NUST COLLEGE OF
ELECTRICAL AND MECHANICAL ENGINEERING

DESIGN AND FABRICATION OF 6-AXIS ROBOTIC MANIPULATOR FOR PAINT APPLICATION

A PROJECT REPORT

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Abstract

The ever-growing advancement in science has led humans to make their everyday tasks easy and fast. One of the key reasons for achieving milestones in this process was the development of robots, an ideal tireless worker. Since the recorded history, the very concept of robots and robot-like machines can be found. The idea behind undertaking this project was to create a 6-axis robot for efficiently painting surfaces with a better finish, while reducing the human input. Study of previous work conducted in this field was performed and various technicalities involved in undertaking the task were determined. Multiple parameters that impact the end-product were analyzed and carefully selected. Using basic geometry, relationship between work volume, the dimensions of linkages of manipulator, and the size of work cube was found. The CAD model of robotic arm and auxiliary systems were made and refined based on ease of manufacturing and FEA simulations. Various manufacturing processes were used for the fabrication of robotic arm like acrylic sheet cutting and conventional machining processes of turning and milling. To increase ease of maintenance, several standardized components were used. Ultimately, a prototype of 6-axis robot was created. Modular design and six DOF resulted in achieving high maneuverability. Control system was also made for efficient operation of the robotic arm.

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Chapter 1: Introduction

In the 21st century, robots have become a common sight and with each passing day, integration of robots in our daily lives will keep on increasing. In this report, the design and development of 6 axis robotic manipulator will be discussed. First, we will start with a brief background of robots and robotics.

1.1 Background

From ancient times humans were tasked with certain goals in the battles for their survival. Humans have been making things and simple tools for achieving these goals. From Stone Age till now, humans have changed the world drastically. With the advent of technology, humans have reduced tedious tasks to simple ones, just by using machines and tools. 21st century is marked by the use of advanced technologies, to mass-produce products. Usage of robots has become commonplace.

According to Meriam-Webster, the term robot means "*a machine that resembles a living creature in being capable of moving independently and performing complex actions*" [1]. So, in short, anything can be classified as a robot, as long as it performs a human-like task independently. J. M. Selig sums up the definition of robot as, "difficult to describe, but you will know one if you see one" [2]. Robots have become an integral part of today's world. Ranging from their use in manufacturing units in factories, to performing complex tasks in outer space, and waiting tables in restaurants, robots have penetrated every segment of our lives [3]. These are only some of the applications of robots and certainly, the applications and usage of robots are in no way an exhaustive avenue.

6-axis robots are generally used to classify the robots that are capable of achieving six degrees of motion. These 6 degrees of freedom allows the robots to operate in whole 3D space, which is defined by physical constraints of robots. These robots are especially suited for performing complex tasks, involving complex motions. Six axis robots have dexterity comparable to human arm and hence are able to perform the normal functionality expected from humans. For example, 6-axis robots are generally used in automobile assembly lines for welding, painting and to assist in various tasks for reducing the production time.

1.2 Motivation

The 21st century is marked by consumerism. There is an ever-growing demand for products. To fulfill these demands, better production and manufacturing solutions are required. Greater part of manufacturing capabilities of world is under-utilized due to the lack of modern technology and automation. To fill this void, we opted for designing and developing 6-axis robotic manipulator. By making an efficient robotic manipulator, we can provide a better automation solution. By use of automation, we can reduce the wastage of resources. One of the major components of UN Sustainable Development goals is to protect the planet [4]. By the optimized consumption of resources and waste reduction, we can protect the planet. While along the way, we are also achieving the responsible production goal. By reducing the production time and increasing the production efficiency, we are able to fulfill the demands of consumers and enhance their ease of access to affordable and readily available products. So, by providing automation, we are actually increasing the ease of availability of products to consumers and hence are serving the society.

Whenever in the manufacturing sector there is an interaction between humans and the environment, there is a potential chance of human injuries. To reduce these chances of incidents and to ensure a safer working environment, robots have an integral role to play. By increasing the use of robots, we are reducing human exposure to hazardous materials and environment. By doing so, we are preventing potential injuries and fatalities. So, by integrating robots in the manufacturing industry, we are providing humans with a safer work environment, which is the ultimate goal in the field of occupational safety and health. This is in line with the mission of OSHA, "*to ensure safe and healthful working conditions for working men and women*" [5].

1.3 Objectives

Under the scope of our project, our goal is to achieve the following objectives:

1. To design a robotic arm capable of achieving six degrees of freedom
2. To develop / manufacture a robotic arm for paint application
3. To achieving manual control of the robotic arm
4. To designing an automatic control system for the 6-axis robot based on forward kinematics

1.3.1 Six Axis Motion

The goal is to achieve the six degree of freedom motion. 6 degrees of freedom will allow us to achieve any type of motion in three-dimensional space. By employing this technique, a wide variety of complex maneuvers can be performed in 3D space.

1.3.2 Improved Efficiency

The goal of the project is to design and manufacture a 6-axis robot with increased efficiency. Primarily, our focus is to cut short the dead weight of the robotic manipulator, thereby increasing payload to intrinsic weight ratio, so as to reduce the power requirements and enhance the maneuverability.

1.3.3 Speed

Speed is a fundamental pillar of automation. The usage of robots in the industry is primarily on the basis of their ability to perform tasks at high speeds, as compared to humans. With the increased speed, there are greater chances of overshooting the given location and enhanced risk of vibrations. So, another target of the project is to improve the speed of robotic manipulator, while keeping the vibrations to bare minimum.

1.3.4 Repeatability

The feature that tips the balance of power in favor of robots over human-operated machines, is the ability of robots to perform the same task with high accuracy and repeatability. According to Meriam-Webster, repeatability means “to make, do, or perform again” [6]. While author John Craig defines it as the ability of the robot to return to a point that is already taught to it [7]. The ability of robots to perform the same task again and again several times, with the same steps and accuracy is the cornerstone of their existence. So, the goal is to achieve enhanced repeatability and reduce the errors associated with it.

