FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

# Collaborative Robotics in Industrial Automation

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Dissertation for MSc in Mechanical Engineering

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# Abstract

In order to potentiate versatility and flexibility within collaborative environments, an automatic tool changer was designed and developed using Additive Manufacturing. Due to the lighter loads involved with Collaborative Robotics the application, as final products, of components fabricated through this process which usually doesn't promote good and homogeneous mechanical properties is possible. Furthermore, Additive Manufacturing allows for quick adaptation of the different components to fit whichever application and assembly requirements within the hour. Testings proved the design is impact resistant and supports loads up to 10 kg. The automatic coupling isn't working reliable at the time of publishing, however all systems were tested with manual engagement.

**Keywords**: Additive Manufacturing, Collaborative Robotics, Industry 4.0, Automatic Tool Changer

# Resumo

Por forma a potenciar a versatilidade e flexibilidade em ambientes colaborativos, uma mecanismo de troca de ferramenta automático foi desenvolvido utilizando Fabrico Aditivo. Devido às baixas cargas envolvidas na Robótica Colaborativa a utilização de componentes materializados por Fabrico Aditivo, como produtos finais, é possível, independente do facto de este tipo de fabrico não garantir boas, nem homogéneas, características mecânicas. Os testes realizados aprovam a capacidade de resistir a impactos e de suportar cargas até 10 kg. O mecanismo de acoplamento automático não está funcional aquando da publicação deste documento, contudo o sistema foi testado manualmente.

**Keywords**: Fabrico Aditivo, Robótica Colaborativa , Indústria 4.0, Tool Changer Automático

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# Chapter 1

# Introduction

The growing presence of collaborative manipulators in the industry, associated with the evolution in the industry 4.0 segment, promotes an ever-expanding need for versatility in applications that each manipulator can be used at. For this purpose, a smart storage unit that can carry multiple grippers and tools would be essential to help production lines achieve a friendlier collaborative environment implementation where product customization is required.

## 1.1 Motivation

What arose my interest on this subject can be divided into two main groups: the industrial aspect and the household aspect. In addition, the pandemic state that has loomed over the world the past couple of years led to a generalized awareness about the importance of collaborative robotics as well as autonomy and independence of the market.

On the one hand, stricter border control - enforced to counteract the spread of the pandemic in hand - adds a series of implications on import and export of goods. This scenario surfaced concerns about the decentralization of manufacturing and assembly lines and how dependant companies have become of emerging countries to reduce costs of production.

Notwithstanding, and considering this issue has been discussed before for political reasons, its importance grew and instituting measures to face the consequences of component shortages becomes a priority. This is where the fourth industrial revolution has a big impact. The ability to communicate and coordinate production lines across vast distances - using IoT - allows for companies to specialize their machinery in manufacturing specific components of each final product, allowing for better flexibility and higher customization of each element.

The flexibility of the production line is further improved by the implementation of collaborative robotics that have access to multiple tools, called modularization by Brettel et al. [1].

On the other hand, confinement and mandatory curfew hours hamper caregivers' ability to assist elderly or disabled people during their daily activities.

Based on the research presented on article [2] it is plausible to assume that it would be beneficial to implement a collaborative robot to assist in basic tasks. In the scenario studied, people with impairments and disabilities - which are usually more sensitive to noises and fast movements - adapted quickly to their presence and were able to interact with it within a short time interval. Additionally, considering yet again the advancement of industry 4.0 and IoT applications, the implementation of "Context-Aware Assistive Systems" - as sensorial, physical and cognitive aid systems - allows a constant monitoring of the person's health.

Complementing the impact of the pandemic, a sudden rise of 3D Printing, as the most widespread household method of Additive Manufacturing, was registered. Panic buying, rising demands and disruption of global supply chains, as mentioned before, have resulted in shortages in many countries. This emergency situation promoted the ideal opportunity for researchers in the Additive Manufacturing field to provide immediate contribution.

The concept of infrastructure sharing was implemented as a crisis solution. This idea is based on making infrastructures, such as 3D printers, available for external purposes such as covering the demand for emergency products. Since these machines are currently available to the public, associated to the advantage that Additive Manufacturing has over conventional manufacturing processes - short response time - this infrastructure sharing enables individuals to join in such activities and support their communities in times of critical shortages to cover extraordinary demands [3], [4], [5].

This proved the flexibility and reliability of the manufacturing process and cemented its capability in reacting to the day-by-day needs and arising challenges to cope with the novelty of required solutions and uncertainty.

## 1.2 Problem Definition

Robotic manipulators have proprietary coupling interfaces for tools and grippers. We want to develop a "universal" tool changer that features automatic coupling/decoupling of different gripper configurations, in order to better suit any sort of collaborative work, improving versatility and adaptability of the manipulator for any application desired.

In order to further this goal, a smart storage that can house multiple grippers and can be implemented with any product on the market (after installing the correct interface) will also be briefly studied and a *future work* installment will be presented.

## 1.3 Objectives

This research proposes a solution for the multiple tool applications in *cobots* and robotic manipulators alike. The main objective is to fit into the *cobot* market. Being so, the loads involved are usually under 10 kg; this assumption allows for Additive Manufacturing, and specifically Material Extrusion Machines that use thermoplastics as *feedstock*, to be used as a manufacturing process for the end product.

A fundamental pre-requisite for the tool changer assembly is versatility and flexibility. For this reason, simplicity and ease of manufacturing are paramount. The ability to quickly replace or adapt different components to better suit the application on hand is also a strong motif for the approach chosen when designing and developing the different components.

## 1.4 Document Structure

This document starts by presenting a rather extensive review of the current state of the art concerning Additive Manufacturing, with emphasis on Fused Filament Fabrication (FFF) using common thermoplastics such as polilactic acid (PLA), referencing also the current state of the fourth industrial revolution and how this research subject fits into collaborative robotics.

Followed by the design and development of the main portion of the interfaces and different tool options, while noting considerations taken during the thinking process to facilitate the manufacturing process and/or the usability of each part.

Once the different parts are test fitted, the real tests on a robotic manipulator - UR5e - take place.

Finally, a concept for a smart tool storage unit is also presented as a complement to the concept of multiple tools and single automatic "universal" coupling interface.

# Chapter 2

# Literature Review

The present manufacturing industry is facing it's fourth revolution, partially leveraged by the disruptive presence of the concept of Industry 4.0. The digital principles introduced and developed during the third revolution are reaching a point of departure from the classic implementation of technology in the manufacturing processes.

The heavy presence of Internet of Things (IoT) allows for a large amount of data collection and seamless communication between equipment cells, plant floors or even facilities in different locations .

As mentioned before in 1.1, the solution found by small and medium enterprises (SMEs) to claim a share of the market with competitive priced products is by cooperating and sharing information amongst each-other. This allows individual factories to plan and organize the floor plant into modules that accommodate specific parts of each final product. Which in turn promotes a larger flexibility and introduces a faster response to customized mass produced components [6], [7].

Quoting Brettel et al [1]: "Modularization is already accepted as a mean to increase the variety of products, which are produced by tool-based technologies".

## 2.1 Industry 4.0

Conceptually, Industry 4.0 surfaced in Germany, in the mid of 2010s, in order to explain the process of applying digital technologies to the manufacturing industry. This idea is commonly used as a synonym for the fourth industrial revolution, albeit being a part of it. The Fourth Industrial Revolution is comprised by the impact in all areas of the social-economical scene of its segment, meaning that it encompasses a much broader range of concepts including changes in markets, flow of information, employment trends, environmental outcomes and shifts it balance of global power; whilst Industry 4.0 focuses on the relationship between digitalization, organizational transformation and productivity enhancements in manufacturing and production systems [6], [7].

Nevertheless, the full spectrum of the Fourth Industrial Revolution is not relevant to this dissertation subject. The focus will be on Industry 4.0 and IoT in Smart Manufacturing, more so regarding the Digital Twin and Big Data concepts.

As this project revolves around developing a smart storage for collaborative manipulators, communication between both units is required as well as the ability to predict wear and failure of the components. Considering the approach of 3D printed parts for most components developed, it is imperative to develop a well defined digital model that follows its real life counterpart. After all, there are not many applications for industrial use that have a final product manufactured by additive processes while using PLA, hence the response of such material to the industrial environment and work load during its life cycles is still not very well documented.

For this purpose, pairing the information from Big Data with a Digital Twin allows for higher data acquisition and processing, providing a more trustworthy set of information to update the virtual model, better predicting the wear and failure point.

All the advancements towards automatizing processes concerns many in terms of unemployment, as jobs that involve monotonous and repetitive tasks are already done by robotic manipulators [8], [9], [10].

## 2.2 Additive Manufacturing

Additive Manufacturing, commonly known as Rapid Prototyping, or even through the more popular term 3D Printing, is the current formal way to describe the technology that allows the fabrication of components where there were nothing previously, hence the name.

This manufacturing method sustains itself on the basic principle of materializing a virtual three-dimensional (3D) object - usually produced using a Computer Aided Design (CAD) software - through the stacking of layers of 2D sections of said object. The final product is as close to the wanted design as the layer height reduces.

When compared to other manufacturing processes, Additive Manufacturing is clearly less complex and faster to develop from a virtual concept to a palpable product.

Conventional manufacturing processes, like Computer Numerical Controlled (CNC) machining centers, require a more intricate knowledge of the part to be produced, since everything from the material to the geometry affect the decision making when programming the machine. Tools and process choice, use of coolant, order of features and even surface finish have to be detailed before-hand. Additive Manufacturing, however, only has as prerequisites the type of material and style of machine used [11].

Building upon the concept of easy modeling and fast fabrication, Additive Manufacturing has evolved through the years alongside applicable materials and overall quality of the output, allowing the model fabricated to be a viable source of information about what is known as the "3 Fs" of Form, Fit and Function. Initially used to help understand the products presence in the real world, as the process' dimensional accuracy improved, the model became more relevant at the assembly stage where tolerances are stricter. Nowadays, with better material properties, the object fabricated can be applied directly to the final stage and tested within conditions that are similar to what it would encounter when in service.

Considering the time frame in which this technology became relevant, there have been many terms that referred to it and, to a certain extent, still maintain a relevant description of what Additive Manufacturing has developed into. Concepts like Automated Fabrication (AutoFab) and Freeform Fabrication remain applicable since this is a manufacturing process that requires no manual intervention during the actual part fabrication and have the ability to create complex geometries without adding considerable manufacturing time when compared to simpler shapes, if the enclosing volume is maintained; however they also encompass some "*subtractive*" technologies, like the aforementioned CNC machine centers. Layer-Based Manufacturing and Stereolithography are also used to describe Additive Manufacturing and, compared to the previous terms, do a much better job at providing a comprehensive explanation to what the technology represents. Both glance at the concept of turning a 2D process into a three-dimensional fabrication method by stacking or layering successive cross-sections of the desired object. None the less, Additive Manufacturing - and any other term - may describe a process that is not purely additive, as some more products may require *subtractive* processes at some stage [12].

In short, Additive Manufacturing processes often involve the following steps: ideation of the product through a CAD Model; conversion to .STL (the most used format to export a 3D model into a slicing software); uploading the processed file and setting up the machine; building the model; removing it from the machine; post-processing the "crude" model into the desired specification; implementation.

From here it is visible that much of the product development process relies on computers. This is the main reason why Additive Manufacturing is faster than most conventional methods; helping the matter is the relatively seamless transfer of the 3D CAD model to format readable by the machine controller. Regardless of the complexity of the parts to be built, there is much less concern over the data conversion or interpretation of the design intent. In addition, contrary to many other manufacturing processes where multiple and iterative steps are required to achieve the final product, building within an Additive Manufacturing machine is generally performed in a single step.

Furthermore, any required change to the model during the testing phase is readily introduced using Additive Manufacturing, whilst conventional fabrication processes take much longer to reassess the Computer Aided Manufacturing (CAM) programs in order do accommodate the new features [11].

### 2.2.1 Types of Additive Manufacturing Machines

There are a plethora of Additive Manufacturing machines, developed to fit a broad range of applications, materials and price. From cheap domestic versions, which are desktop sized, based on the Fused Filament Fabrication (FFF) technology applied to polymers and achieve moderate quality parameters - keeping in mind that "cheap" is different from "affordable", as there is a growing range of 3D Printers aimed at the consumer market that can output surprising quality for the overall cost; to high power industrial units that can use metals as a raw material to achieve better mechanical properties [11].

