AN ENERGY EFFICIENT ELECTRO-HYDRAULIC CONTROL SYSTEM FOR A COLLABORATIVE HUMANOID ROBOT

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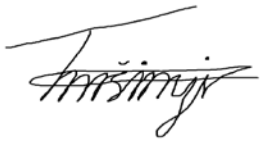
Declaration

I, Teboho Ntsinyi (Student Number _________) hereby declare that this thesis represents my own work which has been done after registration for the degree of **Master of Engineering** at the Central University of Technology, Free State, and has not been previously included in a thesis or dissertation submitted to this or any other institution for a degree, diploma or other qualifications.

The work was done under the guidance of Prof. E.D. Markus at The Central University of Technology, Free State as the main supervisor as well as MR L.Masheane of the Central University of Technology, Free State, as the co-supervisor. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions.



Signature **Date: 24 August 2021**

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I would like to thank my supervisor and co-supervisor for all the hard work they put into my studies as well as consistently ensuring that I am always on track with my work. Through their hard work and dedication this research was possible.

I would like to thank my parents for always believing in me and constantly encouraging me to studying further, I thank you for your support thoughout my studied.

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Abbreviations

AM	Additive Manufacturing
COT	Cost of Transport
DEA	Dielectric Elastomer Polymer
DOB	Disturbance Observer
DSS	Dual Stage Supply
EHA	Electro-Hydraulic Actuator
EMAS	Electro-Mechanical-Actuation Systems
ICS	Industrial Control System
IIT	Italian Institute of Technology
ISA	Integrated Servo Actuator
PID	Proportional–Integral–Derivative
SDP	State Dependent Parameter
SMC	Sliding mode control
SMCSPO	Sliding Mode Control with Sliding Perturbation Observer
SPO	Slide Perturbation Observer
SPP	Serial Port Protocol
SSS	Single Stage Supply

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Abstract

This study presents the design of an energy efficient electro-hydraulic control system for a collaborative humanoid robot. Robots can be found in almost every aspect of our lives with different applications such as manufacturing, construction, agriculture, surgery, and transportation. The need for robots is on the rise as they perform certain tasks much faster and with more precision than humans. The lack of them having cognitive ability limits them in certain tasks as human interaction is often needed. Humans are currently better than robots in performing some tasks such as decision making and problem solving. In collaborative robotics, humans and robots are required to work together to achieve a common goal. In most cases, this is achieved by confining both entities in the same space. This allows for better accuracy for these robots with the flexibility and cognition of humans. Furthermore, research lately shows an increase in robots that use hydraulics with most showing that these hydraulics have energy saving abilities in robotic actuation. It is known that hydraulics have a high power to weight ratio thus allowing for more powerful yet compact robots to be built. An electro-hydraulic control system is thus described in this research in which the system allows the human user to manipulate the robot by having it mimic the user's moves. This approach allows the user to not do any strenuous activities while the robot does the heavy lifting. Furthermore, the system does not need to be reprogrammed for a new task therefore reducing the reconfiguration time of the system. The proposed approach further allows the robot to work in hazardous situations while the user is in a safe environment. The system uses a proportional-integral-derivative (PID) algorithm to control a hydraulic cylinder allowing it to move with the user. Experiments performed to validate the study shows the reaction time as well as energy saving abilities of the system. Additionally, the results show that hydraulic systems have the ability to save energy during stall as well as increasing power density of the robot. Furthermore, an improved response time was recorded for the hydraulic system when being controlled by a remote operator.

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Chapter 1

Introduction

Humanoid robots are built to resemble humans and adapt to their surrounding environment [1]. Such robots can be used in places where human effort is needed but would be too dangerous for humans to access [2], [3]. Applications of these classes of robots may include rescues in hazardous environments such as fires, mines, and places where there are high radiation levels. Humanoid robots have not reached a point where they are intelligent enough to make decisions by themselves and thus human interaction is still needed. Research has shown that human-robot interaction yields the highest output in production when compared to human-human and robot-robot [4].

The first encounter of robotic machines dates back to the 1950s when Joseph Engelberger invented the Unimate which was the first industrial robot ever [5]. These robots were used for various tasks such as loading and unloading machine tools. The demand for robots increased rapidly as the industry required more robots to work faster than humans over prolonged periods of time. Today the demand for robots is on the increase as we move into a new industrial era, namely industry 4.0.

1.1 Human-robot collaboration

As the 4^{th} industrial evolution advances, machines will become more autonomous and thus more complex manufacturing environments can be achieved [6]. Interaction and collaboration between humans and robots are therefore one of the major emphases of the 4^{th} industrial revolution whereby the two entities are able to act together in achieving different tasks. Moreover, collaborative robots are expected to be more efficient when it comes to assembly applications which are mostly carried out manually [7]. This type of interaction may occur either by direct manipulation or with the help of a user interface [8], [9]. For the User interface, Human-Machine Interfaces (HMI) are commonly used, this is a place where human operators can manipulate different machinery through the Industrial Control System (ICS). HMI panels come in different types, they can be touch-based video screens or terminals, pushbuttons auditory feedback, flashing lights or graphs and displays that all help the user interact with the machine easily [10]. Direct

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manipulation has been said to be a good form of interface design. This type of interaction is often achieved by reducing the distance between the interface and the machine, this helps the user feel more direct with the system as it reduces the effort required for the user to accomplish different goals. Generally, with direct manipulation, the system is used to link the user to the machine to ensure that the user can behave as if they were the machine itself. This helps provide the feel of directness of manipulation while at the same time reducing strain on the user [11]. Smart systems should be developed in such a way that they do not always replace humans, but in many cases help in enhancing human capabilities.

1.2 Humanoid robots

The development of the HONDA humanoid robot known as P2 triggered the world's research in humanoid robots after its development. This was the first robot ever to be designed to have two arms and two legs, thus humanoid. Its research and development began in 1986 and was announced in 1996 [11]. The main reason for the development of this robot was to enable a robot to coexist and collaborate with humans also to perform tasks humans were incapable of doing. According to HONDA, a robot with arms and legs that could walk like a human is the most practical as the robot would need to be able to adapt to the human environment where there are obstacles such as staircases, doors, furniture, and even and uneven terrains. Since then more and more development has been done in the field of humanoid robotics like the WABIAN series of Waseda University, ASIMO, Partner, QRIO, H6 and H7, HRP, JOHNNIE and many others [1], [2], [12]–[14].

With the increasing number of robots working in factories, humans are becoming afraid of robots taking their jobs. Robots are good at doing repetitive tasks and heavy duty tasks which is the main function of most factories [15]. When it comes to cognitive tasks however, humans are best suited for such tasks as robots cannot currently think, make decisions and solve problems. Even when looking at the most sophisticated robot today, cognitive tasks such as decision making, problem solving, attention and judgement have not yet been achieved [16]. The best solution is a collaboration between the two entities where a human can help a robot and vice versa. This means that the human can do all the cognitive tasks such as decision making and reasoning, while the

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robot works on other tasks such as heavy lifting and all the repetitive tasks. Moreover, human-robot collaboration has the ability to assist humans who lack certain abilities to achieve tasks that they would not be able to achieve solely.

1.3 Problem Statement

Humanoid robots tend to use excessive power when constructed using traditional servo motors as they suffer from stall current during operation. This increases the operational costs and could hamper productivity of the robot. The reliability of the robot is also affected as shorter battery life and more servicing costs poses a threat to efficient operation. Furthermore, robots are still not good at cognitive tasks and if collaboration is introduced, then more power would be needed for extra sensing and motion requirements in the real-time human-robot.

1.4 Research Aim

This research aims to design and construct an electro-hydraulic collaborative humanoid robot system that will mimic human motion in realtime while helping reduce the energy consumption of humanoid robots during operation but mostly when idle.

1.5 Research objective

The objective is to:

1. Review existing humanoid robots as well as actuation mehods used in different robots
2. Design a robot arm that will demonstrate an increase in the energy efficiency of collaborative humanoid robot.
3. Construct the electro-hydraulic humanoid arm with increased overall power density to enable it lift heavy loads.
4. Design and implement a control system for the collaborative human robot arm.

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1.6 Hypothesis

This research hypothesises that incorporation of Hydraulics in robots can increase the overall power density of robots as well as decreasing their power consumption and at the same time keeping a small form factor.

1.7 Research question

Can an electro-hydraulic increase the efficiency of a robot during stall and also increase the output power, while achieving the same accuracy as an electrical system?

1.8 Research methodology

The methodology addresses the research objectives and is structured as follows:

1.8.1 Literature review

The literature review provides knowledge of humanoid robots, actuation methods used, as well as human-robot collaboration (HRC). In this chapter, the topics are discussed in depth where different humanoid robots that have been developed in recent history are laid out together with the type of actuation used by each of them as well as their advantages and disadvantages. The last part of the chapter addresses the importance of HRC by looking at some robots that have been developed to work alongside humans.

1.8.2 Humanoid robot design

The robot design section defines all the components that are used for the proposed robot system design and how they all interact together. In this chapter, the theoretical as well as the practical aspects of the proposed robotic system are described in detail.

1.8.3 Hydraulic system configuration

The hydraulic system configuration describes how the hydraulic components were assembled and how they work together. The hydraulic cylinders, hydraulic pump and servo valves integration are described systematically as well as additional parts that were 3D printed and used in order to achieve the objectives.

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1.8.4 Control system Design

This part of the research focusses on the PID system used to control the robot and how it ensures the system's stability for realtime mimicking. Furthermore, the program used to control the hydraulic actuators is described.

1.9 Publications during the study

The following were written during the study.

1.9.1 Conference Papers

- T. Ntsinyi, E. D. Markus and L. Masheane, "Prospective Electro-hydraulic Control System for a Collaborative Humanoid Robot," 2019 Open Innovations (OI), Cape Town, South Africa, 2019, pp. 109-114, doi: 10.1109/OI.2019.8908198.

1.9.2 Awaiting publication

- T. Ntsinyi, E. D. Markus and L. Masheane. "A Survey of an energy efficient electro-hydraulic control system for a collaborative humanoid robot" in 2021 IOT with Smart Systems, Springer. (In Press)

- T. Ntsinyi, E. D. Markus and L. Masheane. "Design of an electro-hydraulic control system for a collaborative humanoid robot" (submitted to Robotica)

- T. Ntsinyi, E. D. Markus and L. Masheane. "PID Control for a collaborative humanoid robot" (conference paper submitted)

1.10 Contribution to knowledge

This study presents the design of an electro-hydraulic control system for a collaborative humanoid robot. Modern humanoid robots are built using electrical motors which in most cases are servo motors. In this study, hydraulic actuators would be used to control a robotic arm that would mimic human actions in realtime. There are multiple reasons for this decision. The two main reasons are torque and power consumption. Hydraulic actuators are known to have more power than electrical motors at the same time having less weight than an electric motor of the same size. This

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knowledge is used in this study to design a robot arm that would consume less power and have the ability to carry heavier objects. This would help in designing robots that can lift heavy loads while consuming less power. Furthermore, the ability of the robot to be mimicking allows for easy and more agile control of humanoid robots. This knowledge could be used further in teaching robots how to do tasks easily without the need for complex programing.

1.11 Structure of the dessertation

This dissertation is divided into five chapters. Chapter 1 is the introduction which provides an overview of the research as well as a description of how different technologies are used for robot actuation.

Chapter 2 is the literature review which explains the different approaches and techniques taken by different researchers as well as common problems that arise when using such approaches. This part of the research further explains the different technologies and methods used to solve problems that occur.

Part three comprises chapter 3, the research methodology which explains in detail the steps taken in designing and constructing the robot arm used for testing.

The fourth part of the research in chapter 4 looks at the results obtained and explains the different tests that were conducted to achieve those results.

Finally, the conclusion chapter explains some of the challenges that were faced during the research and areas of improvement for future work on the topic.

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Chapter 2

Literature Review

This chapter describes the background study that was done prior to starting with the practical work. Different types of control systems used in humanoid robots as well as actuation methods are discussed as well as the need for these classes of robots in present day life. Furthermore, the advantages and disadvantages of the robotic actuators, namely; pneumatic, hydraulic and electrical are discussed. Human-robot collaboration and the need for collaboration between the two entities are also discussed later in the chapter.

2.1 Background of humanoid robots

Various companies and institutions have been on a quest to develop humanoid robots and numerous have succeeded. Robots such as Honda's P2 [11] were the first ever humanoid robot while others like Little-Dog, ASIMO, WABOT followed a few years after and have now come to be some of the world's well-known humanoid robots [13]. These robots however are built using electromechanical systems and rely solely on lithium batteries as their energy source. This type of system has been investigated and results have shown that they have a very low power density which more than often results in poor load capacity, low speed and limited strength [17]. These are some of the main factors that play a huge role in the overall performance of any type of robot and thus need to be resolved if a perfect robot is to be built. Another major key in developing a good humanoid robot is to develop an actuation system that could drive the robot with the minimum cost of transport (COT) as possible. COT can be defined as the power consumption divided by the weight, multiplied by velocity [13].

2.2 Development of actuation systems

Different actuation methods have been used worldwide for different applications and some work better than others. These ranges from electrical servos, hydraulics, pneumatics, soft robotics and many others. Of all these, electrical servos and hydraulics are the most used in mobile robotics due to their precision [18]. These methods are

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discussed below. Table 1 highlights the advantages and disadvantages of the most commonly used actuation methods namely; pneumatic, electric and hydraulic actuation. It also demonstrates some of the problems found with these systems while also acknowledging the challenges with hyraulics. However, one of the aim of this research is to address the setbacks of hydraulic actuation.

Table 1: Summary of advantages and disadvantages of different actuation methods

Actuation Method	Advantages	Disadvantages
hydraulic	• Small components with predictable power output to pass massive power. • Actuators can be controlled with high precision. • Has the ability to move even under high initial loads. • Under varying loads, it creates even and smooth motions since the fluids are not compressible and valves can control flow rates accurately. • It provides consistent power compared to pneumatic systems at moderate speeds. • Heat may be dissipated easily and quickly.	• High maintenance cost due to regular fluid change and filters. • More prone to failure due to oil leaks. • Aeration which occurs from air entering the system may cause foaming and erratic actuator movements. • Can be expensive to purchase. • Rapturing of high pressure lines may cause injuries. • Performance may be affected by temperature changes.
Pneumatic	• More efficient and cheap to use as they use air, which is abundant and may easily be stored and transported. • Can operate at very high speeds. • No risk of leaks that could be messy. • Cheaper than hydraulics. • Safe to operate • Could function in harsh environments.	• Less powerful than hydraulics. • Generate a lot of noise during operation. • Due to air being compressible pneumatics are less accurate. • Before use, air needs to be cleaned by removing water as well as any dust particles.
Electrical motor	• Easy to use and integrate than pneumatics or hydraulics. • High level of precision and control. • High speed.	• Poor motor cooling often causing motor overheating. • High initial installation. • Damage due to motor overloading.

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	• Little to no maintenance. • Safest method of actuation. • Costs less to run as well as to maintain. • Easy to connect and assemble with only a few wires. • They can be modified for almost any purpose or force requirements. • Adequate torque for their size	• Stall current.

After looking at Table 1, hydraulics seem to have more disadvantages when compared to other systems. Most of these however, do not affect the operation of the system and can often be taken care of by ensuring that the system is well designed. The next section will discuss these systems in more detail.

2.2.1 Hydraulic actuation

Though hydraulics are only trending now, they have been around even longer than electrical systems. They can be traced as far back as 287 BC though they only became more popular during the 18th century when the London Hydraulic Power Company was set up to provide water hydraulic systems that would power theatrical scenery, lifts and other systems. Figure 2-1 shows the trend in hydraulics and the two types of hydraulics that have been used throughout time.

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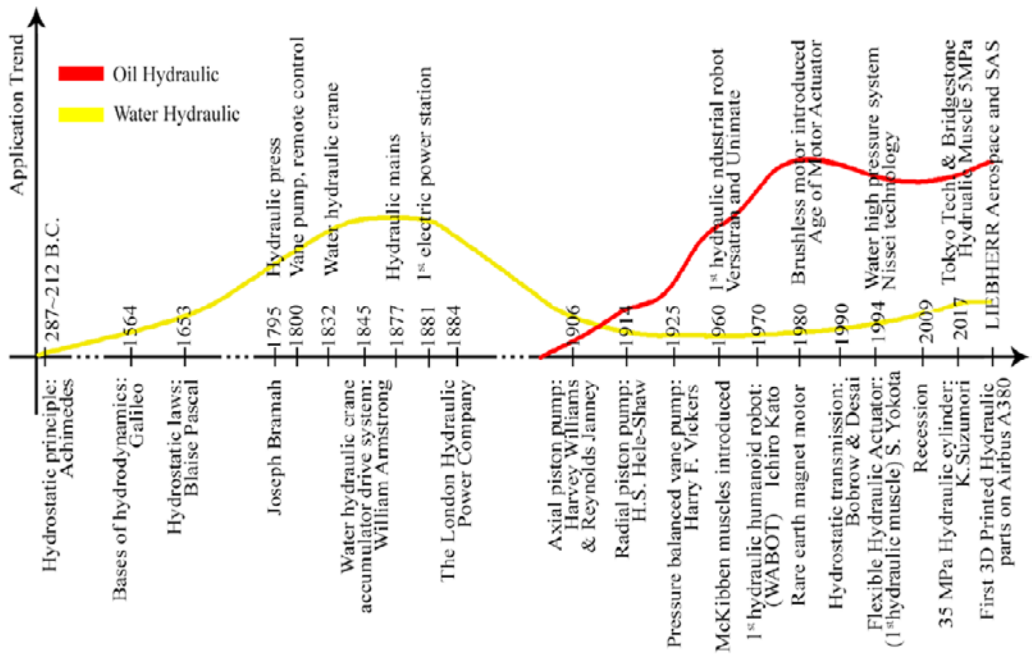

Figure 2-1: Trend in hydraulic technology [12]

Hydraulic actuators are well known for their high torque to weight ratios. They yield higher power outputs when compared to electrical actuators and are the inexpensive choice of the two. It is for this reason that researchers use hydraulic actuators over electrical actuators in some applications [19]. These actuators can be found in heavy duty machinery where high force and precision are required [20]. They can be fairly lightweight when compared to the weight they are able to lift. The origins of hydraulics date back to about 200BC though it gained popularity in the eighteenth century. These systems were initially water based and later moved to oil based systems during the nineteenth century. Though these systems are said to be much slower and less accurate than electric motors, they have proved to have higher efficiencies during operation than electrical systems, thus the trend in robot designing shows more and more researchers migrating to hydraulic systems [12], [17]. Hydraulic actuators work with hydraulic fluids and a hydraulic pump is required to ensure the flow of fluid within the entire system. These systems are fairly complicated to design as they operate at very high pressures and a small amount of leakage could cause the entire system to fail. These systems obey Pascal’s law which states that “pressure at a point has infinite direction, and thus a pressure change at any point in a confined incompressible fluid is transmitted throughout the fluid such that the same change occurs everywhere” [21]. When applying this law to a double acting hydraulic actuator it is noticed that if both the chambers are sealed and both have a sufficient amount of fluid in them, the actuator would remain at rest even when an external force is applied to the actuator provided that the force is not greater than the maximum operating force of the actuator. Moreover, applying this concept in robotic design would mean that, power would only be consumed when work is done and not when idle. Furthermore, if a humanoid is designed using this concept then it may be able to lift a heavy object while only requiring energy to lift it up. This would require little to no power in keeping the object at the desired place which ensures very efficient use of power.

A conventional electrohydraulic control system consists of a solenoid valve that operated at three states to control the flow. When the valve centred there's no flow, shifted to the right to route the flow in one direction and shifted to the left to route flow in the opposite direction. Due to its simplistic design the valve tends to move the load with rapid acceleration and deceleration as it is either fully opened to the left, fully opened to the right or completely closed. The result of this is pressure spikes within the system as well as mechanical shock to the load. This effect can be really fatal to the system especially in cases where the load is of a large mass. This can result in stress within the whole system eventually leading to premature leakages and failure of the system. Furthermore, these systems are known to have poor repeatability of the stopping position. The actual stopping time is dependent on a number of factors being:

- Scan time of the controller
- Fluid viscosity
- Shifting time of valves
- Valve internal leakage
- Cylinder internal leakage
- Friction in the cylinder and load
- Magnitude of the load mass

To fix the above mentioned issues proportional control is implemented instead of discrete directional valve. Although the use of proportional control introduces a more complex system as well as additional components, it ensures smooth flow throughout

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the system by eliminating abrupt flow surges. Furthermore, when the controller issues a stop command, it is often issued before the desired position is reached so that the valve is not centred immediately but will be controlled gently to bring the actuator smoothly to a stop. This is achieved by regulating directional flow as well as the velocity based on the actuator position input received by the controller. Below is a comparison of the two systems where Figure 2-2 displays the conventional control and Figure 2-3 shows proportional control [22].

