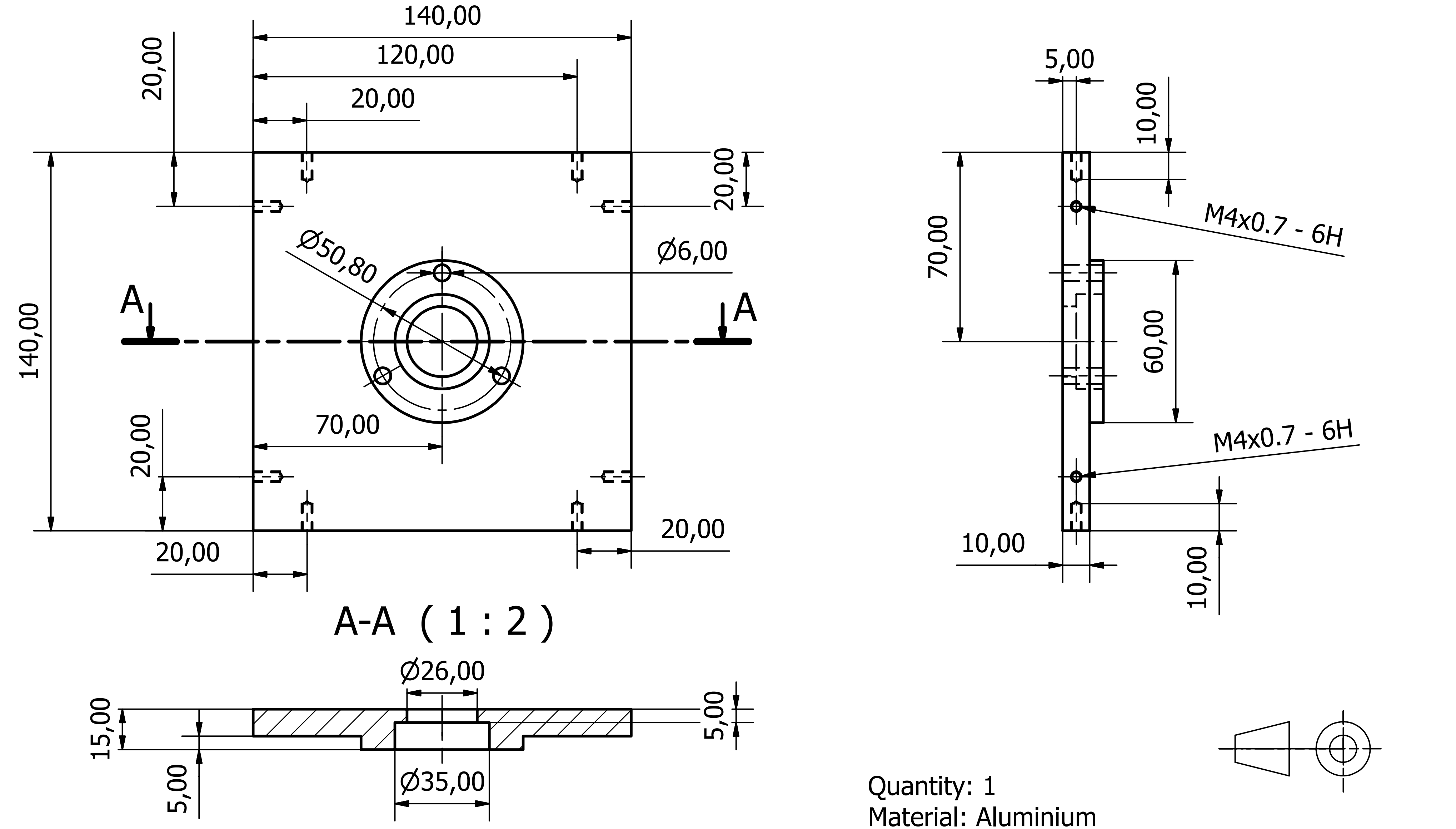
University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Side Plate 2 - work table - rotary
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Quantity: 3
Material: Steel rod

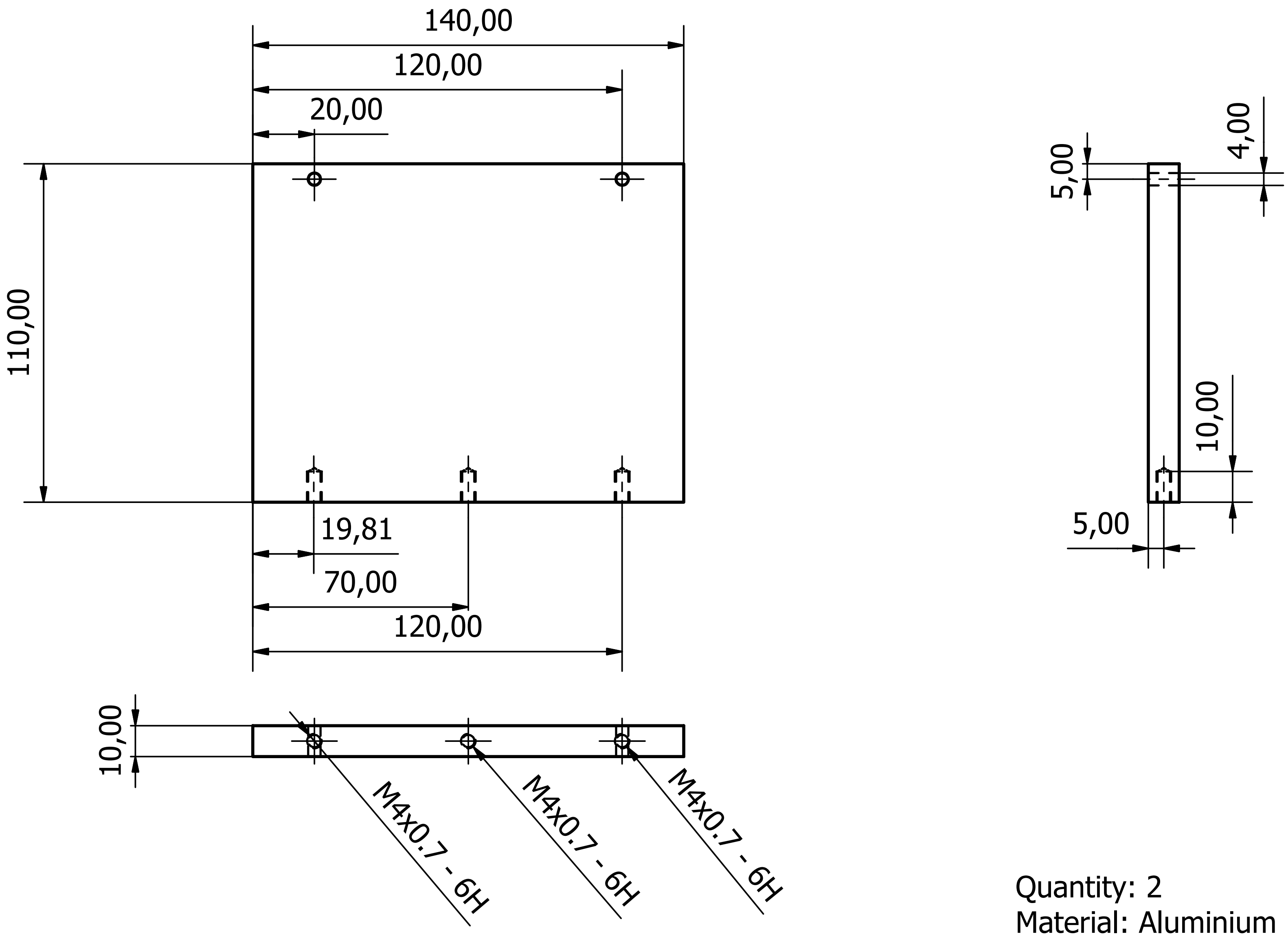


University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 3:1		TITLE Motor Spacer - work table - rotary
	◁⊕ OR ⊕▷	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399



Quantity: 1
Material: Aluminium

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Top plate - work table - rotary
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Quantity: 2
Material: Aluminium

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Side plate 3 - work table - rotary
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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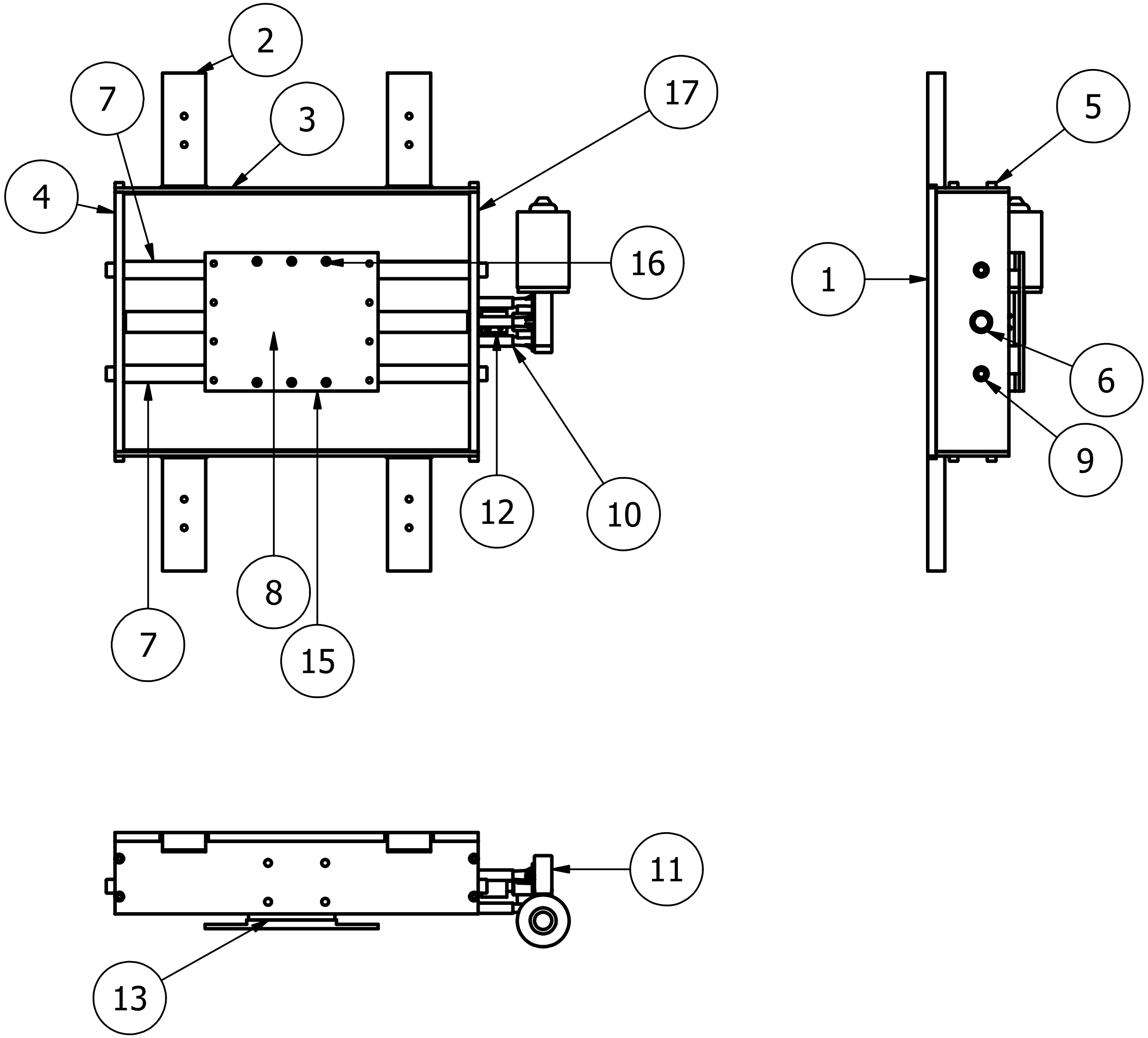