1.3.5 Responsible Production and Waste Reduction

Protecting the environment and Earth is the social responsibility of every human being. So, keeping in mind the responsible production goals set by United Nations, our goal is to reduce the wastage during production and to make an efficient robot, which will further cut short the wastage of crucial resources and increase productivity. Ultimately, the goal is to achieve the objects while taking into account the environmental impact.

1.4 Scope

With the global population increasing every day, the demand for products is also increasing. To cope with this ever-increasing demand, manufacturing needs to be ramped up and automation is the need of the hour. By integrating robots in manufacturing sector, production time can be cut short. Robots, when used in manufacturing, result in more efficient manufacturing and lesser resources wastage. Robots have become an important part of automotive industry. In automotive plants, robots are used in assembly lines, paint shops, and welding units, etc. Usage of robots in these processes of manufacturing have resulted in improving the efficiency of manufacturing drastically. Similarly, robots are finding their application in servicing and maintenance industry. The most famous example being CANADARM 2, the Space Station Remote Manipulator System, a 17 meters long robotic arm present on International Space Station, used for maintenance, moving equipment and handling payloads etc. [8]. All these applications of 6-axis robotic manipulator are of industrial nature. But given the temporal and budgetary constraints, the scope of this project is limited. The project will serve as a scaled-down prototype for a 6-axis robotic manipulator.

The designed robotic manipulator has six degrees of freedom. It is designed to have a working volume of approximately one cubic foot. The robotic manipulator is designed such that wide variety of end effectors can be used with it. For demonstration purposes, we have designed and developed two end-effectors: a universal gripper and a bell atomizer. By using a universal gripper, wide variety of objects can be gripped, and hence robotic manipulator could be used for pick & place applications. In case when bell atomizer is used as an end-effector, the intended use is for automated paint application, as generally done in automotive industry. The salient features of the developed robotic manipulator are:

- High Speed
- Low Vibrations
- Low Weight
- High Efficiency

Chapter 2: Literature Review

Before starting any project, it is essential to study the relevant literature. It helps in getting up to speed in the relevant field and a unique opportunity to get to know new avenues of research. The time spent during this step assists in avoiding catastrophic failures and problems in further stages.

2.1 History of Robotics & Automation

The word robot is derived from a Slavic word called "*robata*" meaning work or worker [2]. While according to another source, the etymology of about robot is of cognation i.e., its presence can be found in German, Russian, Polish and Czech language, used to describe a special type of serfdom, where tenant's rent is paid through forced labor & service [9]. The word robot got its introduction in modern English language through the use of the word by Czech author Karel Capek, in his famous play Rossum's Universal Robots [2] & [9]. That play presents the robot as an ideal, tireless worker, capable of performing every task that humans can do. The only difference between humans and robots is robot's lack of soul. So, from the very beginning, the concept of a robot is that of a perfect worker, commanded by humans, capable of doing human-like tasks, essentially an inanimate anthropomorphic machine. The very concept of robots can be traced back to Greeks and Egyptians, where in pictures, human-like characteristics were given to inanimate objects. Like the Greek legend of Pygmalion, where a statue is brought to life. In 400 B.C., Archytas of Tarentum, an inventor famous for inventing pulley & screw, invented a wooden pigeon that could fly [10]. His famous pigeon is shown below in Figure 2-1. Hydraulically operated statues were commonplace in Hellenic Egypt, during the 2nd century B.C.

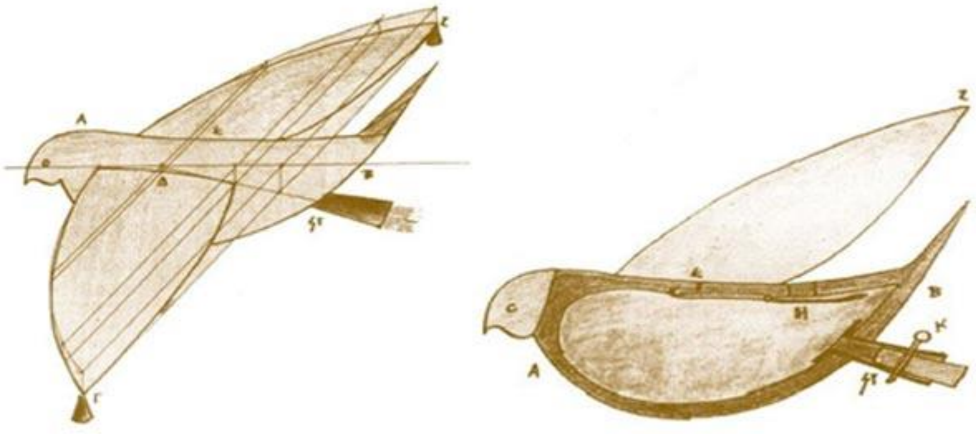


Figure 2-1: Archytas of Tarentum's Steam Powered Pigeon [11]

Around 10th century, mechanical automata emerged. The famous Cosmic Engine, a 10-meter-long clock tower, with mannequins that chimed & played gongs to demarcate hours, was built by Su Song in China in 1088 [12] . An image of Cosmic Engine is shown below in Figure 2-2.