Currently the main technologies used for Additive Manufacturing can be differentiated by the type of material used: powder, molten material, solid sheet and photopolymer (from a vat or ink-jet deposited).

Powder-based systems are amongst the easiest to set up for a simple build, as there is no need to account for supports. The powder itself acts as a mean to support the printed parts in place while the rest of the object is still unfinished. The main disadvantage of this technology is the volume of unused powder that is left over after each use, especially the area around the part. Those areas have been subjected to a certain amount of heat and may diminish the quality of future prints if reused unwisely; hence a well designed recycling strategy needs to be applied.

Molten material systems fall under the most wide-spread spectrum of this technology. As low-cost 3D Printers availability is increasing, followed by the ease of use by providing predefined printing parameter that fit most of the applications, every "maker" or engineer now has access to them. These machines follow a principle that is not as straight forward to use as the aforementioned one, since there is a requirement for supports. They can be automatically generated by the slicing software or manually introduced by the user. In either case, experience is required to achieve the best result both in print quality and efficient manufacturing.

Solid sheets systems also don't require supports, as the sheets are stacked and cut in place. However, there is a need to post process the part as there is a reasonable amount of waste material surrounding it. Even though most of the times it is an automated process, sometimes it requires the technician to have a good idea of what the final part looks like in order to not damage it during the "cleanup" process if the geometry isn't simple enough to have it robotized. When using metal with this technology, the sheets are typically cut first and stacked after, not requiring any post processing.

Photopolymer-based systems despite being easy to set up, require files to be created which represent the support structures. All liquid vat systems use supports from the same material as that used for the part while Material Jetting systems can have a secondary support material. This technology generally has superior accuracy when compared to the others but very poor material properties. The main drawback of photopolymer materials is a rapid degradation when exposed to UV light, if no protective coatings are applied [11], [13].

### 2.2.2 Software

Essentially, all commercially available solid modeling CAD systems have the capability to output information in a file format - namely .STL, which derives from the word STereoLithography - that can be used for Additive Manufacturing, as long as the model is fully enclosed. This is possible due to the fact that, in most cases, Additive Manufacturing processes only require information about the external geometry.

Editing software for Additive Manufacturing uses STL data, repairs errors, performs minor edits on the design and prepares for the part to be built. Since STL files only have an approximated representation of the boundaries - using a mesh of triangles - and lose all parametric relationship and feature identities of the original 3D model, most CAD-based functions for model manipulation are unavailable to the user. To circumvent this issue, some companies sell software that can detect all the lost information and allow for post-editing. For this reason, a shift from STL files is currently happening. It also allows for more information to be carried over and so to be utilized in more advanced Additive Manufacturing processes that can benefit from i.e. material and colour differentiation [11].

Once this file is ready, it uploaded to the *slicing* software. This is an algorithm that converts the 3D information of a model into the stacked layers to be read by the Additive Manufacturing machines. Most of these machines already include a slicer on their software, making the transfer from CAD to real life model very seamless.

However, the cheaper models that are now commonly found in many homes do not. For this situations an external slicer can be used. There are many available for purchase, as well as open source variants. These slicers have the same functions as the *built-in* counterparts, allowing for part visualization, positioning on the bed and, in some cases, slight adjustments of the model design using simple geometries - squares, rectangles or spheres [11], [14].

### 2.2.3 Material

The current Additive Manufacturing technologies allow for the usage of a variety of materials. When applied on the subject, the materials are referred to as *Feedstock*. These materials can be bio-inks, ceramics, metals, composites, glass, paper, graphene-embedded plastics, food, concrete or yarn, among many other sub-variants and combinations.

This range of materials grants the ability to choose more precisely the service properties for the intended application, such as mechanical properties, biocompatibility, transparency, colour, moisture resistance, fire retardancy, toxicity emissions, sterilization, cost and more.

For this research, the focus will be on solid feedstocks - filaments - which are consumed my the style of Material Extrusion machines used.

Material Extrusion machines typically use amorphous thermoplastic polymers to manufacture parts by thermal layer adhesion. These materials are generally stable and maintain dimensional accuracy over time, being available at different price points, as composites or flexible materials. Each variant offers a different set of properties that can be tailored to fit a specific application. As an example, PLA (polylactic acid) is inexpensive and has good strength and siffness properties when compared to ABD (acrylonitrile butadiene styrene), making it a good choice for fast prototyping; flexible TPU-based filaments (thermoplastic polyurethane) have good impact resistance and damping characteristics.

There are also some downfalls when choosing these materials and type of manufacturing. Counterbalancing the speed and ease of production, additive manufacturing as a technology has some specific known issues inherent to its working principles [11]:

- Build Orientation: the chosen part orientation on the print area will dictate its mechanical properties. 3D printing, especially using thermoplastics, doesn't generate homogeneous parts when it comes to traction forces; the bonding between layers is heavily impacted by extruding/ambient temperatures as well as the type of material used, leading to a better response along the filament deposition plane, while having *delamination* problems between layers;

- Delamination: as stated previously, the bonding strength between layers isn't as strong as the properties along the continuous deposition of filament along each plane. This translates into a need to choose a part orientation according to the axis where it will be strained most;

- Distortion: as this process is temperature dependant and parts are manufactured through the heating and cooling of the feedstock, it becomes prone to distortion of the produced part. Using heated beds and printing in low ambient temperature rooms may promote a more noticeable influence of this issue, as the temperature differential along the $z$ axis is more pronounced. The faster cooling of the deposited material higher up the axis, means it will shrink at a faster rate, pulling the warmer material under it distorting the print. The working principle is the same as the one used in thermocouple, albeit the fact it being intended in the latter;

- Porosity: feedstock impurities, jerk motion from the movement axis or temperature fluctuation may cause air pockets throughout the printed part. These defects will affect mechanical properties and generate fracture points from where a catastrophic failure may ensue;

- Cracks: this issue is more of a consequence from the previously presented ones, poor planned build orientation, delamination, distortion and porosity may induce cracks along the part;

- Poor Surface Finish: self explanatory, and in most cases easily fixed by post production. However, in some cases, imperfections on the surface may not be recovered from if the wall thickness parameter isn't set to account for this process, as well as clearance issues. Post processing of the surface may induce larger gaps between assembled parts and void any usability;

- Shelf Life / Feedstock Lifetime: the finished part usually has a very long shelf life and, aside from the occasional discolouration, generally deals well with time degradation. Nevertheless, some types of materials used as feedstock might not do well in high humidity environments or with direct sunlight exposure, degrading quicker over time.

## 2.3 Collaborative Robotics

The word "Robot" was first introduced by Karel Capec in 1921, in Europe, at his play *R.U.R.* - Rossum's Universal Robots. "Robotics" appeared some years later, in the early 1940s by Isaac Asimov whom used it to describe the art and science of robotic technology.

What started as science fiction, began to materialize during the second world war. Technologies in the areas of servo-mechanisms, digital computation and solid state electronic, which started developing during this period, helped kick-start the robotics *revolution*.

The great success of *Unimation* during the 1960s brought large companies in the USA, such as General Motors, General Electric and IBM, to take interest in this new technology.

Soon after, the implementation of adaptive and communicating Robot Systems opened the road towards the development of what could be considered the first implementation of Collaborative Robotics. These robot systems included a separate low-level processor for each degree of freedom and a master computer supervising and coordinating these processors while providing higher-level function.

In the book [15], the author also states that "sensing and interpreting the environment are key elements in intelligent adaptive robotic behaviour. [...] Extracting relevant information from sensor signals and subsequent interpretation will be the function of inexpensive, high-performance computer processors. With these advanced sensors a robot will in time have the capability to detect, measure and analyze data about its environment [...] using both passive and active means for interaction."

In 1995 Northwestern University and General Motors Corporation initiated a project in the emerging area of Intelligent Assist Devices (IADs). These devices, through an appropriate combination of robotic technology with manual labour, intend to improve ergonomic working conditions, overall product quality and, inherently, productivity. This research is resented on the paper *Cobots*, which focus particularly in Collaborative Robotics and their applications.

This paper makes a statement that "the philosophy behind *cobots* is that shared control of motion, rather than amplification of human power, is the appropriate metaphor for collaboration" [16].

On the present day, allied to Industry 4.0, robots become flexible, mobile and more intelligent, transcending the previous concept of separating the human operator and the robotic complexes according to safety standards and beginning to work together in a single working environment.

According to the conference [17] robotics is evolving in three directions: industrial robotics - industrial re-programmable and multi-purpose manipulators using three or more axis; collaborative robotics: progressive stage in the development of industrial robots that assumes close interaction with humans in a safe manner; service robotics: mobile autonomous/semi-autonomous robotic complexes used in various field of human activity outside the industrial environment.

At the conference [18], in 2020, the speakers *Rinat Galin and Roman Meshcheryakov* elaborated further on the current ideas and implementations for cobots explaining that these robots should not only perform sequential tasks, but also parallel ones, since the smart software built into them allows for machine learning. Different sensors and software enable self-learning by technical vision and speech besides movements.

Human robot interaction (HRI) allows to combine the capabilities and effectiveness of robots with human cognitive abilities into a single flexible system.

Introducing collaborative robotics brought new problems into the industrial scene. Along the improvements in safety and reduction of work related accidents, by replacing human workers in dangerous environments, it also introduces a new layer of unpredictability associated with increasing autonomy and decision making ability of *cobots*. This incurs in new legal problems especially when attributing responsibility for eventual accidents.

Paper [19] introduces a tactile technology, named *AIRSKIN*, developed by Blue Danube Robotics. This aims to prevent accidents by giving *cobots* the ability to recognize touch in any part of their body and, subsequently, react to it.

## 2.4 Multiple Tool Solutions

In order to further extend the versatility and amplitude of scenarios a single *cobot* can partake on, assisting a human operator, offering the access to a multitude of tools is paramount. Installing an automatic tool changer interface on the wrist of the manipulator and adding a storage system where multiple tools can be kept is the common way of doing so, negating the need to have an extra step performed by the operator to suit the *cobot* to the task at hand.

### 2.4.1 Automatic Tool Changer

Starting with the ability to switch tool automatically, a tool changer has to be taken into consideration. As such, many options are available on the market, from pneumatic to electric couplings, either manual or automatic.

(a) ATI Industrial Automation: QC-7 - Automatic Robotic Tool Changer.

(b) TripleA Robotics: WINGMAN - Automatic and Manual Tool Changer.

(c) DESTACO: TC1 - Manual Tool Changer.

Figure 2.1: Examples of Automatic and Manual tool changers from some of the leading manufacturers.

Table 2.1: Specifications of Automatic and Manual tool changers from some of the leading manufacturers

| | ATI QC-7 | TripleA WINGMAN | Destaco TC1 |
|---|---|---|---|
| Type | Automatic | Automatic and Manual | Manual |
| Dependencies | Compressed Air | Robots Movement | Human Operator |
| Height | Master Side: 43.6 mm<br>Tool Side: 32.6 mm | Combined: 30 mm | Combined: 25 mm |
| Weight | Master Side: 0.415 kg<br>Tool Side: 0.342 kg | Combined: 0.260 kg | Combined: 0.330 kg |

As seen on paper [20], a solution for a round bit storage system is presented and the coupling is done via pneumatic power. The issue presented on conference [21] alerts to the precision and repeatability parameters of older, or lower end manipulators, while offering a solution for self-centering mechanisms.

The thesis [22] elaborates further on the subject of a multi tool solution for robotic manipulators. This research revolves around finding a simple implementation for a multi tool static storage that is easy to use and doesn't depend on the manipulators movement precision.

On this study case the approach chosen was to use an existing proprietary tool interface for the automatic tool change capability and add the support structure that serves as a guide and coupling with the tool holder. This interface is proprietary technology, from Universal Robots meaning that the "tool changer holder" needs to be adapted to the interface the client is currently using.

Furthermore, it uses pneumatic systems to engage the coupling device. This adds the requirement of pressurized air on the working site, as well as all the necessary plumbing.

This tool holder is bulkier and sturdier in order to accommodate for heavier tools and less precise storing movements that might involve heavier loads. It was designed for applications on non collaborative manipulators, which have a much higher cargo capacity.

A design for an automatic tool changer, specific for collaborative robots, is presented in [23] . Here a UR5e is used as a template to test the proof of concept of the tool changer and elaborate further on it's usability. This tool, similarly to the one proposed in [22], is not meant to be used as a product of Additive Manufacturing and the storage option proposed is also a static racking system.