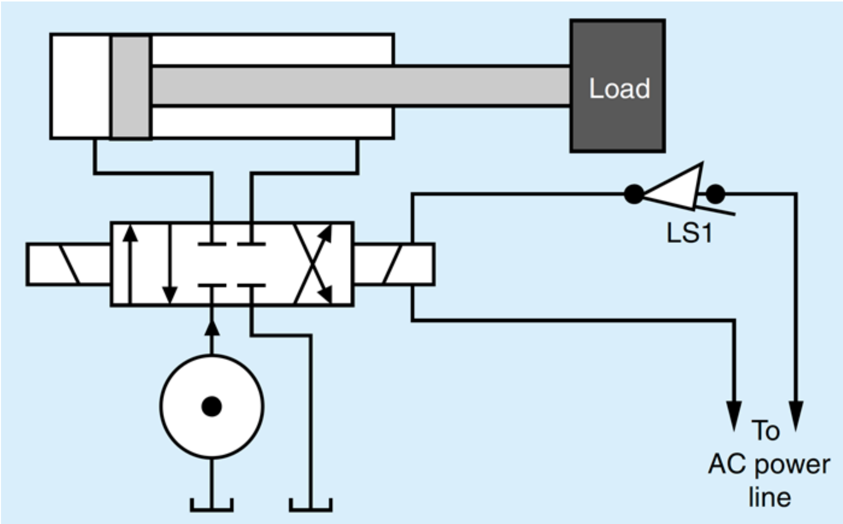

Figure 2-2: Hydraulic system conventional control layout.[23]

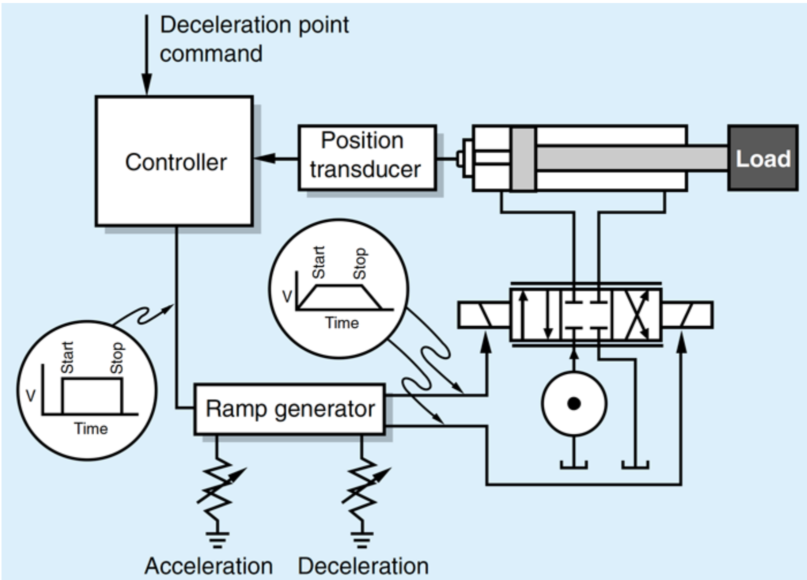

Figure 2-3: Hydraulic system proportional control layout [23]

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A study conducted in [24] estimates the demand for high power robots to be about one trillion dollars by the year 2050 as they will be used for nuclear plant dismantling [24]–[26]. The study discusses the control to estimate the reaction force of master and slave at the end effector of hydraulic servo system using sliding mode control with sliding perturbation observer (SMCSPO). In the research, a two similar robots are designed, where one is a master and the other a slave. The slave can be placed in a remote place where humans cannot acces due to high degree of radiation. The operator moves the master device which in turn controls the slave robot. The operator can feel the reaction force of the slave at the master device as the system uses slide perturbation observer (SPO) to estimate the reaction force without using any sensors. Other studies such as [25], [27]–[30] discuss the non linearity of hydraulic systems. According to the authors precision control of hydraulic manipulators is a challenge due to the system's high nonlinear dynamics. This can be caused by oil leakage, isothermal oil compressibility, cavitation amonst the many causes. As such studies [26], [31], [32] have investigated this non linearity and authors [26], [32] proposed a quasi-linear, state-dependent parameter (SDP) model as a solution. The model is however dependent on joint angles an well as velocity in the case of manipulators and is ideal for capturing essential nonlinear behaviours of the system. This approach however, can only be applied to individual manipulator joints and not a the whole system as it can be comprised of complex mechanical interactions between various hydraulic, electrical and mechanical components.

One of the other methods that has been proposes is by assuming that the system's states are measurable then synthesizing a disturbance observer (DOB) which eliminates the hydraulic as well as the mechacical disturbances affecting the system. The draw back of observers however is that they assume that the measured variable is continuous where in practice that measurements are sampled [33]–[36]. Because of this, microcontrollers become responsible for the sampling and due to the way they operate, the change in the event on the hardware will not be synchronous with the exact moment when the controller looks for the event change. This often results in random variations in the actuator stop position [10].

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To design a perfect motion control servomechanism, the following three things must be catered for:

- Adequate amount of power
- Satisfactory closed-loop bandwidth
- A command motion description

The motion description is how acceleration, velocity, as well as position, are controlled concurrently. This will not be achieved if there isn't sufficient power within the system to manage the load at the required speed as well as meeting the accuracy and stability requirements [37]. Figure 2-4 shows a typical contruction of a hydraulic cylinder.

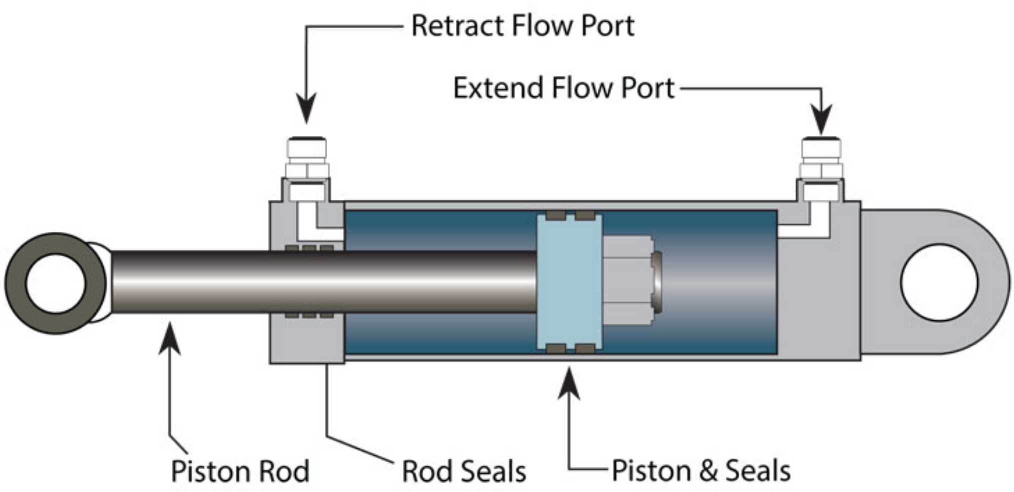

Figure 2-4: Hydraulic cylinder breakdown [23]

When looking at the construction of a double acting hydraulic cylinder, the piston rod is situated on one side of the cylinder and because of this, the retraction stroke speed and extension stroke speed will differ to a great extent for any given constant flowrate. This characteristic makes it difficult to predict the behaviour of the actuator as the retraction speed will always differ from that of the extension [38]. This is demonstrated in Figure 2-5.

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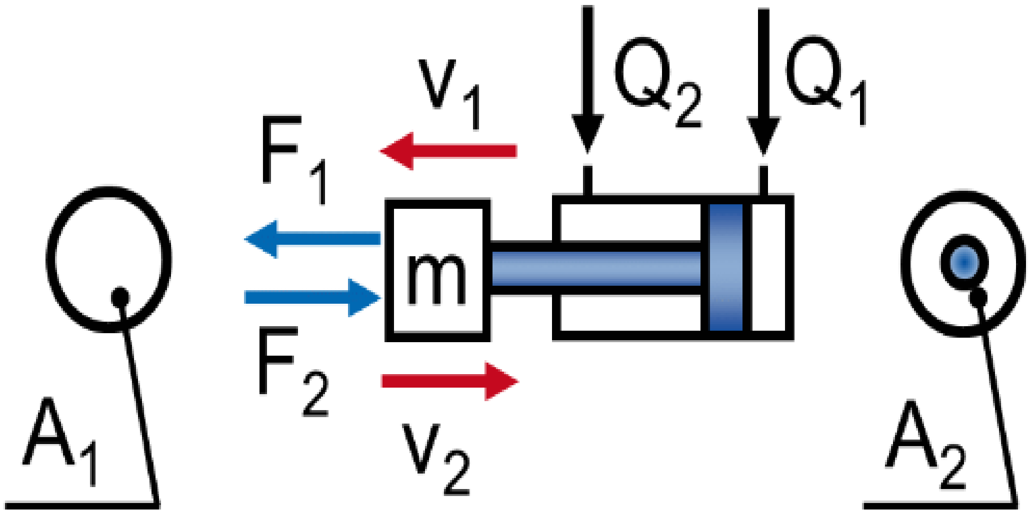


Figure 2-5: Double acting hydraulic actuator [39]

In the figure, A1 = Extension cross-sectional area; A2 = Retraction cross-sectional area; F1 Extension force; F2 = Retraction force; V1 = Extension velocity; V2 = Retraction velocity; Q1 = Retraction flow rate; Q2 = Extension flow rate. To calculate the speed of the cylinder, we will need to know the size of the cylinder itself, being the bore area (A1), stroke length and rod area (A2). To demonstrate, let us assume a cylinder with the following specification :

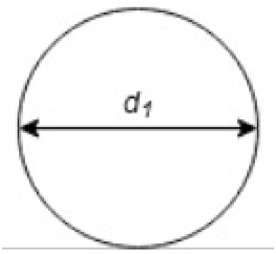
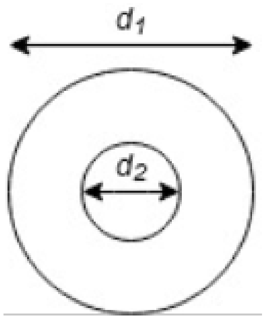
- Bore diameter = 12 mm
- Stroke length = 20 mm
- Rod diameter = 6 mm
- Load = 0 kg
- pump flow rate = 1 L/min

By using the formula below we can calculate the velocity of the actuator.

$$\text{Velocity} = \frac{Flow\ rate}{Area\ on\ one\ side\ of\ the\ piston} \qquad (1\text{-}1)$$

According to the diagrams in Table 2, d could be outer diameter of piston/rod or inner diameter of the cylinder/bore. The subscripts 1 and 2 differentiate the two.

Table 2: Extension and retraction speed of a hydraulic cylinder

Extension	Retraction
	
$= \frac{Flow\ rate}{d1^2 \times 4.71}$	$= \frac{Flow\ rate}{(d1^2 - d2^2)\ 4.71}$
$= \frac{1}{0.12^2 \times 4.71}$	$= \frac{1}{(0.12^2 - 0.06^2)\ 4.71}$
$= 0{,}147\ m/\ s$	$= 0{,}197\ m/s$

As mentioned before, there is a difference in the retraction and extension speed and this is caused by the area of the annulus, the bigger the area, the greater the force, and vice versa.

According to authors in [38] an electro-hydraulically controlled cylinder driven by a servo valve can be modelled using Formula 1-2:

$$y = \frac{\frac{K_q}{A_1}X_v - \frac{K_c\left(\frac{V_e}{(1+4n^2)\beta_e K_C}s+1\right)F_L}{{A_1}^2}}{s\left(\frac{s^2}{{\omega_h}^2}+\frac{2\varepsilon_h}{\omega_h}s+1\right)} \qquad (1-2)$$

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In which :

$y = Displacement\ of\ load$

$X_v = Displacement\ of\ the\ spool$

$K_L = flow\ gain$

$K_c = pressure\ flow\ coefficient$

$\beta_e = effective\ bulk\ modulus$

$F_L = vector\ force\ acting\ on\ the\ control\ volume$

$A_1 = piston\ area$

$V_e = equivalent\ volume$

$\varepsilon_h = coefficient\ of\ damping$

$\omega_h = natural\ frequency$

$n = area\ of\ rod\ end\ and\ piston$

2.2.1.1 Hydraulically actuated robots

Researchers predict that due to technological advances, newer hydraulic components would be smaller yet able to output higher power and have faster responses [12]. Figure 2-6 shows a typical layout of an electro-hydraulic system being either a closed

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or open loop system while Table 3 shows some specifications of previously designed quadruped robots.

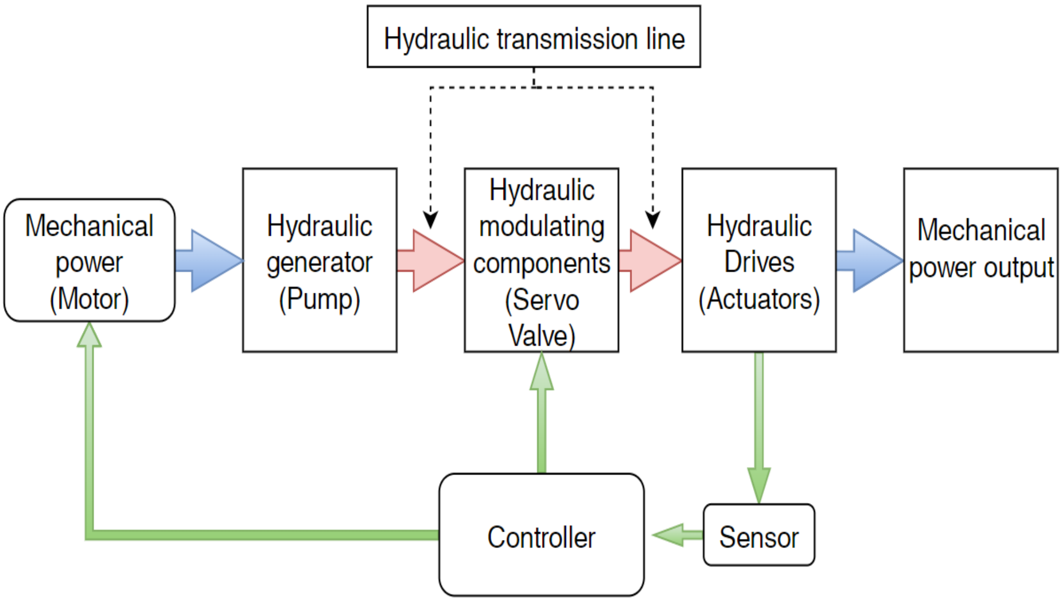

Figure 2-6: Typical layout of an Electro-Hydraulic System

Table 3: Specification of quadruped robots

Robot	Weight (kg)	Payload (kg)	Payload-weight ratio	Actuation
SpotMini	30	14	0.47	Electric
Spot	75	45	0.6	Hydraulic
Scalf-II	130	140	1.08	Hydraulic
Scalf-II	200	200	1.00	Hydraulic

Many research efforts have shown the effectiveness of hydraulic actuation in robots. For example Zhiyong et al presented a Sliding Mode Electro-hydraulic based control method for human walking in patients and therapists. The control was applied to lower limb exoskeletons and the result of the study indicated a better dynamic performance in the controllers [38].

Furthermore, an Electronic and hydraulic Bilateral Control system was designed for a Non-humanoid robot in [40]. The application was based on Robots manipulated by operators and driven by electric actuators and slave robots which work in remote places. Their proposed method resulted in a stable and precise contact motion while conventional methods were oscillatory. Their research was however focused on controlling a secondary hydraulic robot using a primary electrical robot and not necessarily integration of the two systems hydraulic and electric [40].

Humphreys and Bookproposed a study to develop a device that would assist in transferring mobility-limited patients and in particular, patients who are heavier or bariatric[22], [41]. They developed a hydraulically actuated patient transfer assist device with the aim of taking advantage of hydraulic actuators in terms of force over electrical actuators. They further investigated the utilisation of electro-hydraulic power in human power scale and how to overcome control challenges faced with these systems. Their results showed a significant reduction in collision forces and an even greater reduction in cases where the machine was moving fast and had very high momentum. They concluded that their applied techniques made the device more efficient, safer and easier to use [22]. This device was however human operated and does not require high precision when being controlled. Furthermore, the system relied on a typical hydraulic handle for control which meant that it only had a single control input to compensate for.

In another study conducted in by Ko et al, the authors developed an Electro Hydrostatic Actuator driven humanoid to investigate biped locomotion [3]. This is a study that focused on robots that performed tasks in environments with uneven terrain. According to the researchers, servo motors and other types of heavily geared motors are not ideal for such applications as they have limited back drivability [42]. This means that the motor would delay to counter turn if it were moving in a particular direction, developing the EHA system was the ideal solution to solve the problem. The drawback to this approach is that when an EHA system has multiple axes, then each axis needs to have its actuator and each actuator its exclusive pump. This ends up increasing the overall cost of the design as well as the overall weight and size.

Xue et al on the other hand focused on improving the efficiency of hydraulic systems for legged robots using a method called double stage energy supply (DSS) and comparing it to Single Stage Supply (SSS). The two systems differ in the following manner, a DSS uses small hydraulic accumulators with a low-pressure variable pump as well as other high-power sources that are distributed throughout the system. A SSS system on the other hand uses a single hydraulic accumulator to drive the entire system.

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Different tests were done to test the two systems and results revealed that that the efficiency of the system increased significantly when using the DSS method over the SSS, though trim control of the actuators became more difficult [13].

In a paper written by Suzumori and Faudzi, the authors reviewed hydraulic trends in robot applications that focussed on legged robots such as humanoids and other types of robots. The research aimed at investigating new innovations of different hydraulic components such as actuators, pumps and other accessories. The research showed that the use of hydraulic components has decreased due to the mass usage of powerful brushless motors as well as rare earth magnetic motors in the industrial sector since as early as the 1980s. Moreover, the demand for more powerful and lightweight robot development had significantly increased in modern-day robotics as researchers are now starting to look into hydraulic systems in order to take advantage of their high torque to weight ratios [17]. Boston Dynamics has developed some robots that use hydraulics like the BigDog, Wildcat and Ls3 to name a few. These robots have proven to be very successful and have paved the way for more advanced future robots, although they are all four-legged robots and not humanoid. Likewise, hydraulic humanoids have been developed; a few of them include PETMAN developed by Sarcos Inc, Atlas by Boston Dynamics which erected from the mechanical advances of PETMAN and Hydra Developed by the University of Tokyo in collaboration with the New energy and industrial technology development organisation (NEDO) [12]. These humanoid robots are programmed to be autonomous and manoeuvre themselves around an environment through the use of sensors and cameras. This means that the robots do not need any human interaction and can-do tasks independent of any human input thus emphasising the scarcity of collaboration between human beings and robots.

2.2.1.2 Exoskeleton robots

Exoskeleton robots are developed for various uses. Their uses can range from muscle strengthening to rehabilitation training. These types of robots can be seen as one of the basic types of collaborative robots. Furthermore, they are designed using various methods from passive to active type. Passive type exoskeletons use no power but rather mechanical systems such as levers to assist the user in lifting heavy objects. On the other hand, the active type relies on a power source in assisting the user. Active type

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exoskeletons may be broken down further into muscle-assisted exoskeletons and muscle-strengthening exoskeletons [19], [43], [44]. The muscle-assisted is normally used for rehabilitation training for paralysed patients as well as elderly people to provide additional muscular strength. Muscle-strengthening types assist the user by multiplying their strength to allow them to carry heavy loads as well as allowing them to perform tasks that they would normally not be able to.

In traditional hydraulic systems, the hydraulic pump needs to keep operating, regardless of whether the hydraulic actuators are active or inactive. This results in continuous energy consumption, thus lowering the energy efficiency of the overall system. Lee et al (2019) worked on the development of an electro-hydraulic actuator system for an exoskeleton robot to address the limitations of unidirectional pumps in these types of robots. In their design, the EHA was designed with both hydraulic and electric advantages. The system itself consists of a bidirectional hydraulic pump, electric motor, the hydraulic cylinder as well as hydraulic valves. To minimise the design, the valves were made from a single manifold, thus simplifying the design. Furthermore, a piston pump was designed by analysing the gait cycle in consideration of the flow rate and pulsation rate within the system. The design of the system is non-linear therefore a sliding mode control (SMC) was used and compared with a proportional integral derivative (PID) controller [19]. In this system, when the actuator is not moving, the motor is not driven and the direction of the actuator is changed by changing the control of the motor. This helps reduce the overall internal leaks that may occur. This however comes at a cost. By using this approach, the actuator direction cannot be reversed as quickly as it would be when using valves, as the motor would first have come to a complete stop and then change direction and this could end up resulting in high current spikes. According to the research, electrical motors are currently not able to be used as muscle-strengthening exoskeletons as their power output is very little.

Since then the use of hydraulics has been on the rise. Many advancements have been made in hydraulic technology that has made hydraulics the go-to option when it comes to joint actuation. Sakurai and Faudzi discussed the use of a load sensing hydraulic system and found it as one of the most effective systems of energy saving in hydraulic systems [45] while Zhang et al proposed a method of optimising and improving the

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stability of Electro-hydraulic robots by analysing the driving system of these robots [46]. In the latter, the proposed system was able to satisfy the use of multiple actuators at the same time without interference while having load sensitive function in pressure, being energy efficient and having the ability to respond quickly.

The migration into hydraulics will however require amongst many things, the development of new components that do not exist yet, such as new cylinders, drive systems and other different components that are used specifically for robotic systems. Such works have been observed in many hydraulic robot designs such as BigDog, Hy-Mo, IHEA, ISAv4, and ISAv4 to name a few. The study in [47] discuss a novel, highly-integrated Hydraulic Servo actuator with an additive manufactured titanium body. The two versions of the actuator are discussed below, these are Integrated Servo Actuator (ISA) developed by Moog in collaboration with the Italian Institute of Technology (IIT). The first version of the actuator was designed to fit into the HyQ quadruped robot. It weighs 0.92 kg and has a maximum force of 4 kN, while the second version was for the HyQ2Max, which weighs 1.15 kg and can produce a maximum force of 6.2 kN. Its body is made of titanium alloy through the use of additive manufacturing (AM). These smart actuators incorporate a lot of components all built-in, which are a hydraulic cylinder, servo valve, sensors such as pressure sensor, position sensor, temperature sensor as well as all the electronics needed, communication module and overload protection. Figure 2-7 and Figure 2-8 shows the design of the cylinders discussed above [48]. Altare and Vacca discuss a design solution of efficient and compact electro-hydraulic actuators [49]. The actuator as shown in Figure 2-7 has an overall size of 300 mm x 90 mm x 70 mm with a maximum force of 2000 N, and a maximum travel speed of up to 20 mm/s.