Parts List		
ITEM	QTY	PART NUMBER
1	1	Base
2	4	Base Legs
3	2	Side Plate
4	1	Back Plate
5	8	ISO 4762 - M6 x 20
6	2	SKF 61803-2RZ
7	2	guide rail
8	1	Lead Screw
9	4	ISO 4762 - M10 x 20
10	3	Motor spacer
11	1	Wiper Motor
12	1	Coupling
13	1	Carriage
14	1	Collar
15	1	Interface Plate
16	6	ISO 4762 - M4 x 20
17	1	Front Plate

University of Kwa-Zulu Natal

School of Mechanical Engineering

Orthographic Projection

OR

SCALE 1:8

UNITS : mm

	Date	Checked
Project Supervisor		
Workshop Technician		
Technical Manager		

TITLE Work Table Full assembly

PROJECT RMS Project

STUDENT NAME Jared Padayachee

TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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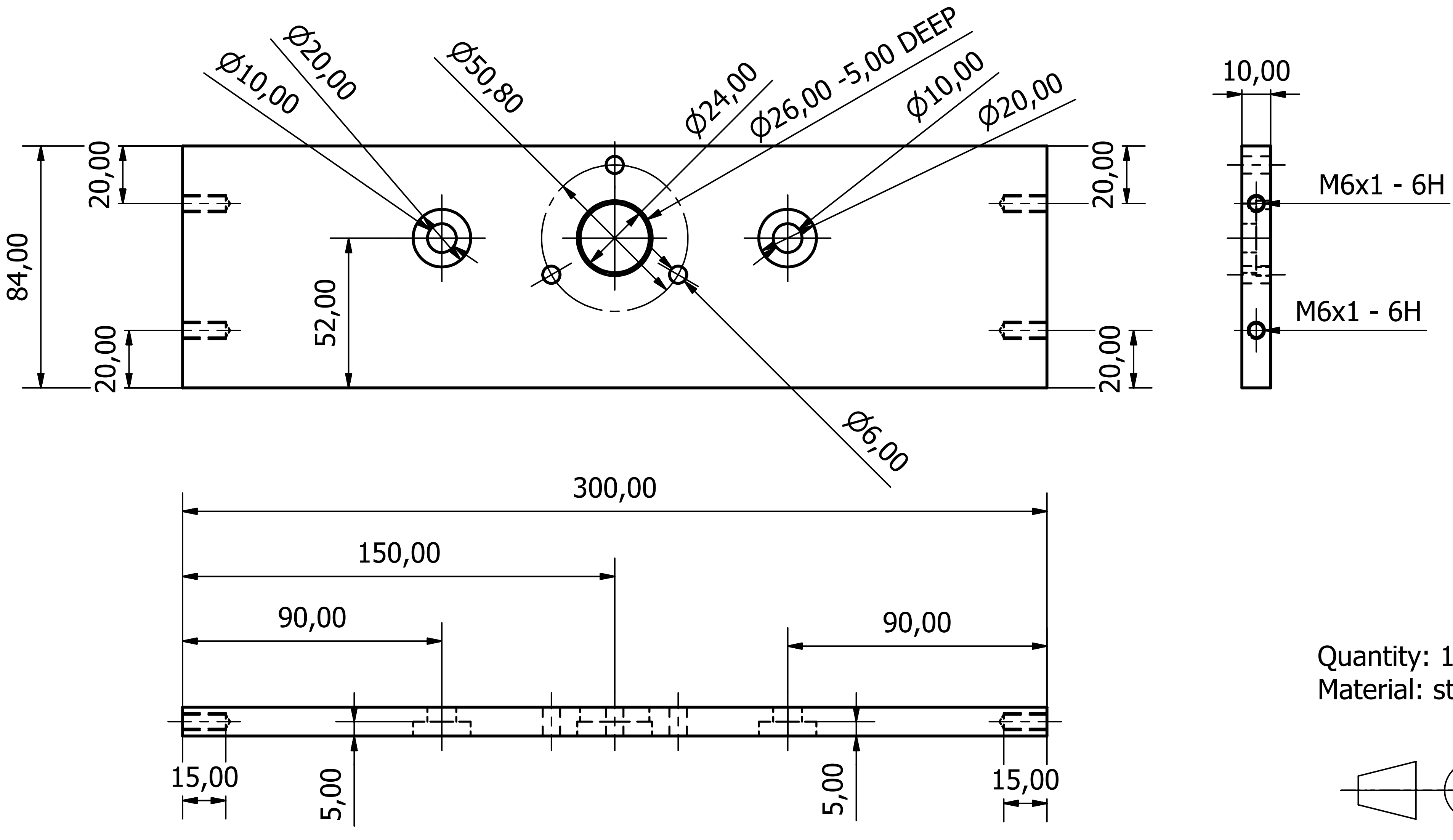

Quantity: 1
Material: steel supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:2 / UNITS : mm	TITLE Front Plate - Work Table Base
		Date	Checked
	Project Supervisor			PROJECT RMS Project
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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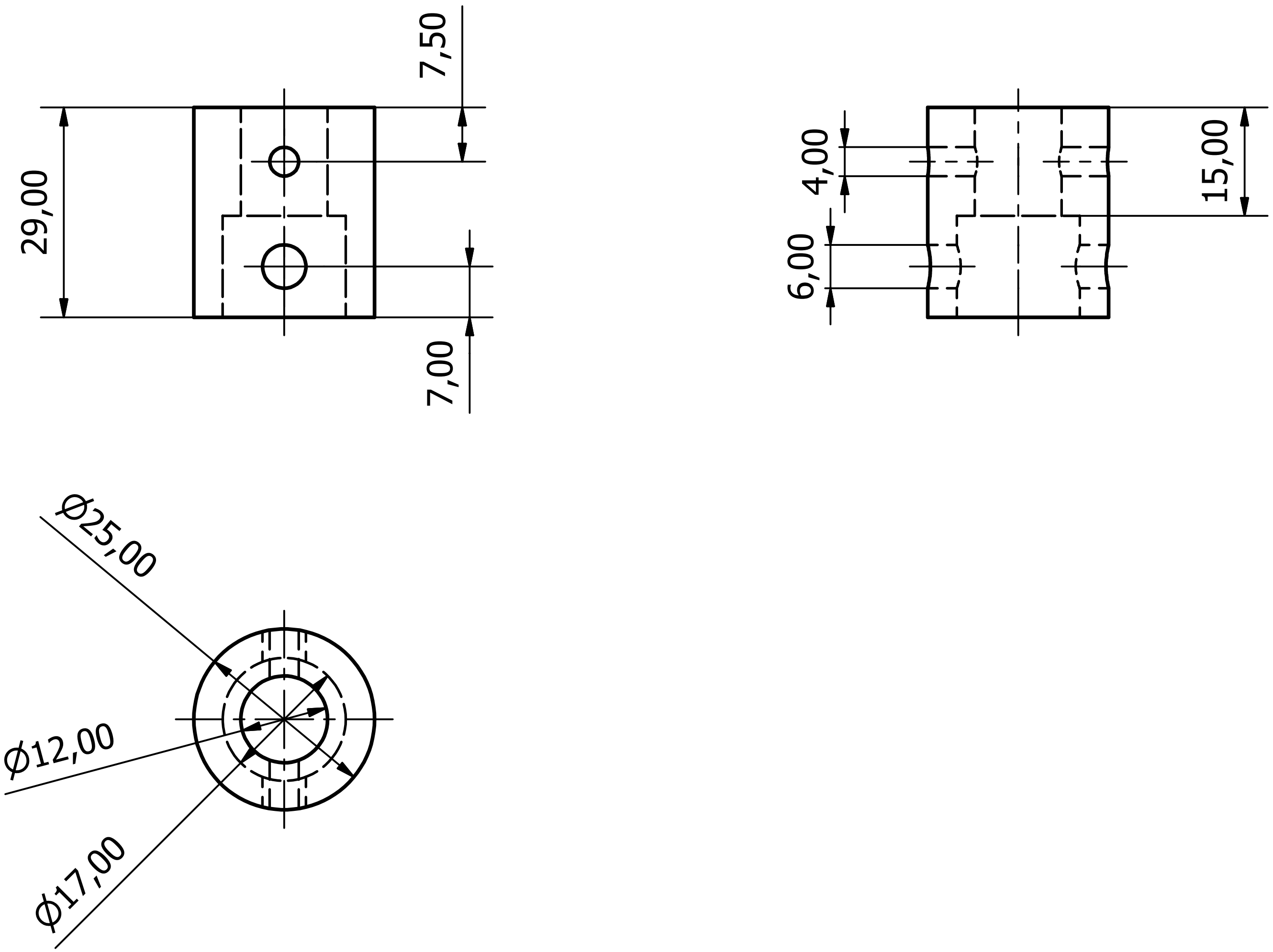
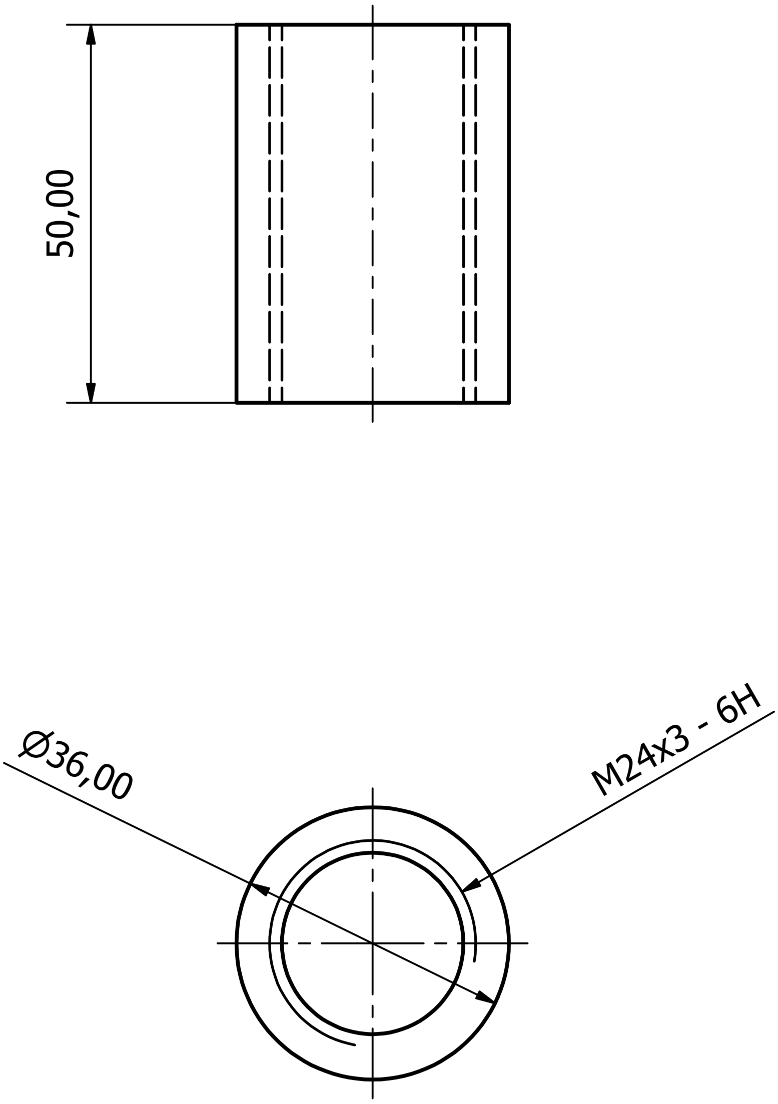


Quantity: 1
Material: Steel Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Motor coupling: Work Table
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Quantity:1
Material: Brass Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Collar - Work Table
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399