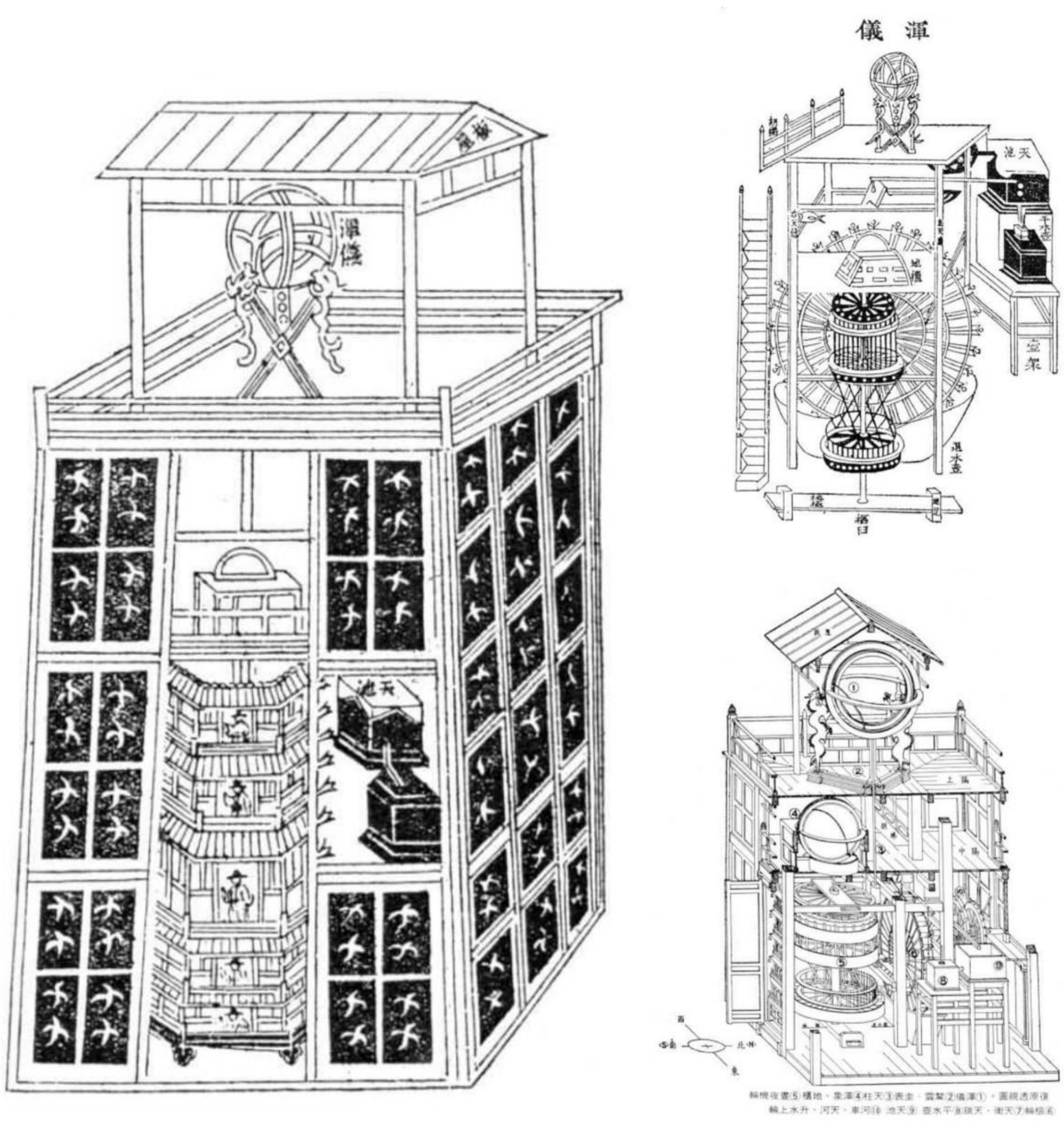


Figure 2-2: Su Sung's Cosmic Engine [12]

The most notable progress in automata came around 1495 when Leonardo da Vinci (1452-1519) made his famous mechanical knight, commonly referred to as Leonardo's Robot [13]. Through Leonardo's notebooks, discovered in 1950, we discovered detailed drawings and depictions of a robot capable of moving its head & jaw, waving arms, and sitting up [13]. Figure 2-3 shows a depiction of what might have been Leonardo's Mechanical Knight.

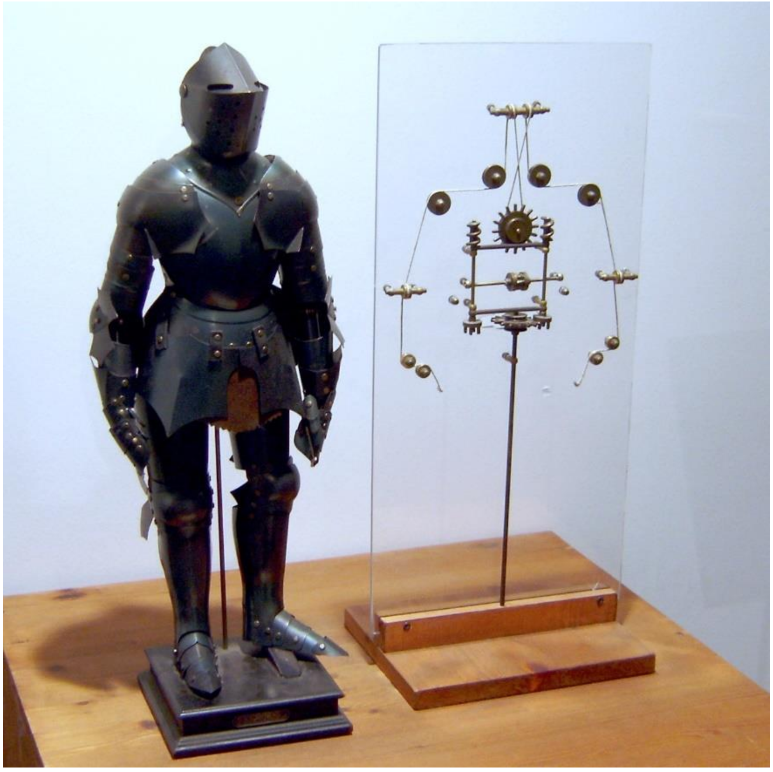


Figure 2-3: Leonardo's Mechanical Knight [13]

The field of robotics gained widespread popularity and kindled a public interest with the release of Mary-Shelley's famous "Frankenstein", a being created by human that ultimately kills its own creator. In the 1950s, an American play writer Isaac Asimov proposed his famous 3 laws of robotics, a simple code of ethics that robots, should follow. According to J.M.Selig, it seems that the term "Robotics" was coined by Isaac Asimov [2]. The 3 laws of robotics are:

- A robot may not injure a human being or, through inaction, allow a human being to come to harm
- A robot must obey the orders given by human beings except where such orders would conflict with first law
- A robot must protect its own existence as long as such protection does not conflict with first or second laws [13]

Later Asimov proposed another law, known as Zeroth Law of Robotics, a law preceding the above-mentioned three laws. The zeroth law state that:

"*A robot may not harm humanity, or, by inaction, allow humanity to come to harm*"

These Asimov's laws serve as the fundamental ethical guiding principles in the field of robotics and artificial intelligence.