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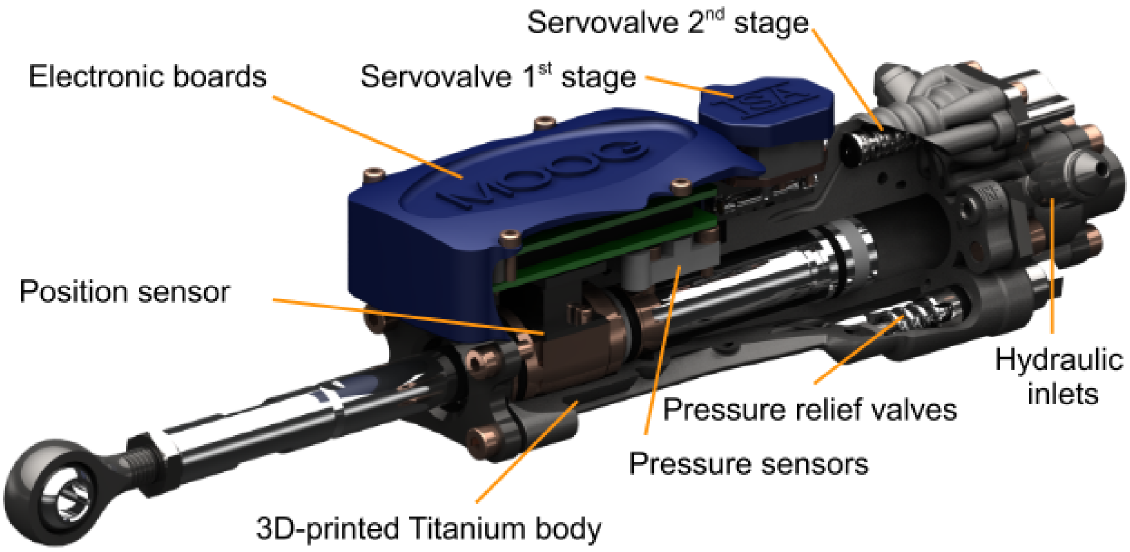

Figure 2-7:CAD rendering of the ISA v2 with a cut-out section to illustrate the main features of the actuator and integrated components [29]

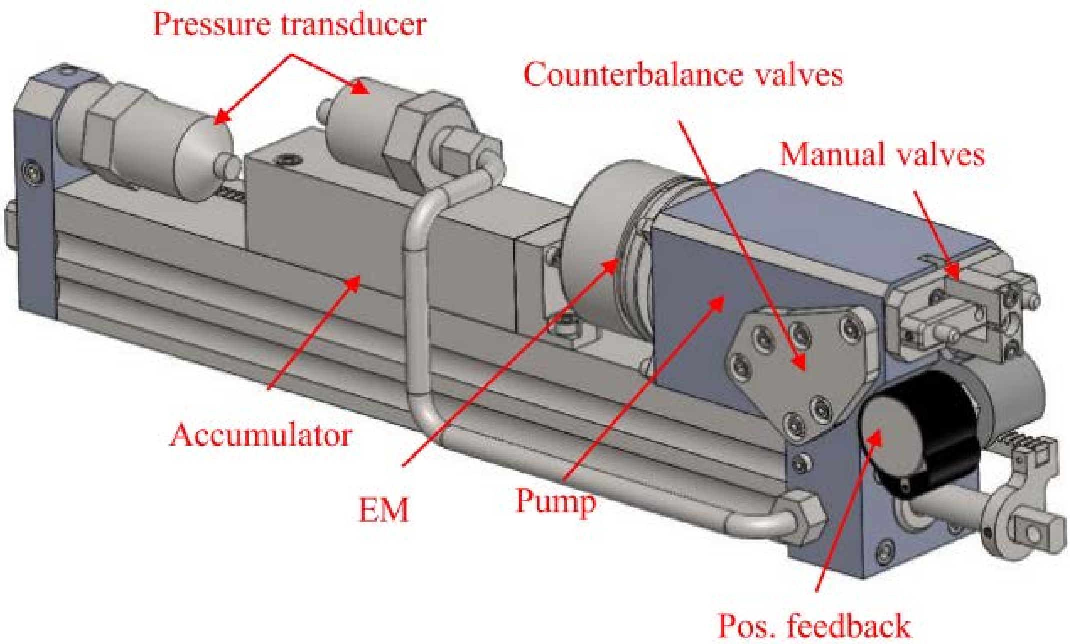

Figure 2-8: Design of a compact EHA system proposed in [18]

Some researchers are now trying to replace traditional hydraulic actuation Systems with Electro-mechanical Actuation Systems (EMAS) due to the ease of use of such systems. An EMAS system uses a gearbox to lower the actuation torque so as to allow the use of small electric motors. Altare and Vacca discuss the efficiency as well as the limitations of EMAS. One of the downsides of using this system is that the gearbox increases the overall weight and size of the system as well as having some disadvantageous effects on the overall performance of the system since the inertia would be recognised from the motor [49].

The performance of a hydraulic system is influenced by controlling the servo valve in the system. Due to this, it is important that the servo valve is of high quality and has accurate control with precision feedback. Moreover, the control system needs to be properly designed to ensure that the maximum overshoot of the system is less than 5%. The authors in [50] used a nozzle flapper type 2 stage valve with a spring mechanism for spool feedback. The valve has a flow rate of 63L/m @ 210 bar and has a current consumption of 40 mA @ 10 VDC. Position sensor has a maximum travel of 1 mm with a resolution of 1 µm. A setup of two different hydraulic systems can be seen in Figure 2-9 and Figure 2-10. The experimental results showed that a PID control system could drastically improve the control performance, as well as the frequency response of the hydraulic system. In addition to this, oscillations within the system could be solved by including a low pass filter.

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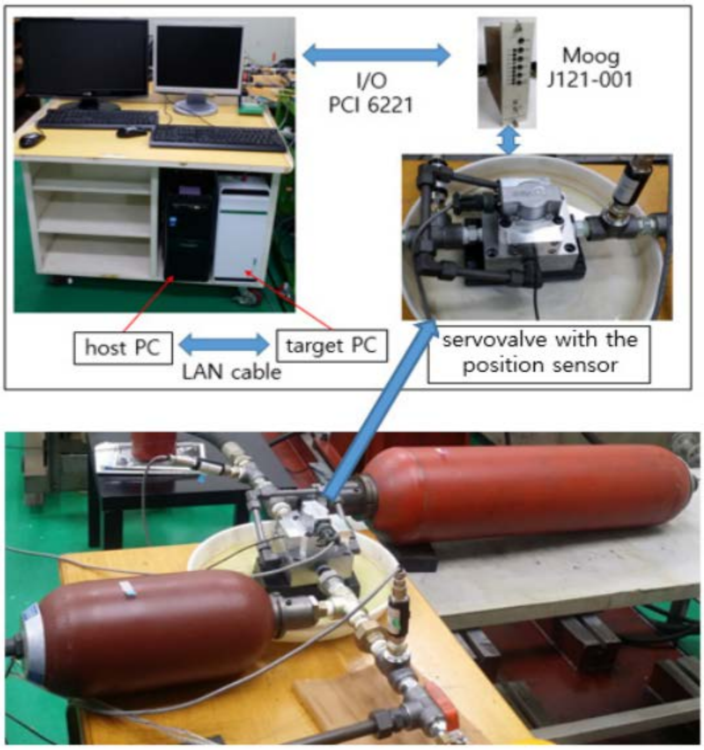

Figure 2-9: Nozzle flapper type servo valve with electric position sensor [50]

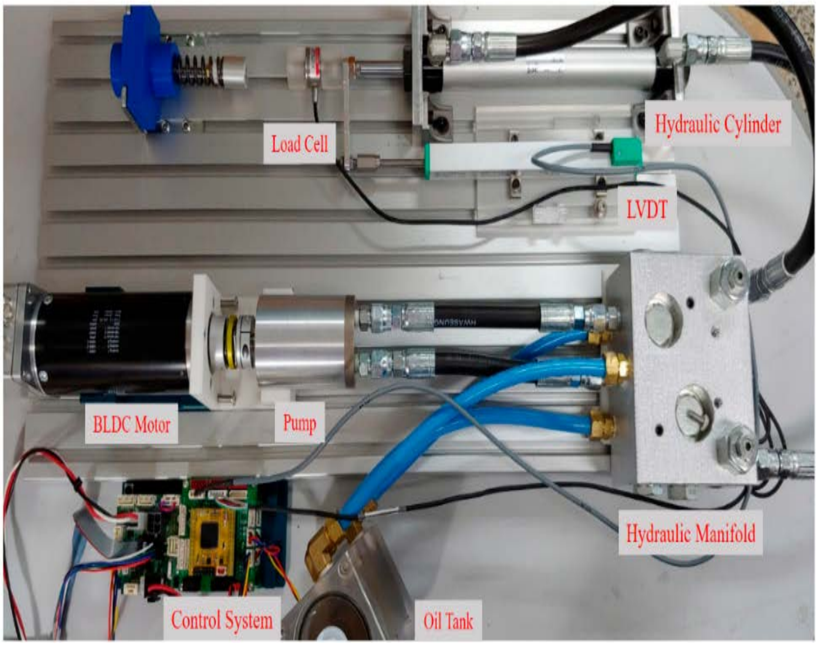

Figure 2-10: Control of an Electro-Hydraulic Actuator System for an Exoskeleton Robot [19]

2.2.2 Electrical / Servo actuation

Standard humanoid robots are built using servo motors mounted in a human-like structure to achieve their movements. This approach is ideal when building small scale humanoid robots as the motors are relatively light and have enough torque and adequate speed for their size [51].

Of all the mentioned disadvantages for these types of motors, stall current is usually overlooked although it plays a crucial role in the overall operation of a motor. Stall current is when a motor is applying torque, either because it is being prevented from moving entirely or because it can no longer accelerate due to the load it is under. The motor then draws more power from the supply source as it tries to overcome the load. This often ends up in the motor dying due to overheating, damage to the gear train, or just draining the battery, while no work is being done. In more advanced motors such as the Robotis Dynamixel actuators, additional circuitry is added to detect this and shut down the motor when too much torque is applied. This method however only protects the motor but does not stop it from consuming power unnecessarily.

When building larger humanoid robots, servo motors could be a problem as bigger servo motors are required, thus introducing the same problems on an even larger scale. When designing an electrically actuated robot, a motor is connected to a reducer to increase the output power, a larger reducer is therefore installed to increase the power on each joint and this results in a more complicated and heavy structure as well as increasing its volume, noise, weight and development cost. As mentioned before, humanoid robots consist of multiple motors that are attached in such a way that some servo motors need to carry the load of other motors and most of these motors consume power when idle. Typically, in an example where a humanoid robot is utilising only the upper body to achieve a task, the use of servo motors would tend to consume more power as the servos on the lower part of the body would still be consuming power to try and keep them in their desired position. Again when looking at the design of a servo motor, they are comprised of a single dc motor connected to several gears of specific gear ratios to achieve very high torque. Designing a servo motor that would be able to have even higher torque ratios would mean that the servo motor would have to be designed using a bigger motor with even bigger gears. This introduces more weight as

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well as larger volume to the entire design, not forgetting production costs as well as the increased total weight of the robot itself. This means a different approach is needed in the design.

2.2.2.1 Electric systems in robots

Electrical motors serve as the main drive system of most robots that exist today. Several techniques are used as actuation when using electric motors and they can be achieved through the use of Servo motors, stepper motors, Brushless DC (BLDC) motor, EMAS [52]. Different manufacturers use one of the above or a combination of them to achieve actuation in their robots. KUKA has nearly 40 years of designing and manufacturing industrial robot arms. The first robot arm to use the 6 axes was the FAMULUS robot which is now set as their standard. The six axes of the robot are as electric motor driven even up to date with their latest robot designs [53]. Since the development of their first robot, industrial robots have been dominant in large industries and have further become much faster, more efficient, more accurate and most important of all, more accessible and affordable. The main focus of these robots is more accuracy and repeatability for manufacturing.

In 1996, Honda announced the development of its first-ever humanoid robot with two arms and 2 legs and the robot named P2 [11]. Its research had begun 10 years prior and the desired goal was to develop a robot that can coexist and collaborate with humans and do tasks that humans cannot do. P1 has 30 degrees of freedom and each joint is controlled with a servo motor. The latest design from Honda is ASIMO. After the development of the P1 robot, Honda developed several other robots P2, P3 before releasing its latest, ASIMO. The actuation systems that these robots use have been investigated and results have shown that they have a very low power density which more than often results in poor load capacity, low speed and limited strength. Due to these factors, developing practical legged robots is still an issue. Moreover, these factors play a huge role in the overall performance of any type of robot and thus need to be resolved if a perfect robot is to be built [17]. Another major key in developing a good humanoid robot is to develop a system that can drive the robot with a minimum cost of transport (COT) as possible. COT may be defined as the power consumption divided by the weight, multiplied by velocity [13]. The main advantage of using electric motors

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over any other system is the ease of use, as the wiring can be simplified a lot depending on what motor is used, moreover, higher accuracies and precision may be achieved.

2.2.2.2 Pneumatics

Pneumatics are normally used for lightweight devices and often travel between two positions, fully extended and fully retracted. These systems are very inaccurate as they work using air. Air is compressible and thus it is difficult to predict its resultant movement in an enclosed chamber. For this reason, pneumatic cylinders normally require mechanical limits or hard stops at the end of their travel. This makes them ideal for high speed travel and control. Pneumatics may achieve higher accuracy through adding regulators and valves, but this comes at the cost of giving up their high speed.

2.2.2.3 Soft robotics

Soft robotics are still in their infancy. These types of actuators are composed of soft materials such as rubber, plastics and other polymers. These actuators are often thermally responsive polymers fluidic actuators both pneumatic and hydraulic and lastly, dielectric elastomer actuators (DEA). Pneumatically actuated are the most common of all the above mentioned as they are versatile and can achieve higher actuation forces and longer stroke much like actual muscles [18]. However, these systems have been tested and results show them to have low efficiencies during operation and often require bulky reservoirs and air compressors for high power operations. Alternatively, electrically powered DEA systems offer advantages such as high operating speeds, high strain, silent operation as well as self-sensing. DEAs can be rather sensitive as they are driven by high electric fields which often leads to damage to the dielectric resulting in an irreversible breakdown of the actuator.

2.3 Human-robot collaboration (HRC)

This part of the research focuses on the need for human-robot collaboration and why it is necessary to have robots that can work alongside humans.

As the need for human assisting devices increases several studies have been conducted to determine suitable interaction strategies to assist humans. These studies showed that the one thing that needs to be determined to building a meaningful robot that can assist humans, is to find out how people perform under load while being assisted or working in collaboration with a robot. This part of the study focuses on a design system for a collaborative humanoid robot that can work remotely from the human by mimicking all the human motions.

Collaborative robots are classes of robots that work together with a human in achieving a certain objective [54], [55]. As mentioned earlier, robots are known to be good at repetitive and heavy-duty tasks although when it comes to cognitive tasks, decision making, problem solving, attention and judgement, humans are still best suited for such tasks. There are several types of these robots though their function stays the same, to reduce work done by a human. Some of these robots achieve this through physical interaction while others are service robots and others are socially assistive, meaning they can assist through their presence and social interaction.

2.3.1 Humanoid type

A study conducted by [56] discusses the development of ARMAR-6 shown in Figure 2-11 which is a collaborative humanoid robot for the industrial environment. The main purpose of the robot is to perform maintenance tasks in warehouse environments. The robot works by providing assistance and support to technicians that perform maintenance tasks. Once the robot recognises that the human worker needs help it then provide the appropriate assistance. ARMAR-6 is mainly constructed using electric motors of different sizes to achieve 27 degrees of freedom. The robot stands 192 cm high and has a width of 310 cm. It can stretch 40 cm more in height using its prismatic joint actuator situated in its torso. It has 3 different actuators that are custom designed and contain a brushless dc motor each. The motors can only achieve a payload capacity of 10 kg per arm with torque capacities of 176 Nm, 123 Nm and 63 Nm, respectively. The actuators are then powered by a 48 V power unit. The overall weight of the robot is 162 kg without a battery pack with a nominal power consumption of 460 W and 1050 W peak.

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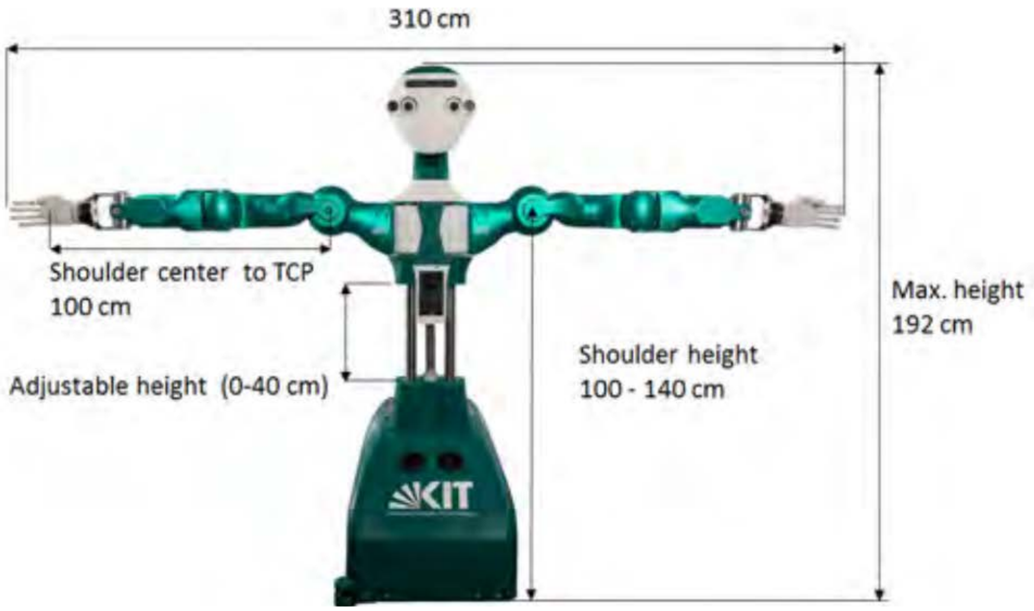

Figure 2-11: Overall dimensions of ARMAR-6 [54]

The robot is artificially intelligent and does not require any human input for control. Robots such as this one need to comply with Asimov's three laws of robotics which state that [1]:

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given to it by human beings except where such orders would conflict with the first law.
3. A robot must protect its own existence as long as such protection does not conflict with the first or second law.

2.3.2 Robotic arms

As the robotic industry is growing more rapidly than ever, more research is being done to find better and more effective ways in which humans can, not only work alongside robots, but can quickly and easily program industrial robots. Research has shown that the programming phase of robots may be long and time consuming especially in industries that need to constantly change their manufacturing environment. Feragguti et al discuss a software control architecture to obtain human-robot cooperation during the programming phase of a robotic task [57]. The method discussed is a walk-through programming which is a method that enables humans and robots to coexist in the same workspace and cooperate to achieve a common task. This programming technique can easily be achieved and is done by manually guiding a robot to teach it a specific task [57]. As mentioned previously, the approach taken in this research focusses mainly on creating a software platform that can be used on existing industrial robots to convert them to collaborative ones. Newer robots however are built with this in mind and thus require no additional software.

There are still a few factors that need to be taken into consideration for effective human-robot collaboration. Safety is a significant factor. In addition to this, a properly designed intuitive user interface that takes full advantage of both robot and human abilities being high levels of accuracy, speed, reliability from robots together with flexibility as well as cognitive skills of humans. In [58], three different types of human-robot interactions are discussed and can be seen in Figure 2-12.

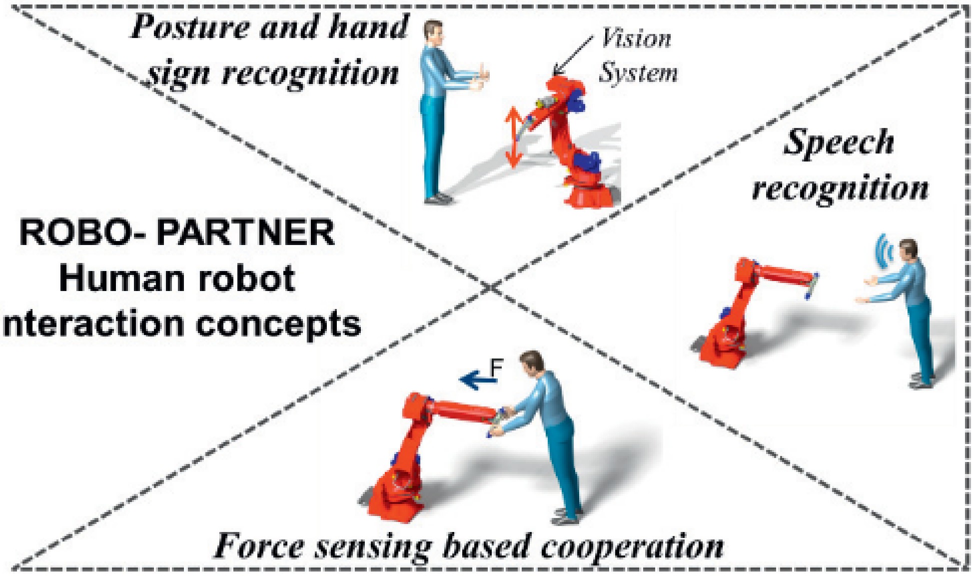

Figure 2-12: human-robot interaction concepts [58]

A 2016 paper by the International Federation of robotics (IFR) studied the trend of industrial robots for 4 years and found that industrial robots increased annually by an average of 13% with a final estimate of 2.6 million industrial robots at the end of 2019. Furthermore, other researches showed that the automotive industry presented the highest demand for industrial robots with the electronic industry posing the second

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highest demand. This is because of the affordability and ease of use of collaborative robots [55].

Statistics of the Occupational Health and Safety published by the department of health in the US Department of Labour indicate that more than 30% of European manufacturing workers are affected by lower back pain, and this results in enormous social and economic costs. It is for this reason that some researchers have embarked on a quest to designing assembly line robots for workers that would reduce ergonomic concerns that arise due to on-the-job physical and cognitive loading, while at the same time improving safety, quality and productivity [58]. Cherubini et al conducted a study on a Peugeot Citroën assembly line, where Rzeppa homo-kinetic joints are manufactured and the process still utilises manual labour. In the study, they found that the workers were experiencing muscular pains, and further showed that this part of the assembly generated more Musculoskeletal Disorder (MSDs) than any other part of the assembly. Furthermore, due to the complexity of the manufacturing process, a human worker could not be replaced and thus the researchers found this would be the ideal scenario for collaborative humanoid research and so they proposed a novel, collaborative human-robot design shown in Figure 2-13 that would outline the following:

- A framework that would successfully manage direct physical contact between robot and human as well as between robot and environment.
- A robot that alternates between passive and active behaviours during assembly to lighten the burden on the operator when in passive mode and to comply with the operator when in active mode.