This tool solution includes the ability to be compatible with pneumatic systems and the locking system of the master interface with the tool interface is done by cannibalizing over one of the manipulator's degrees of movement.

Finally, there are also studies similar to [24] that research the applicability of Additive Manufacturing as a final process to fabricate the tool changer components. On this study a reverse engineered model of an existing tool changer is manufactured by the means of a FFF - Fused Filament Fabrication - 3D printer, concluding that it is usable but require the combination of non 3D printed parts to guarantee structural integrity.

### 2.4.2 Smart Tool Storage

There seems to be a lack of options for how the tools are stored while not in use. Most use a static racking system that can hold 3 or 6 tools similar to the ones present on papers [21], [23] and [24]. Apart from robotic manipulators, only Machine Centers appear to have a widespread range of automatic tool storage options.

As an example, in figure 2.2 are presented two different manufacturer that offer options of CNC Automatic Tool Changers - ATC - either as add-on kits or as an optional for their own CNC machines. On this figure, an Automatic Tool Changer kit from *Tormach* is seen on the left - (a) - and it is sold independently of the CNC machine; on the right - (b) - is present the mechanism of the Automatic Tool Changer that comes optioned into a CNC Router machine from *IEHK*.


(a) Tormach ATC kit - 1100 Series 3.

(b) IEHK ATC 1325 CNC Router with Servo automatic tool changer.

Figure 2.2: Examples of Automatic Tool Changers for CNC machines.

## 2.5 Summary

In order to organize the information stated on the former section, as well as clarify the goal, the following keywords are used as a foundation: versatility, flexibility and readiness.

Since the main goal is to manufacture an Automatic Tool Changer, applicable to any manipulator available on the market while retaining aspects like ease of use and simplicity of construction, it is necessary to, firstly, understand the concept of Internet of Things and Collaborative Robotics and how these two are part of the bigger picture called Industry 4.0.

The new found ability to communicate with and control automatons over great distances opened the possibility to specialize smaller factories in determined areas without compromising the readiness to adapt to new fields if the necessity arose. Having capable and intelligent machines, that can be programmed in different ways to perform a multitude of tasks alongside a human operator becomes the staple of these smaller factories.

To further the flexibility of these machines, the possibility to equip them with different tools is a must. For this purpose, many manufacturers started selling manual and automatic Tool Changer kits, that allow for a fast change of the working tool on a determined machine. The main issue with these would be price and compatibility, as well as the ability to fix any breakages or malfunctions right away.

As collaborative robotics often dwells with small loads, using a manufacturing process that produces weaker components, when compared to traditional methods, isn't an issue. Supported by data provided from the book *Additive Manufacturing Technologies* [11] as well as papers [25], [26] and [27] it is safe to say that fabricating components through Additive Manufacturing should exceed the mechanical requirements of most applications.

# Chapter 3

# Solution Design

Chapter 3 defines the Proposed Solution, which envelops the idealization of a Smart Universal Tool Changer, as well as the early stages of a Smart Storage solution to store, organize and keep track of multiple tools.

Elaborating further, it was proposed to design and develop a tool changer that should be simple and fast to manufacture, as well as easy to repair/replace in case of malfunction or catastrophic failure. To accomplish this, Additive Manufacturing will be applied as the final stage of production, instead of only being used during the prototyping phase. This tool changer will be modular and have a small processing unit inside the hub to allow for rapid coupling and detection of any change of working parameters, such as the maximum grip force or axis of freedom associated with the chosen tool.

The Smart Storage solution is briefly discussed and introduced as a central control unit that can communicate with the tool changer hub, other Smart Storage units and the robotic manipulator itself. This would allow for a fast response to tool change by requiring to map only one frame for the tool home position.

## 3.1 Smart Tool Changer

As mentioned previously, the proposed technology is a Smart Tool Changer that should be capable of automatic coupling and decoupling, to assist in collaborative robotics applications. This section will present and discuss the solution found, along with the reasoning behind each decision made, as well as a comprehensive balance between the benefits and disadvantages of each particular application.

### 3.1.1 Overview

The main issue faced is the multitude of robotic manipulators available on the market. Each manufacturer having its own proprietary interface to mount tools is one challenge to overcome, in order to offer a product that can be marketed as universal and accessible.

Versatility opens a wider application range, that is not dependant on the type of robotic manipulator chosen, as well as allowing for a combination of multiple manufacturer brands and model generations.

Another obstacle to overtake is the current market availability, hence the possibility to manufacture, in house, the product itself and any replacement parts needed would benefit the end user.

For this, the solution was to have Additive Manufacturing, specifically FFF 3D printing, in mind while developing all the parts.

In order to increase longevity of the 3D printed parts, the contact areas where friction is higher - promoting premature wear of the components - can be sealed with primer and coated with a protective layer of heavy duty paint. Metallic inserts can also be considered for this, in case the tool is assembled/disassembled with a higher frequency.

This tool changer only requires 2 electronic elements on the master side - a micro-controller unit and a servomotor for the coupling movement - and 1 on the tool side for the desired movement - for example, a servomotor for grippers or a stepper for drills.

In order to facilitate the exchange of these elements, a universal mounting plate was designed into the tool side interface, allowing the user to customise it in order to fit any component best suitable for the application. For demonstration purposes, two interfaces were designed - for a SG90 servo and for a MG995 heavy duty servo.

The aforementioned micro-controller is used in order to allow the tool changer to recognise the parameters of the tool it is picking up, as well as communicate with the storage unit and/or the robotic manipulator. For this application, a raspberry Pi 3B was chosen since it has been used previously for similar applications and is an element familiar to everyone involved on the project within the DIGI2 - Digital and Intelligent Industry Lab.

Summarising, the proposed Tool Changer set is comprised of 5 main components that are common to any configuration of the tool. These are:

1. Master Side Interface - Bottom plate (customised to fit the manipulator in question);
2. Master Side Interface - Top
3. Tool Side Interface
4. Actuator Mounting Plate
5. Protection Housing

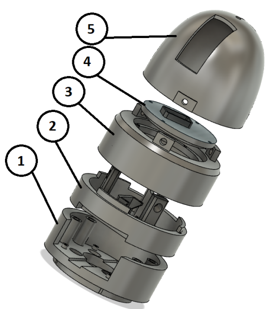


Figure 3.1: Exploded view of the main components of the Tool Changer set.

Finally, the cylindrical shape chosen for the tool changer and the generalized round shape portrayed throughout the design was inspired by both the UR5e body shape and safety during contact on collaborative tasks.

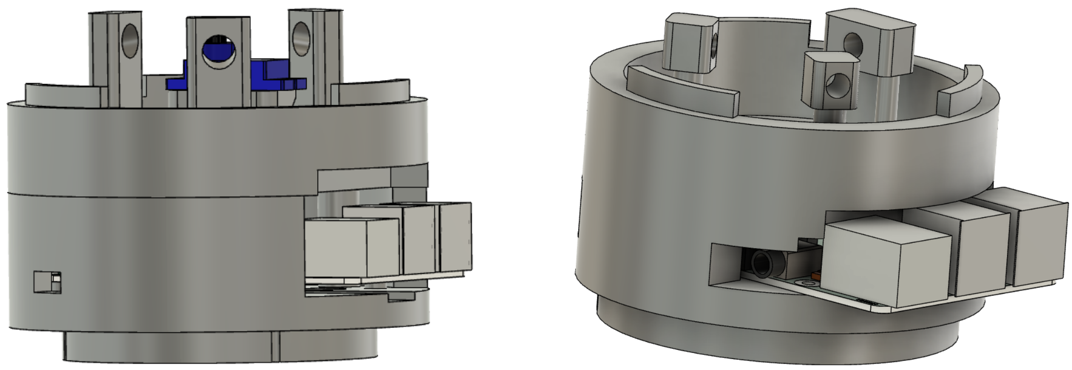
As maintaining as much of the work volume usable as possible is an advantage, keeping the tool changer as compact as possible is one of the main constraints from a design standpoint. As a starting point, the outer diameter was defined by sizing it as closely as possible to the last linkage of the manipulator. From here, and taking advantage of the strengths of Additive Manufacturing, building support structures into the design itself minimize the need for screws/bolts and other external fixation methods - which require assembly space for tools to operate.

### 3.1.2 CAD Models

#### 3.1.2.1 Master Side Interface

For this application, the master side is required to house the micro-controller and the coupling mechanism in order to reduce costs and simplify the installation/use principle. Two similar designs were proposed for manufacturing and testing.

The main difference, as seen on figure 3.2, is the division of the part into two. This simple change helps the fixation process of the interface to the manipulator's wrist, as well as the installation of the Raspberry Pi 3B, at the cost of added weight.



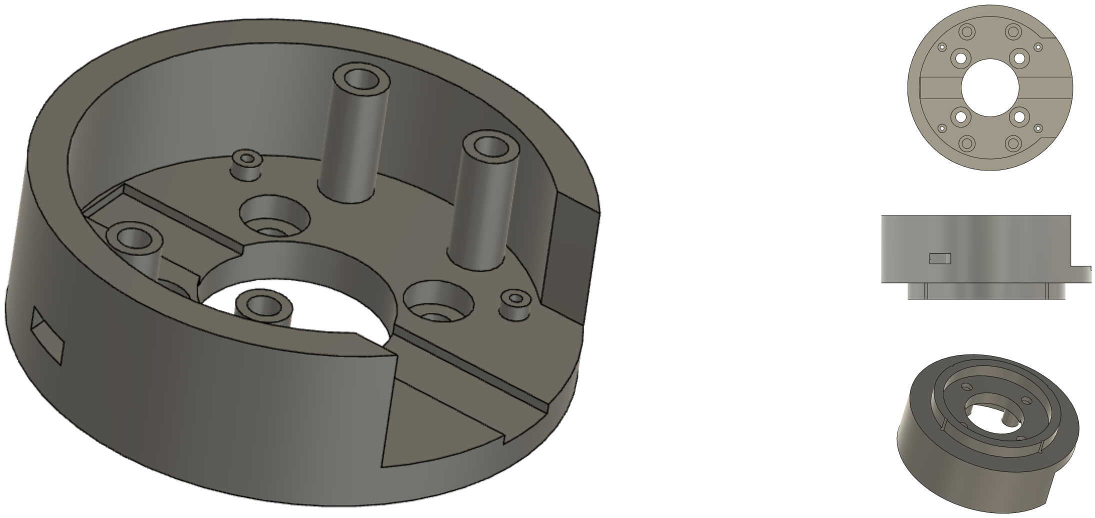
(a) (b)

Figure 3.2: Single (b) and Dual (a) part Master Side Interface models.

Here it is clear that the development stage of both parts isn't the same. After an early stage test print, which the main purpose was to roughly compare both installations before tackling smaller details, the single piece design was discarded as the weight saving was minimal, thus not justifying the extra complexity while manufacturing.

As the chosen solution contemplates two parts, the preferred orientation for describing positioning of each component - which will carry over to whenever it is necessary to explain relative position - is considering the gripper portion the top and the surface which bolts to the manipulator the bottom.

The bottom portion of the Master Side Interface - shown on figure 3.3 - contemplates the bolting pattern for the UR5e, which was used for testing. The four columns are meant to house inserted nuts, where the top part should bolt.



(a) (b)

Figure 3.3: Bottom part of the Master Side Interface.

For this specific application, as a Raspberry Pi 3 B is used, the opening is a requirement to fit all the ports on this board. The decision to not make the interface larger, allowing the enclosure of the whole board, is based on the fact that more recent boards have been released to the market, which are smaller but retain the same bolting pattern. Using, for example, a Raspberry Pi 3 A+ allows for a closed variant of this part, which is more desirable for both structural integrity and dust protection.