2.1.1 From 1920s to 1950s

In 1927, the Japanese came up with a compressed air-actuated robot named Gakutensoku. The purpose of the robot was a diplomatic one. Using compressed air, it was able to write and close its eyelids [14]. Similarly, in 1928, 1st humanoid robot, Eric (The Man of Tin), was invented by W. H. Richards and was displayed at the annual exhibition of Model Engineers Society. Eric had an aluminum body, with 11 electromagnets and a single motor powered by 12 V. Eric could move its head and hand. It could be remote or voice-controlled [15]. Below in Figure 2-4, Eric is shown.

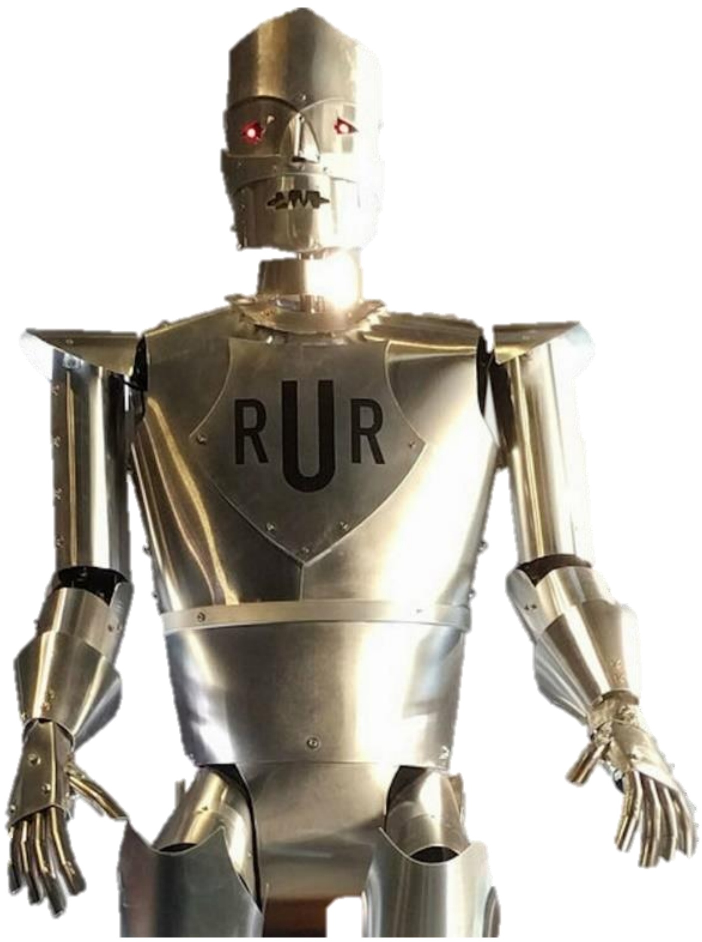


Figure 2-4: Eric, the Tin Man [15]

During the next decade, progress was made in the field of joint modeling. This time period is marked by the earliest design of the industrial robot. The first programmable robot was also invented during this period. The 1940s saw the publication of Asimov’s laws of robotics. The field of cybernetics, the interdisciplinary science of communication & control of machines, was introduced. In 1954, the foundation of modern industrial robotics was laid with the development of Unimate. George Devol created Unimate. It was 1st digitally operated and programmable robot. It was six degree of freedom robotic arm that followed step-by-step digital commands [16].

2.1.2 From 1960s to 1990s

In 1961, the first robot was used in an industrial manufacturing plant. Unimate was installed in General Motors Assembly plant, for retrieving and stacking hot metal die-cast pieces [16]. In 1969, a mechanical engineering student named Victor Scheinman, developed Stanford Arm. It was 1st recognized electronic computer-controlled robotic arm [17]. The next decade was marked with significant development in humanoid robots by the Japanese. 1973 saw the development of WABOT-1, the first full-scale humanoid intelligent robot. WABOT-1 had limb system i.e., it walked using its lower limbs and was able to grab objects using its upper limbs [18]. KUKA a German manufacturer developed a six-axis electromechanically driven robot, FAMULUS [19]. SCARA, Selective Compliance Assembly Robot Arm, was created in 1978. It was a highly efficient 4 axis robotic arm. It was ideal for pick & place applications on assembly line [20]. The 1980s is marked with significant progress in robot transmission technology. With the creation of first direct-drive arm in 1981, a robot with internally contained motors was made, thus eliminating the end of complex power transmission linkages and mechanisms [21].

By the 1990s the field of robotics and interdisciplinary knowledge was significantly developed. So much progress was made that work started on making robots for one of the most critical tasks, performing surgery on humans. John R. Adler rose to the occasion and first robot designed for performing robot-assisted surgery, Cyberknife, was installed at Stanford University in 1991 [22]. Food and Drug Administration (FDA), approved the use of robot-assisted surgery on humans.

2.1.3 From 2000-Present

In 2000, Honda introduced an advanced humanoid robot, ASIMO, capable of running, walking, communicating with humans, interacting with the environment and recognizing humans, environment, voices, and posture [23]. ASIMO is unique in the sense that it was first of its type humanoid intelligent robot, which had such a vast range of intelligent faculties. Shown below in Figure 2-5 is the image of ASIMO. International Space Station (ISS) is the biggest man-made structure sent in space. Something so colossal in size requires regular maintenance and servicing. So, CANADARM2 was launched into orbit along with ISS in 2001. It is a part of the Mobile Servicing System (MSS) employed at ISS. It is 7 joint robotic manipulators having a length of 17.6 meters. This 7 DoF robotic arm weighs 3300 pounds and its duties involve assembly, maintenance, and resupply of ISS [24]. Given below in Figure 2-6, CANADARM2 can be seen in space at ISS.

Figure 2-5: Honda's ASIMO [25]

Figure 2-6: CANADARM 2; Part of Mobile Servicing System at ISS [24]

In Feb, 2016 a Hong Kong based company called Hanson Robotics developed a social humanoid robot, Sophia. It is one of the most intelligent and sophisticated humanoid robots ever built [26]. According to the designer of Sophia's brain, it is cutting-edge in terms of dynamic integration of perception, action & dialogue.