The approach taken should apply to standard robots, as well as non-torque controlled robots. The results of this research indicate that the proposed system reduced the operator load by about 60%. However, the system's cycle time was much slower than that of manual assembly and the solution to this problem would be to increase the number of robots a single operator interacts with. This would result in

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high installation costs but would reduce MSDs injuries and associated costs [59].

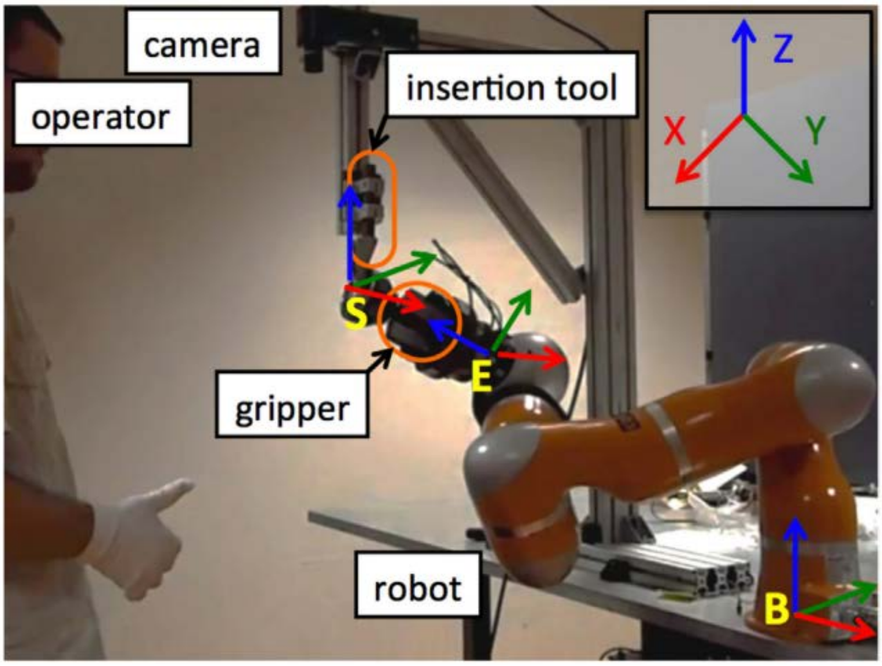

Figure 2-13: Top: experimental setup for collaborative Rzeppa joint assembly with: insertion tool support (S), end effector (E), and robot base (B) reference frames[59].

This study focuses on a design system for a collaborative humanoid robot that can work remotely from the human by mimicking all the human motions while the method of actuation is the SSS system for controlling the actuators. The design is comprised of a master and a slave device.

Traditionally robots were isolated to safeguard human operators from hazardous interactions. This is normally achieved by placing demarcations such as bearer lines or even caging the robots in such a way that humans cannot physically be in the same working area as the robot. However, this approach comes as a problem as the isolation of robots works best for manufacturing tasks that often have repetitive tasks only. For cognition tasks and dexterous tasks, this approach is rather challenging as it does not allow the human operator to interact with the robot cooperatively or collaboratively [7].

A thorough understanding of the existence of hazards is critical to reap the perceived benefits of Collaborative Operation. Furthermore, it is worth noting that designers do not have a record of known hazards during the innovation and design stage. Although robot safety standards such as (ISO 10218-1/2) contain a list of hazards that are common

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in robotic systems, there is still a huge lack of knowledge of the nature of hazards. The ISO 15066 standard shows different guidelines that designers and robot users need to consider when embedding passive and active guards in collaborative robotic workspaces as well as when dealing with robot systems.

Several studies have been conducted and research published that discusses collaborative workspaces as well as collaborative robot operations. Researchers in [60] discussed safety in human robot interaction as well a breakdown of some literature studies from eleven different institutions contributing nine research papers. The research is broken down into different categories; the first being the analysis and design of safety aspects needed for direct human-robot interactions. The second part of the research discusses the design of robots to ensure safety through the use of correct mechanical or actuator systems. The third part talks about the design of low and medium level controllers that can achieve safe compliance via direct force compliance. Last in the discussion is a high level recognition, control and decision making algorithms for human-robot interactions (HRI). These studies discuss guidelines and decisions as well as control that needs to be done to avoid HRI relate accidents. This could not have been achieved without the Finnish databases which contain twenty five severe accidents that have occurred during HRI.

Another research discussed the design principles for safety in HRI. In the research, hardware and software requirements of HRI systems are investigated. The robots used in the research track the human's position using special sensors and also use human's verbal and non-verbal utterances. Moreover, the software focuses on ensuring the robot's safety during an interaction. [61]. In [62], the authors show how to increase the safety of interactive robots using Proxy-Based Sliding Mode Control (PSMC) while using Pneumatic muscles that are lightweight HRI system. The researchers found that the low weight of the system allowed for excellent hardware safety characteristics.

The design of a manipulator that is intrinsically mechanically safe was proposed by authors [21]. The robot used sensors to limit the actuator torque when the human skin pressure pain threshold was exceeded. The design introduced a spring balancing system that could counteract gravity in all configurations and in turn, allowing for smaller DC motors to be used in the system resulting in lower power consumption. "Safe Adaptive

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Compliance Control of a Humanoid Robotic Arm with Anti-Windup Compensation and Posture Control", was written by authors in Safe Adaptive Compliance Control. The study used a 4 degree of freedom (DOF) humanoid robotic arm to implement an adaptive compliance model reference controller that uses a reference mass-spring-damper system model through an external sensed force. The main problem that was encountered in the study was actuator saturation and was addressed by incorporating a novel anti-windup (AW) compensator. The authors of [63] on the other hand, realised the Empirical Copula technique and is proved to outperform other techniques in terms of recognition rate when using hand gestures as a way to deliver messages such as the content of human safety for the avoidance of potential safety hazards. In [64], a mobile manipulator robot that is designed to interact with humans proposed. The robot platform used Perspective Placement, Soft motion trajectory planner as well as Manipulation planner to generate natural robot motions while keeping human safety as a priority.

2.4 Mobile robotics

Mobile robots are robots that work autonomously or remotely from humans [65]. They can range from humanoid robots to unmanned rovers and drones. Remotely operated robots, also known as teleoperated robots rely on an operator controlling it from an off-site location [66]. Different methods are often used for teleoperation and they often depend on the application of the robot. In a typical system a joystick controller is used to manipulate the robot. While this method works well, in controlling any robot, the biggest challenge in this form of control is that it requires a skilled operator or extensive training for the operator. For this reason authors in [67] and [68] have developed a system that uses a Kinect sensor to recognise human gestures to manipulate a robot. The main advantages if this method are that it frees the operator off any controllers while ensuring that the system requires little to no training. The system is vision based and uses a camera to get human gestures, for this reason data intensive computing is often required and even with this, the system is often too slow to respond in realtime. Furthermore, the system is never accurate as it relies on estimates rather than actual positioning [54], [67]–[70]. Honda developed the THR-3 robot shown in Figure 2-14 as a real-time human mimicking robot, which has a human sized controller dedicated for a human operator. This gives the robot the ability to mimic human motion in realtime [71]. This research uses a similar approach by designing a body attachment

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to control a remote robot in order to increase accuracy and improve response time of the robot.

Figure 2-2: Honda THR-3 teleoperated mimicking humanoid robot [71]

2.5 Summary

Human-robot collaboration have proven to be very beneficial in the robotics industry. It has been shown that these classes of robots reduce the payload on humans by up to 60% while in some studies it has assisted humans in various technical tasks. There is still a lot of work that needs to be done in order for collaboration between the two entities to be effective. More so, a lot more is required for both humans and robots to co-exist in the same environment while ensuring safety for human workers. Humans need robots to achieve most tasks and vice-versa. All that is needed is finding the right balance of interaction between the two.

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Chapter 3

Methodology

3.1 Introduction

This chapter describes the research design of an energy efficient system for the collaborative robot. The aim of this chapter is to present the practical design as well as programming of the robotic arm using the knowledge obtained from literature. In order to demonstrate the energy efficiency of the proposed system, a master and slave humanoid robotic device was built. A step by step approach on how this was done is explained in this chapter.

3.2 System overview

The master device is mounted on the human user, while the slave works remotely from the user as shown in Figure 3-1. The Figure shows how the different components interact and a simplified setup of the robot arm. The full system is broken down further later in the chapter. Device A is the master device and is responsible for reading the human pose of a specific joint in this case the right elbow. Device B is the robot arm and its motion are controlled by Device A. The two communicate wirelessly via Bluetooth where Device A transmits its data to Device B.

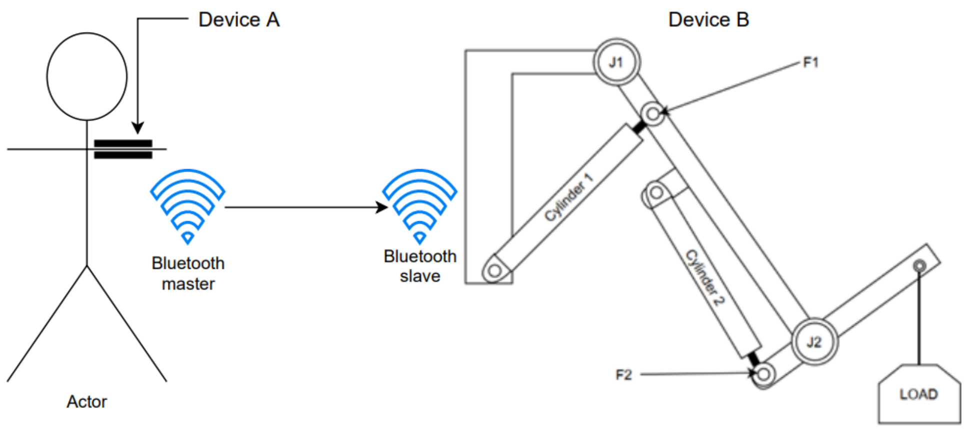

Figure 3-1: System overview

As shown in Figure 3-1 a two linkage arm is designed and controlled with two hydraulic actuators. As this is an open-chain robot, the joint velocity, as well as torque may be calculated using Euler-Lagrange equations where the forward dynamics are used for simulating the robot and the inverse dynamics Formula (3-1) and (3-2) are used in controlling the motion of the arm.

$$J_1 = (h_1 + 2h_3 \cos\theta_2)\ddot{\theta}_1 + (h_2 + h_3 \cos\theta_2)\ddot{\theta}_2 - h_3\left(2\ddot{\theta}_1 + \dot{\theta}_2\right)\dot{\theta}_2 \sin\theta_2 + h_4 \cos(\theta_1 + h_\tau) + h_s \cos\theta_1 \tag{3-1}$$

$$J_2 = (h_2 + h_3 \cos\theta_2)\ddot{\theta}_1 + h_2\ddot{\theta}_1 + h_3\dot{\theta}_1^{\,2} \sin\theta_2 + h_\sigma \cos(\theta_1 + \theta_2) \tag{3-2}$$

In which the coefficients h_i where $(i = 1, 2, \ldots\ldots, 7)$ are functions of the arm and the link mechanism and θ is the angle of each joint .From observing the formulas it can be noted that the system joints are nonlinear.

The motion of the control system is shown in Figure 3-2. Cylinder 1 drives J1, which is the shoulder joint, and cylinder 2 drives the J2 which is the elbow joint. The motion of the system should match human movements of two joints in only the sagittal plane. Since the retraction force is much smaller than that of the extension, cylinder 1 is designed to act as a class 3 lever while cylinder 2 acts as a class 1 lever. This is to ensure they always deliver the maximum force possible as this is the point where they mostly work against gravity since the robot is in its upright position during most operations.

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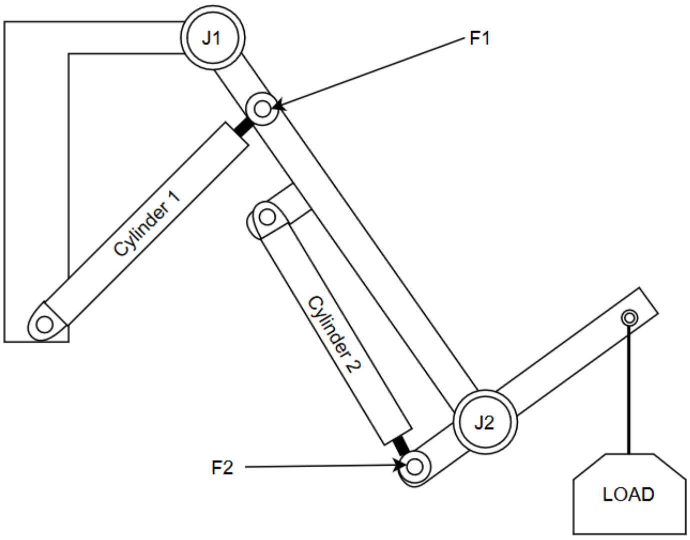

Figure 3-2: Schematic of the position control system for shoulder and elbow joints.

The resultant forces acting on F1 and F2 are not constant and differ based on the angle of inclination. These forces can be calculated using the formula:

$$F_r = F_n \cos \emptyset \tag{3-3}$$

Where F_r is the resultant force, F_n is the output force of the cylinder and $\emptyset$ is the angle of inclination of the cylinder. The resultant forces of cylinder 2 can be seen in the Figure 3-3.

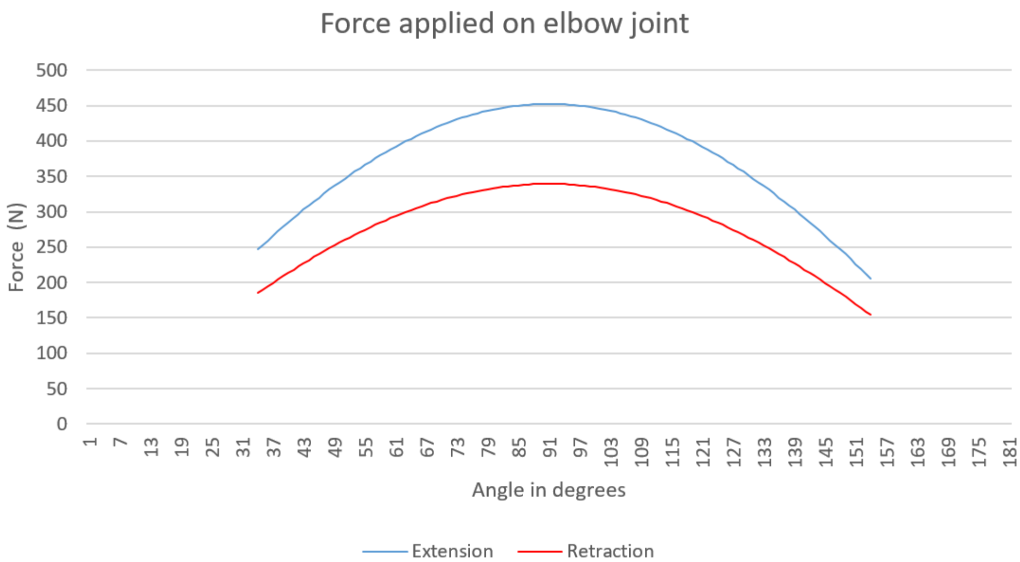

Figure 3-3: Elbow force output

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As seen in the graph of Figure 3-3, the cylinder delivers the highest force at 90^0 and decreases with angles above and below. The joints have a travel less than 120^0 and are restricted and most of the human joints would not exceed 120^0 of travel [72].

3.3 Control system

To increase the scan time of the system, each cylinder has its control system which uses an Arduino Uno with a PID algorithm to drive the cylinder shown in Figure 3-4.

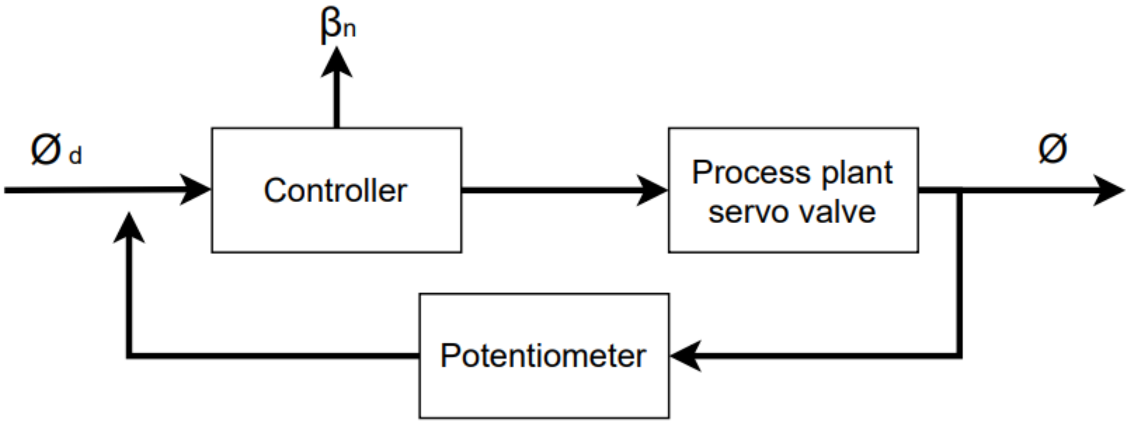

Figure 3-4: Process control schematic of a hydraulic servo valve

In the Figure 3-4, $\emptyset_d$ is the desired trajectory of the joint and $\emptyset$ is the actual trajectory of the joint. β_n is the output to the hydraulic pump control system which is shown in Figure 3-5.

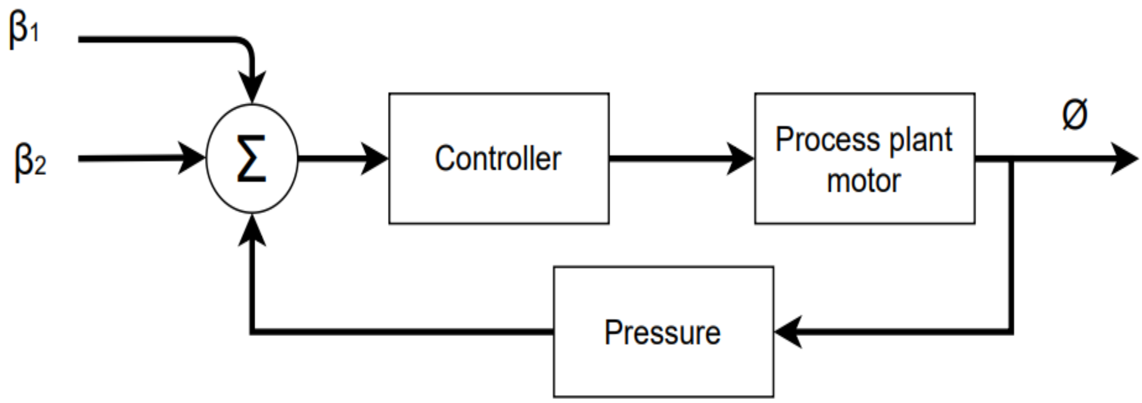

Figure 3-5: Process control schematic of hydraulic pump

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As shown in Figure 3-4 and Figure 3-5, the PID controller used for this system is a closed-loop control system, and the transfer function is shown in Equation 3-3.

$$T(s) = \frac{X(s)}{R(s)} = \frac{K_d s^2 + K_p s + K_i}{s^3 + (10 + K_d)s^2 + (20 + K_p)s + K_i} \qquad (3-3)$$

Where, X(s) is our output, R(s) is the input and K_p, K_i and K_d are the Proprotional, Intergral and Derivative gains, respectively. The PID controller was designed using the following guidelines:

1) Obtaining the open-loop response of the system in order to determine what need to be improved.
2) Adding the proportional control to increase the rise time
3) Adding the derivative control in order to improve the overshoot
4) Adding the intergral control in order to eliminate the steady-state error
5) And finally adjusting the the three gains to obtain the desired overall response.

The gains of the system can be adjusted using table 4

Table 4: Characteristics of P, I and D controller on a system

CL Response	Rise Time	Overshoot	Settling Time	S-S Error
K_p	Decrease	Increase	Small change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small change	Decrease	Decrease	Small change

The motor controller receives a request from the servo valve controllers and then adjusts its speed accordingly and increase the pressure to the desired pressure within the system. To decode human joint position a 3D printed mount that houses a 5 kΩ potentiometer was designed, this is discussed later in the chapter. The mount is attached to the arm using elastic fabric straps for it to work for any user. The joint motion is read through the potentiometer then transmitted through Bluetooth to the desired joint. Each joint has its Bluetooth transceiver to ensure that there is no delay in data transfer between

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the controllers. Furthermore, the transmission of data only happens when there is actual movement in the arm or shoulder to ensure that only relevant data is sent.

3.4 Hydraulic system configuration

The hydraulic system design and components is discussed in the next session. Figure 3-6 shows all the components in the system as well as how they interact with each other. The full system is described in detail below.