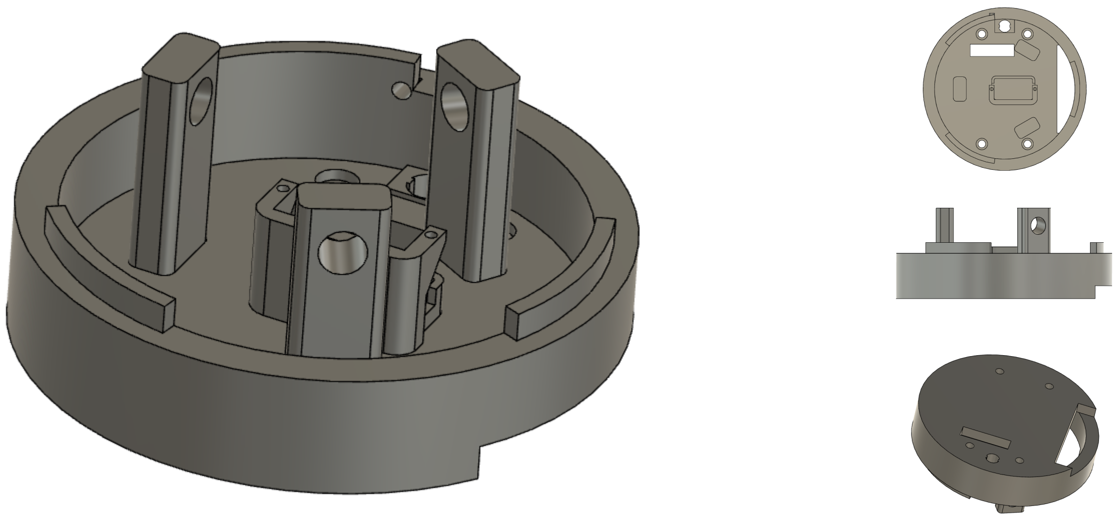
The top part, shown on figure 3.4, is fixed using 4x M4 bolts to the bottom part. This part has two passages for the wiring needed to control both actuators. The connector for the gripper's actuator is mounted on a moving shaft that sits on a spring, allowing it to automatically plug into place as the gripper is coupled.

The three towers support the locking pins, having angled holes to promote a flush fit of the Tool Side Interface to the Master Side. The ridges on the outer ring are meant to help align both interfaces, guaranteeing a proper coupling.

#### 3.1.2.2 Tool Side Interface

In order to follow the desired geometry, this interface allows for a tool coupling by the fixation of a relatively small round plate on it's center opening. This plate is shown on the sub-section 3.1.2.4.

For this reason, this interface doesn't exactly follow the same operating principle as other Tool Side Interfaces present on the market, as it is - to an extent - an integral structure of the gripper assembly.



(a) (b)

Figure 3.4: Top part of the Master Side Interface.

This part has three mounting points for the Protection Housing, shown on the sub-section 3.1.2.5, which might be used as a simple component cover or as an integral part of the gripper as well.

Internally, there are the corresponding coupling orifices, angled and slightly miss-aligned from the respective column hole on the Master Side Interface. This is to compensate the inherent dimensional imprecision of Additive Manufacturing, in a way that guarantees proper coupling.

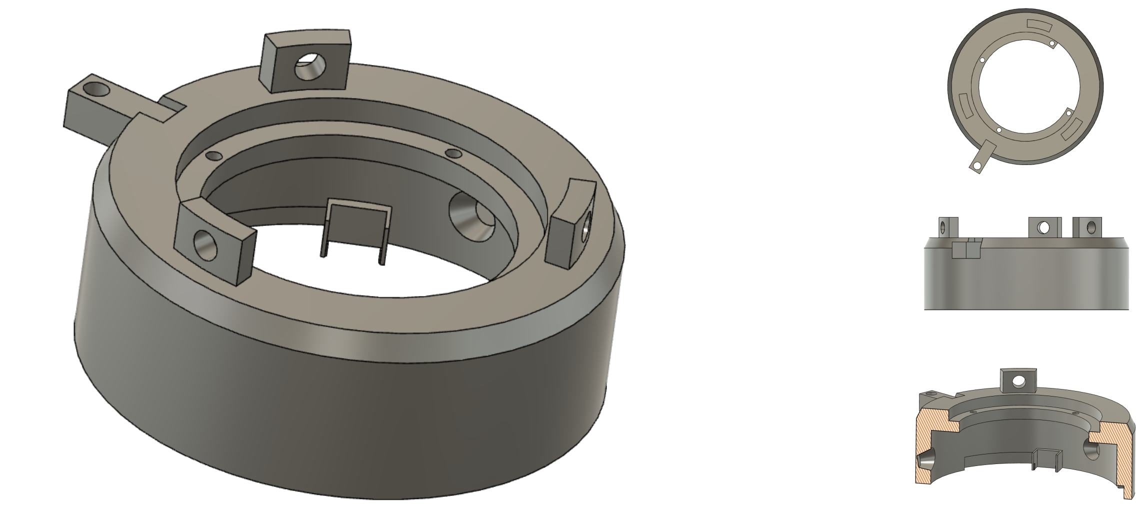
An important note is that the most important structure on the tool side is the cylindrical portion where the coupling happens. In other words, the suggested way to secure the tool actuator - being it a servomotor for a gripper function or a stepper motor for drilling/screwing motions - is best suited for an application that also uses the Smart Storage Unit, presented on section 3.2. This part can be changed according to each specific application, adapting to any tool that might already exist and was not purposely designed and manufacture to be assembled with the suggested dimensional pre-requesits imposed by the Actuator Plate detailed on section 3.1.2.4.

#### 3.1.2.3 Coupling Mechanism

The method chosen to lock the master side interface to the tool side interface is by the use of locking pins. These pins are normally closed, passively pushed into it's position by springs. A servomotor is used to actively engage the decoupling movement, which retracts the pins and allows for the separation of both interfaces.

The alignment of the interfaces is helped by grooves, as stated before, and the inclination given to the pins enforces a permanent closing pre-load on it.

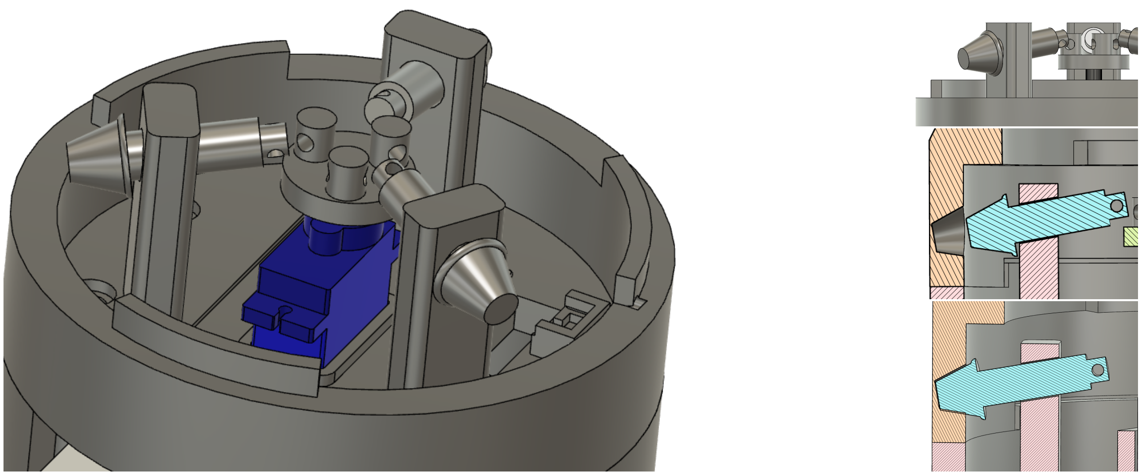
Figure 3.6 shows the pins assembled on the Master Side Interface. These pins are moved either by the spring situated between the columns and the cone shaped end or by the actuation of the servomotor. This motor is connected to the pins by the means of wires or strings, since the



(a) (b)

Figure 3.5: Top Side Interface.

clearance and overall dimension of these parts is in the millimeter range. This method of fixation also allows for compensation of the dual plane movement, which would be physically impossible by the use of ball joints without changing the distances from the pivot points due to dimensional constraints.



(a) (b)

Figure 3.6: Figure shows the coupling mechanism, both in it's opened and closed positions.

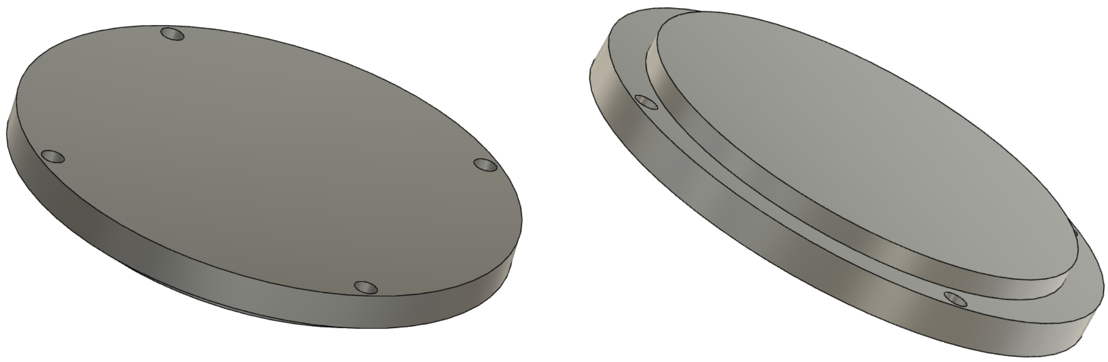
Other methods of coupling were briefly studied, but in order to keep the principle of simplicity and flexibility, this method prevailed as the easiest to understand and simplest to repair or re-engineer to allow for other actuation mechanisms.

This style of coupling mechanism, by the use of pins, also facilitates the transition from angular actuation - by the means of a servomotor - to linear actuation. This would only require the adaptation of the pins in order to allow for a metallic core and of a small extension of the support columns to house the coil; since the mechanism is normally closed, using the working principle of an electromagnet would not cause sufficient heat issues [28] to compromise structural integrity as actuation times would be very reduced. Another application would be installing linear actuators, or solenoids, directly where pins are currently. This solution would require adjustments to the columns and, possibly, orientation in order to accommodate the bigger components - in case the outer diameter is kept the same.

Such solutions were left for future works, as the servomotor is the most economic and should perform adequately under the operating circumstances imposed by the tests.

#### 3.1.2.4 Actuator Fixation Plate

The Actuator Fixation Plate can be considered as the first true element of the gripper assembly in this application. Here is where the chosen actuator support can be designed and created. Figure 3.7 shows the basic construction of the Actuator Plate, that should be customised to fit the desired application.



(a) (b)

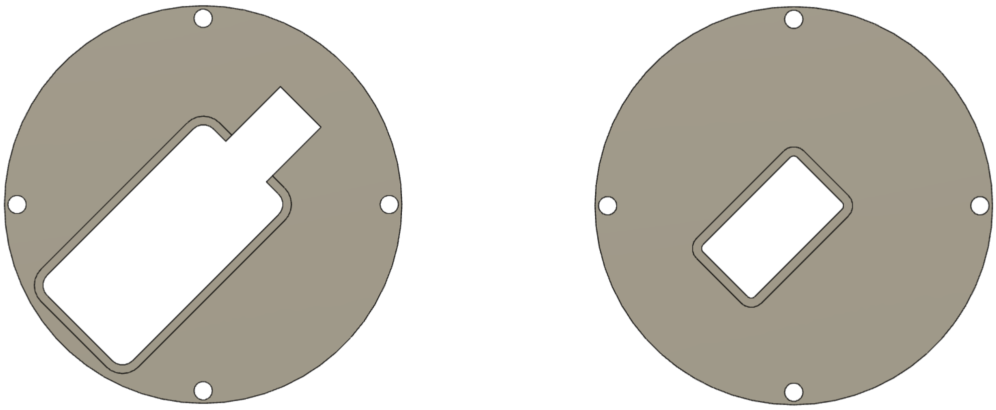
Figure 3.7: Base configuration of the Actuator Fixation Plate.

On figure 3.8 a couple examples are presented, respectively for mounting a servomotor MG90 and a servomotor SG90. On the particular models used, the SG90 has the wiring done on the bottom of its case, hence why there is no cutout to allow for cable management on that configuration.

For the moment, pressure fitting the servos into the PLA plates has proven to work without issues, however there might be the need to screw them in place in case heavier loads are applied. For this situation, no design changes are required, only the drilling of two holes in the correct position.

#### 3.1.2.5 Protection Housing

This part is meant, as the name states, to be used as a protective cover for the working parts of the gripper assembly - whichever it may be. With a simple construction for easy manipulation of



(a) (b)

Figure 3.8: Base plate configurations to accommodate a MG90 servomotor (a) or a SG90 servomotor (b).

the openings, as well as a simple fixation pattern in order to allow for other desired designs more easily.

In figure 3.9 a blank example of the part (a) is presented as well as a custom example for a gripper with 2 fingers (b).