2.2 Types of Robots

In this section, we will be discussing the types of robots based on the degree of freedom that robot allows and the type of motion that can be achieved. So, on this criterion, the robots can be broadly classified in following categories:

2.2.1 Cartesian Robots

Cartesian or rectangular robots are robots that are capable of moving linearly in a straight line, along three axes i.e., x, y, & z [27]. These axes are called Cartesian coordinates and hence the name Cartesian robots. These robots have a cube-shaped workspace and are very easy to program and use [28]. These are the most commonly used robots. They are ideal for pick & place applications. The work area of such type of robot is similar to that of an over-head crane, one generally used in foundry. Figure 2-7 shows a Cartesian robot.

Figure 2-7: Example of the Cartesian robot [28]

2.2.2 Cylindrical Robots

If the robot has both linear and rotary actuators, such types of robots are known as cylindrical robots [28]. These robots allow the arm to rotate about the base or shoulder and the other two axes allow in-out and up-down motion [27]. The workspace generated is the space between two concentric cylinders of the same height. The internal cylinder denotes the fully retracted arm and outer cylinder represents fully extended arm. For specifying the location of the end-effector, angle theta (ϴ), arm length (R) and up-down axis (z) should be defined. Cylindrical robot's motion is analogous to a construction crane placed on top of a building [27]. A depiction of cylindrical robot is shown in Figure 2-8.

2.2.3 SCARA

Selective Compliance Assembly Robot Arm (SCARA) is a type of robot allowing motion in x, y, z coordinates & rotation in a plane parallel to the base of the robot [27]. The work area generated is the same as that of cylindrical robots, but SCARA robots provide an edge, as it allows reach around obstacles. Secondly, SCARA robots are usually more compact [27]. It is also observed that this type of robots is generally quicker [28]. Figure 2-9 shows a SCARA robot.

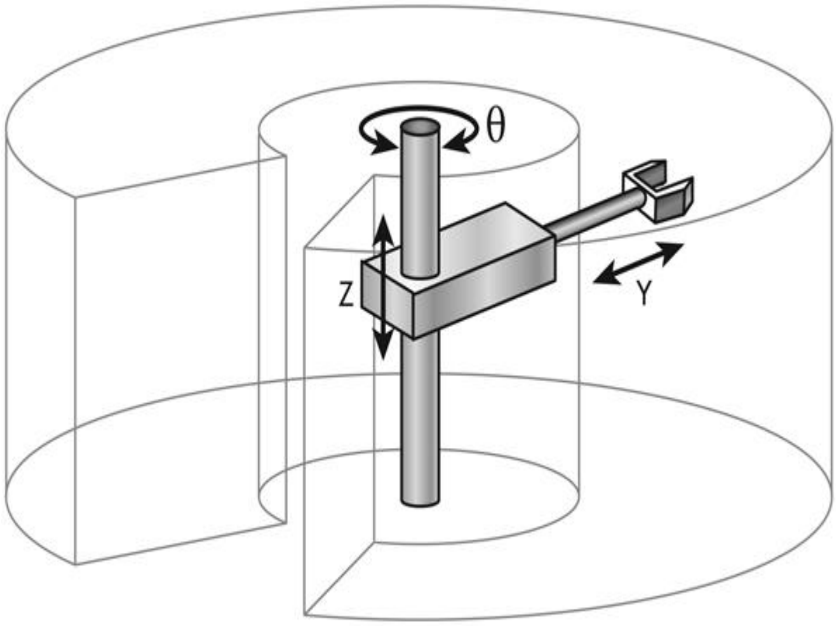


Figure 2-8: Example of cylindrical robot [29]

Figure 2-9: Example of SCARA robot [28]

2.2.4 Delta

Delta robots are the fastest and most expensive among the given types of robots [28]. It is based on the idea of using parallelograms to create a parallel robot, allowing three translational and one rotational degree of freedom [30]. Speed and precision are the cornerstones of delta robot's design. Delta robots are ideally suited for pick & place applications and are widely employed in assembly lines and packing stages in various manufacturing plants. An example of a delta robot is shown below in Figure 2-10.

Figure 2-10: Example of Delta Robot [30]

2.2.5 6-Axis

6-axis robots are robots having six degrees of freedom, allowing the robot to undergo versatile motions [28]. These robots are fairly quick but require complicated programming and controls. 6-axis robots can be scaled from toy level to large ones used in assembly lines. Figure 2-11 shows six axes of robotic manipulator. This type of robot will be further discussed in the next section.

Figure 2-11: Example of six axis robotic arm [28]

2.3 6 Axis Robotic Manipulator

6-axis robotic manipulator is a type of revolute coordinates, articulate, jointed arm, or anthropomorphic robot. Hence, such types of robots are humanoid in shape and mimic the human arm [27]. Such types of manipulators are characterized by the presence of three revolute type of joints, specified according to Reuleaux Lower Pair [27]. According to Reuleaux, a Revolute or R-pair is generated by any surface of revolution [2]. These robots provide largest working area for the smallest floor space. This quality makes them better suited for paint applications. Generally, these robots use direct drives and are controlled through a closed loop system, using servo motors. The workspace generated by such an arm is the volume created between two concentric spheres. Due to physical constraints present, full 360 degrees rotations are not possible [27]. So, in reality, the work space lies between two concentric cylinders. The outer cylinder is swept by the arm when it is fully extended. And the inner cylinder is swept by a fully retracted robotic arm. Kinematics is the study of possible movements and in robotics, it is important to know how the system will move. If by using the joint variables we calculate the final orientation and position of the end-effector, it is known as Forward Kinematics [2]. On the other hand, if by using the specified end-effector's location and orientation we try to calculate the joint variables, it is known as Inverse Kinematics [2]. Here the term joint variables denote the Euler Angles, three angles that are used to describe the rotations of the body. The Control system for the robotic manipulator can be designed based on any above-mentioned kinematic approaches. For each desired final configuration, there are number of methods and it is dependent upon operator discretion. Usually, the algorithm used first converts the entered x, y, z coordinates into respective joint angles and then it follows one of the several options to reach designated place in space [27].