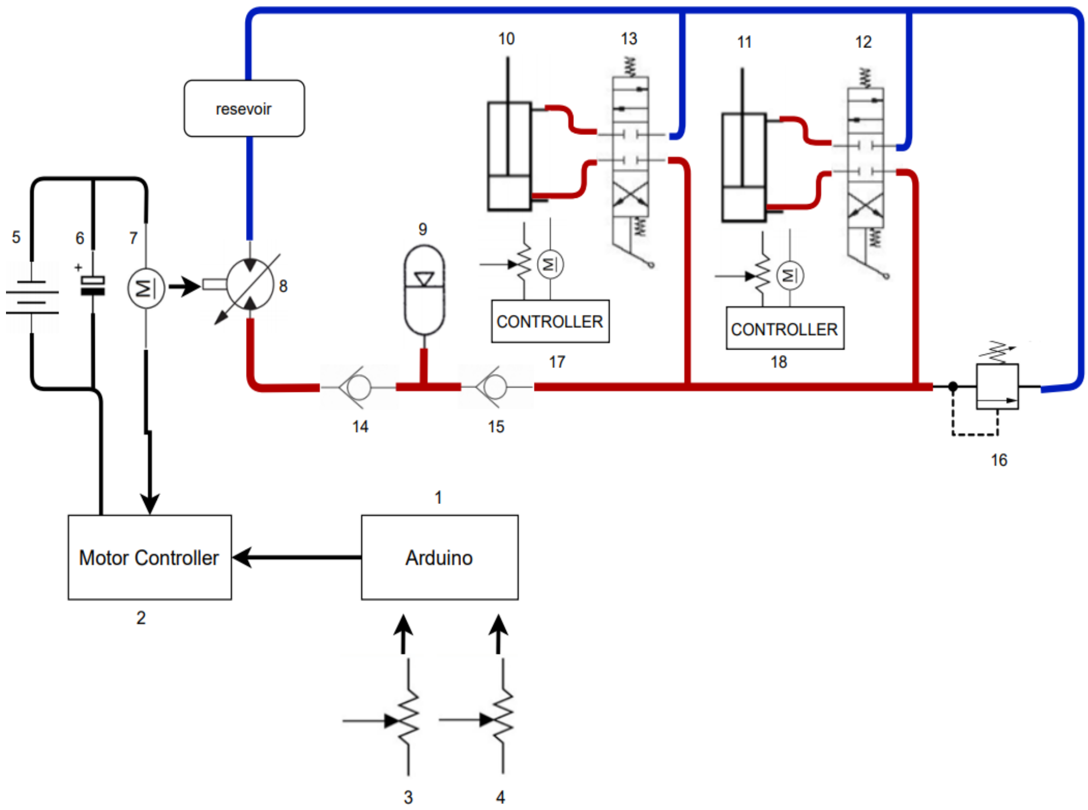

Figure 3-6: Proposed hydraulic system configuration

The red line represents a high pressure line while the blue line represents a low pressure line.

A component list of the items used in the design of the electro-hydraulic system is shown below:

1. Arduino UNO
2. Motor controller
3. Shoulder Potentiometer

4. Elbow Potentiometer
5. Battery
6. Super capacitor
7. Motor
8. Oil pump
9. Hydraulic pressure resevoir
10. Shoulder Hydraulic actuator
11. Elbow Hyraulic actuator
12. Elbow valve controller
13. Shoulder valve controller
14. Motor check valve
15. Pressure reservoir checkvalve
16. Hydraulic pressure relief valve
17. Shoulder controller
18. Elbow controller

A graphical diagram of the electro-hydraulic system used in this research is shown in Figure 3-7.

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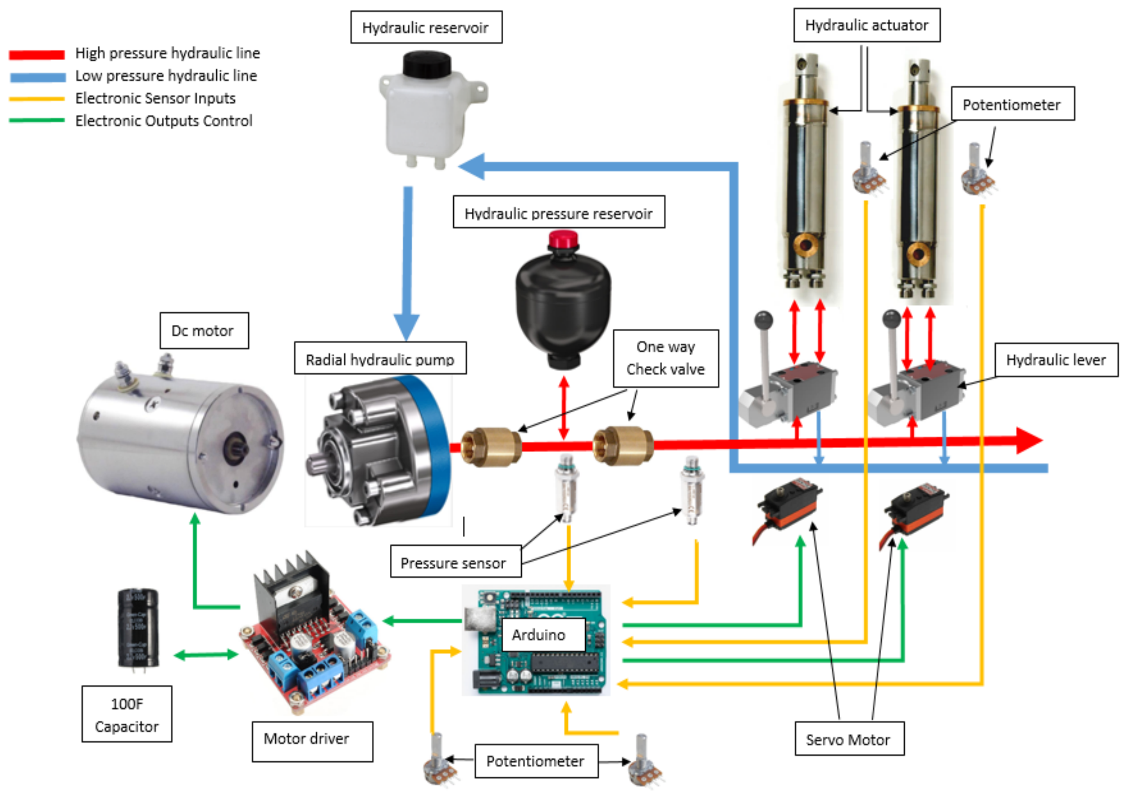

Figure 3-7: Graphical representation of the system

3.5 System component breakdown

As mentioned in the literature, hydraulics work with fluids that are not compressible, having air within the system introduces other problems that make the system unable to function as required. To ensure that the system works at its best, all the air in the system needs to be removed. This process is called bleeding. This process is necessary after connecting all the hydraulic components as none of the components would be able to function. To bleed the hydraulic system, one has to follow the following steps:

1. Stop the pump if it is running.
2. Manually set the actuator stroke to fully open or fully closed.
3. Remove all the air bleeder valves.
4. Fill the hydraulic reservoir with fluid halfway in the reservoir.
5. Set the servo valves to fully open to drive the actuator in the opposite direction in which it currently is.
6. Run the pump at low speed continuously.

7. During step 6, the actuators connected in the system would start to retract to their fully retracted positions. Once they reach full retraction, turn the servo valve to fully open in the opposite direction. The actuators would start extending until they are fully extended.
8. Monitor the hydraulic fluid level in the reservoir and ensure that there is still fluid within it. If the fluid levels have dropped, repeat the process from step 4.
9. Once the fluid levels start remaining constant in the reservoir, turn the pump speed up by 10%, turn the servo valve to fully retract, once the actuator is fully retracted, turn the valve to fully extend.
10. Continue extending and retracting until the actuators start moving smoothly. You would know that the process is completed once the actuators start pushing or pulling with a lot of force during extension or retraction.
11. Top up the reservoir oil and then replace all bleeding valves and the priming procedure is complete.

3.6 Operation of the system

When the system starts, the PID algorithm is loaded with the pre-calculated PID gains. Thereafter, the motor pressure sensor would check the pressure in the accumulator to determine if there is sufficient pressure or not. If not, the error is calculated and corrected and as soon as the pressure level has been reached. Thereafter, the actuator positions are compared to the human joint positions then corrected if the values are not the same. After the first correction of all the actuators, the system would constantly check if it is overloaded and stop all actuators to prevent system back flow in the title or heads unless they are unavoidable.

3.6.1 Motor

A brushed DC motor is proposed for driving the hydraulic pump as it has high torque at low rpm and doesn’t require a highly complicated motor control like a Brushless DC motor (BLDC) or AC motor. Again the motor would only be rotating in one direction as the fluid would only ever be moving in one direction as well. This means that it only needs a speed controller which would control the motor speed to in turn control the flow

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rate of the fluid through the pump. The motor is controlled using the PID algorithm for error correction when the pressure is not reached in the hydraulic pressure reservoir.

3.6.2 Check valves

Check valves are used to block fluid back flow and to also protect the pump and the hydraulic pressure accumulator from excessively high pressures when the actuators have a load on them.

3.6.3 Hydraulic pressure accumulator

The hydraulic pressure accumulator is used as an energy storage device to store all pressurised hydraulic fluid ensuring that the entire system always has enough pressure and the actuators would always move in the intended direction [13], [17], [20], [73]. As an actuator moves, the motor would not run, yet as the accumulator would start to deliver the required fluid to the system since all the pressurised fluid is stored in it. The motor would only start to run once the pressure in the accumulator becomes too low to supply the system. A PID algorithm would assist in properly controlling the flow of the fluid and also ensure that the right pressure levels are kept within the accumulator during operation.

3.6.4 Pressure Sensors

Pressure sensors are used to measure and control the pressure in the system ensuring again that the system does not exceed maximum operating pressure. If sensor senses low pressure the controller would calculate the error difference and based on that, start the motor and pump more fluid into the pressure accumulator to maintain the desired pressure levels [73]–[75]. The second pressure sensor is used to sense whether the system is overloaded or not.

3.6.5 Super capacitor

Because the motor selected is a dc motor and draws very high currents on start-up, a large capacitor is needed to deliver the required current. Capacitors are known to deliver large amounts of current for short periods of time, they are therefore the best solution to deliver the required motor start-up power. Batteries may be able to deliver the start-up current, but may suffer in the long run as they would get damaged due to excessive

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amounts of current being drawn at once. The battery therefore charges the super capacitor in order for it to stay charged for the next start up cycle then the battery can maintain the speed of the motor once its running.

3.6.6 Hydraulic lever

The hydraulic levers are controlled by the servo motors to move them to the required position while the potentiometers measure keeps track of the actuator's position. The system also uses a PID control system to accurately control the actuator to move them to their desired positions.

3.6.7 Hydraulic reservoir

The reservoir keeps all the hydraulic fluid operating within the system. However, as this is a closed system, the reservoir will be relatively small because most of the fluid is within the system and only needs to compensate for the calculated fluid difference. This is assuming that there are no leaks within the system as it should be. Furthermore, a spring loaded reservoir is proposed to reduce possibility of cavitation within the system.

3.6.8 Linear actuators

Though the motion of most of the joints is somewhat rotary, linear actuators are preferred over rotary actuators because of their weight. Rotary actuators are about three times heavier than linear actuators. A linkage mechanism would however be required in order for the joint to achieve a rotary motion of approximately 145 degrees. Different size actuators are required as all the joints have different requirements based on the application of the actuator e.g. an actuator controlling the elbow joint would have less force requirements than an actuator working on the knee [3], [22], [74], [76]. The knee actuator needs to carry the weight of the rest of the upper body while the elbow joint only needs to carry the weight of an object being lifted. For this reason, proper actuator sizing method would also be used in order to determine the cylinder specifications of each actuator being its maximum force, stroke as well as bore required for each one of them.

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3.7 System Design

The system was designed using a 1:14 scale RC excavator hydraulic system designed for a HUINA 580 miniature excavator by the manufacturer in [77]. The kit consists of the following items:

- Hydraulic power pack
- Excavator boom assembly with 4 hydraulic actuators
- 3-way hydraulic directional valve
- Hoses

Figure 3-8 shows the excavator boom assembly used for the construction of this research. The boom assembly contains hydraulic actuators that are to be used for the design the robotic arm. .

Figure 3-8: Excavator boom assembly [77]

The boom assembly has 4 hydraulic cylinders with the following specifications:

- Bore = 12 mm
- Rod = 6 mm
- Stroke = 75 mm
- Maximum pressure = 7 MPa

The cylinders are constructed of brass and stainless steel and can be seen in Figure 3-9.

Figure 3-9: Miniature hydraulic cylinder

The hydraulic power pack is compact and has all the necessary components built into it. It has a brushless motor which drives a hydraulic gear pump with a flow rate of 1 L/min and a maximum pressure of 4 MPa, a 100 ml reservoir, and an adjustable pressure relieve valve. Figure 3-10 shows the hydraulic power pack. The pack has a dry weight of 468 g. The BLDC motor has a working voltage of 11.1 V and and a maximum current consumption of 20 A.

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Figure 3-10: Hydraulic power pack [77]

The 3-way directional valve shown in Figure 3-11 uses a 3-metal gear servo motors to control the flow and direction of the hydraulic fluid which has a maximum operating pressure of 7 MPa. The servo motors have a maximum operating voltage of 6 V and a maximum running current of 120 mA.

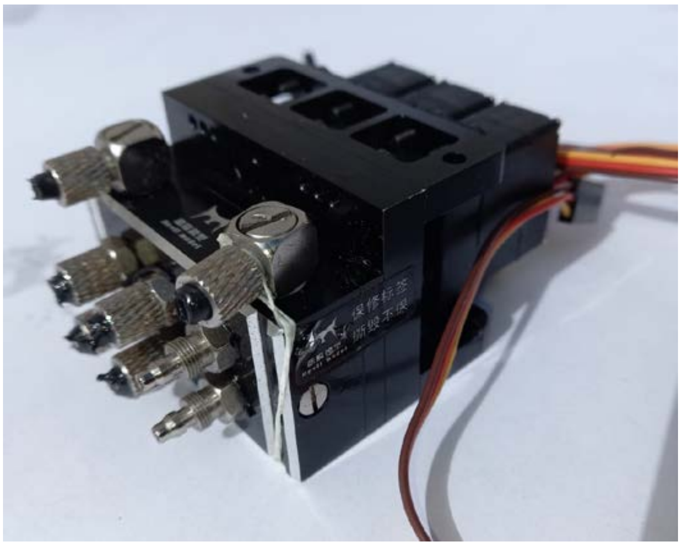

Figure 3-11: 3-way hydraulic directional valve

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3.8 Part design

The system components were designed in SolidWorks and 3D printed on a geeeetech M1 3D printer using PLA material. To ensure maximum strength, the parts were printed with 80% infill and 0,15mm layer height. The designs of the arm are shown and discussed in Figures 3-12 to Figure 3-16.

3.8.1 Elbow potentiometer mount

The elbow mount shown in Figure 3-12 is designed to house a 5kΩ D-shaft single gang potentiometer which is responsible for decoding the angle of the elbow. Moreover, the hole that appears on top is used to insert the carbon fibre rod that is used to hold all the parts.

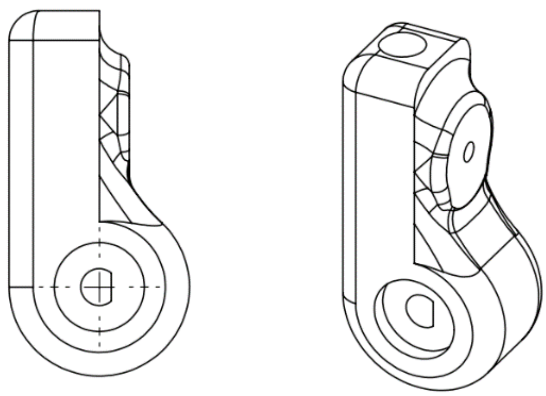

Figure 3-12: Elbow potentiometer mount

3.8.2 Shoulder Potentiometer mount

Two of these pieces shown in Figure 3-13 are printed and used to sandwich the shoulder pivot piece that would allow the arm to move up and down. These two parts only have a thickness of 5mm as they do not require much strength due to their mounting position. The one piece is modified slightly in order to mount a potentiometer. This is the potentiometer that would read the shoulder angle of the robot.

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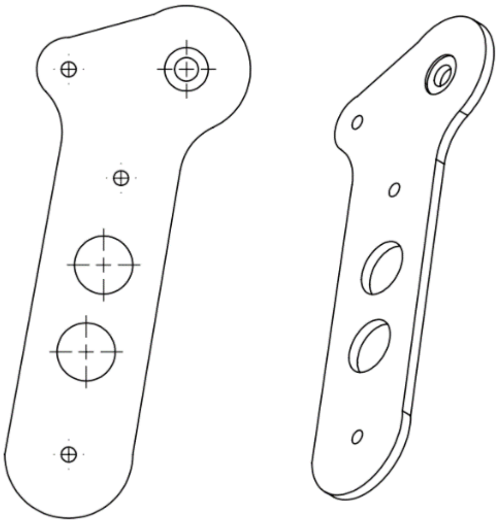

Figure 3-13: Shoulder potentiometer mount

3.8.3 Elbow piston mount

The elbow piston mount shown in Figure 3-14 is used to mount the piston that is controlling the elbow. The part is designed in such a way that it can be adjusted after assembly to ensure the perfect position for the piston. This is the position that allows the piston to operate at its maximum and deliver the most torque at this point.

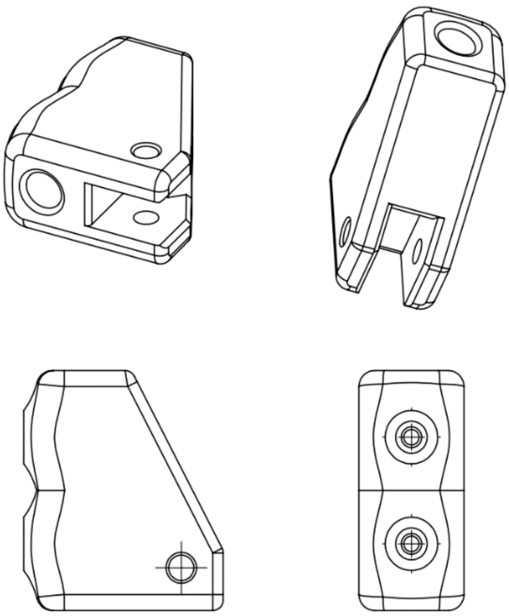

Figure 3-14: Elbow piston mount

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3.8.4 Wrist mount

Two of these parts are printed and pivots around the elbow mount and they sandwich the elbow mount and also hold the elbow potentiometer. This part acts as the lower arm of the robot. The wrist mount is shown in Figure 3-15.

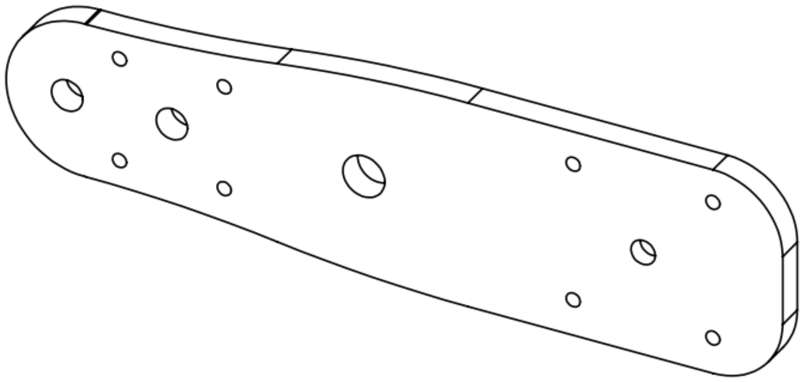

Figure 3-15: Wrist mount

3.8.5 Shoulder pivot

The shoulder pivot is shown in Figure 3-16 and acts as the arm and is extended using a carbon fibre rod. Furthermore, the piston rod eye is mounted on this part and is the pivoting point of the shoulder. This part is also extended with the carbon fibre rod that acts as the upper arm.

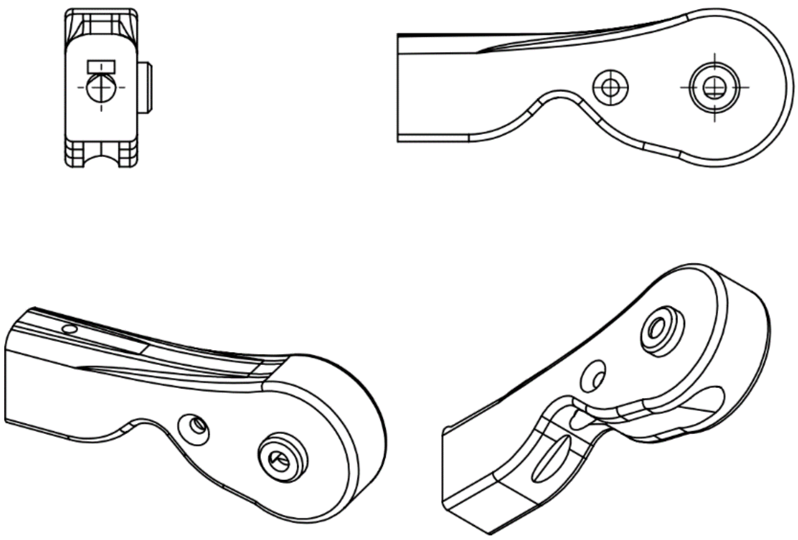

Figure 3-16: Shoulder pivot

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3.9 Assembly

In this section the researcher discusses the assembly of the arm from Figures 3-17 to 3-19, beginning with the shoulder assembly. Figure 3-17 shows the assembly of the shoulder pivot, shoulder mount, potentiometer and the piston.

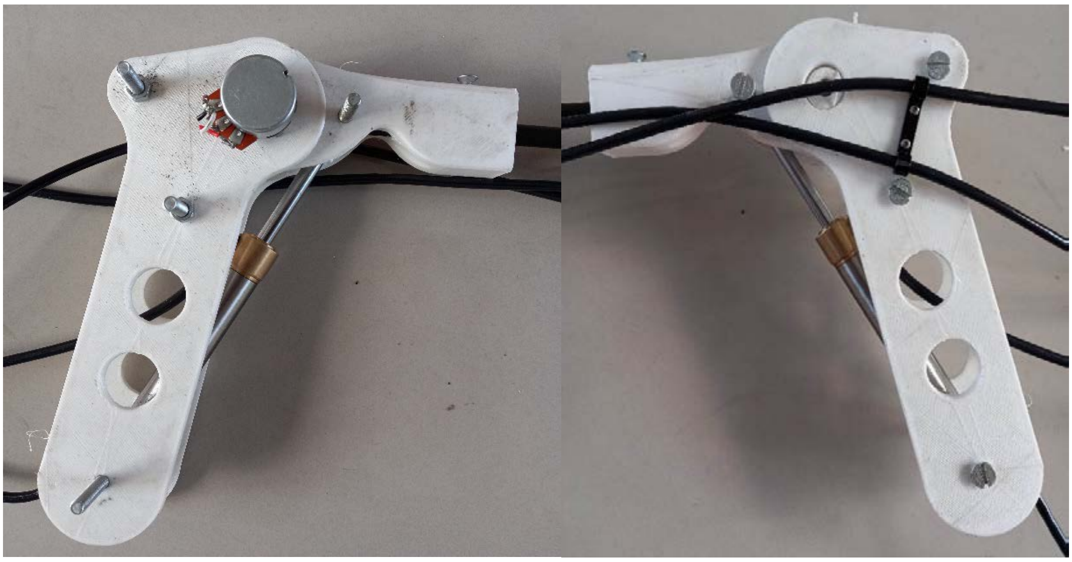

Figure 3-17: shows the elbow control assembly both top and bottom view

The rest of the arm is shown in Figure 3-18 which houses the hydraulic cylinder, elbow piston mount, elbow potentiometer mount, elbow potentiometer, and the wrist mount. The elbow potentiometer mount and the elbow piston mount are connected together by a carbon fibre rod.