(a) (b)

Figure 3.9: Protection Housing: blank (a) and custom for a 2 finger gripper (b).

## 3.2 Smart Storage Solution

As a complement to the main subject of this research, the development of a Smart Tool Storage was proposed. It allows for an easy way to keep track and transport the different tools from work-space to work-space.

This unit will remain as a concept and be treated as a future work, so there will not be real world testing, production methodologies nor evaluation metrics outside the discussion about possible applications and theoretical obstacles presented along this subsection.

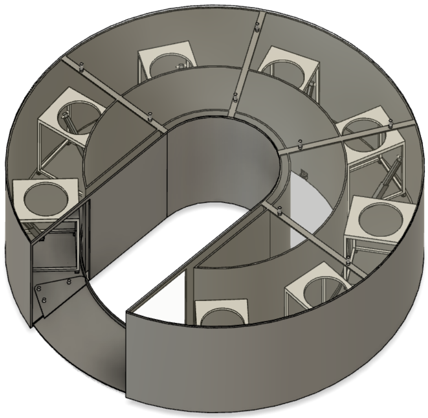


Figure 3.10: Overview of the Smart Storage Unit

Starting with geometry and functionality, the inspiration for this design was a conventional tool belt used commonly used by construction workers in order to always have the tools within arm's reach, no matter where they are. Additionally, the rotation aspect of the each individual tool location comes from machine centers. This allows for a single tool home frame and faster robot programming.

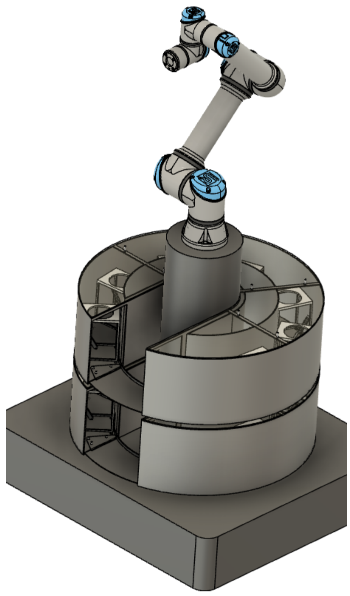


Figure 3.11: Example of a stacked application on a pedestal with a UR5e. The base has the rough dimensions of a *MiR100*.

In terms of dimensions, the aim was to keep it withing the boundaries of a *MiR100* where it could be assembled and, if chosen to be stacked like shown in figure 3.11, to stay withing a decent height to fit under a working bench. This would allow the UR5e to maintain full reach within the work area on the table - assuming a similar mounting position at the edge of the workbench - and easy access to the "tool belt" storage unit.

Delving deeper into the Smart Storage's tool carry capacity, it can carry up to 12 units per ring and, with the current pedestal height, stack up to three rings. This means each storage combination can have up to 36 slots for storing tools. When it comes to stacking the rings, it adds a home slot for each ring in terms of tool frames and, to avoid clearance issues, the tool holder is able to tilt, allowing for the manipulator to reach all of them without having to move the upper ring front gate piece out of the way - as shown in figure 3.12.

Speaking of the front gate, it was designed to allow for an easy removal of the storage ring. It simply slots into place on 4 pins. These pins could also be threaded in case extra structural rigidity is required to prevent warping and allow for a smoother rotation of the base plate.

The holes on the gate itself match the top fittings which are used for ring stacking, allowing for convenient placing of the gate while not in use.

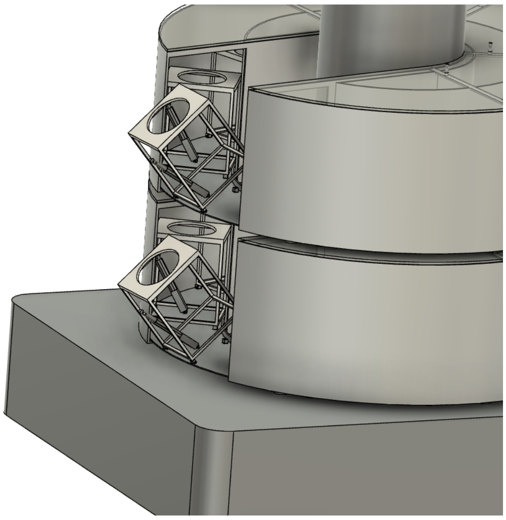


Figure 3.12: Tool access position demonstration, showcasing the clearance from top level ring.

The storage unit follows the same principle applied to the tools, being easy to manufacture, repair and replace any part to fit the user's requirements. Controller unit and rotation motor are placed inside the open space between the pedestal column and the inside of the tool storage ring. This motor works by friction and thus doesn't require alignment of gears - it, however, has clearance to install one in case the tools are heavier and more torque is required to rotate the plate.

Tilting mechanism is proposed by the use of a linear actuator, however it is not hard to replace with a stepper motor or a servo, as shown bellow.

Tools are kept in position passively, by the use of gravity. This is accomplished by the conical shape of the holder's hole; rotation of the tool relative to the holder structure is guaranteed by the positioning slot used to orientate the tool during coupling/decoupling.

# Chapter 4

# Implementation and Tests

## 4.1 Additive Manufacturing

For this application, parts were printed without any specific consideration in regards of mechanical properties impact of the printing orientation. Filament is PLA based and the way parts were positioned on the print bed was solely focused on facilitating the manufacturing process, by reducing the need of supports, as well as keeping the number of layers as low as possible to reduce print time.

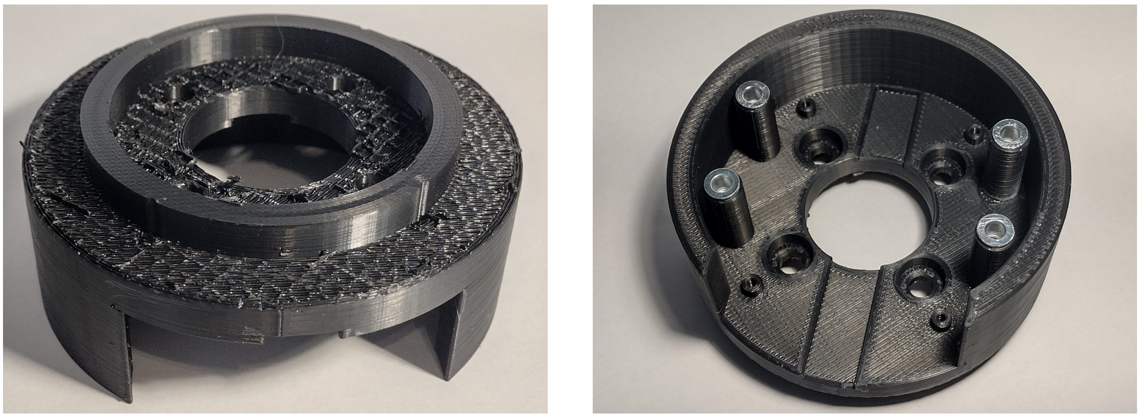
There is a direct correlation of better response to traction forces when their vectors are aligned with the filament lines - layers - leaving the adhesive forces between layers with the lowest values for the same tests. Nevertheless, this lack of homogeneity in the part didn't prove to be an impairment to any of the tests performed, considering a maximum load of 5 kg - being that in reality, as the tool itself weighs approximately 750 g, the maximum load carried by it would always be under 5 kg due to limitations on the UR5e itself [29], [30].

Parts were manufactured using several different printers, by different operators with different print settings. This allows for a better understanding of how the real use scenario of them would be as clients interpret the guidelines and use slicer parameters according to each individual experiences. The material used, aside from different manufacturer brands and colours, was PLA filament. The 3D Printers ranged mainly from Creality Ender-3 lineup (V1, V2 and Pro); printers from Ultimaker and BQ were also used for certain parts. All of the printers followed Cartesian working principles.

The profiles used on the slicers followed loose parameters in order to minimize print times, while maintaining some structural integrity for the parts under load. Parameter as temperature and print speed were not specified, being chosen by the operator, while layer height - (0.25 +/- 5) mm - and infill - (30 +/- 5 ) % - revolved around fixed parameters.

### 4.1.1 Master Side Interface

The bottom part of the master side interface doesn't have major overhangs and is a simple part to print. As figure 4.1 shows, the dimensional accuracy of the Additive Manufacturing isn't the best. Smaller details don't show on the part, which was expected, and had to be added in post processing by hand. The pressure fitted nuts' holes also showed signs of incorrect materialization of tolerances; this is a problem - even though the objective was for them to be smaller than the nut itself in order to allow for pressure fitting - as some previous test prints where no post processing was done in order to correct this issue ended up having the columns split under the pressure of inserting the nut into the desired place.



(a) (b)

Figure 4.1: 3D Printed Bottom Part of the Master Side Interface.

Aside from those smaller problems, the overall shape and functionality remained as intended, allowing for correct mounting on the robotic arm and bolting of the rest of the tool changer parts.

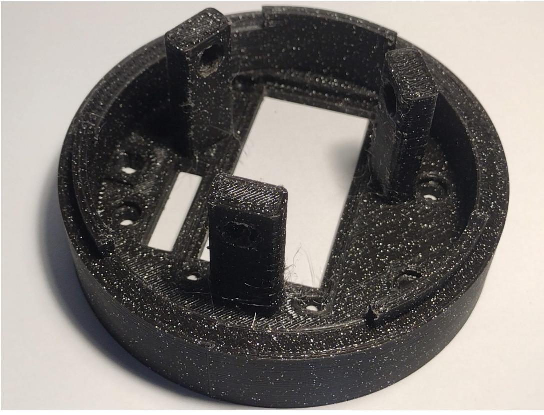
Contrary to its counterpart, this part doesn't have any overhangs and doesn't have any small detail to not be recognized by the slicer software, thus printing all the desired features flawlessly.

It, however, requires post processing to allow correct fitment of the locking pins on the guiding holes. This is due to the fact that the slicer, in order to produce easily removable supports, leave a small air-gap between those and the part on both ends.

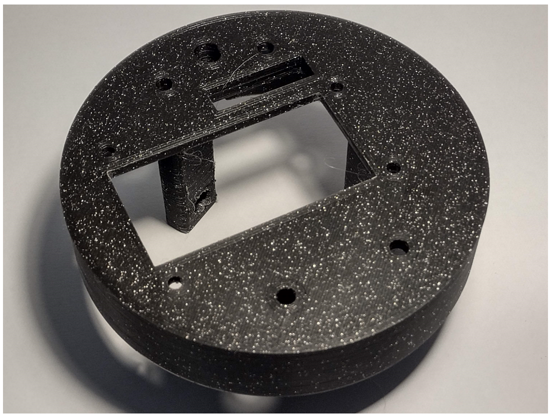
Adding this to the already "stair" like surface promoted by the layering, leaves the inside surface with a considerable amount of hard to remove jagged edges.

As the PLA used to print this part is hard to photograph, a previous iteration was used to showcase smaller details. The only difference between both versions is the change from a permanent actuator mounting configuration to a removable one, all other details remained unchanged from one version to the next.

Figure 4.3 highlights the pass-through, designed to house a moving piece that allows the connection of the gripper's actuator to the processing board mounted on the bottom part of the Master Side interface. This opening has two guides on each end that should keep the moving piece aligned correctly.



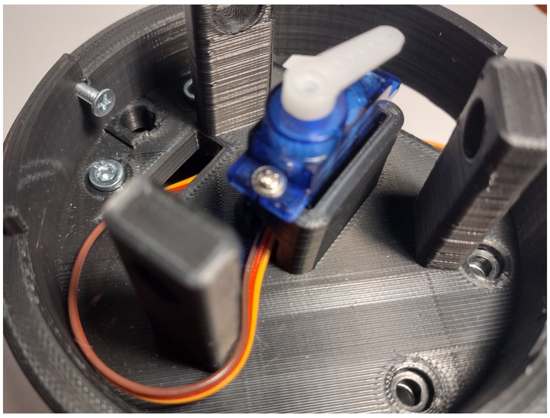
(a)



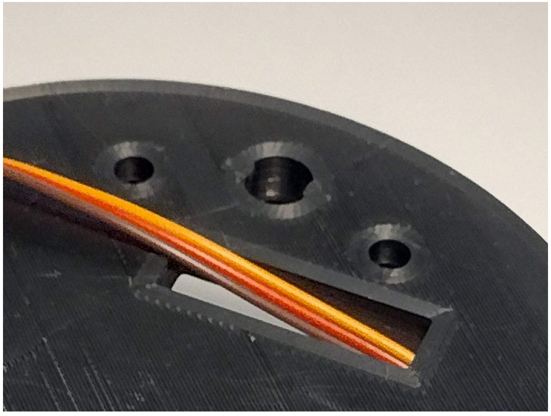
(b)

Figure 4.2: 3D Printed Top Part of the Master Side Interface.