2.4 Paint Applications

Painting is an essential part of manufacturing process. Apart from providing the necessary pleasing aesthetic outlook, it also serves many other technical purposes. One of the most prominent advantages of using paints is that it serves as the first layer of defense against harsh environmental conditions. Secondly, it assists in curbing corrosion. So by using paints, we are improving both the appearance and durability of the product [31]. Paints are widely used in automotive industry. According to an estimate, automobile paint shops are major energy consumption areas in automotive industries, in addition to being the most expensive part of the assembly process [32]. Paint jobs constitute 30% to 50% of the total manufacturing cost of an automobile and about 70% of the total energy cost associated with assembly plants [32].

Most of the spray booths present in automotive industry are very small in size, around 5 meters wide [33]. Further, due to the presence of volatile solvents, a potentially hazardous working environment is created. Furthermore, due to stringent workspace conditions like dust-free workspace, temperature-controlled environment, the paint booths are highly inconvenient for the operator [33]. Apart from these hazardous working conditions, the operator is subjected to low force movements, involving actions like twisting, pinching, and flexing, which are known causes of Repetitive Strain Injuries (RSI) [34]. According to a survey conducted by U.S. Bureau of Labor Statistics, RSI caused approximately 476,700 non-fatal injuries alone in 2015 [34]. Considering all of these potential safety hazards, the use of robots for paint application was an ideal candidate for robots' usage in the industry. It is generally accepted that spray-painting robots must have the following characteristics [34]:

- High manipulator motion dexterity
- Compact wrist
- Small payload
- Relatively low accuracy & repeatability
- Large working volume with a small base

High manipulator maneuverability allows the manipulator to reach difficult-to-access locations. By using a compact wrist, the manipulator can paint inside small openings. Generally, repeatability of 2 millimeters is considered sufficient for paint applications [34]. As the paint applicators are usually lightweight, small payload capacity manipulators are ideal for paint jobs. In addition to these characteristics, manipulators used for paint applications must follow National Fire Protection Association guidelines in standard related to spray application using flammable or combustible materials, NFPA 33 [35]. According to this standard, intrinsically safe electronics should be used in robotic manipulators [35]. These stringent constraints are applicable because of presence of volatile combustible organic solvents that are generally used in paint applications. By using robots for paint applications, we can save in the following areas [35]:

- Exhaust: due to precise paint application, lesser amount of Volatile Organic Compounds (VOC) is present in the exhaust
- Overspray: reduced amount of paint is used
- Reduced Rework: precise paint application initially reduces the need for reworking

As a result, paint usage is reduced by around 15-30% [35]. Instead of using conventional spray guns for paint applications, rotary bell atomizers are used in automotive painting. The working principle of a bell atomizer is that a cylindrical body is rotating at very high speeds, approx. 20,000-

60,000 rpm, when the paint is injected from the center of the base. As the paint molecules move along the cylinder, their kinetic energy increases and when they reach the opposing end of the cylinder, paint is atomized in the form of fine mist. Using bell atomizer results in 20%-40% in paint savings [36]. Rotary atomizers have a transfer efficiency of about 95%. By using robots for paint applications, we prevent the operator from being exposed to hazardous chemicals and avert RSI. In addition to it, a significant about of paint is saved, which is both economically and environmentally desirable. Ultimately, the usage of robots in paint booths results in better paint jobs.

2.5 Universal Gripper

Gripping different types of objects for pick and place applications is one of the basic desired features in robots. An ideal gripper is one that can imitate the gripping and pick-and-place capabilities of a human hand. As human hands are capable of picking a wide variety of objects, irrespective of their objects shape [37]. Although a wide variety of grippers are available, but they are usually exclusive to handle a certain type of objects. So, if such grippers are used, a specific type of gripper will be used for specific objects. Hence the need arises for the development of a universal gripper that can closely imitate the human hand. The passive type of universal grippers requires minimal control for grasping objects [38]. They have a unique ability to conform to an object’s shape. The universal gripper consists of a single mass of granular material enclosed in an elastic membrane, rendering it an ability to conform to an object’s shape and then grip can be tighten by creating a vacuum [38]. By using positive pressure, the grip can be loosened and the gripper will return to its original state. A universal gripper is shown below in Figure 2-12.

Figure 2-12: Universal jamming gripper [37]

Chapter 3: Design Consideration

Robots are developed for doing some certain tasks. The designer of the robot has an exact idea about the requirement and minimum criteria that need to be met for the successful completion of the project. So, in reality, every project is constrained and controlled by some specific parameters. These parameters need to be carefully adjusted and considered for the successful development of robot, for the desired purpose. Hence, these parameters are known as design considerations; parameters that need to be considered during the design stage. In the succeeding section, some of these design considerations are discussed.

3.1 Weight

Compact, lightweight and efficient machines are the demand of the 21st century. The robotics industry also follows the same trend. With the advancement in technology, old and bulky robots are replaced by compact and lightweight ones. This has resulted in improved efficiency of robots.

Following are some of the variables that are dependent upon the weight of the robotic manipulator:

3.1.1 Power Requirements

Every machine requires power to work and perform the designated tasks. Generally, in case of robotic manipulators, the movements of robots are powered by motors or some kind of actuators. As the size of robotic manipulator increases, larger actuating/moving forces are required. Usually, greater the amount of force required, larger the size of the driver is and consequently, more weight is added. So, it is kind of a perpetual cycle, resulting in an increment in the net weight of the robotic manipulator. Secondly, larger the force required; more energy is required for the driver. Hence, an increase in weight results in poor energy efficiency.

3.1.2 Center of Gravity

The Center of Gravity (CoG) of a body is the point at which the whole weight of the body acts. Theoretically, if a body is pivoted at CoG, the body will be in a balanced state. Balancing the robotic manipulator is very important for its smooth operation. Center of Gravity of the body is the function of the geometry of the body. As in the case of the robotic arm, the shape of the whole arm is changing continuously, due to the moving of linkages, the center of gravity is not a single point. Rather in such a case, the center of gravity changes continuously. It is a known fact, that for stability, following two conditions are ideal:

- Lower center of gravity
- Wider base

In order to ensure stability & smooth operation of robotic manipulator, special attention was given to the center of gravity.