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Figure 3-18: System design

Figure 3-19 shows the complete robot arm from shoulder to elbow as well as the hydraulic cylinders and hydraulic pipes.

Figure 3-19: Robot arm

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3.10 Arm mount controller

The arm mount controller shown in Figure 3-20 is used to control the robot and is mounted on the arm as shown in Figure 3-21. This part uses elastic fabric for mounting on the arm and decodes the arm movement using a potentiometer. After the data has been read from the potentiometer and processed locally using an Arduino, it is then sent to the robot controller to update it with the new position for test purposes the same arm mount is used for both the shoulder and elbow joint. This is used as the remote controller to mimic the precise location of the human arm before sending it to th robot.

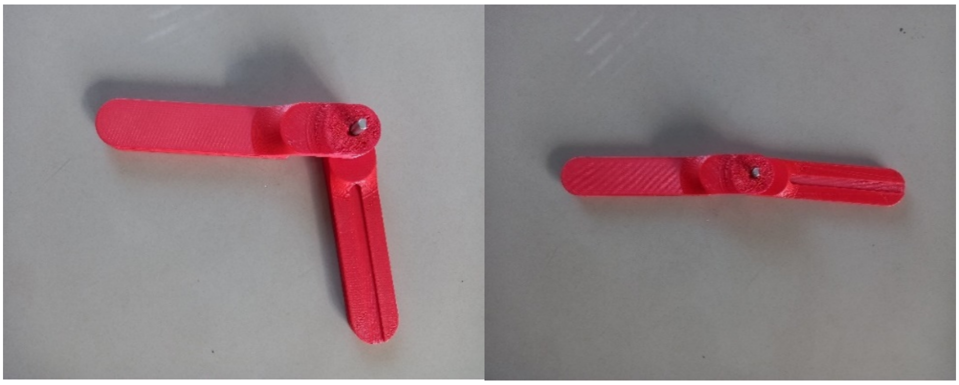

Figure 3-20: Arm mount controller

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Figure 3-21: Arm control mount on arm

3.11 Circuit diagram

In this section, the electrical circuit is explained. The circuit was designed and simulated in tinkercad. There are two separate circuits designed, the first is attached to Device A which reads the arm position and then sends position to Device B.which then controls the robot arm and aligns it to the human pose. Device A is the master while Device B is the slave.

3.11.1 Master circuit

The master device uses an encoder on each joint to determine the human pose. The encoders selected are 5 kΩ potentiometers and are attached on each joint using the 3d printed arm mount. Once the pose has been determined, the raw values are sent via Bluetooth at 115200 baudrate to ensure fast communication between the two devices. The circuit diagram is shown in Figure 3-22.

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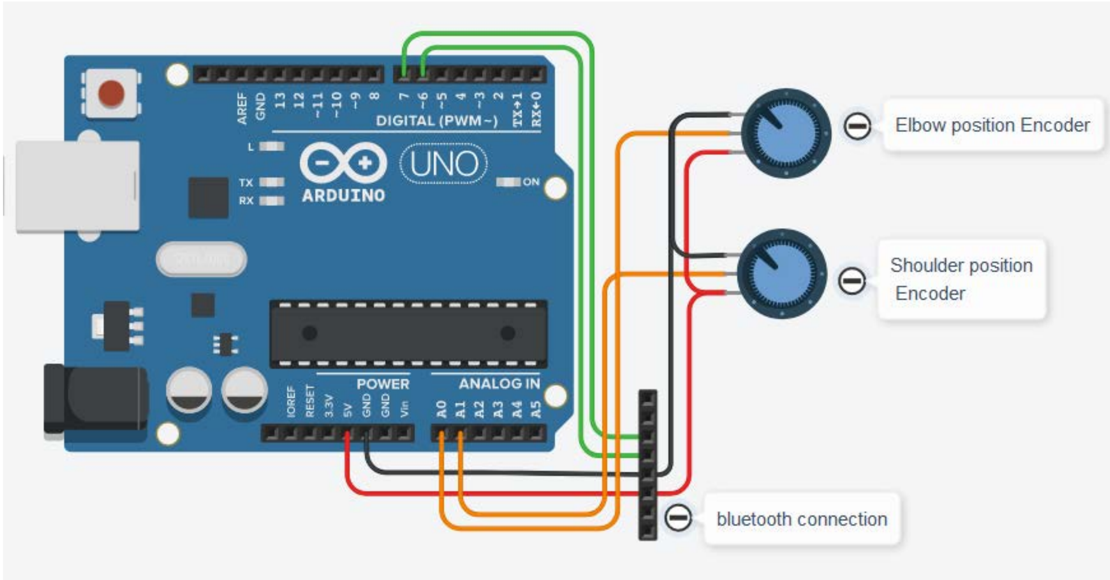

Figure 3-22: Arm mount controller circuit diagram

3.11.2 Slave circuit

The slave device's main function is to control the robot arm and maintain the same pose as the human. This is achieved by controlling the servo valves which will then drive the hydraulic actuators. The slave device receives the arm position from the master device through Bluetooth and will adjust the robot arm accordingly. The circuit is shown in Figure 3-23.

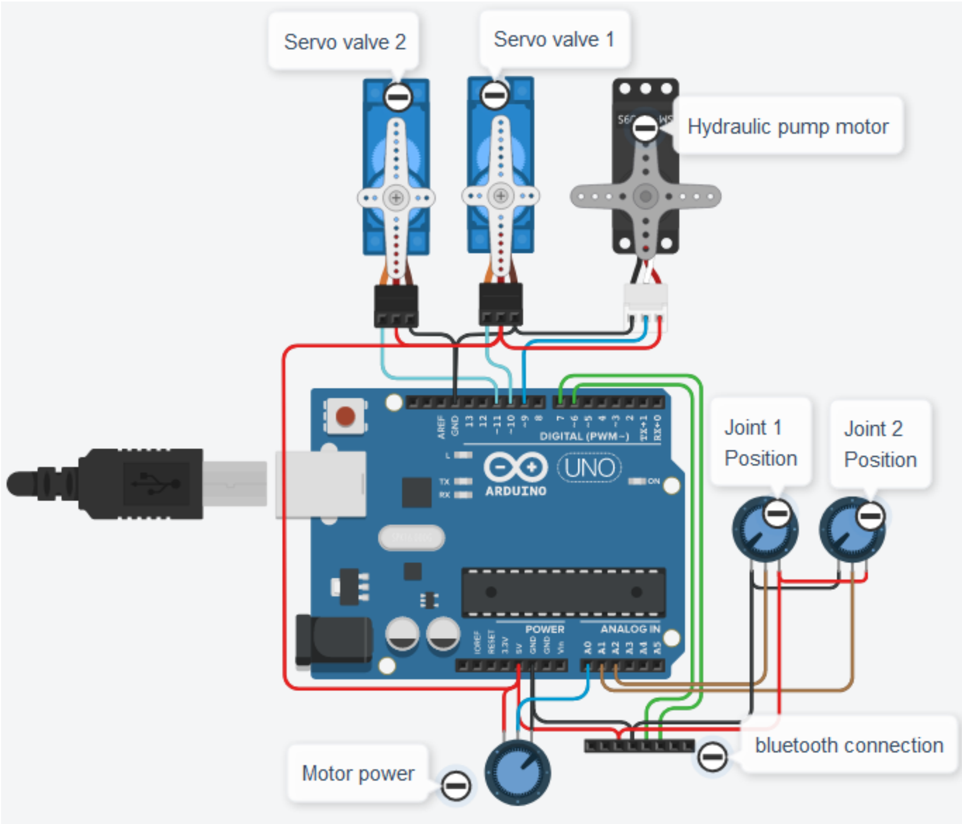

Figure 3-23: Robot arm Circuit

The motor power potentiometer can be adjusted to increase or decrease the response of the system. This can makes it more aggressive or less aggressive by changing the hydraulic pump motor speed. Servo valve 1 and 2 are responsible for moving the hydraulic actuators by opening or closing the valve to allow fluid to flow or stopping the flow. The potentiometers labelled “Joint 1 Position” and “Joint 2 Position” decode the corresponding actuator positions. The system will then be controlled using the PID controller to ensure a more reliable motion while increasing the precision of the actuator.

An LM2596 voltage regulator shown in Figure 3-24 was added to the practical to ensure a stable output to supply the servo motors, as well as potentiometers. This regulator board is a buck converter that can give an adjustable output ranging between 1.2 Vdc to 37 Vdc at 3A. The regulator was adjusted to 5.5 Vdc to supply the servo motors as well as the potentiometers.

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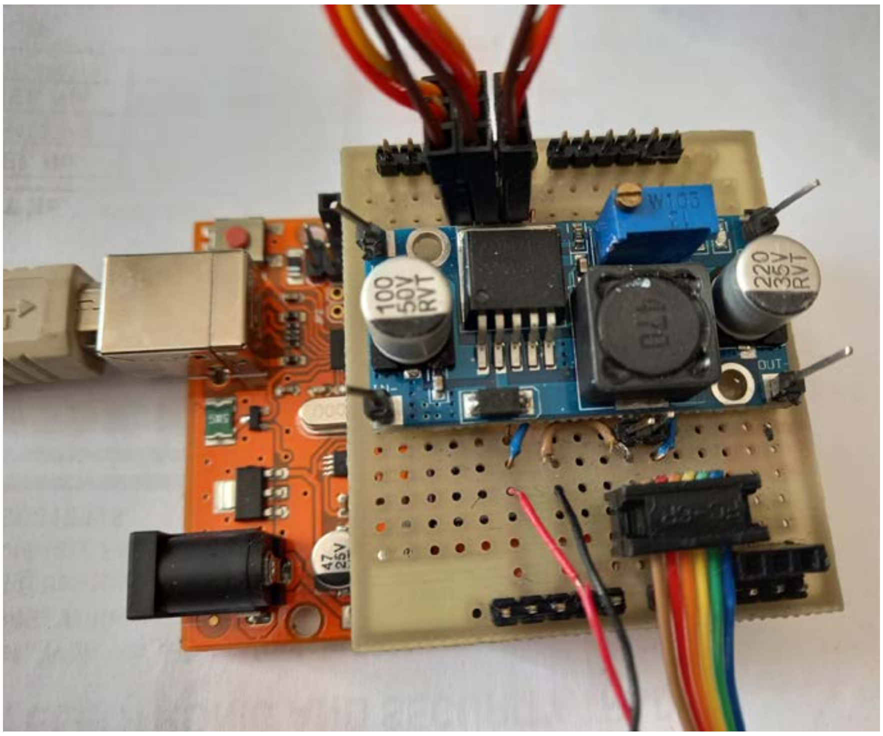

Figure 3-24: Practical circuit for the robot arm

3.11.3 Bluetooth master and slave

The Bluetooth devices used for the master and slave are HC-05 bluetooth modules shown in Figure 3-25. The modules use Bluetooth Serial Port Protocol (SPP) operate at 5 Vdc. These modules communicate with the Arduino through serial communication, which makes them easy to interface with the Arduino. By default the modules are confugured to be slave devices and operate at 9600 baudrate. Due to this, the devices cannot communicate with each other and thus need to be reconfigured to be able to pair and communicate with each other. This can be achieved by following the steps provided in [78]. One module was configured to be the master device and communicate at 115200 baudrate, while the other device was configured as a slave device and communicates at the same baudrate as the master.

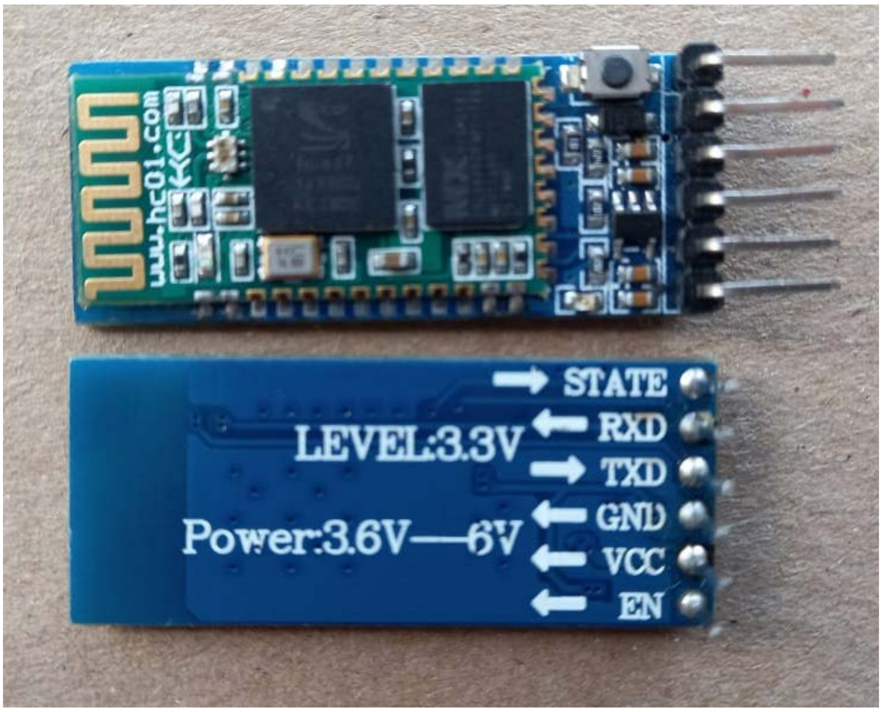

Figure 3-25: HC-05 Bluetooth modules

3.12 Programming

As described in the study, they work independently from one another and thus have their own programs, which is shown in this section. Both the devices use ATMEGA328P microcontroller and are programmed in Arduino ide.

3.12.1 Arm mount program

The arm mount's task is to read the position of the arm using a potentiometer then send the raw data to Device B via Bluetooth. The program uses software serial library to transmit information to the Bluetooth module. The program is presented in Appendix A.

3.12.2 Robot arm program

The robot arm receives data from the arm mount and then proceses this data using the PID algorithm to control the robot arm. The program controls the hydraulic pump as well as the servo valve and the potentiometer that gets feedback for the arm position. The program for this set up is presented in Appendix B.

3.13 Stall power consumption test

Figure 3-26 describes the configuration of the two devices used for Stall power consumption test. The setup was done in order to test the power consumption of the actuators when in idle state. **A** is the dynamixel servo actuator setup and **B** is the hydraulic actuator setup.

Figure 3-26: Weight test configuration

Robotis is one of the leading companies in commercial humanoid robots and it produces different actuators for different applications [20], [79]. The AX-12A and AX-18A actuators were selected from robotis as well as The actuator needs to be connected to a CM530 control board to be able to access its functionality. Once connected, RoboPlus Manager shown in Figure 3-27 can then be used to configure the motor to its desired parameters. For this setup, the actuator was set to its maximum settings. This is done by firstly setting the actuator to be a joint then adjusting the Alarm Shutdown and Goal Torque to maximum and then turning on the motor torque. This will hold the motor in its present position and prevent it from moving.

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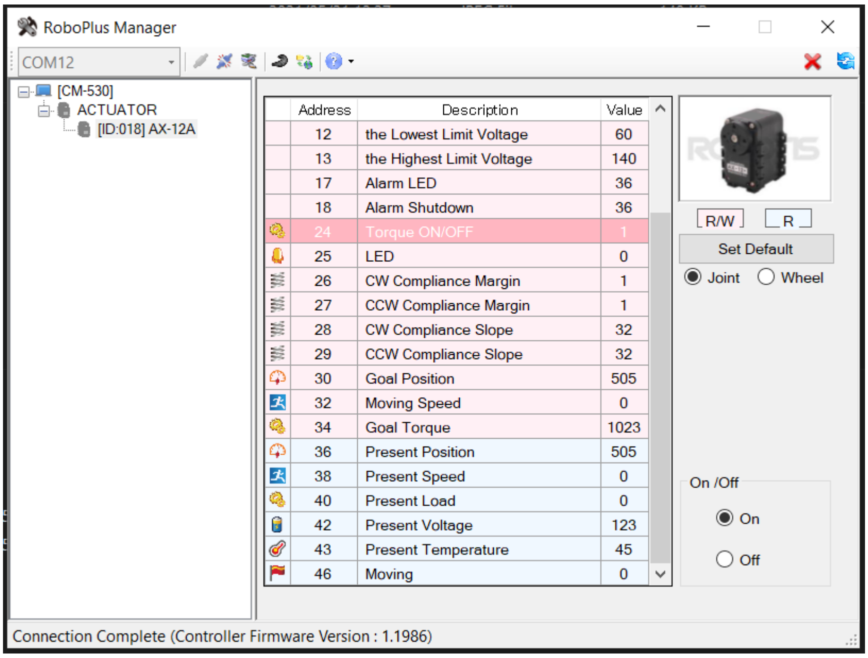

Figure 3-27: Roboplus Manager interface

To test the consumption of the actuator, a lever of length 7 cm was attached to the actuator as a lever. The force applied on the motor may be calculated using the equation below:

$$M = F \times d \tag{3-3}$$

Where M is the moment of inertia, F is the force applied and d is the distance from the actuator to the weight. Since the only force applied is assisted by gravity, F can then be $m \times g$ where m is the mass and g is the gravitational constant of 9,81 m/s^2.

With this test, different weights are used with the assistance of gravity to put stress on the actuators to test how much weight each can handle before failing. The power consumption was measured in order to observe the consumption of the actuators throughout the test. It should be noted that different size weights were used between the two actuators since the hydraulic actuator can handle heavier loads even though the difference in weight between the actuators is only 25 g with the hydraulic actuator weighing more. The practical setup of both the actuators is shown in Figure 3-28.

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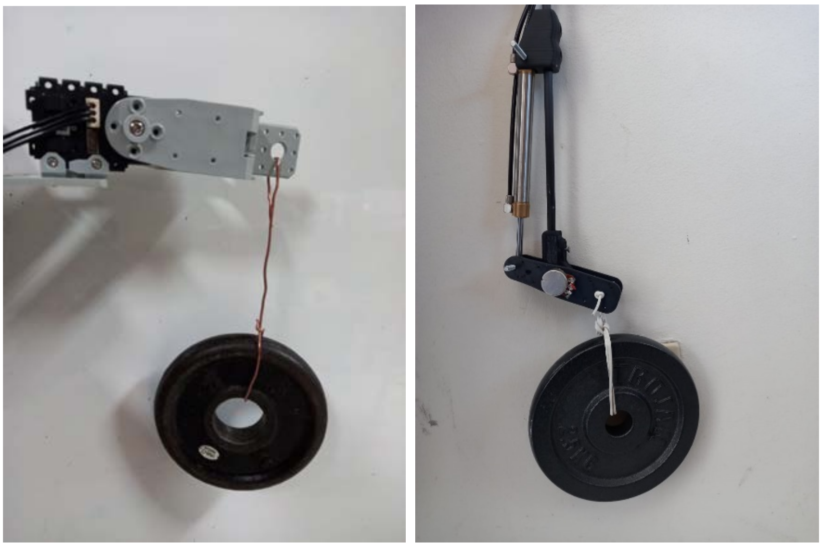

Figure 3-28: Practical weight test setup

3.14 Electrical actuator controllability test

To test the controllability of the electrical actuator, the setup shown in Figure 3-29 and Figure 3-30 was done. In this setup, an electrical arm mount was designed and attached to the arm and for the robot arm a dynamixel AX-12A actuator was used. This test was used as a base comparison for the hydraulic actuator as the actuators are fast and have high precision. The arm mount uses a Dynamixel AX-12W actuator for position control as the actuator can be used to read position.

Figure 3-29: Electrical actuator arm mount

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Figure 3-30: Electrical actuator test arm

3.15 Summary

The arm was designed in Solidworks CAD software and simulated before 3D printing the necessary parts of the design. The main focus of the design was ensuring a system that is able to follow all human movements while consuming little to no power for actuators that are in idle or not in motion. A 3D printer was used to print the parts used in assembling the robot arm. The hydraulic actuators that were taken from a miniature hydraulic boom assembly worked perfectly for designing the robotic arm as it had most of the required parts. An arm mount that controls the hydraulic arm was designed and 3D printed as well. Finally, a test was conducted to determine how well the hydraulic actuator works as well as conducting a stall test for the hydraulic and electrical actuator.

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Chapter 4

Results and Discussion

4.1 Introduction

This chapter reports on all the procedures and tests that were carried out to verify the operation of the system as a whole as well as testing the consumption of the two actuation methods. The first part that is tested is controllability of the hydraulic system, the purpose of this test is to check the reaction time of the system and if it can move in realtime to mimic human actions. In the second part, the energy consumption is tested. The movement of the robot arm was recorded with the pump speed being varied to find the ideal speed as different speed result in different reaction times. Figures 4-1 to Figure 4-4 show results of the controllability test at different motor speeds.

4.2 Hydraulic actuator controllability

As mentioned in section 4.1, the first test that was conducted was controllability of the hydraulic actuator. Figure 4-1 shows the results of the hydraulic motor at high speeds. It can be seen that the actual position of the robot arm tends to follow the desired position quite well. However, as it the arm aproaches the desired position the system overshoots due to the high hydraulic pump motor speed and also the PID controller trying to correct the error. The servo valve is also very unstable as it constantly fluctuates and tries to correct the angle which is shown in the lower part of the figure.