It is also visible the fitment of the bolts that hold the top and bottom parts, as well as a screw used as a stopper to keep the spring loaded moving part in place. This simple mechanism will be shown further down, alongside the Tool Side Interface.



(a) Visible the top / bottom bolt and the screw that acts as a stopper for the wire pass-through.



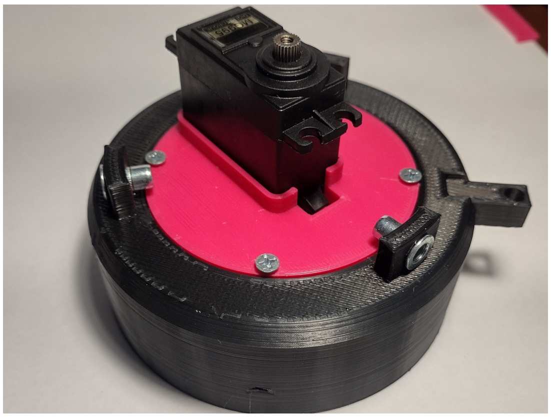
(b) Guide slots for the gripper servomotor wire pass-through.

Figure 4.3: 3D Printed Top Part of the Master Side Interface - Details.

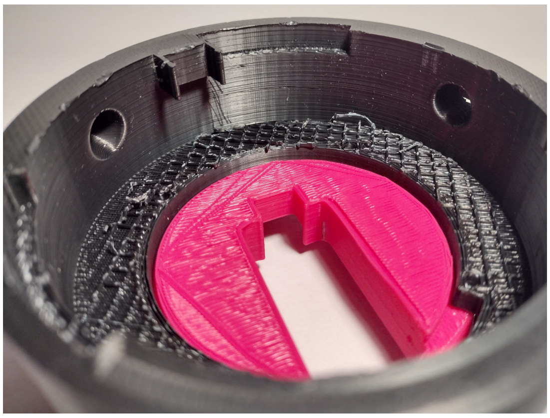
### 4.1.2 Tool Side Interface

Here, on figure 4.4, the Tool Side Interface is presented with the actuator mounting plate screwed in place and with a MG995 heavy duty servomotor in place. This is to showcase an example application of the interface, in case the standard Tool Side Interface is used along with the suggested mounting plate - customized to each particular application.

Considering the possibility of an already built gripper assembly, not modifiable to fit the Tool Side Interface opening - designed to fit the suggested Actuator Plate size - it is possible to build upon the cylindrical portion shown on figure 4.5. This is an exact copy of the previously shown interface, with the top portion removed.



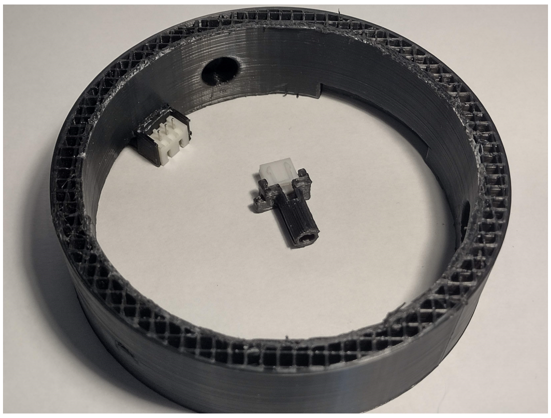
(a)



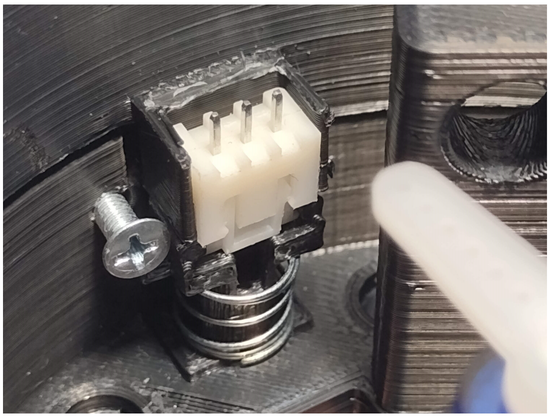
(b) Here is visible the mounting place for the female plug used to connect the gripper actuator to the processing board.

Figure 4.4: 3D Printed Tool Side Interface with Actuator Plate mounted (coral coloured part).

This also allows an unobstructed view of how the coupling mechanisms works, being used here mainly for that purpose.



(a) Visible the female and male side of the plug, with the respective mounts.



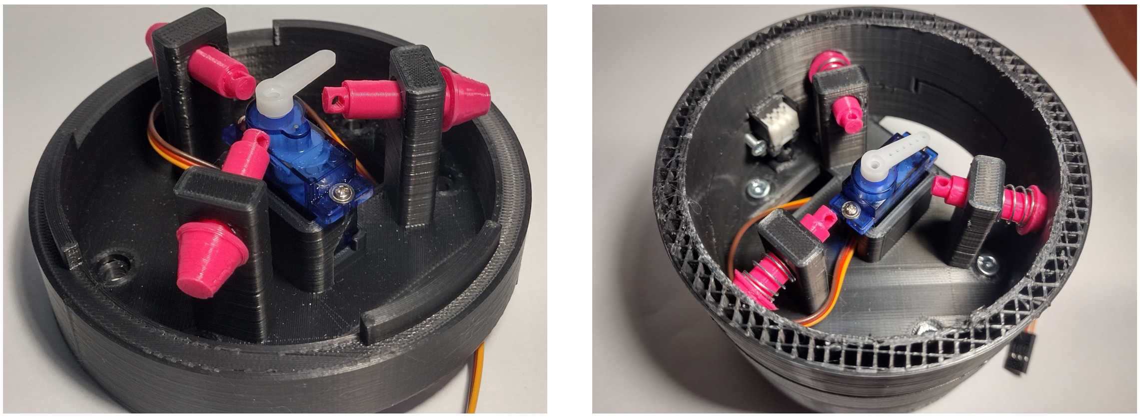
(b) Spring loaded assembly of the plug that guarantees the connection of the gripper's actuator to the board.

Figure 4.5

### 4.1.3 Coupling Mechanism

The coupling mechanism chosen, as mentioned several times previously, follows the working principle of locking pins held in place by loaded springs.

The retraction movement which requires the servomotor is not working as intended at this point in time due to dimensional constraints. The parts necessary to link together the two degrees of motion are unavailable due to the components shortage. 3D printing these parts isn't possible also due to the size.



(a) Open. (b) Closed.

Figure 4.6: Coupling Mechanism.

Alternatives, using strings or wires were tested but didn't provide reliable results being extremely dependant on the assembly technique. This adds an extra layer of complexity to the mechanisms that isn't supported by repeatability or reliability resulting in breakages and malfunctions.

### 4.1.4 Protection Housing

This part displays some issue while printing the inside top portion, if no supports are used and the orientation follows the one showed on the figure 4.7. In case the operator decides to print it upside down, there is a lack of outside surface quality - visible on the housing containing demonstration fingers.

(a) Example Protection Housing for a 2 finger gripper configuration mounted on a standard Tool Side Interface.

(b) Size comparison with model fingers, for dimensional visualisation.

Figure 4.7: Protection Housing example.

These parts have a passage for cables, in case there is a necessity to run extra wiring for auxiliary electronics and it was not accounted for during the design of the actuator plate.

## 4.2 Application Testing and Results

Briefly mentioned on some sections before, several demonstration parts were printed with the purpose of dimensional visualization. Figure 4.8, on the side, shows the overall length of an expected assembly of the tool changer with the respective tool - in this case a 2 finger gripper, mounted on the standard Tool Side Interface with the proposed Protection Housing.

Figure 4.8: Example of an assembled tool changer with a 2 finger gripper protection housing.

This test confirmed that all mounting points, holes and fixations were aligned and allowed for the correct placement of all printed parts.

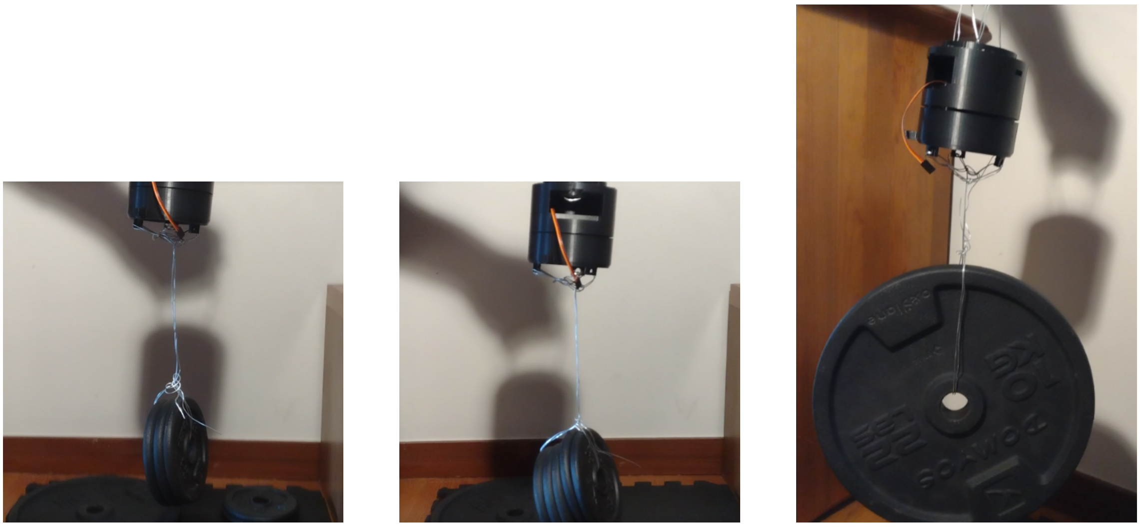
Servos were able to move freely and didn't hit any part of the surrounding structures. Cable management was possible even without shortening the OEM length of the wires, meaning servomotors can be applied out of the box.

On figure 4.9 a crude load test was performed manually, in order to access the load bearing capacity of the main components of the tool changer. Manually lifting a load as shown introduces instability, vibrations and lateral forces when compared to a standard traction test machine. Added benefits of such testing are a closer relation to real working environments with moving loads.

Clearly, the maximum load capacity of the UR5e is 5 kg, therefore loading the tool changer above that value is not applicable to this specific situation. However, as it was mentioned in the beginning of this paper, versatility and the capacity to work with multiple manipulators - independent of manufacturer and production generation - is a core principle. Therefore, proving it is able to hold a load of 10 kg opens possibilities of applications on most collaborative manipulators on the market.

During the load tests, as is visible on the images, there appears to be some separation between the Master Side and Tool Side Interfaces. This is most likely due to the fact that no springs were used on the locking pins in order to allow manual movement, since the servomotor actuation mechanism was not operational at the time. The lack of pre-load on the pins likely allowed for a slight backward movement while load was applied, leading to the separation of the interfaces.

After the load tests, the parts were disassembled and checked for cracks or signs of fatigue. All 3D printed parts were in perfect condition, none of the critical load bearing areas appear to be



(a) 3 kg Load Test. (b) 5 kg Load Test. (c) 10 kg Load Test.

Figure 4.9: Manual Load Testing of the coupling mechanism and load bearing structures of the Tool Changer.

affected by the loads and the locking pins don't show signs of delamination between layers nor flat spots along the shaft.

It was however, noted some movement on the pressure fitted nuts as well as the female plug on the tool side. These should be fixed by applying glue instead of just inserted into the designated slots.

# Chapter 5

# Conclusions and Future Works

## 5.1 Conclusions

Additive Manufacturing is one of the most versatile ways of quickly developing and applying changes to working mechanisms. The ability to completely change the functionality of a tool overnight provides a major competitive advantage on an ever growing market for customized products.

Using this technology to manufacture tools that are able to compete with ones manufactured using traditional methods propels the response times over several degrees of magnitude since those tools can then be used to speed up production of other essential mechanisms.

Adding the possibility to manufacture in house any replacement parts or customized applications for a specific use, without the waiting period inherent to communication with the supplier, fabrication of the part and later transport and delivery, is a major selling point for the Tool Changer application proposed with this thesis.