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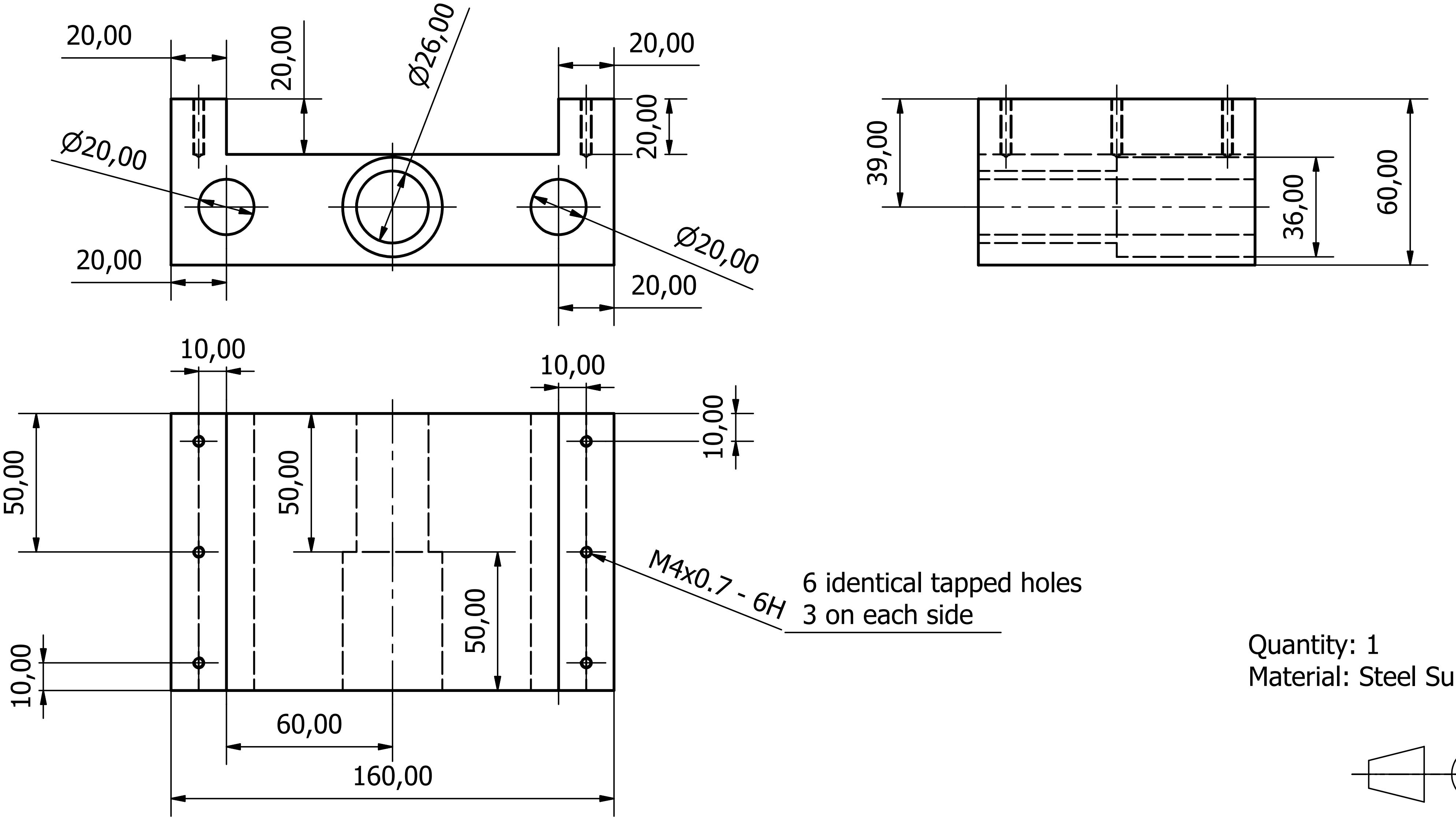
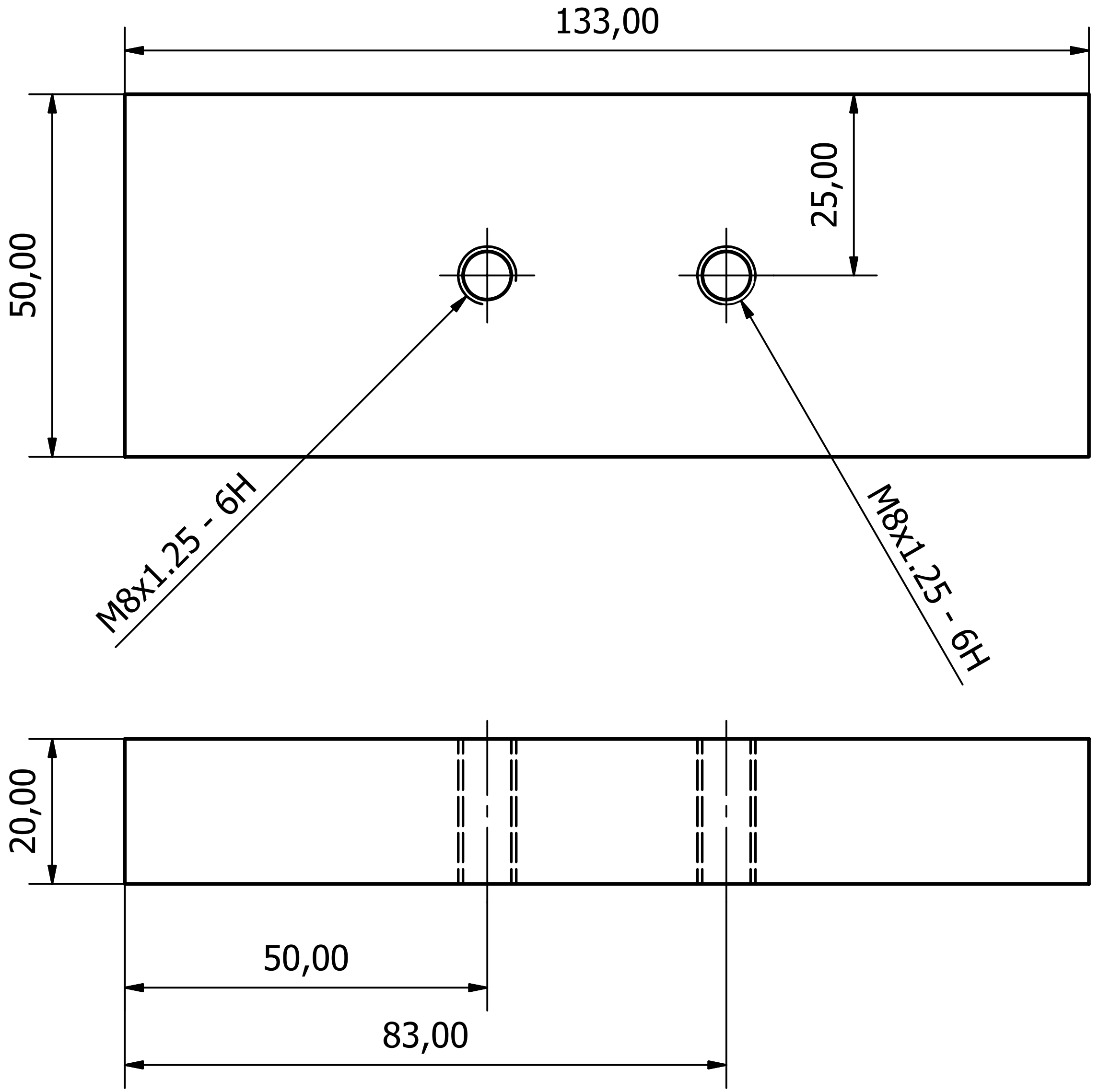
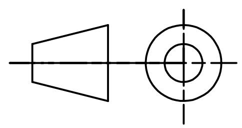


Quantity: 1
Material: Steel Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Carriage - work table
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Quantity: 4
Material: Steel Supplied



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Base Legs - work table
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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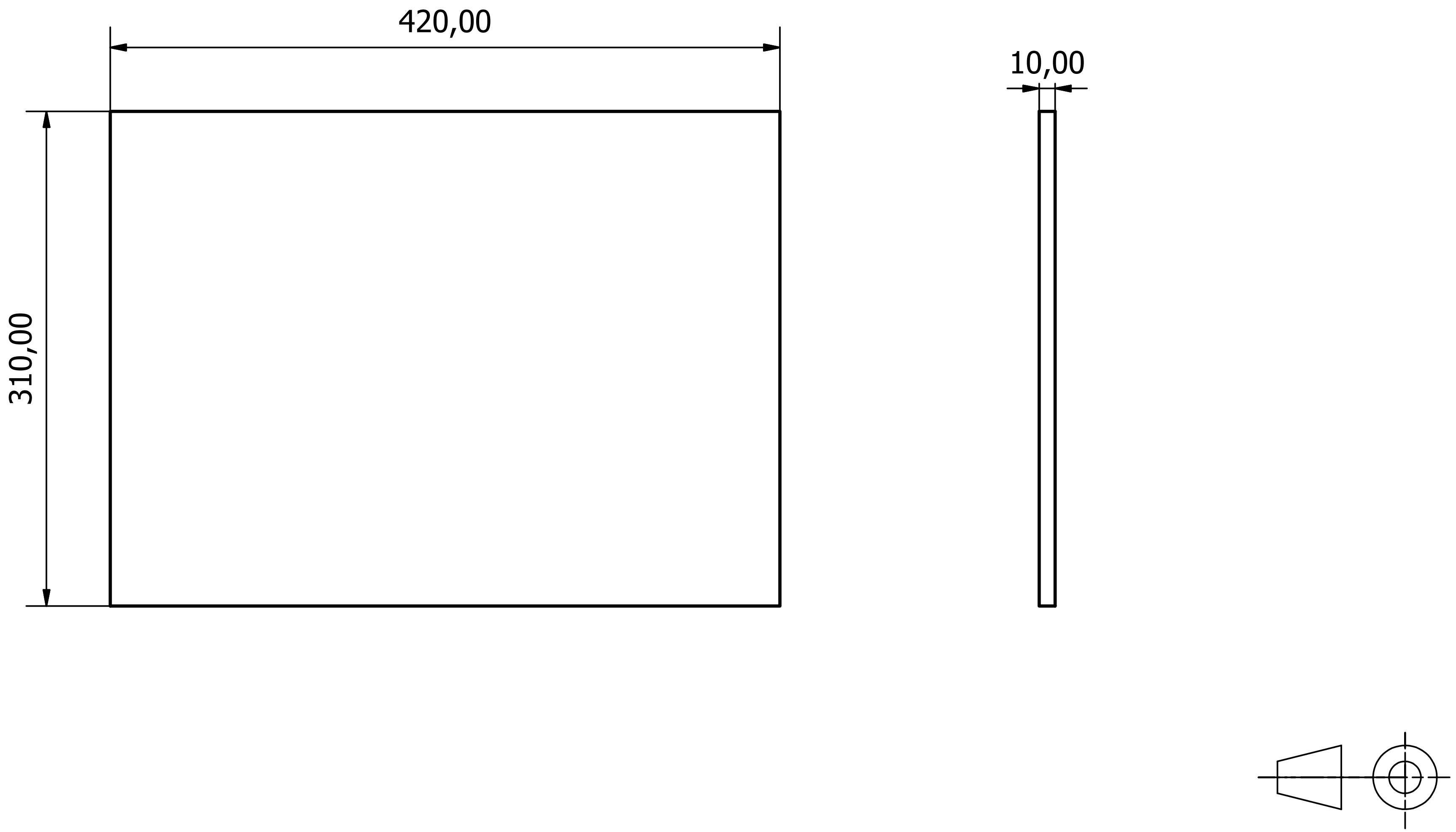