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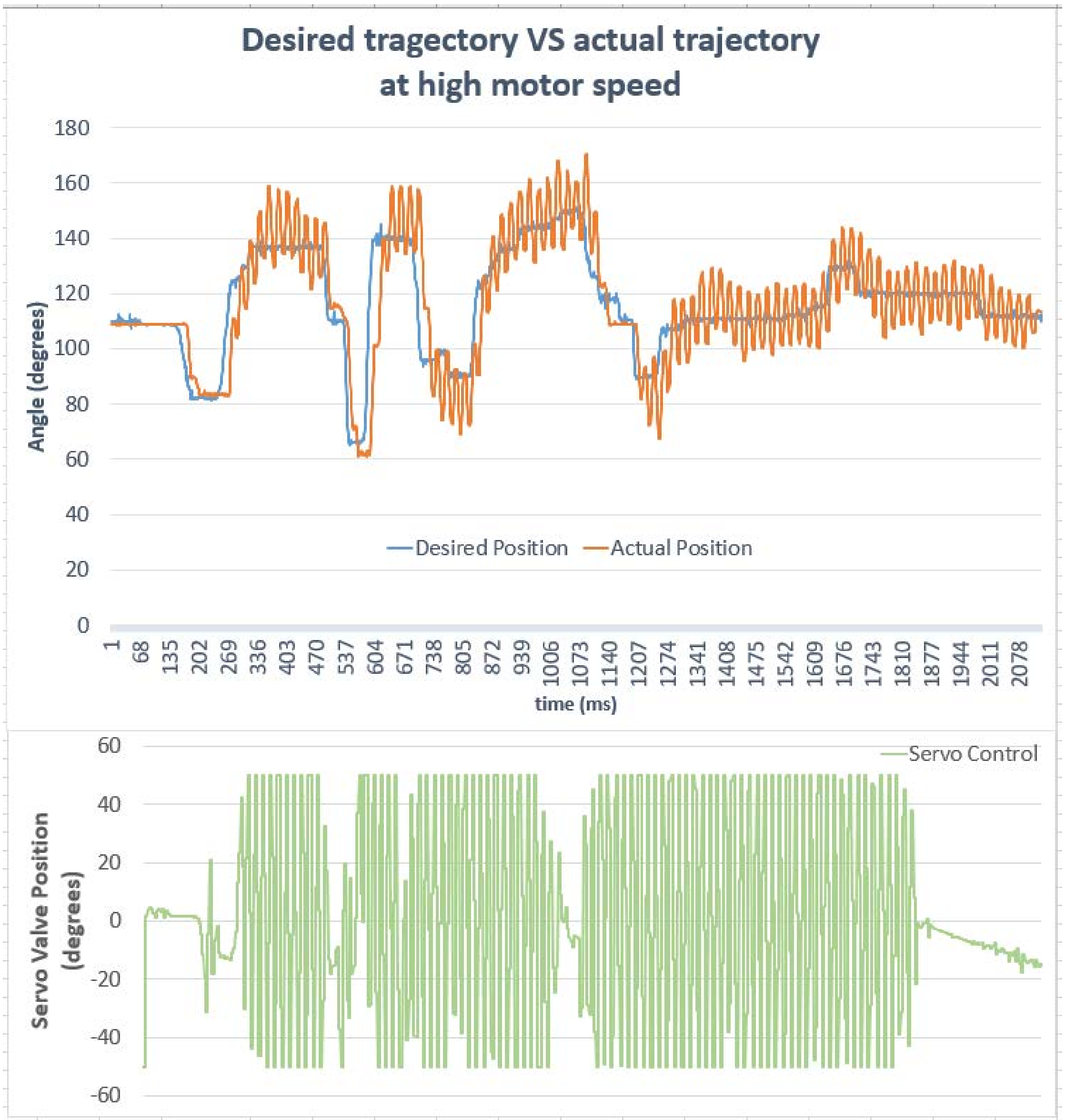

Figure 4-1: Results at high motor speed

Figure 4-2 shows the system with reduced pump motor speed. The motor's power consumption is reduced and the moves less rapidly due to this. The robot arm's actual position follows the desired position fairly well. The difference between the desired position and actual position can be seen to be much larger in this test. There is however a slower response on the actual position when the desired position changes rapidly. Furthermore, the hydraulic system shows to be less responsive than the electrical system in this state. As the servo actuator moves less frequently as it tends to use less power to stabilise the robot arm.

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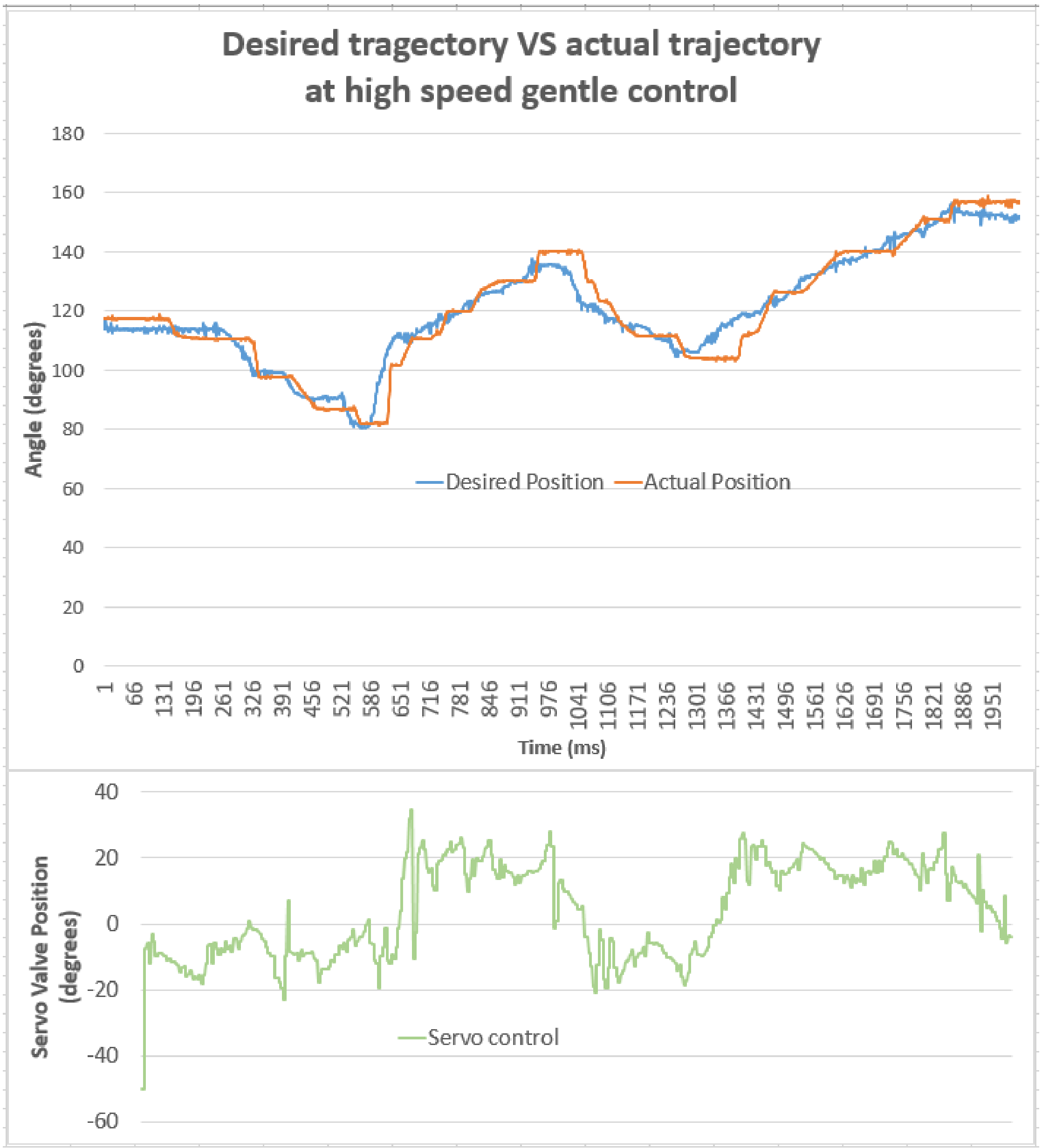

Figure 4-2: Input trajectory vs output trajectory at high speed with gentle input control

As seen in Figure 4-2, the proposed system shows to have a good response time with the actual position following the desired fairly well although there is a lag in some cases. The servo valve also seems to be responding well and not as violently. In Figure 4-3 the motor speed was adjusted manualy to try determining the right speed of operation. The results show how the output changes in respect to the motor pump speed. A slower motor speed resulted in a slower response in the output and the servo valve not being able to correct the error in the system well. This means that the motor speed needs to be

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set to the right speed in order to get the desired position to match the actual position perfectly.

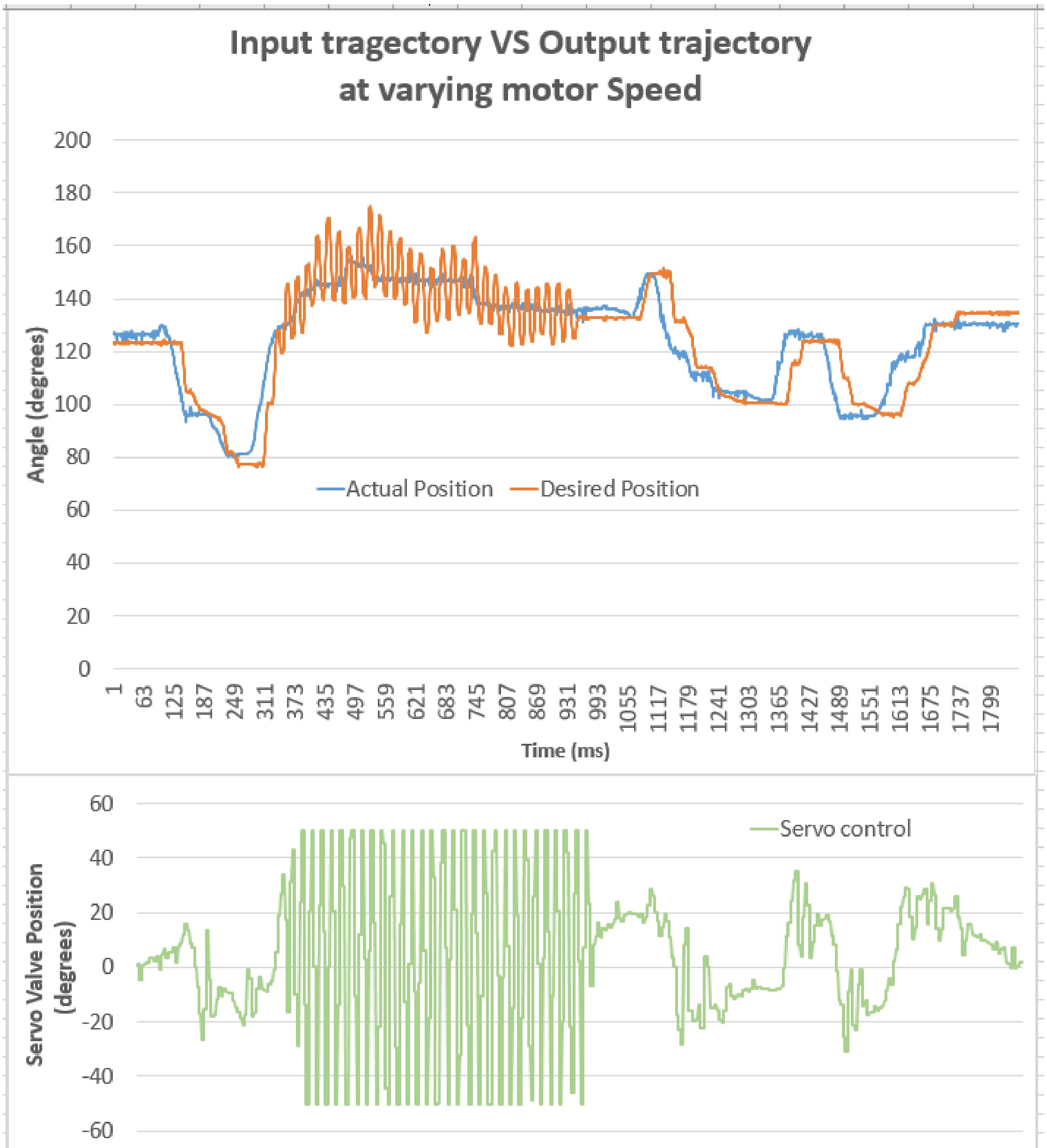

Figure 4-3: Input trajectory vs output trajectory at varying motor speed

Figure 4-4 shows the reaction of the system when the battery voltage becomes low. The actual position's response becomes much slower over time, while the servo continues working normally as its power consumption is much less than that of the motor pump. As stated in Chapter 3, the the servo motors have operate at 6 V at 120 mA while the motor pump operates at 11.1 V with a maximum current consumption of 20 A. This means that the arm can be set to its holding position while locking the joints in place to prevent any further movement in the arm. This feature becomes very helpful when power is needed to run the most crucial parts of the robot where energy is needed the most. The robot is able to still have some of its joints functioning properly as no power is needed to hold the other joints in their respective positions.

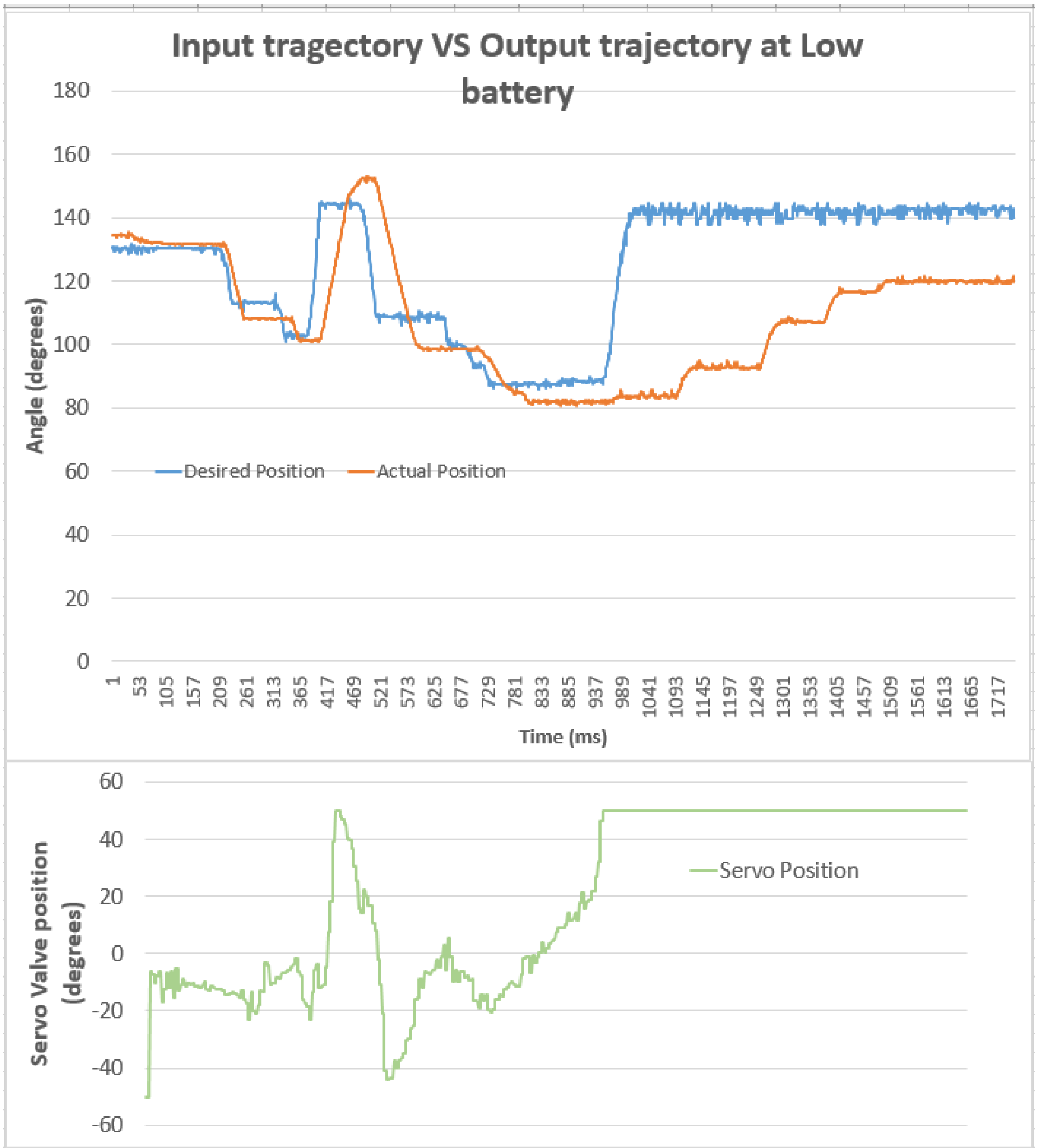

Figure 4-4: Input trajectory vs output trajectory at low power

Although temperature was not considered in the testing of the system, it is worth noting that the temperature of the reservoir elevated to up to 88 ^{0}C during testing. This is most likely caused by the motor being too close to the reservoir and transferring heat to it. Furthermore, this could have resulted in increasing the oil temperature and thus changing its viscosity.

4.3 Electrical actuator

This section discussed the tests done with the electrical actuator for controllability. This test is done to see the reaction time of the actuator as the human moves. The results of the test are shown in Figure 4-5 to Figure 4-7 where the input is the human motion and the output is electrical robot arm position. Figure 4-5 shows the results of a low speed test conducted where the input was controlled gently.

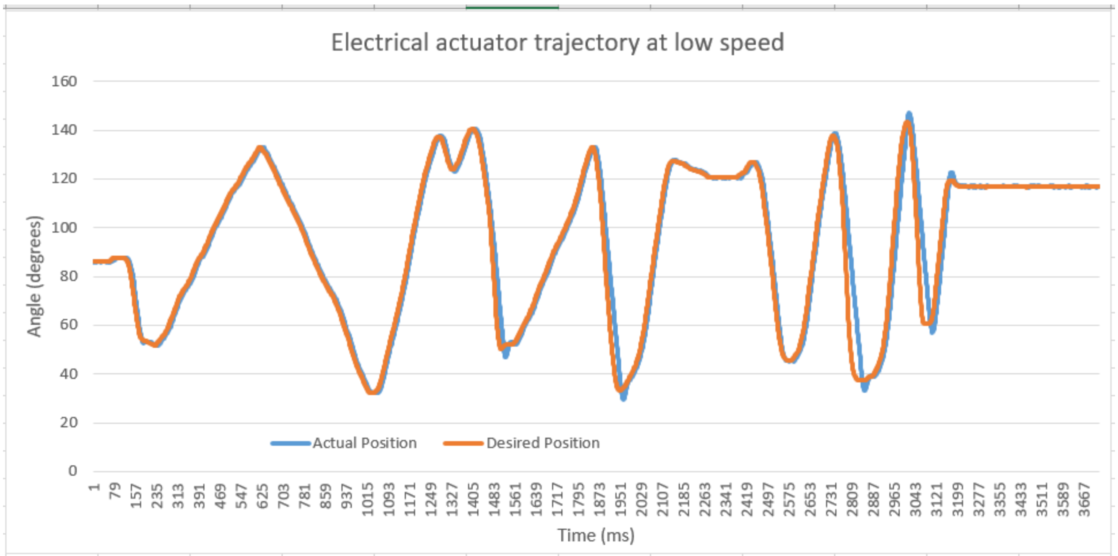

Figure 4-5: Electrical actuator control at low speed

The results show that the electrical motor manages to follow the control seemlesly. the actual is very accurate to the desired position with very small diviations. It can be seen that at much slower speeds the desired position follows the actual very accurately. Figure 4-6 shows the behaviour of the system when the input speed is varied.

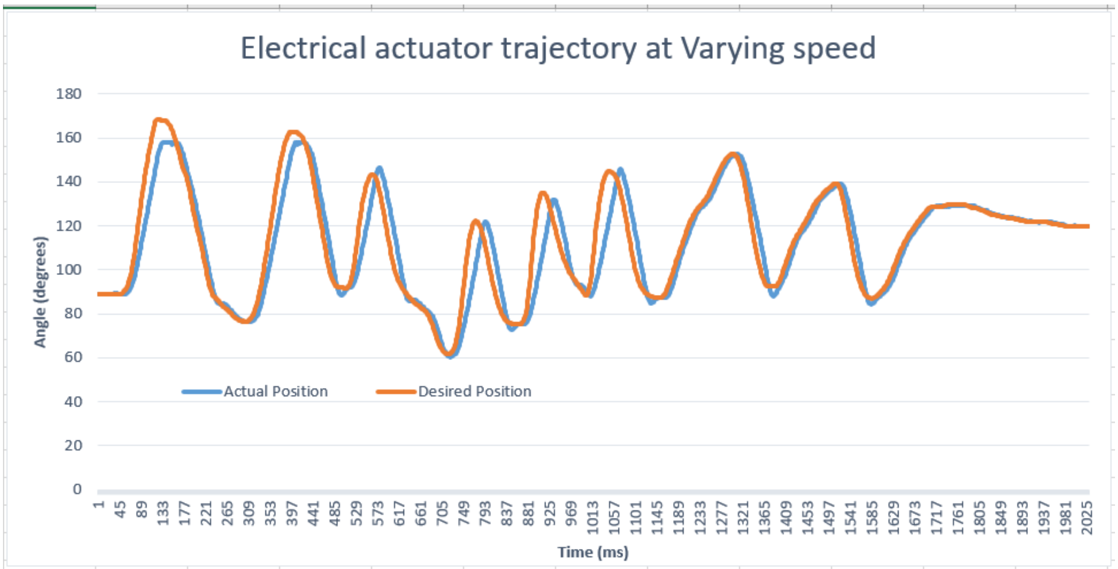

Figure 4-6: Electrical actuator control at varying speed

This Figure shows that the robot arm loses accuracy when the desired position's speed increases, This means that the reaction of the system is not fast enough to keep up with the input when the motion is abrupt. Figure 4-7 shows the behaviour of the system with a fast input.