3.1.3 Compactness

One of the indicators of huge technological progress made in the 21st century is the compactness and smaller size of modern machines being designed. Compact robots are preferred due to the spatial constraints and better efficiency. So, ordinarily, when a robot becomes bulky, compromise occurs on the compactness of the robot.

3.2 Payload Capacity

Robotic manipulators are designed to carry a designated amount of payload. The whole design and controls are optimized for that specific amount of load. If the robot is used for an increased amount of payload, it can result in some problems. Although the manipulator might work, because of incorporation of design factor of safety, but the functioning will be below par. Payload weight plays an important role in manipulator design. Most modern robotic manipulators support a wide variety of end effectors and such robots are capable of performing a wide range of tasks. So, payload weight may vary depending upon the weight of the end-effector and its auxiliary systems. For example, in case of using a jaw gripper, the weight of the gripping structure, its powering system and the weight of the object it is picking constitutes the total payload weight. Payload weight plays an integral role in the development of robotic manipulators. Greater payload weight would require more sturdy linkages and would result in bulky robots.

3.3 Work Space

Every robot is designed to perform a specific set of tasks. There are some physical constraints present that restrict the creation of a universal robotic arm. So, every robotic arm is designed to operate in a certain work space. Work space is the specified volume within which the robotic manipulator can reach anywhere. Workspace plays an important role as it directly affects the length of linkages of the robotic manipulator. So, indirectly the variation in the workspace results in changing linkage length, the intrinsic weight of the robotic manipulator, and the stresses produced due to torque and weight. If we intend to increase the workspace, longer linkages length would be required. This in return yields a bulkier robotic arm. Due to the increased length, the torque produced will significantly increase, due to increase in moment arm. Consequently, higher stresses are generated and stronger materials are required to sustain these stresses. Prior to starting the design of robotic manipulator, the exact required working space should be known. This will help in avoiding redundant and complex designs.

3.4 Materials

As stated in the above section, weight plays a crucial role in the proper functioning of robotic manipulator. So, with that in mind, appropriate material must be selected for the designing & manufacturing of robotic arm. Some of the factors that play a critical role in material selection are following:

3.4.1 Low density

Usually, a material having low density is required. Density is the measure of the body that tells us how much a unity volume of material weighs. Material having low density means that for the same specified volume, the material will weigh less. Hence, by choosing a low-density material, we can keep the weight of the manipulator to bare minimum

3.4.2 Good Strength

Apart from having low density, the material should also have considerable strength. When the robotic manipulator is fully stretched, the lower linkages will be subjected to a considerable amount of torque. This torque is considerably high given the fact that apart from having large moment arm, the force generated due to the payload mass and intrinsic mass of robotic manipulator is high. So, to sustain all these stresses, the material selection must be so, that it has enough strength to bear all the stress.

3.4.3 Ease of Manufacturing

As is the case with every project, the manufacturing facilities available are restricted. In addition to that, some manufacturing processes cannot be used due to the complexity of the part involved. So, our desired material must be so that part of moderate complexity may be manufactured, using the available manufacturing facilities.

3.4.4 Economics & Accessibility

Economics plays an important role in every project. So, while designing the robotic arm, economics need to be considered. The goal was to select a material that was within the allotted budgetary limits. Access to the material was also be considered. Selecting novel materials that were difficult to access & were not readily available, were avoided at all costs. Although selecting such materials was enticing during the design stage but it would have resulted in major problems during the manufacturing part of the project.

3.5 Motor Selection

With the creation of the first direct-drive robotic arm in 1981, motors have emerged as the first choice for driving robotic arms. This huge success of motors in robotics is owed to the fact that motors do not require complex and long power transmission mechanisms. Secondly, high torque motors are available in considerably smaller sizes. Selecting the right motor for driving the robotic arm was very important, for smooth operation of the arm. A trade-off was made between the torque produced and the size, and weight of the motor. The type of motor used is another important factor. With options available between servo and stepper motors, the designer should make a critical decision, based on the accuracy offered, the type of control system used, holding torques provided, requirement for auxiliary devices, and minimum rotation allowed [31]. So, motor selection was made by keeping in mind these variables and making an appropriate tradeoff.

3.6 Safety

Everybody has a role in ensuring the safety of oneself and each other. According to Asimov's laws of robotics, safeguard for humans must be a fundamental feature in robot design. Robots must have in-built features that would prevent them to become a potential hazard to humans. Although the importance given to safety varies from person to person, an ideal way to create awareness regarding robots & safety is Three Rs of Robot Safety [27]:

"**R**obots **R**equire **R**espect"

The generally established order for safety importance is following:

Human Safety > Robot Safety > Safety of Other Equipment

Humans are at great risk at following three intervals during the robot life:

- During Robot's Training & Programming
- During Maintenance of Robot or Auxiliary Equipment Installed
- During Normal Operation

3.6.1 During Training & Programming

While training or programming a robot, a single wrong movement of robot can be catastrophic. Programming a computer is relatively an easy task, as any mistake will only result in a wrong answer. While programming a robot, a single error may lead to such a maneuver by the robot that may cause critical injury to humans or it may damage the robot itself [27].

3.6.2 During Maintenance

The maintenance of robots is another potentially hazardous working environment for humans. While servicing or performing maintenance on a robot, usually humans are in close vicinity of robot. Any wrong motion by an already malfunctioning robot may be disastrous. So, generally, it is an established industrial practice that a robot must power itself down, when it detects human presence close to the predefined safe boundary.

3.6.3 During Operation

The robots that are generally used in industrial settings are very fast-paced. Any mistake on worker's behalf or malfunctioning by robots can cause serious injuries and it may be potentially lethal. So, apart from creating awareness among workers, sufficient safeguards must be intrinsically present in robots to prevent such incidents, as the saying goes, “prevention is better than cure”.

Robots may harm people in three ways:

- Through impact
- By pinching
- By pinning

Some of the safety features that used are:

- Indicators to depict whether the robot is powered on or off
- Sensors to detect human presence and motion
- Creating safety fences and meshes around work space
- Integrating emergency stop buttons

Ensuring safer working environment is the duty of everybody. Care must be taken to incorporate safety features. Secondly, local safety codes were followed.