Quantity: 1
Material: steel plate supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:4		TITLE Work table Base
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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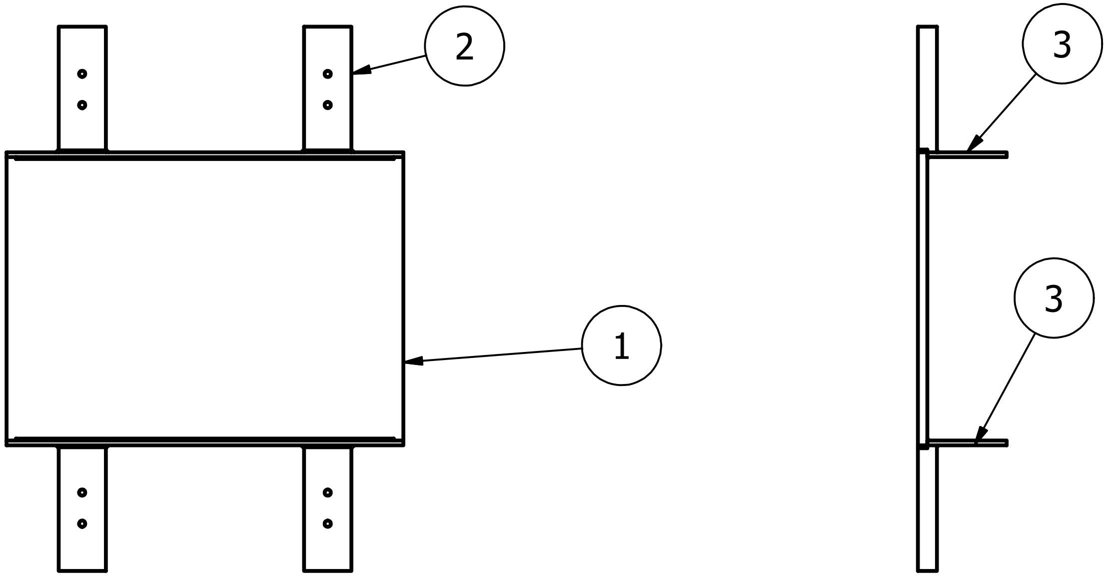

Parts List		
ITEM	QTY	PART NUMBER
1	1	Base
2	4	Base Legs
3	2	Side

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:8	TITLE Base welded assembly 2
	OR	UNITS : mm	
		Date / Checked	PROJECT RMS Project
	Project Supervisor		
	Workshop Technician		STUDENT NAME Jared Padayachee
	Technical Manager		TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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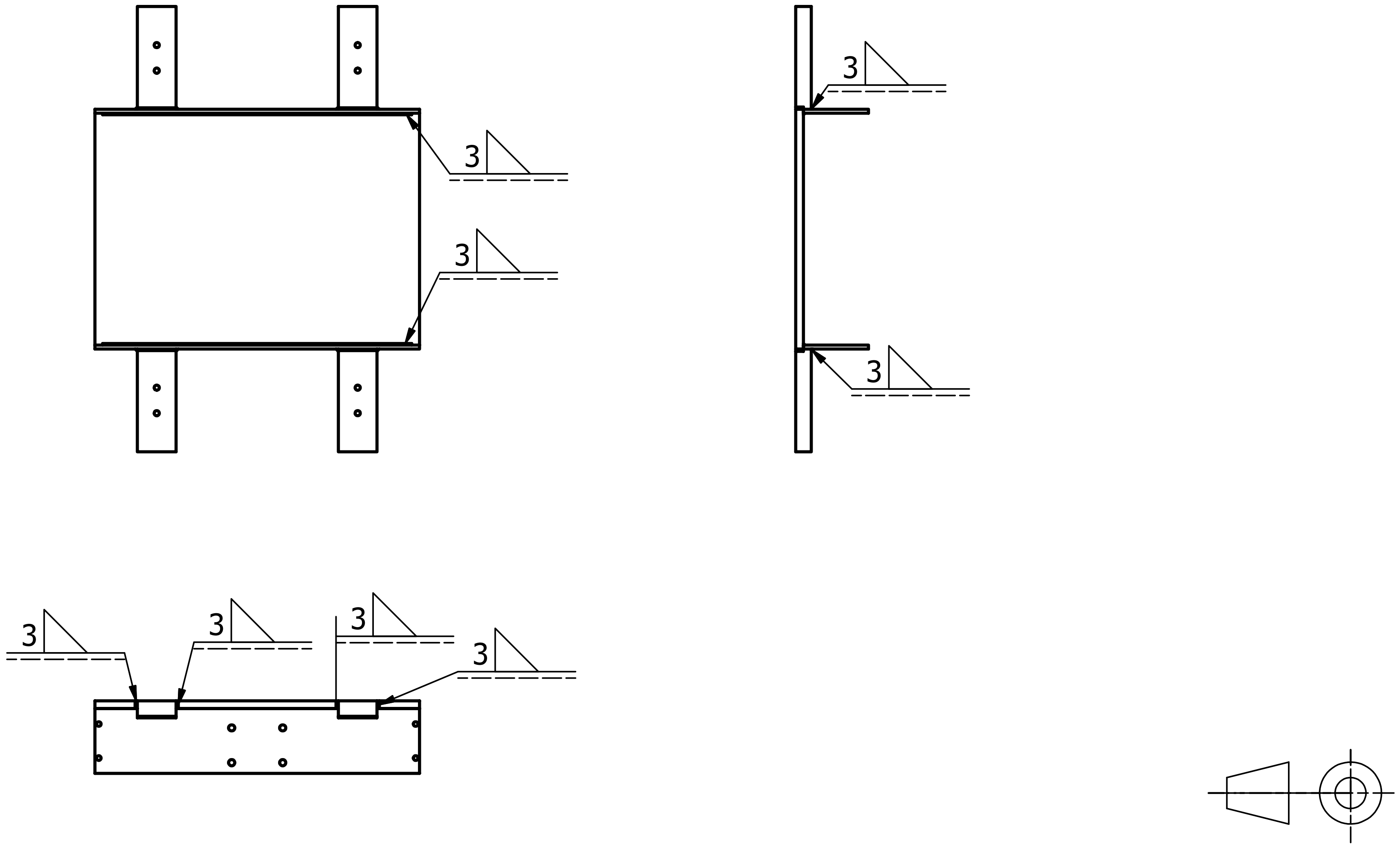
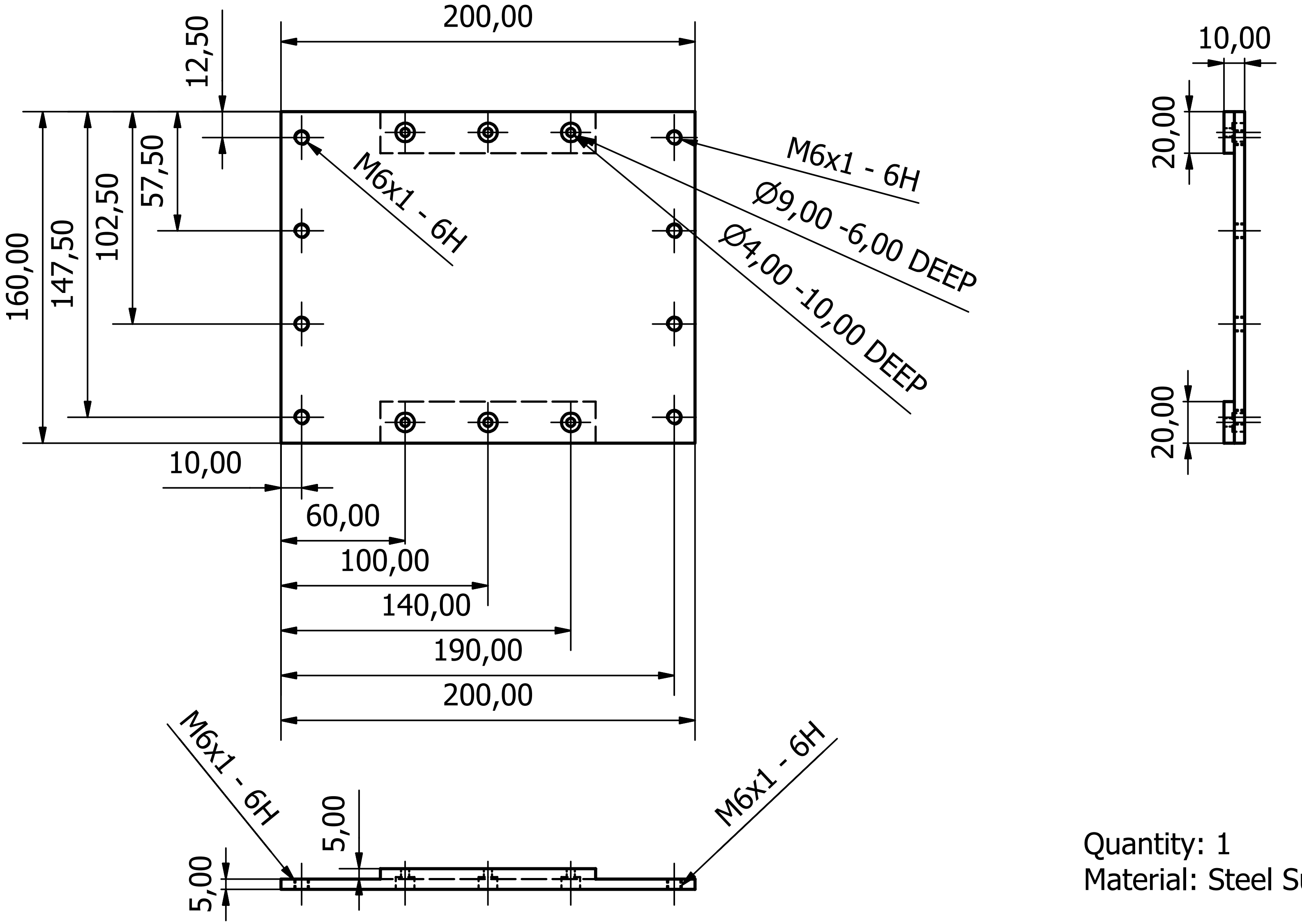