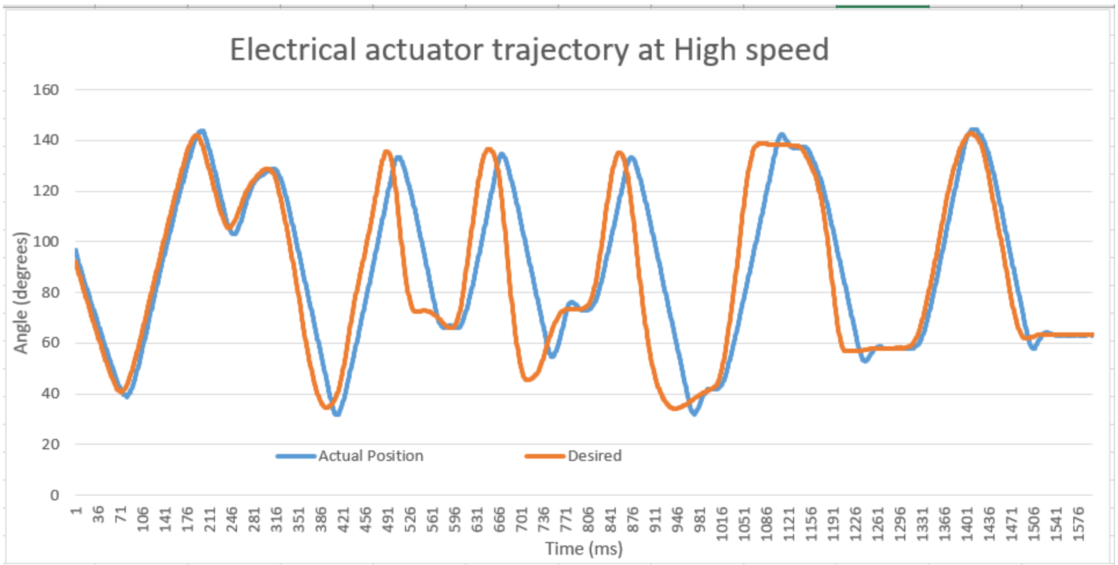

Figure 4-7: Electrical actuator control at high speed

The system is not accurate and is unable to keep up with the desired position. Even though the system still manages to follow the input trajectory there is a clear delay in

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the response time. These results show that the reaction of the actual is affected greatly by the desired speed, a very high change in the desired result in an unstable actual. This means that the desired speed needs to be regulated in order to have a more responsive and accurate system.

4.4 Stall test

The stall test setup was discussed in chapter three. To determine the consumption of the actuators, different weights were added to them and the current consumption was measured to determine how each system performs under load. The weights were added at 10 second intervals throughout the test and the results recorded.

4.4.1 Electrical actuator test

In this test three different electrical actuators are compared namely AX-12A, AX18A and LF-20MG servo and weigh 54.6 g , 55.9 g and 60 g respectively. The difference in consumption between the two actuators AX-12A and the AX-18A boils down to their internal construction where the former uses a cored dc motor and the latter uses a coreless dc motor. Figure 4-8 to Figure 4-10 show the results of the stall test on the electrical actuators.

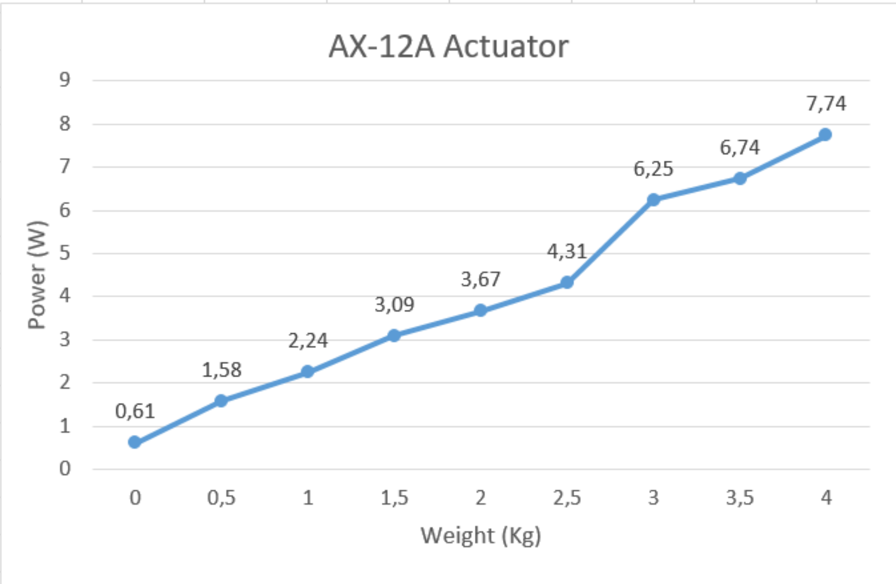

Figure 4-8: AX-12A actuator power consumption test

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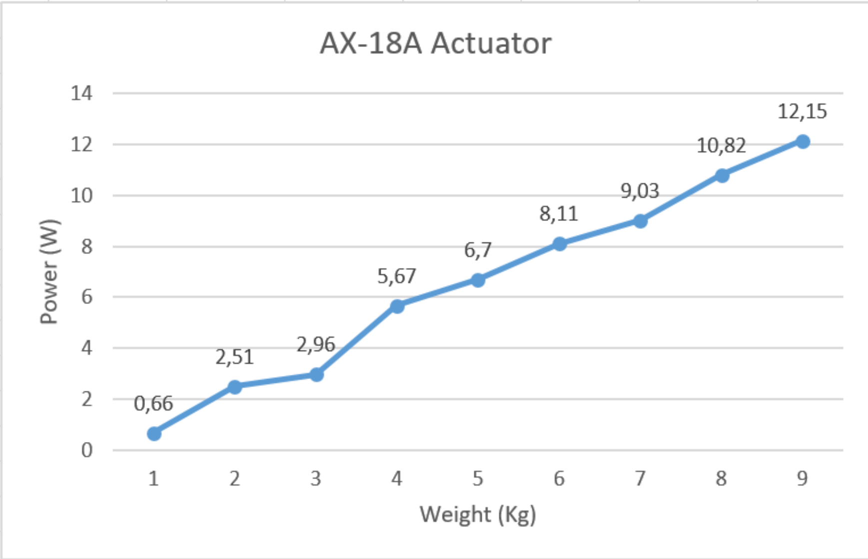

Figure 4-9: AX-18A actuator power consumption test

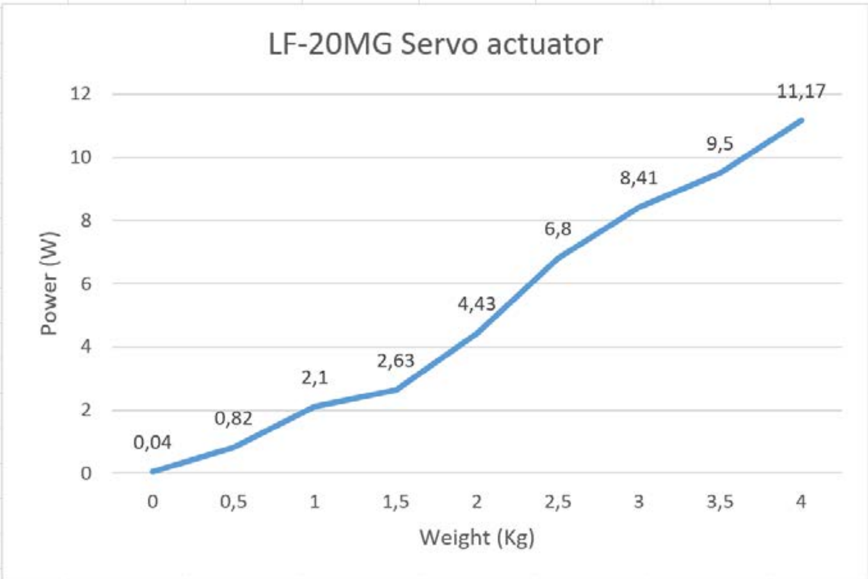

Figure 4-10: LF-20MG servo actuator power consumption test

The AX-12A shows to have the least power consumption of the three motors and the AX-18A having the highest. The trend on the other hand show a direct relationship between the power consumption and the overall weight that the actuators can carry. This means that the power consumption of each of these actuators is directly proportional to the force applied to it. Furthermore, due to the way the actuatrs are designed overall weight of the load in each actuator is carried by the motor inside them thus resulting in continuous power consumption during operation. As the load increases, the motor has

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to compensate by increasing its torque to overcome the load thus resulting in more current being drawn by the motor. Even though the actuators managed to hold the weight, both the AX-12A and AX-18A were unable to counter weights below 2 kg while the LF-20MG stopped at 3 kg. This is due to the high current demanded to overcome the force,

4.4.2 Hydraulic actuator test

The same test conducted for the electrical actuators was conducted on the hydraulic actuator, the results are shown in Figure 4-11. The hydraulic actuator has a dry mass of 80g and maximum operating pressure of 7 MPa.

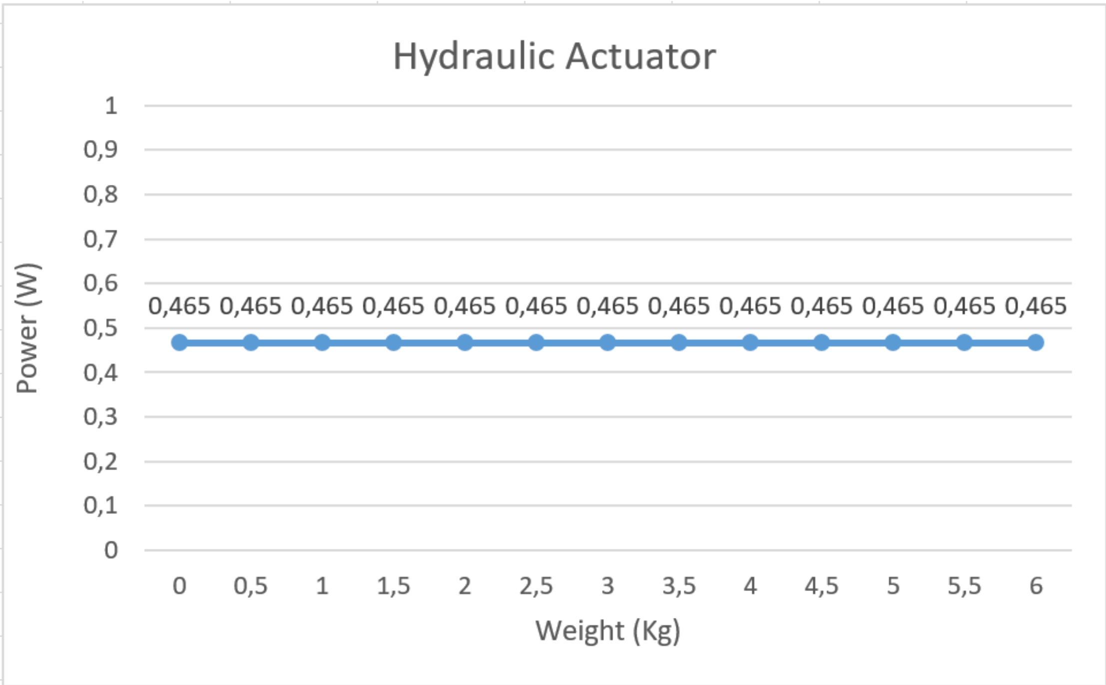

Figure 4-11: Hydraulic actuator power consumption test

The results show that the power consumption remains constant throughout the test regardless of the weight increase. The test was carried out to further to a maximum of 6 kg and the consumption still stayed the same thoughout. The overall consumption of the system is the same as the electrical system at no load. This is because the hydraulic system requires no power to keep the load in the required position, the power is only consumed by the on board computer as well as the sensors decoding the position of the arm. Once the arm is in the desired position, the servo valve locks the actuator in that

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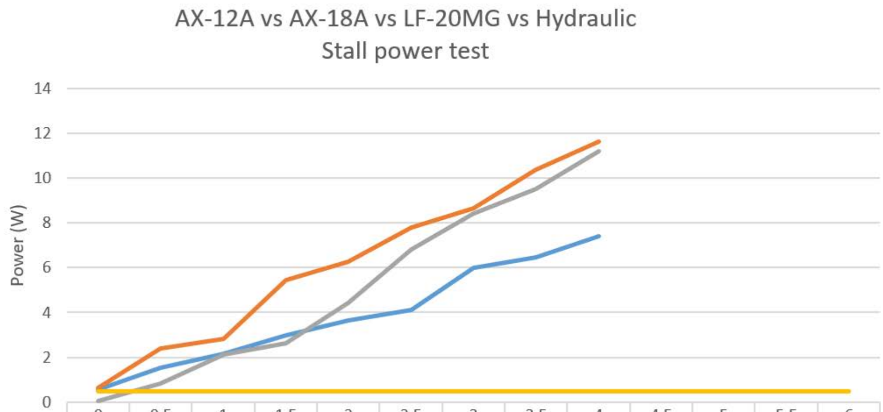
position so that the hydraulic pump motor can turn off. This ensures that the load is carried by hydraulic actuator and not the motors. Furthermore, the pressure accumulator ensures constant pressure within the system while accounting for the small deviations where the cylinder needs to make corrections. The accumulator also helps supply the initial pressure as the hydraulic pump motor is still spinning up to get to the required speed.

A full power comparison of all the actuators is shown in Figure 4-12. In Figure the relationship between weight and the power consumption and the power consumption is shown. The electrical actuators were limited to 4 kg as the motors started overheating. The hydraulic actuator was restricted to 6 kg as the it was constructed of PLA material and the parts started deforming, however, the hydraulic actuator still managed to handle the load without overheating or losing its position.



	0	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6
AX-12A	0,58	1,52	2,15	2,96	3,63	4,13	5,98	6,45	7,41				
AX-18A	0,63	2,4	2,84	5,43	6,25	7,77	8,64	10,36	11,63				
LF-20MG	0,04	0,82	2,1	2,63	4,43	6,8	8,41	9,5	11,17				
Hydraulic Actuator	0,465	0,465	0,465	0,465	0,465	0,465	0,465	0,465	0,465	0,465	0,465	0,465	0,465

Weight (kg)

Figure 4-12: Power comparison test of the electrical actuators and hydraulic actuator.

4.5 Implications of Tests

With the different tests that were done in checking controllability of the actuators and energy consumption, the results show that electrical actuators are much easier to control when compared to hydraulics. Furthermore, the setup and configuration is much easier to achieve with electrical actuators than with hydraulics. However, the hydraulic system

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tested was able to lift a much greater payload than the electrical actuator of the same mass. Controllability is still difficult to achieve as there are a lot of factors involved in ensuring a smooth motion. One of the reasons could be that the components used are off the shelve components and are not neccesarily made for their current use. As mentioned in literature, some manufacturers are working on specially designed hydraulic actuators for robots which incorporate technologies like additive manufacturing, which are usually easier to control.

4.6 Summary

Hydraulic actuators have shown that they are capable of lifting heavier objects and at the same time consume less power during idle operations than electrical actuators. This proves that designing a hydraulically actuated robot could potentially result in a robot that has lower power consumption, while ensuring that the robot has adequate payload capabilities. This however comes as a trade off to accuracy and complexity. The hydraulic system may not be as accurate as the electrical actuator, however this could be ignored in cases where accuracy is not of great concern since the difference is very miniscule. A deviation of less than 5mm as seen in the results for a mimicking robot is seen as very minimal as the robot will be used for lifting heavy objects which will be large in size.

Although the hydraulic actuator needs additional components such as the hydraulic pump and servo valves, these parts can be mounted far from the limbs thus ensuring that the limbs remain as light as possible. This trait cannot be achieved in electrical actuators as each actuator has to contain all its components within it being the motor, gearbox, position decoder and circuitry. As discussed in chapter 2, the internal motor of the actuator as well as the gearbox contribute to its overall weight and both will need to increase in size for a bigger robot thus resulting in a drastic increase in the total weight of the robot.

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Chapter 5

Conclusion and future work

5.1 Summary

In this study, the design of an electro-hydraulic control system for collaborative humanoid robot was presented. Based on the extensive research and literature survey as presented in Chapter two, research in hydraulic actuation as well as collaborative robots has gained attraction. Some researchers are now considering human-robot collaboration as it comes with a lot of advantages. The study used miniature hydraulic actuators to construct a robot arm that mimics a human motion which is done remotely. The results obtained confirmed that hydraulics have the ability to lift heavier loads than electrical actuators of the same size. When measuring the stall power consumption, the hydraulic system out preformed the electrical system as they did not need power in most cases to hold a load thus reducing power consumption during their inactive state. Furthermore, the hydraulic actuators did not need to compensate for additional weight added on the inactive actuators, resulting in a more efficient robot. The hydraulic system works well even although a lot of problems were encountered within the systm. A lot of work still needs to be done in order to improve its realtime contollability for them to compare with electrical actuators. Electrical actuators on the other hand are by far easier to control than hydraulics, making them the go to option for most robotic designers. However, problems such as overheating of motors as well as their inability to hold torque when not in use makes users look for other alterntives. As more research is done in hydraulics, new breakthoughs are being achieved and better controllability of hydraulic actuators can be achieved.

Various authors have shown that replacing humans in the workplace is not always the best automation solution, but rather a combination of both in some instances proves to be the better solution. Furthermore, more research studies have come to show that hydraulic actuation for robots seems to be the more viable solution for the actuation of legged robots as the system has the highest load capacity of all any systems, although it

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still carries the problem of difficulty in designing and manufacturing the necessary parts.

With technologies like 3D printing becoming more available and cheaper to use, newer and better hydraulic systems may be designed in order to increase reliability as shown in the results obtained. Furthermore, the system did not show stability in some cases where high speed operation is required. This is a consideration for further work.

5.2 Future work:

For future work, there are plans to work on backdrivability of the hydraulic system. It is important to have backdrivability in joints using the instrumented compliance method in order to ensure that the robot is safer to work around humans as well as ensuring that it works in unstructured environments [80].

5.3 Recommendations:

Hydraulics have come a long way from when they were first used. Although their use is still mainly in heavy duty machinery, they are slowly finding their way into robotics. This research has show that they have the ability to increase the power density of robots as well as reducing power consumption in different robots. Furthermore, as the demand for smaller and more powerful robots increases, research in hydraulic actuation is steadily increasing. Different techniques have been suggested in designing actuators that may be used for robotic applications. In this research a detailed framework that shows how to use current existing components to help address power issues as well as in building more powerful robots has been outlined. This proves to be useful as other more effective methods require more resources and specialised machinery such as high precision metal 3D printers .

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Appendix A

Arm mount program:

```
#include <SoftwareSerial.h>
SoftwareSerial mySerial(7, 6); //Bluetooth module Tx & Rx is connected to Arduino #7& #6
const int analogInPin1 = A0;  // Analog input pin that the potentiometer is attached to
const int analogInPin2 = A1;  // Analog input pin that the potentiometer is attached to
int sensorValue1 = 0;        // value read from the pot
int sensorValue2 = 0;        // value read from the pot

void setup()
{
  mySerial.begin(115200);
  Serial.begin(115200);
}
void loop()
{
   // read the analog in value:
   sensorValue1 = analogRead(analogInPin1);
   sensorValue2 = analogRead(analogInPin2);
   // map it to the range of the analog out:
   outputValue1 = map(sensorValue1, 0, 1023, 0, 255);
   outputValue2 = map(sensorValue2, 0, 1023, 0, 255);
   // print the results to the Serial Monitor:
   Serial.print(outputValue1);
   Serial.print(":");
   Serial.print(outputValue2);
   //echo results to Bluetooth
   mySerial.print(outputValue1);
   mySerial.print(":");
   mySerial.print(outputValue2);
   // wait 2 milliseconds before the next loop for the analog-to-digital
```


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```
    // converter to settle after the last reading:
    delay(2);
}
```


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Appendix B

Robot arm program:

```
#include <SoftwareSerial.h>
SoftwareSerial mySerial(7,6);
#include <Servo.h>
#include <PID_v1.h>

#define PIN_INPUT 0
#define PIN_OUTPUT 9

//Define Variables we'll be connecting to
double Setpoint, Input, Output;

//Specify the links and initial tuning parameters
double Kp=0.3, Ki=0.3, Kd=0.07;
PID myPID(&Input, &Output, &Setpoint, Kp, Ki, Kd, DIRECT);
Servo actuator1;
Servo MotorPump;
int motorSpeed = 0;
int x_axis = 6;
int pos = 0;
int powerpin = A0
int reset = 0;    //timer to reset when information is not received
int Xaxis = 0;
String xspeed = "";
String incoming = "";
float axis = 0;

void setup()
{
  Serial.begin(115200);
  mySerial.begin(115200);
  MotorPump.attach(10,1000,2000);
  actuator1.attach(9);
```


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```
  Input = analogRead(PIN_INPUT);
  Setpoint = 100;
  myPID.SetOutputLimits(-50,50);
  //turn the PID on
  myPID.SetMode(AUTOMATIC);
  MotorPump.writeMicroseconds(0);
  pinMode(x_axis,OUTPUT);
  analogWrite(x_axis,128);
  delay(5000);
}

void loop()
{
  while(mySerial.available())
  {
   incoming = mySerial.readStringUntil('\r');
   String f = incoming;
   f.trim();
   Serial.print(f);
   int len = incoming.length();
   pos = 1;
   char s = incoming[pos];
   if (incoming.length() > 9)
   {
        while(s != ':')
        {
              s = incoming[pos];
              if (s != ':')
              {
                    xspeed += s;
              }
               pos++;
         }
        while(s != ';')
        {
              s = incoming[pos];
              If (s != ';')
              {
```


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```
                    yspeed += s;
              }
              pos++;
        }
  }
        Xaxis = xspeed.toDouble();
        Yaxis = yspeed.toDouble();
        Xaxis = map(Xaxis,-11,11,-128,128);
        Yaxis = map(Yaxis,-11,11,-128,128);
        int a = 128 + int(Xaxis);
        int b = 128 + int(Yaxis);
        analogWrite(x_axis, a );
        analogWrite(y_axis, b);
        xspeed = "";
        yspeed = "";
        reset = 0;
}
reset++;
If (reset > 50)
{
  while(!mySerial.available())
  {
    MotorPump.write(0);
    actuator1.write(90);
   Serial.println("STOP!!!");
  }
}
else
{
              Setpoint = analogRead(A5) -300;
              Input = analogRead(A1);
        myPID.Compute();
        int motorSpeed = analogRead(A3);
        actuator1.write(90+Output);
        MotorPump.write(motorSpeed);
        Serial.print(Setpoint);
        Serial.print("---->");
        Serial.print(Input);
```


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```
Serial.print("---->");
Serial.println(Output);
delay(1);
}
```


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