Having a lightweight, durable and versatile automatic tool changer which can be paired with an automatic intelligent storage unit should be a stable of any small and medium sized company that manufactures anything from limited number niche products to small batches of slightly customized items.

In conclusion, the proposed solution for an automatic tool changer, fabricated through Additive Manufacturing delivers a solid and reliable product that at the cost of understanding the basic working principles of Additive Manufacture and owning a small household Cartesian 3D Printer delivers an upgraded versatility to collaborative robotics limited mostly by the capacity of designing and implementing new tools.

This tool changer was capable of carrying loads over the maximum allowed by the manipulator chosen for the study without showing signs of fatigue. The downside of not having, at the moment, a fully operational automatic coupling mechanism - considering it works if manually engaged - can be viewed in a positive way since it confirmed the aforementioned ability to quickly fix any breakages or change components required. Within a week, the top part of the Master Side interface was changed about seven times, not including small tweaks to the original design without the removable servo mounting plate to try and accommodate for the clearance issues.

## 5.2 Future Works

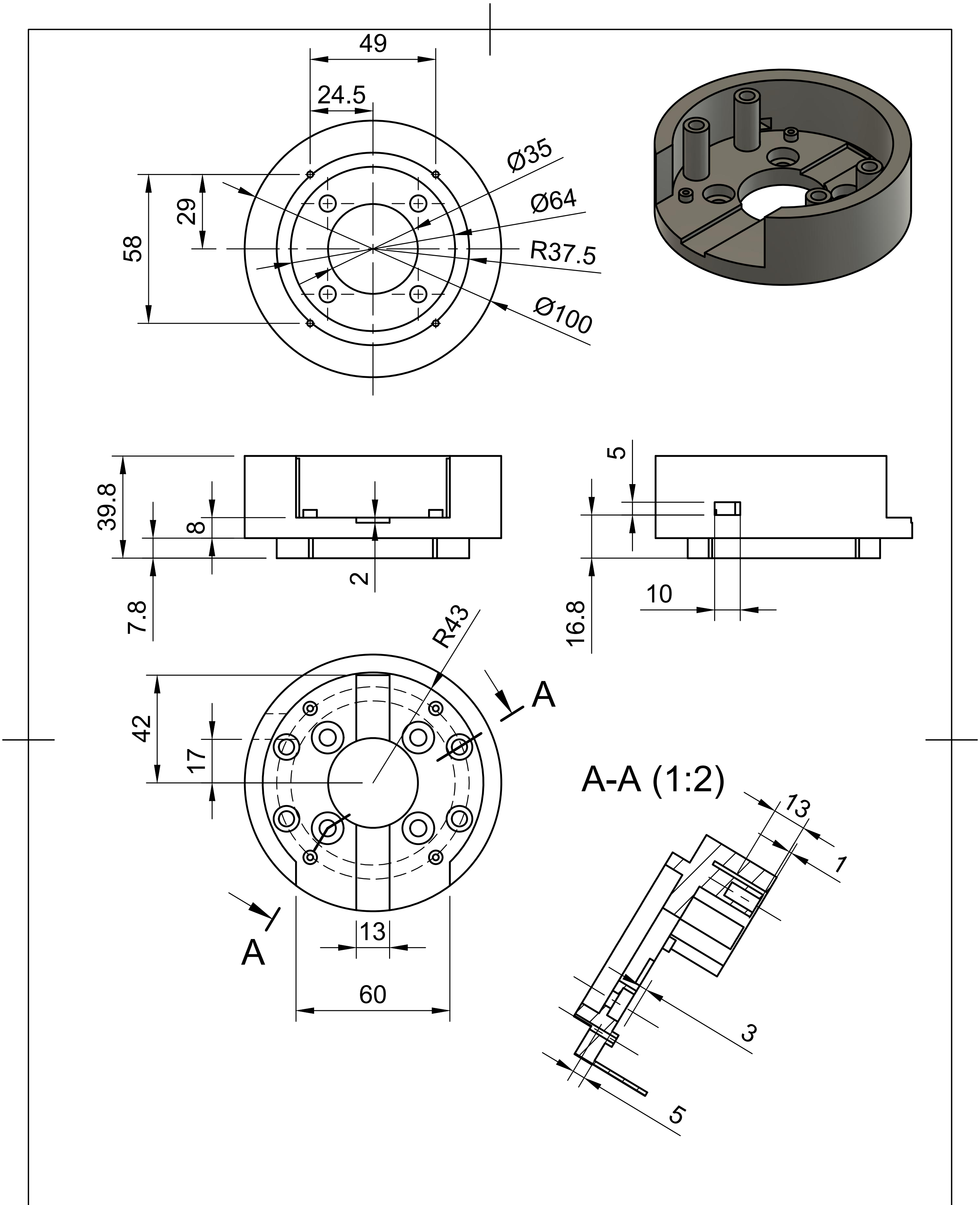
As future works, revising the automatic portion of the coupling mechanism has the top priority. To accomplish this, I find that two new paths should be considered: revising the application for the SG90 or MG995 servomotors by making the inner and outer diameters of the tool changer bigger, allowing for more space inside to apply bigger and more common parts; studying the possibility of using small linear actuators, like solenoids, to move the pins. Since they are normally closed, the action of the linear actuator would be for a short duration and thus not generating a large amount of heat, which in turn could be detrimental to PLA as a filament choice.

Secondly, studying the applicability of other smaller control units to further reduce the overall size of the tool changer. Best case scenario would be using the manipulator's controller. I still believe it is best to not use an available motion from the manipulator itself as it may hinder its usability during the task at hand.

Lastly, the possibility of using more advanced Additive Manufacturing machines to fabricate the parts using other materials outside of PLA, further increasing durability.

# Appendix A

# Technical Drawings

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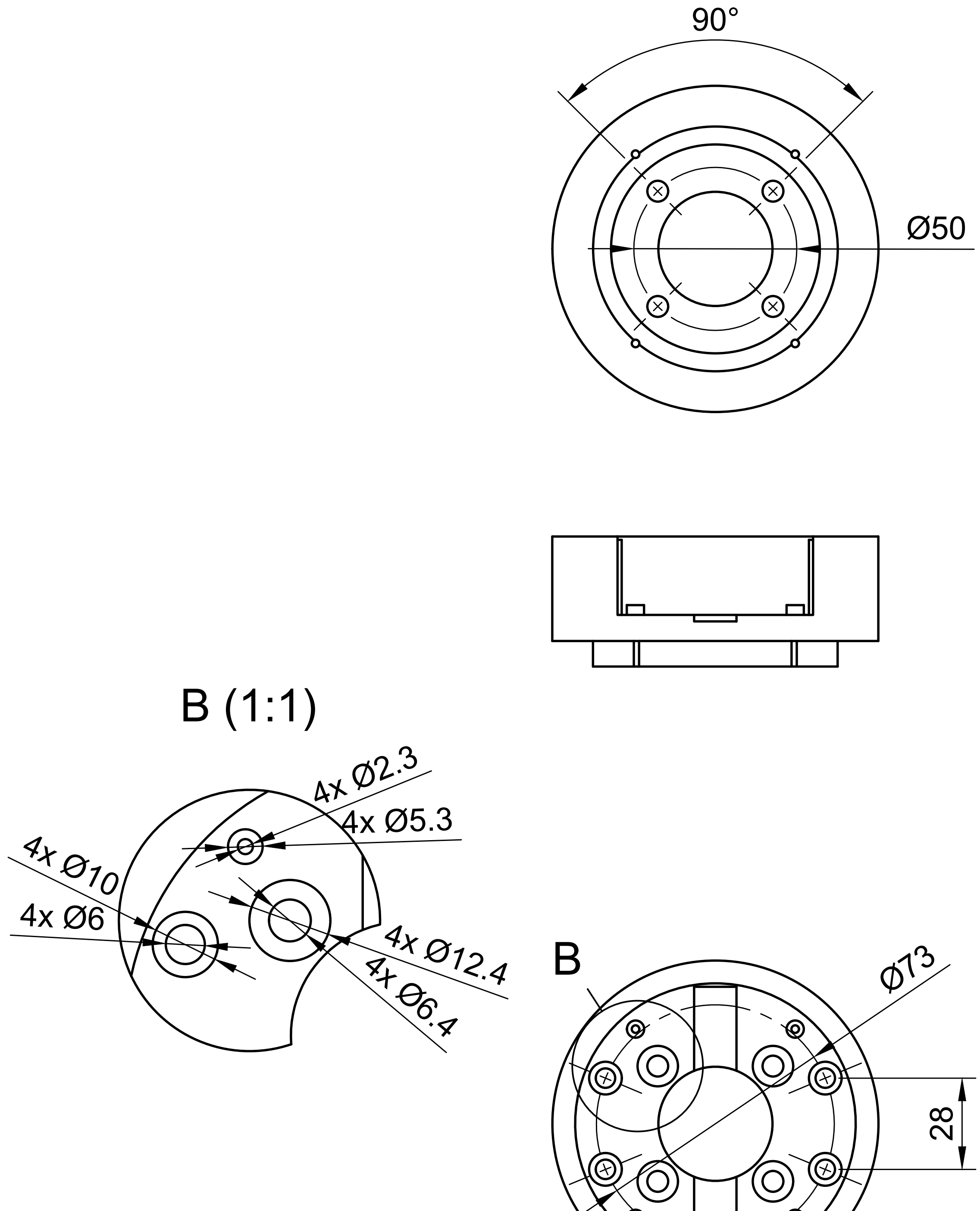


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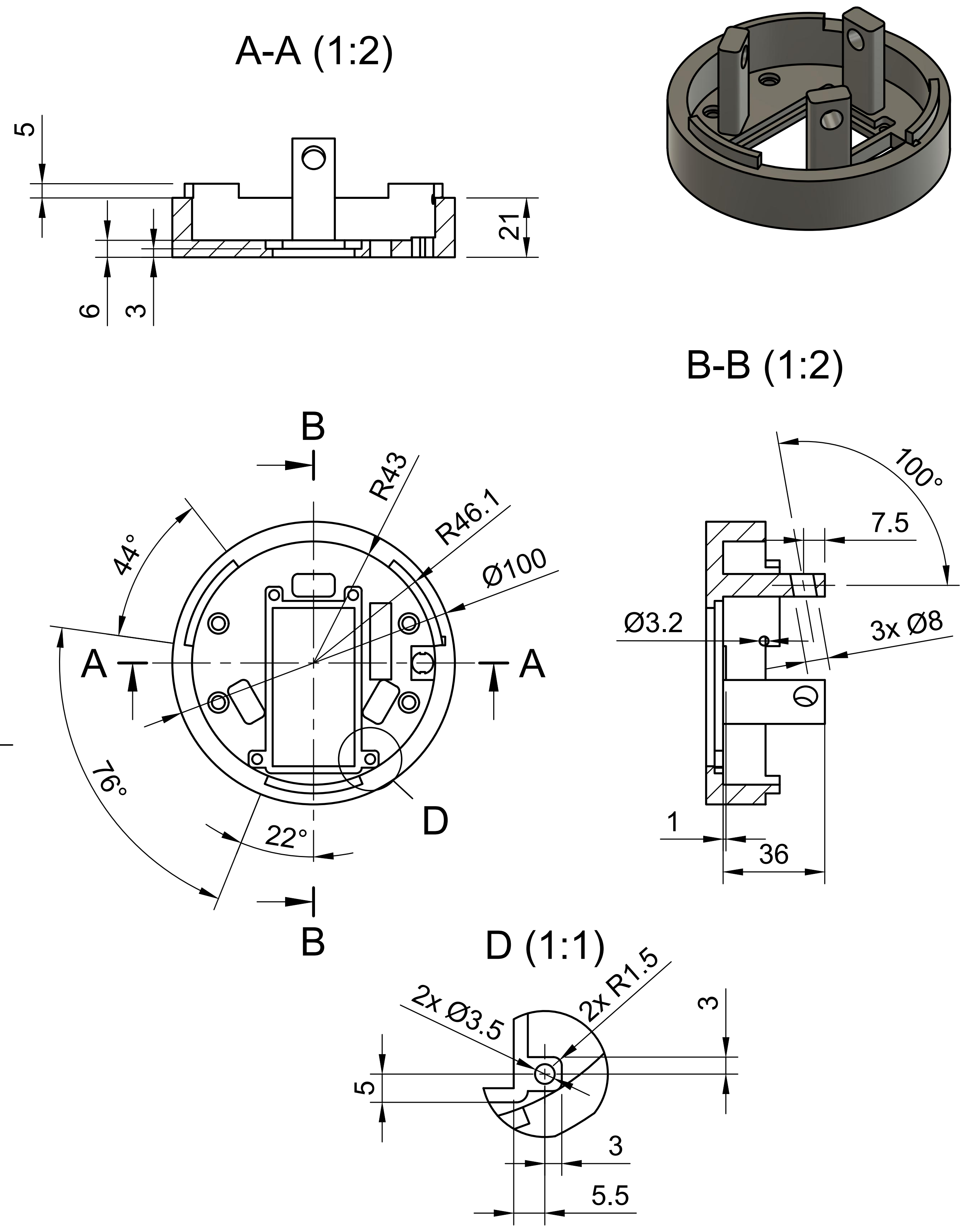