University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:8		TITLE Base - welding diagram
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Quantity: 1
Material: Steel Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:3 UNITS : mm		TITLE Interface Plate - work table
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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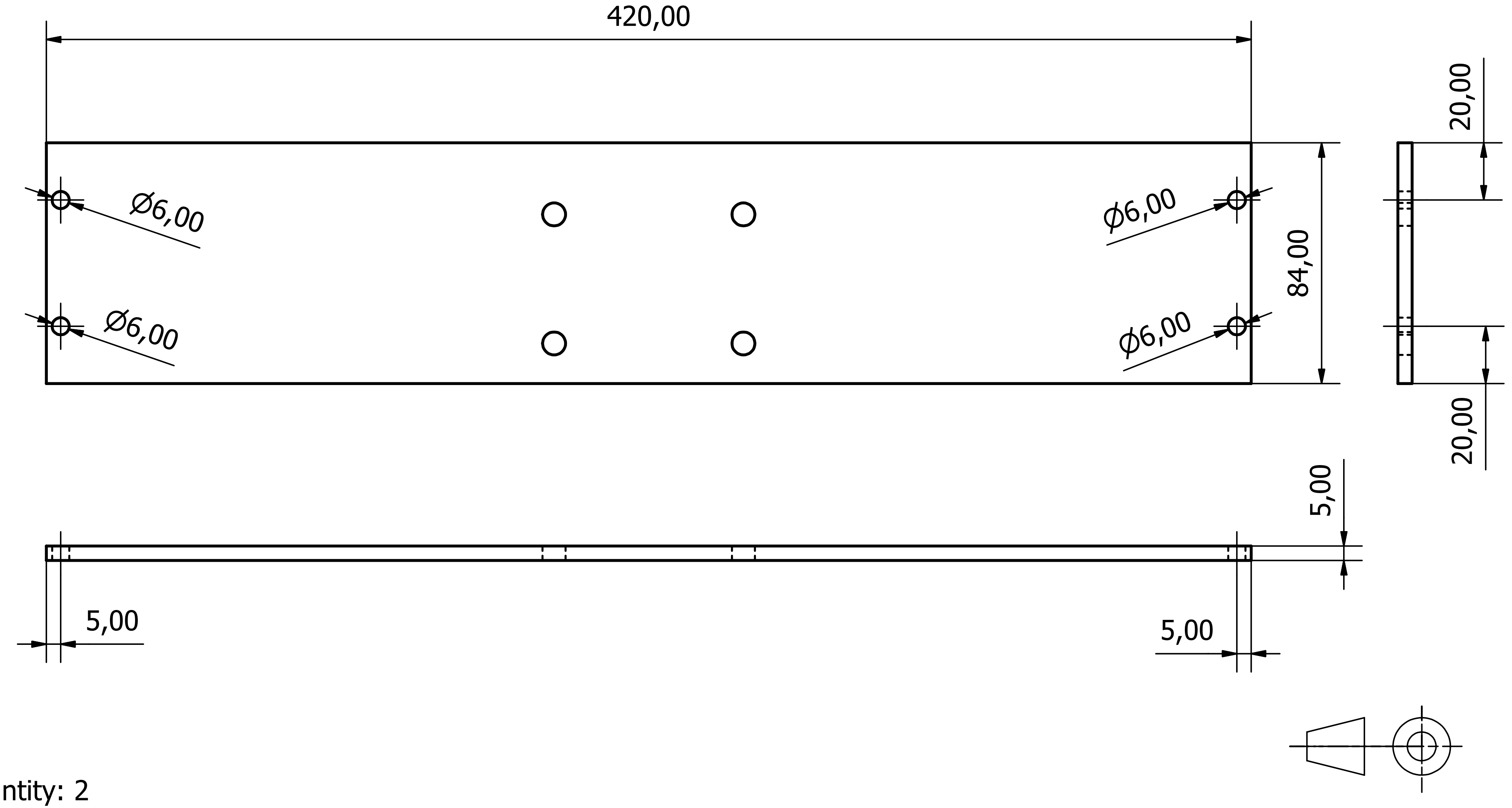
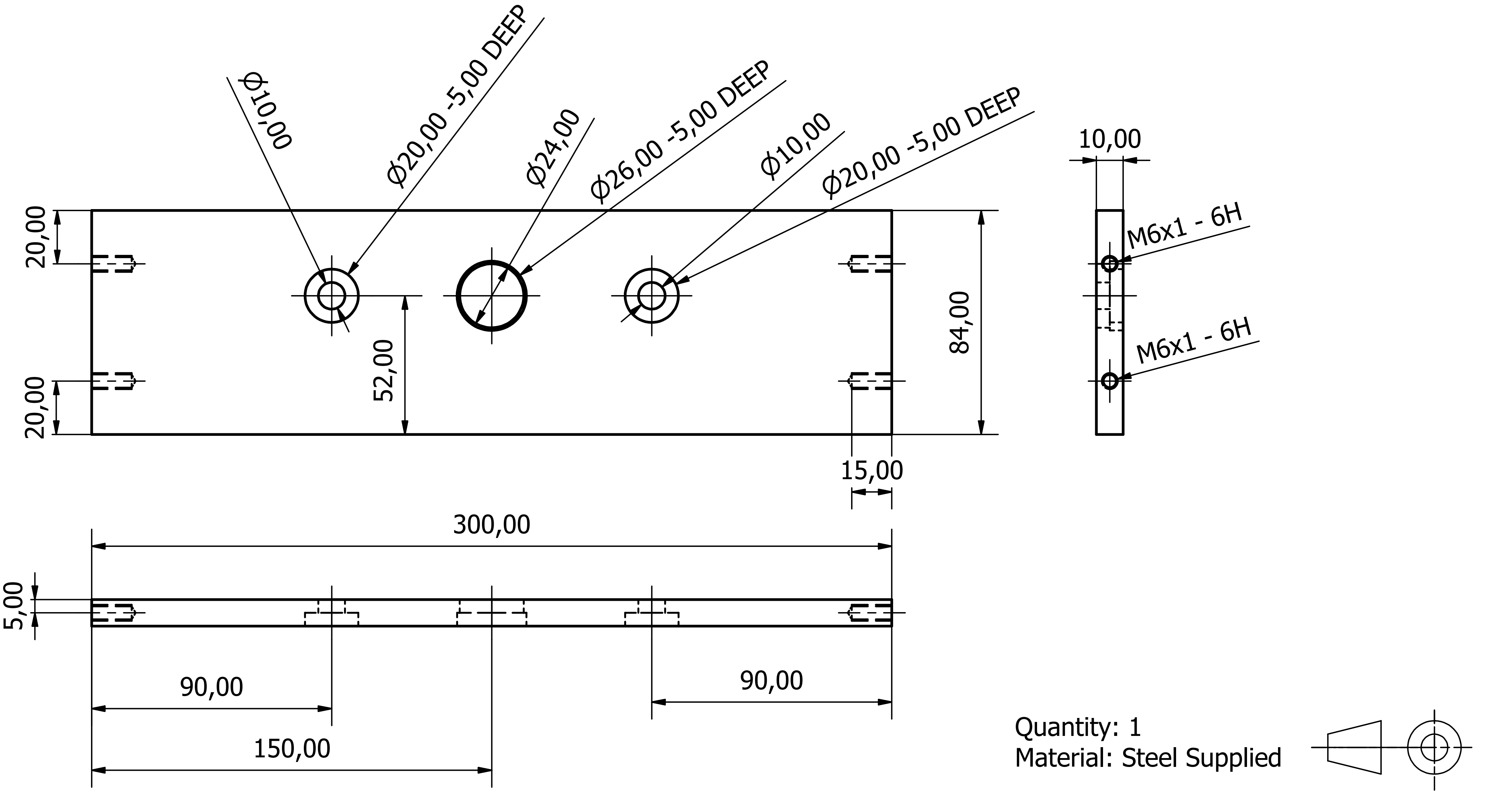


Quntity: 2
Material: Steel Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2		TITLE Side Plate - work table base
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za



Quantity: 1
Material: Steel Supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:2		TITLE Rear Plate - work table base
		UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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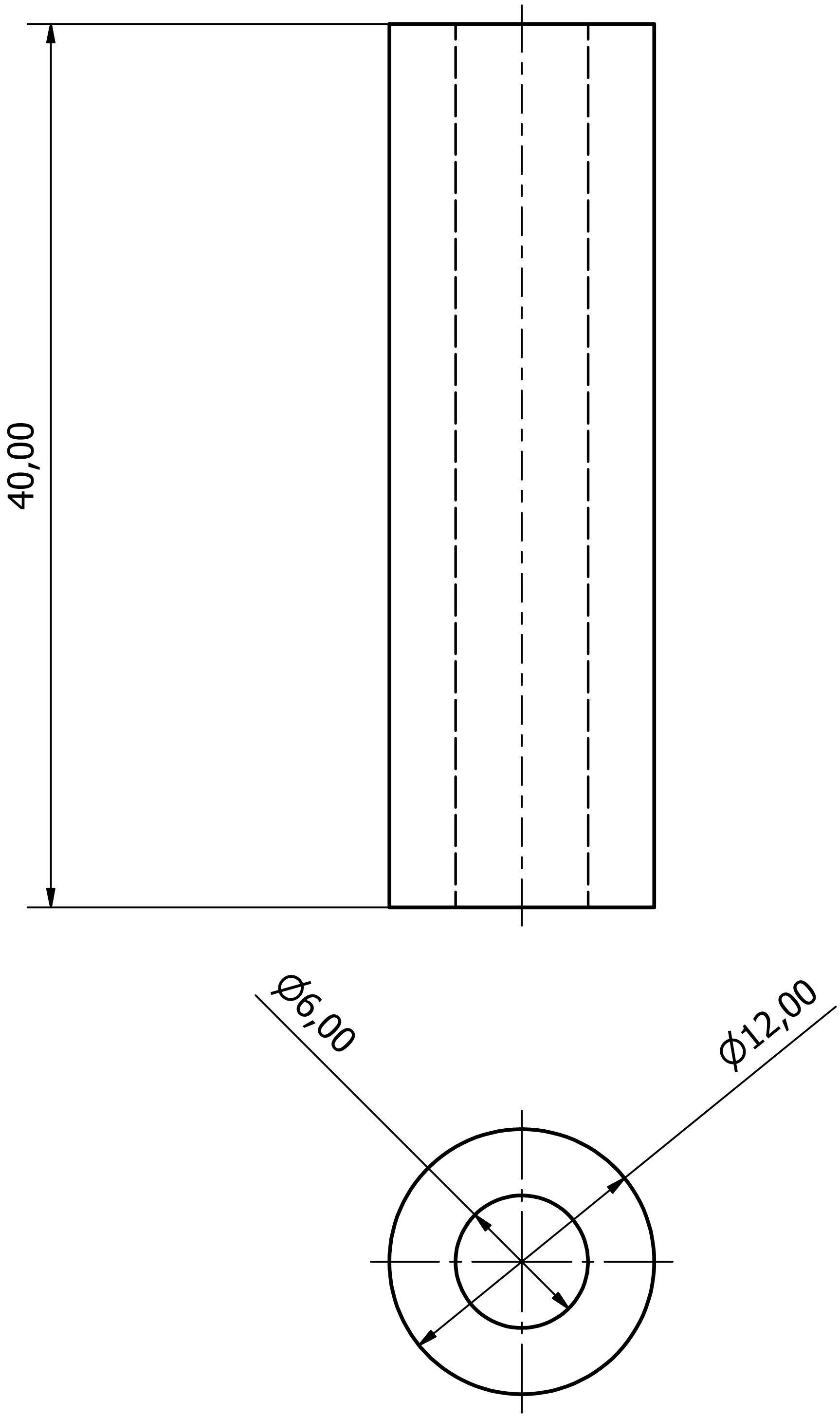
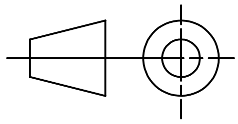


Quantity: 3
Material: Steel supplied



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 3:1		TITLE Motor Spacer - work table
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399

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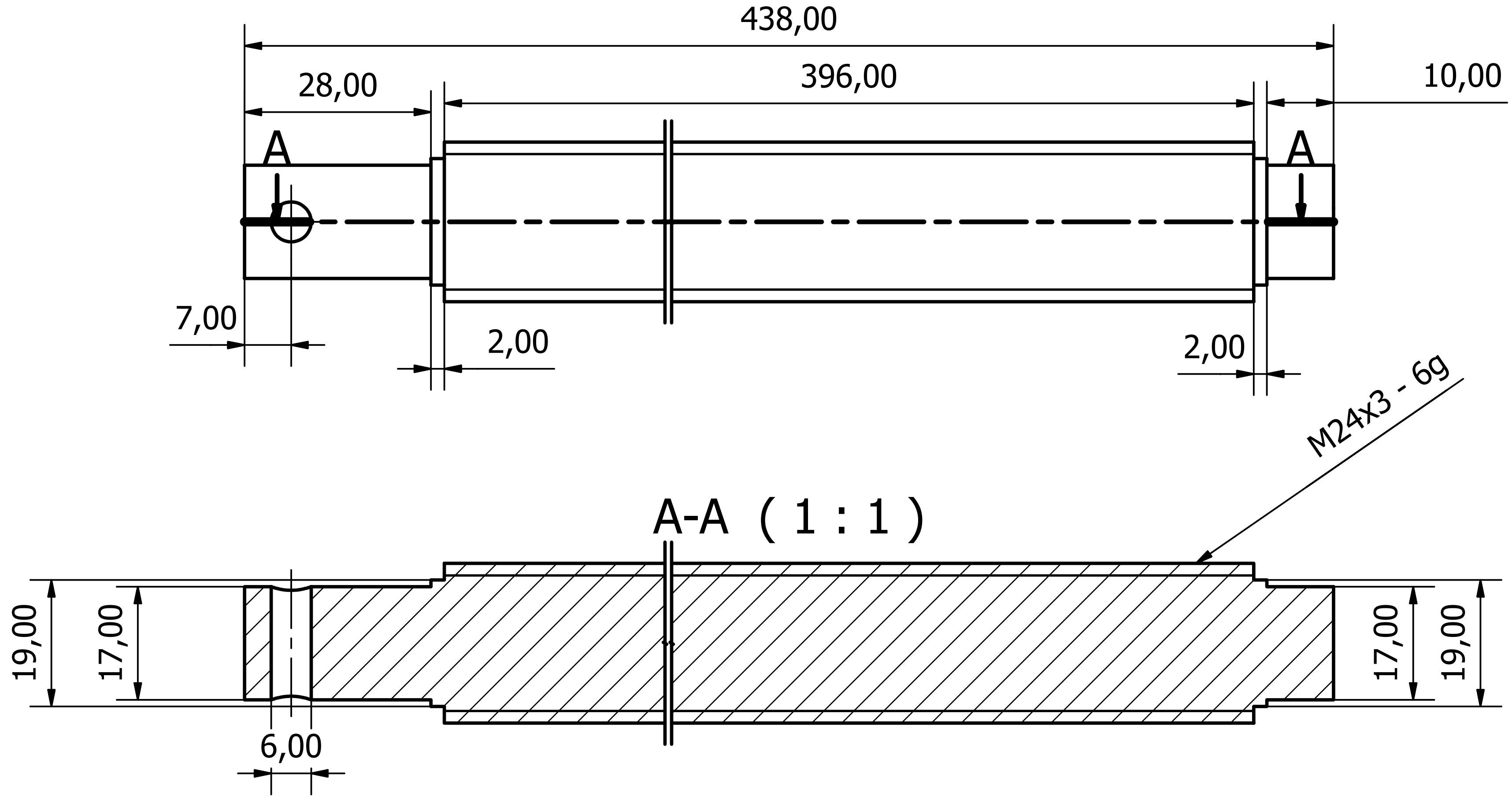
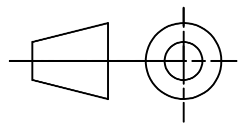
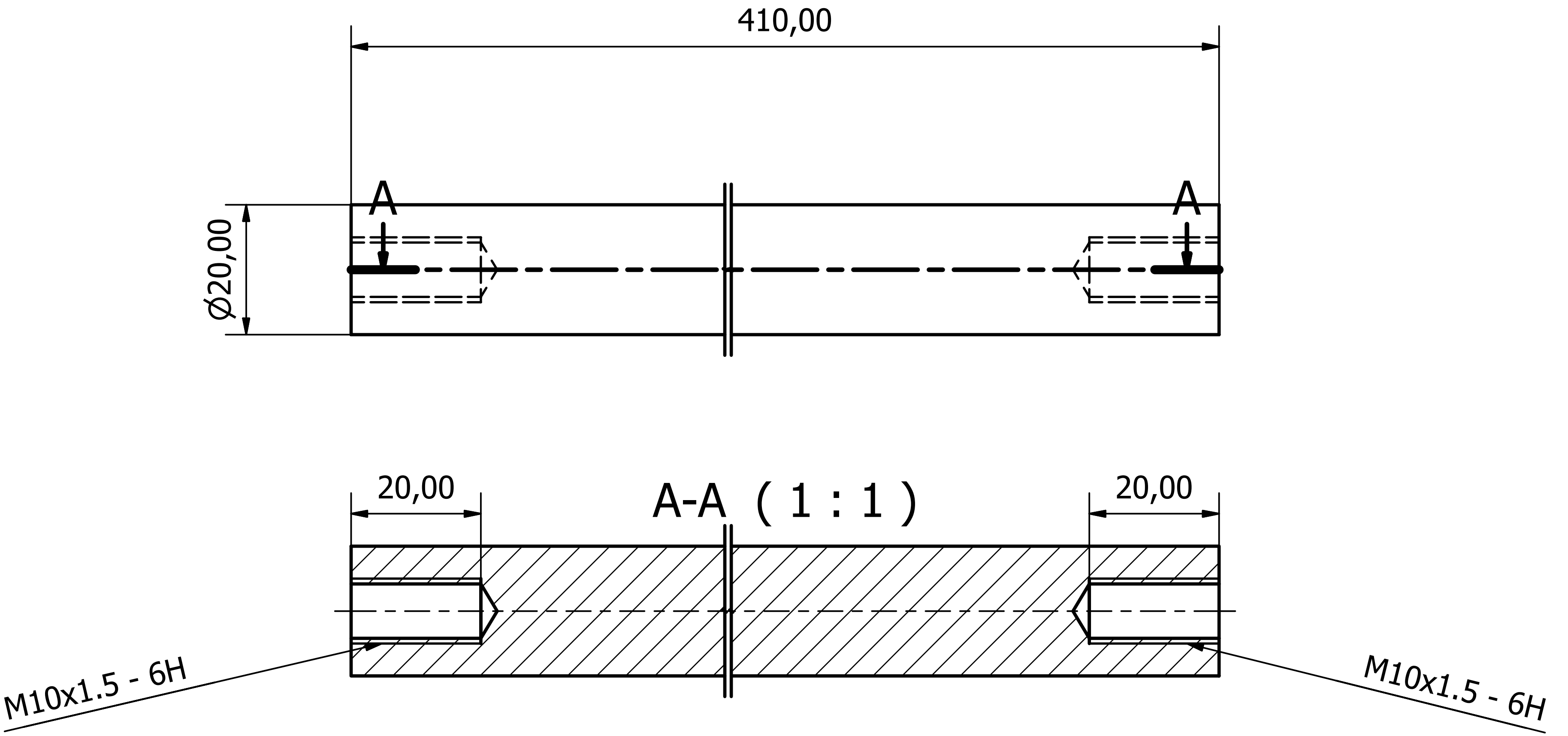
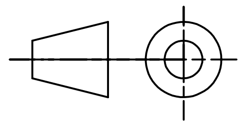




Quantity: 1
Material: Threaded bar supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Lead Screw - work table
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za





Quantity: 2
Material: Steel rod supplied

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:1		TITLE Guide Rod - work table
	OR	UNITS : mm		PROJECT RMS Project
		Date	Checked	
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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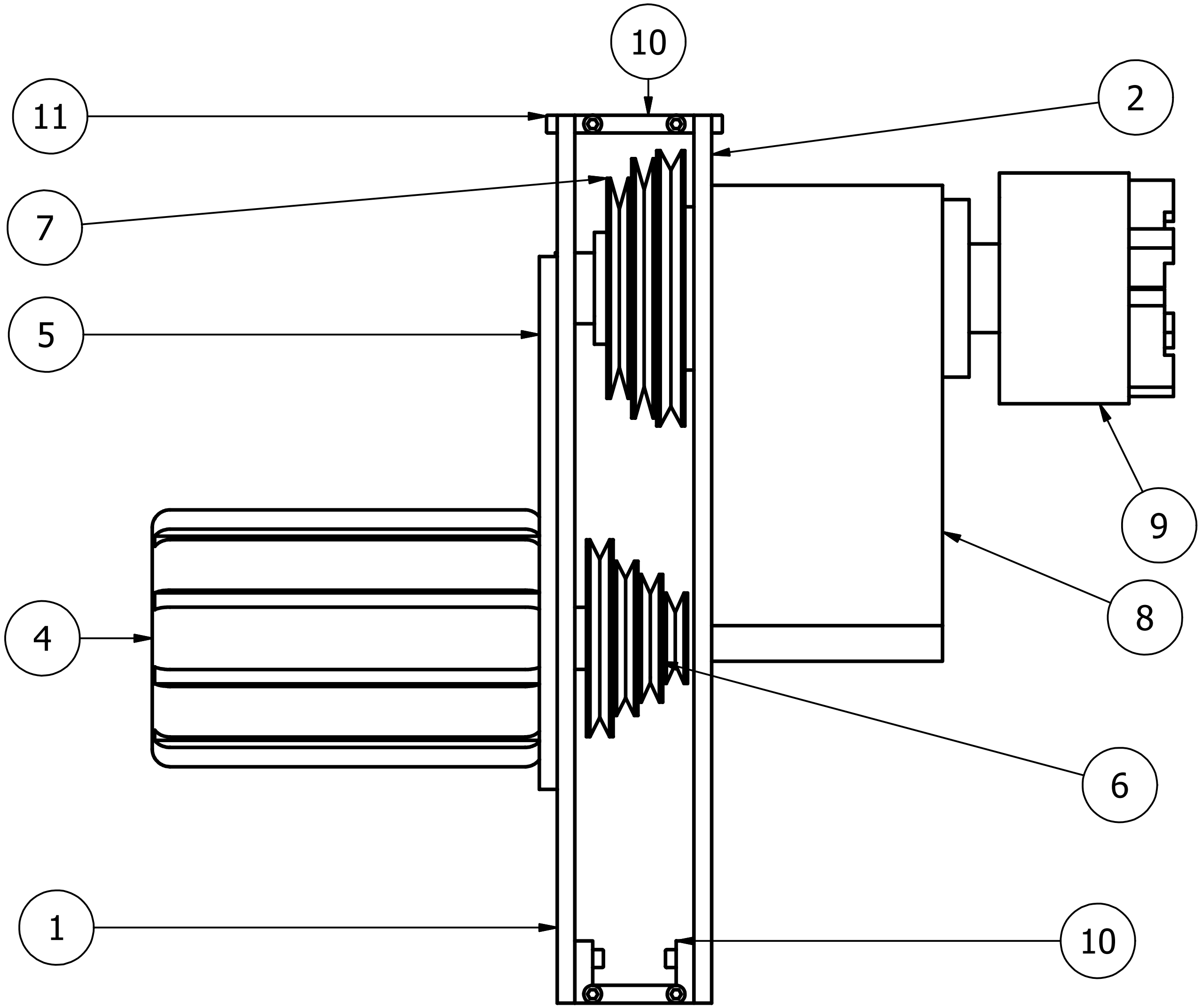

Parts List		
ITEM	QTY	PART NUMBER
1	1	transmission box back plate
2	1	transmission box front plate
3	2	transmission box side plates
4	1	motor
5	1	motor bracket
6	1	pulley two
7	1	pulley one
8	1	Head Stock
9	1	chuck
10	2	transmission box top-bot plates
11	20	ISO 4762 - M6 x 20