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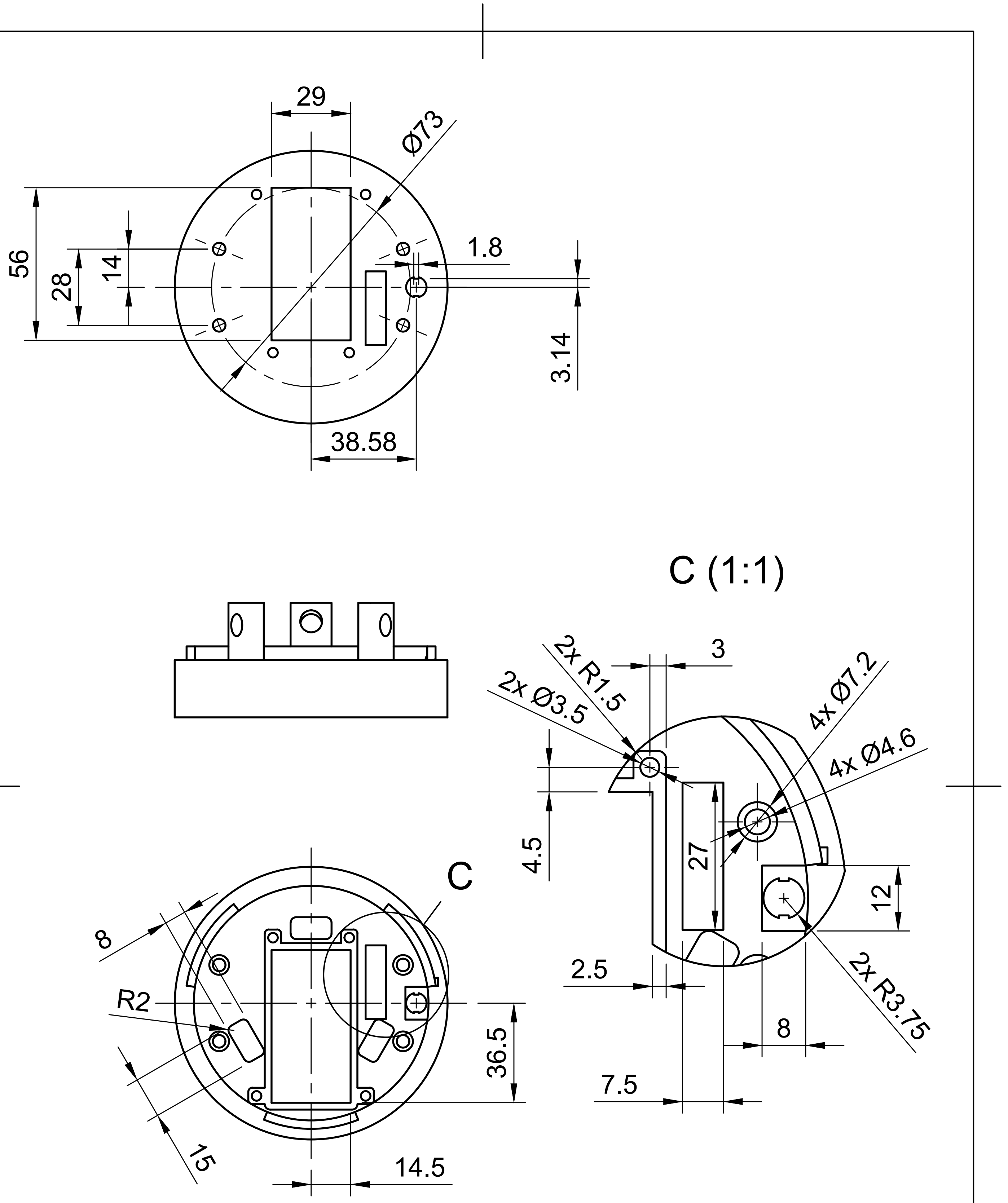


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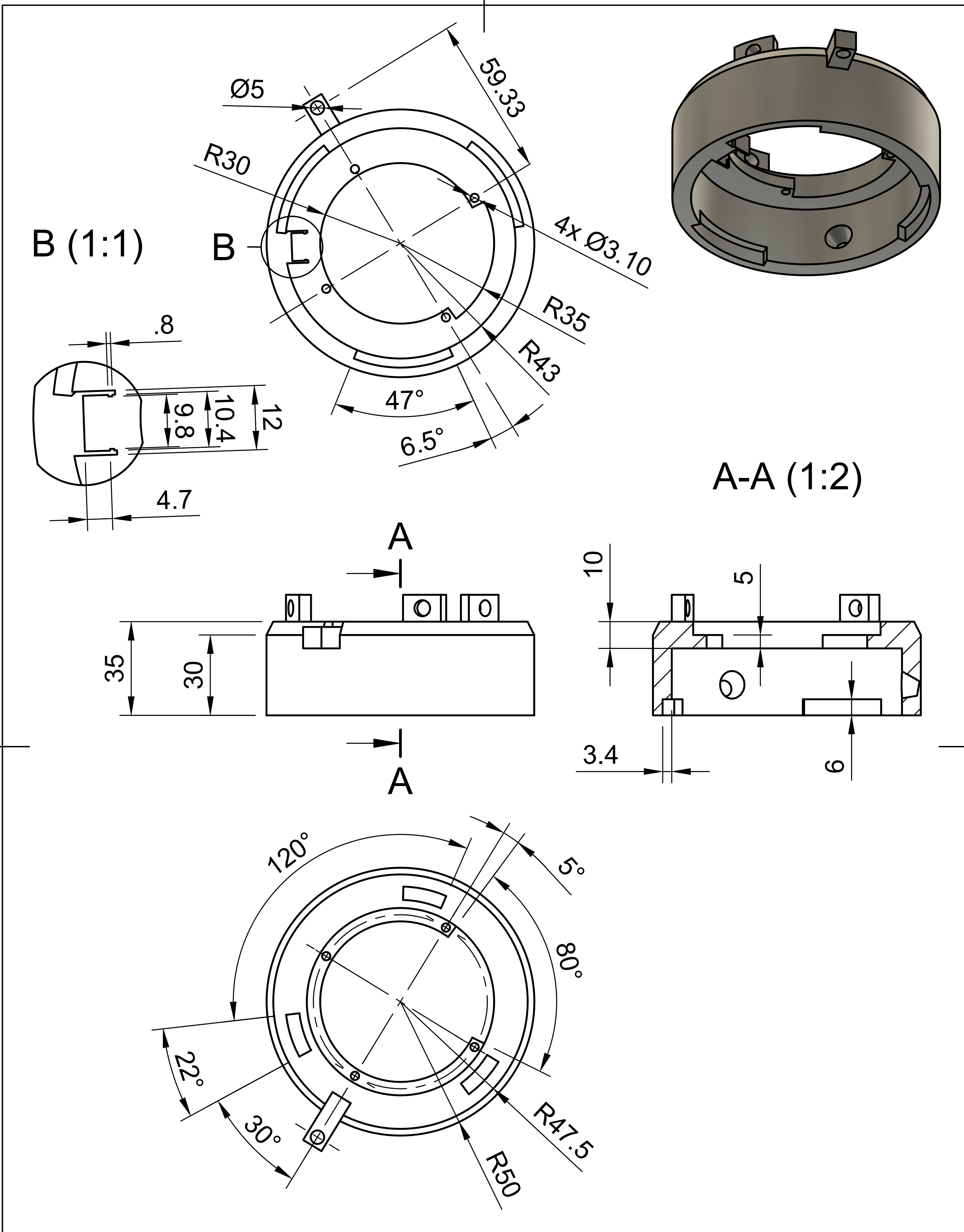


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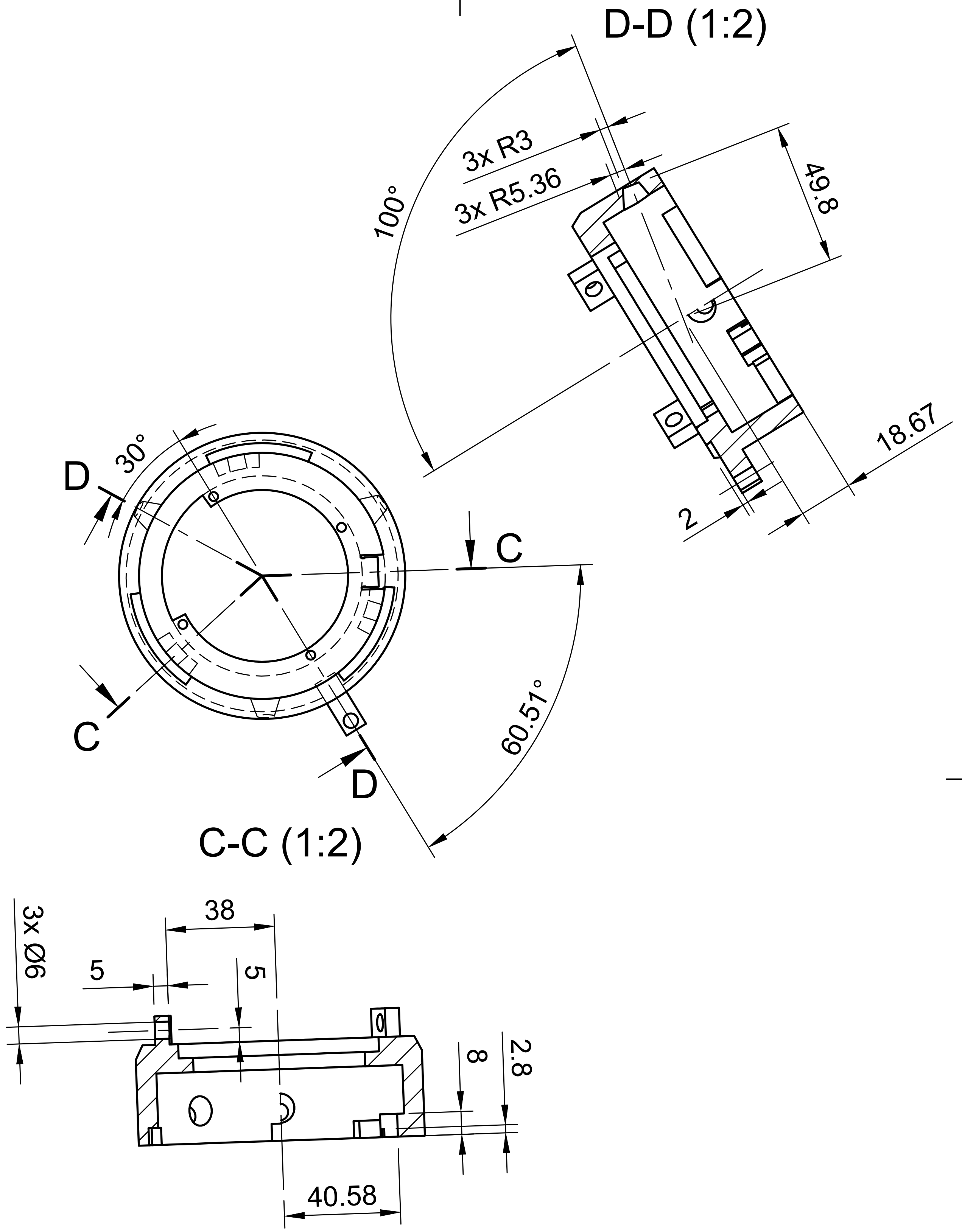


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