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:4 UNITS : mm	TITLE Transmission Box Assembly
		Date | Checked	PROJECT RMS Project
	Project Supervisor		
	Workshop Technician		STUDENT NAME Jared Padayachee
	Technical Manager		TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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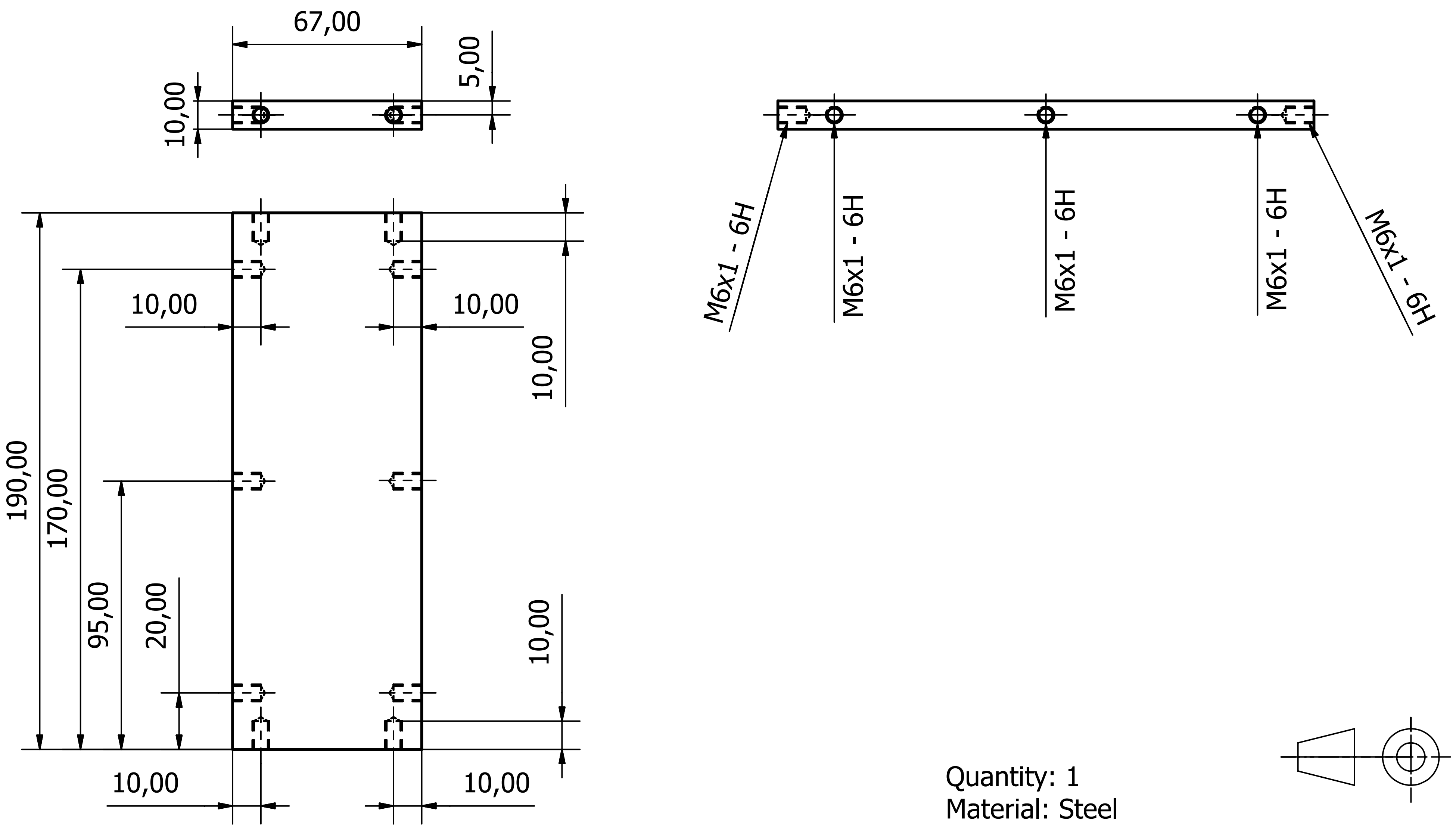
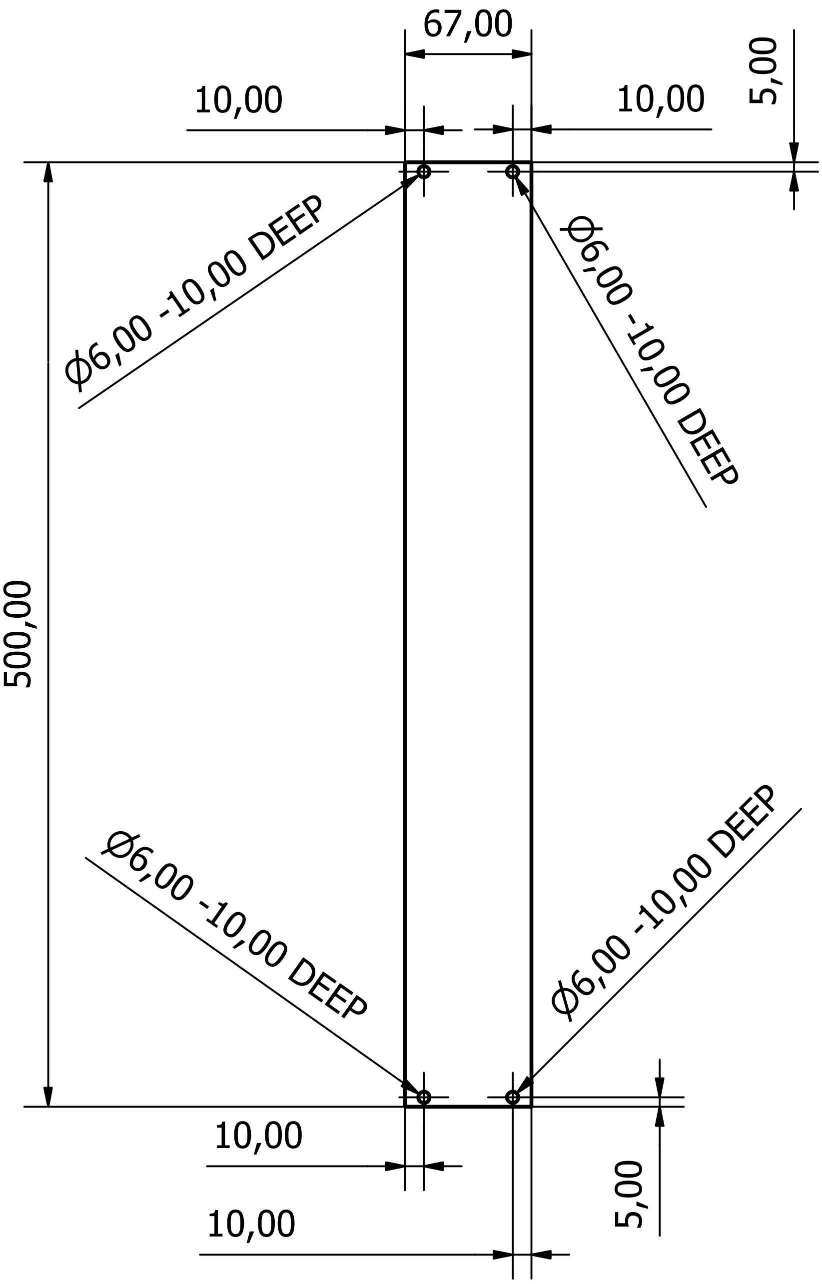
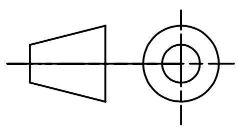


Quantity: 1
Material: Steel

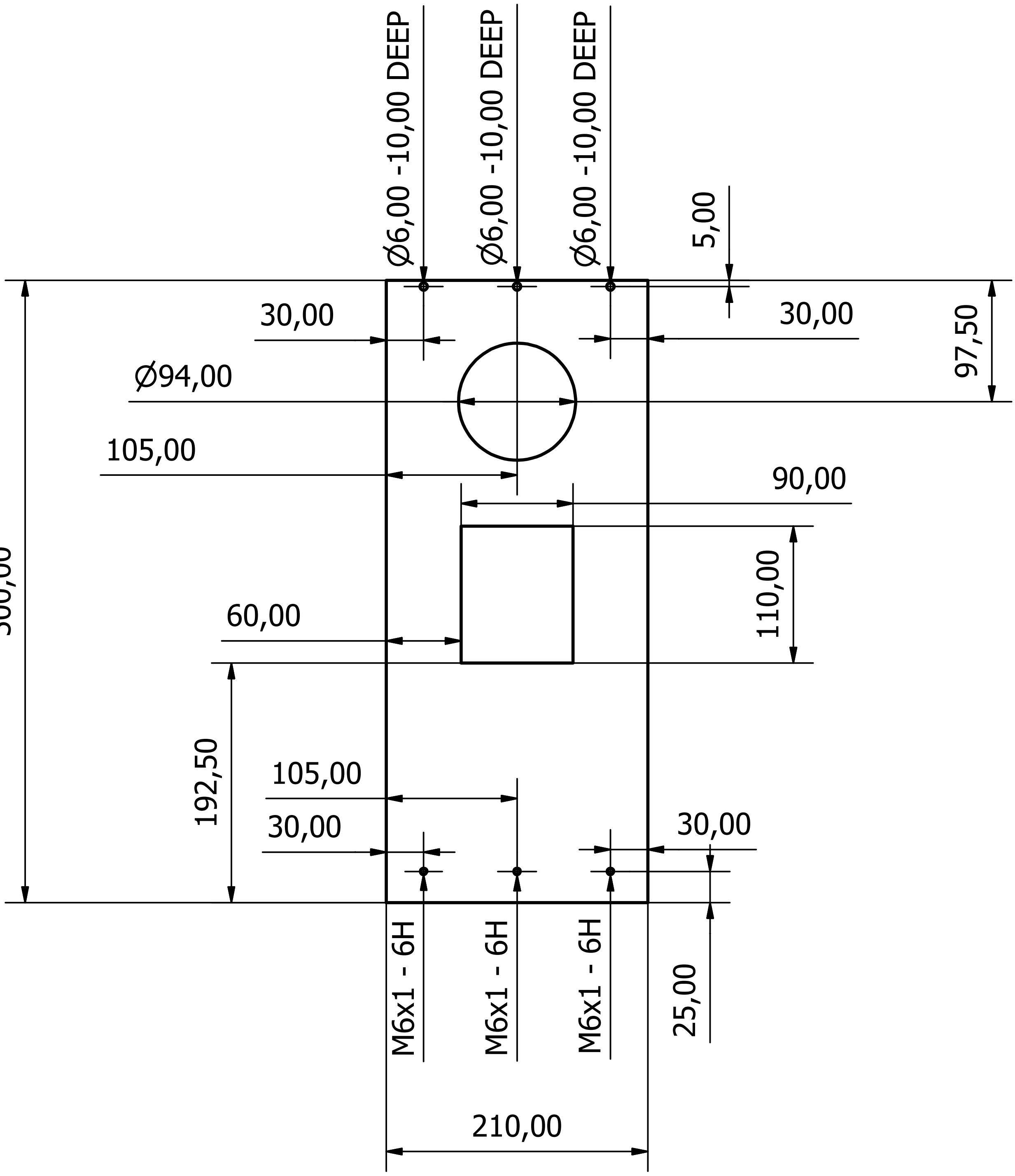
University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:2 UNITS : mm	TITLE Transmission Box Top Plate
		Date	Checked	
	Project Supervisor			PROJECT RMS Project
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za





Quantity: 2
Material: Steel

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:4		TITLE Transmission Box Side Plate
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399



Quantity: 1
Material: Steel

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:5		TITLE Transmission Box - Front Plate
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399

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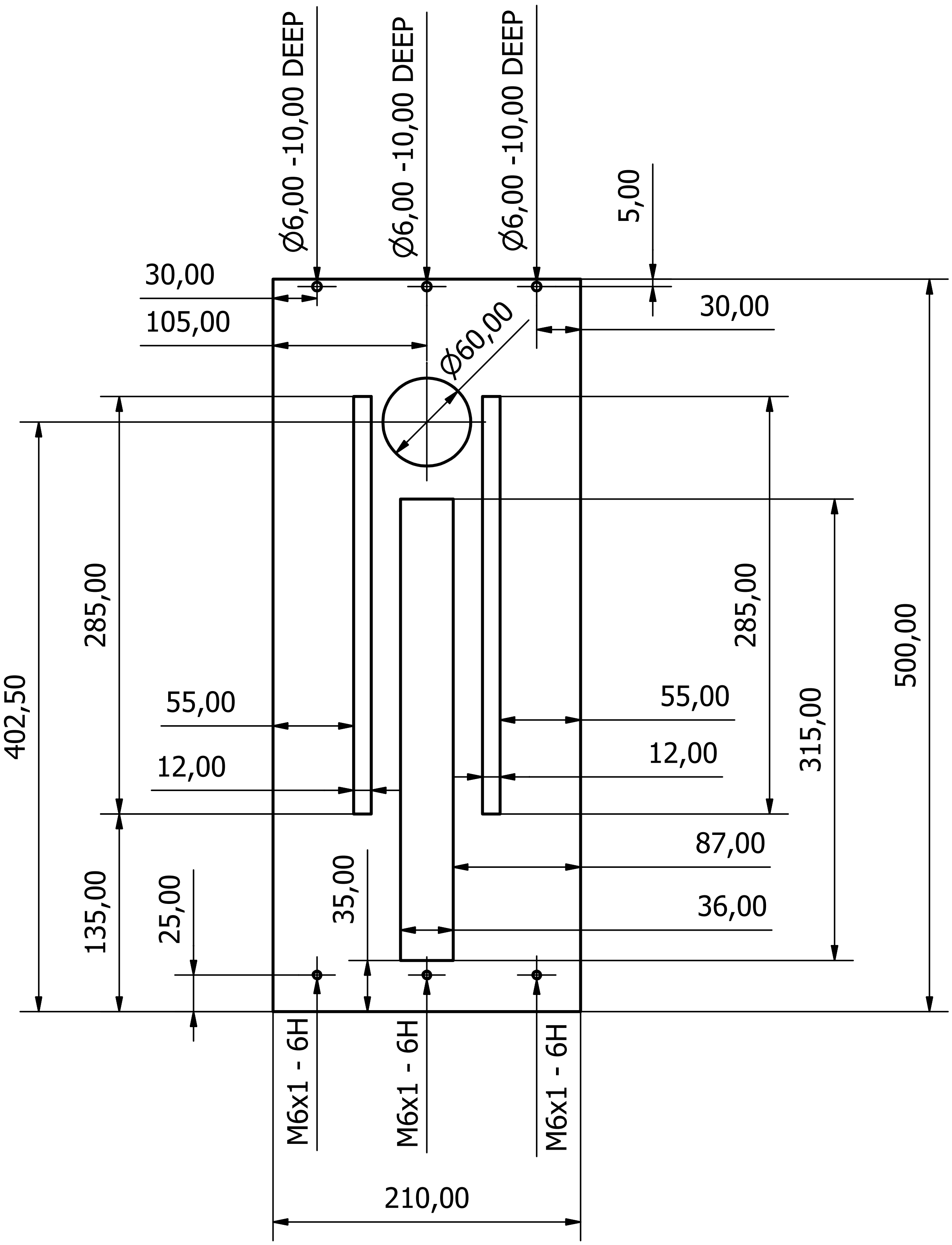
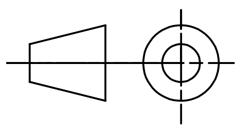
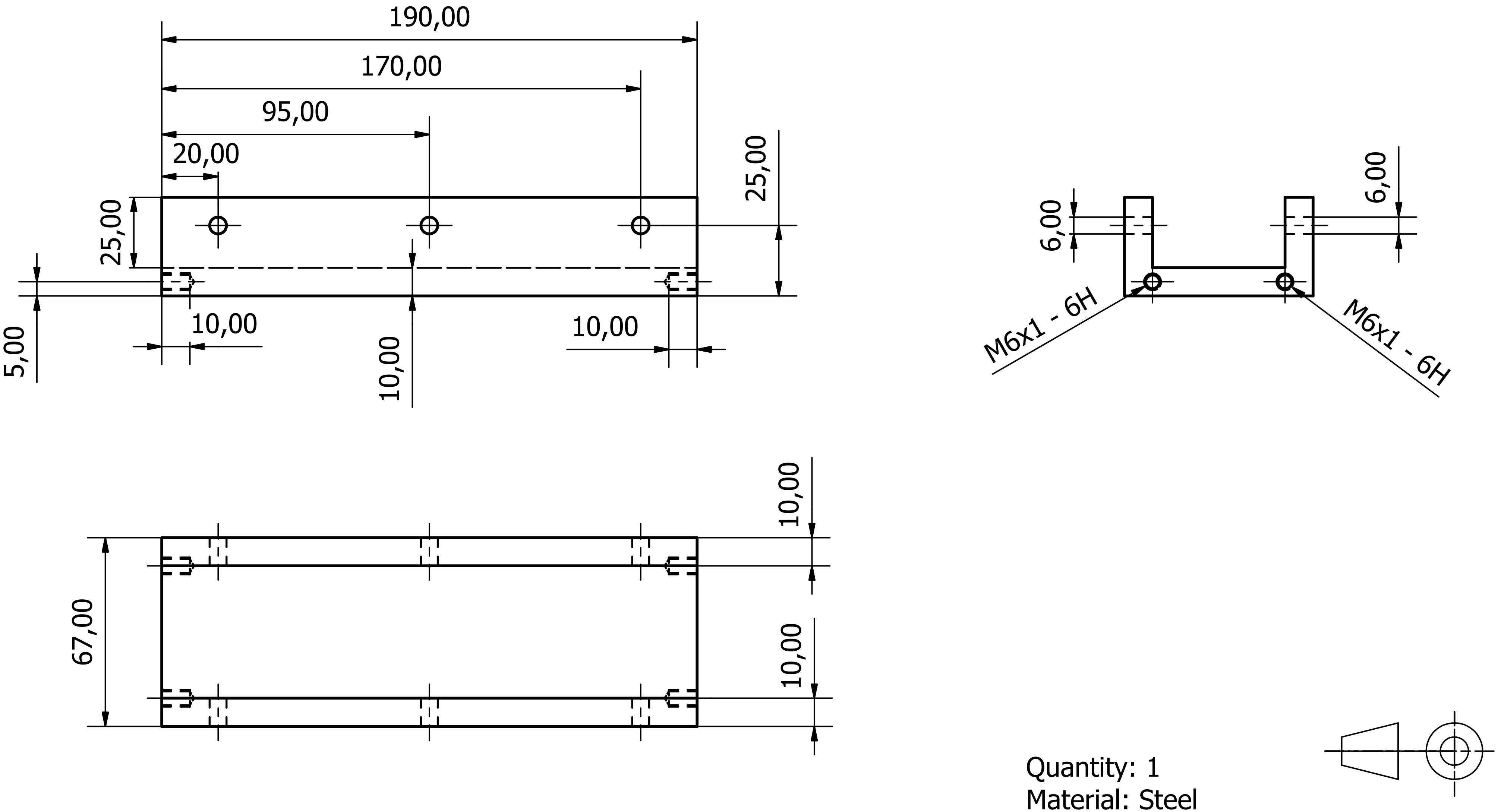


Quantity: 1
Material: Steel



University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection OR	SCALE 1:4 UNITS : mm		TITLE Transmission Box Back Plate
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399



Quantity: 1
Material: Steel

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:2	TITLE Transmission Box Bottom Plate
	OR	UNITS : mm	
		Date | Checked	PROJECT RMS Project
	Project Supervisor		
	Workshop Technician		STUDENT NAME Jared Padayachee
	Technical Manager		TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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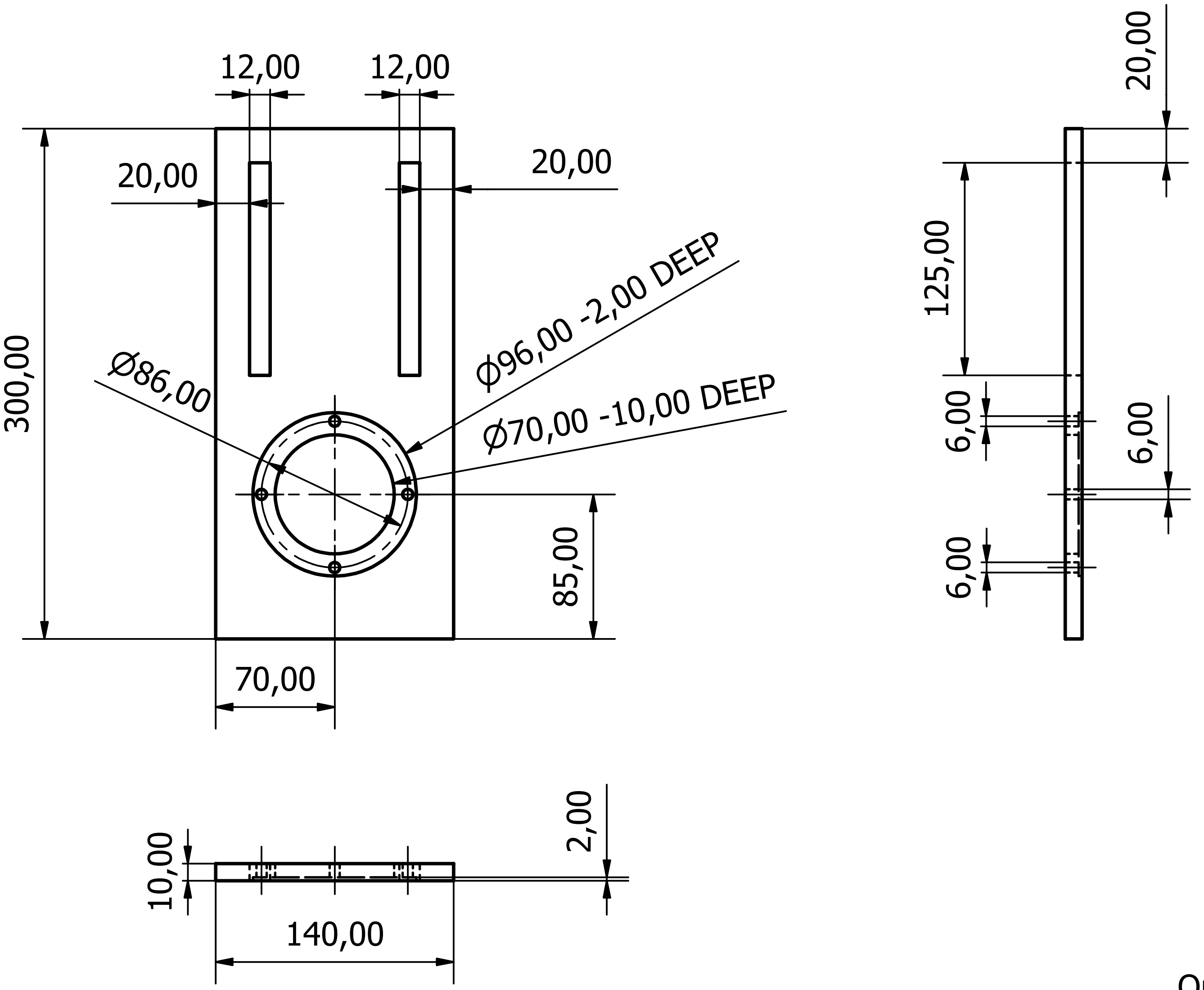

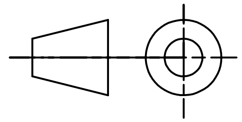

Quantity: 1
Material: Steel

University of Kwa-Zulu Natal School of Mechanical Engineering	Orthographic Projection	SCALE 1:4		TITLE Motor Bracket
	OR	UNITS : mm		
		Date	Checked	PROJECT RMS Project
	Project Supervisor			
	Workshop Technician			STUDENT NAME Jared Padayachee
	Technical Manager			TEL NO. 1227 EMAIL 203505399@ukzn.ac.za

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