Chapter 4: Design

The design was done after studying and analyzing designs of different Arduino-based and CNC-based industrial robots, having different placements of axis and shapes, intended to be used for different applications. The design was made after studying the pros and cons of the robots currently operational in industries. A simple but reliable design was opted for. The selection of axis of motion was such, so as to ensure maximum mobility and control over the movement of the end-effector.

4.1 Work Space

As mentioned previously in Section 3.3, work space is an important parameter of manipulator design. In case of six-axis robots, the work area formed is between two spheres, representing retracted and fully extended robotic arm. So, the work area formed is cube encompassed by above mentioned two spheres, as shown below in Figure 4-1. So, by using the basic geometry and trigonometry, the relationship between work volume and length of linkages of robotic manipulator can be found easily.

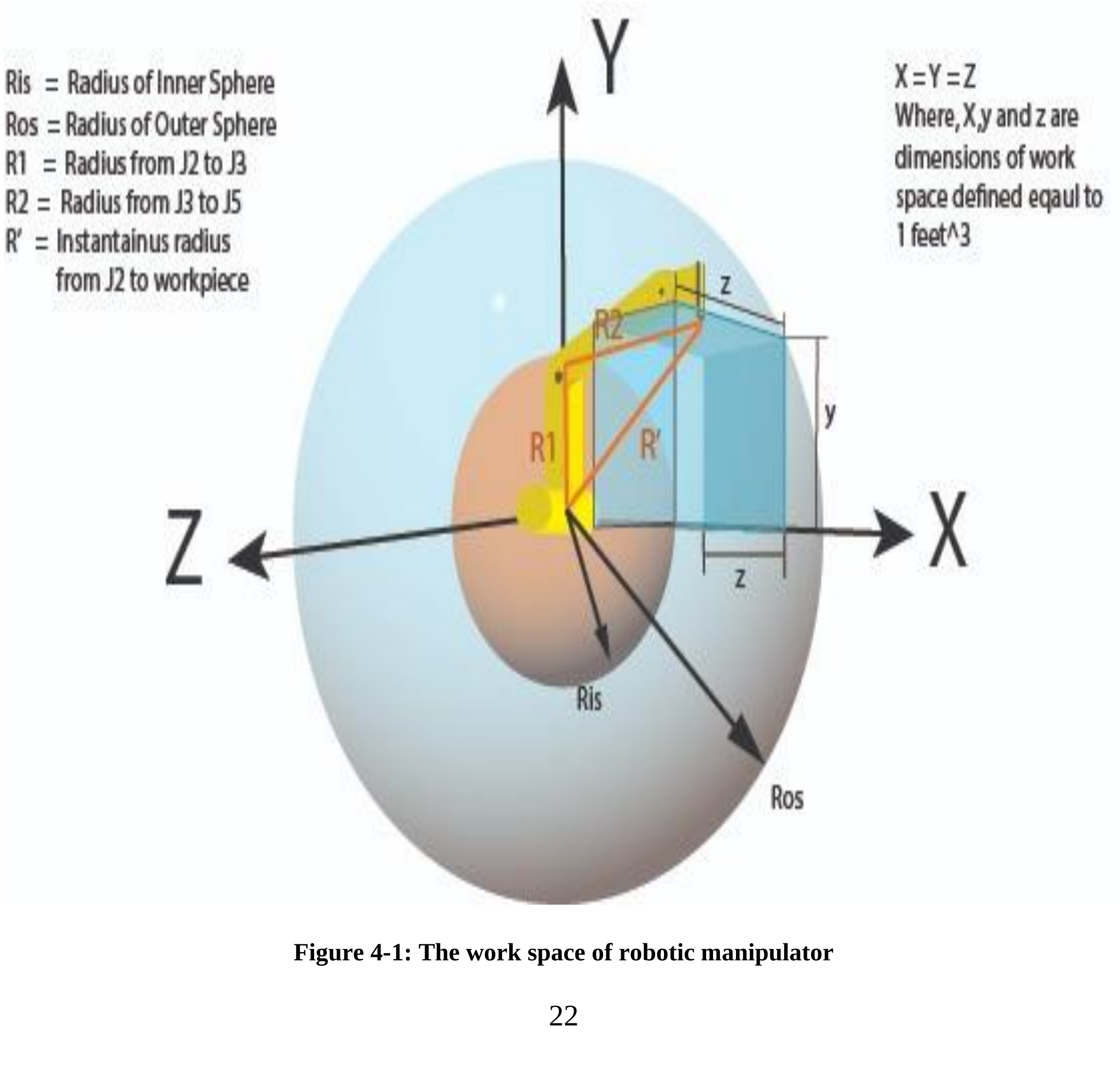


Figure 4-1: The work space of robotic manipulator

Then by using geometry simplifications and manipulations, it was concluded that:

$$Ri^2 = a^2 + x^2 \tag{4.1}$$

$$Ro^2 = 6a^2 + 4ax + x^2 \tag{4.2}$$

$$V = \frac{4}{3}\pi Ro^3 - \frac{4}{3}\pi Ri^3 \tag{4.3}$$

Ri = Radius of smaller sphere

Ro = Radius of larger sphere

V = Work Space Volume

a = Dimension of cube

x = Distance between robot base and cube face center

The detailed calculations were performed using Mathcad. The Mathcad sheet is given in the appendix.

4.2 The Robotic Manipulator

According to unit calculations, the moment at the bottom was found to be 5.5 N.ft and it served as a base for motor selection. After multiple optimizations, the servo “MS24” was selected to operate in pair at the bottom-most axis and the same servo was used at the elbow joint. For remaining joints, servos “MG996R” were selected, owing to their low weight. Secondly, these servos better suited the low torque requirements, towards the free end of the manipulator. The mid-arm twist motion was achieved by using bearing assembly, comprising of 6702 standard bearing, having 21mm housing and 15 mm bore diameter. The bearing was selected due to its dimensions and stress-bearing capacity. The same bearing was also employed for second time at bottom rotational axis.

The links or arms themselves serve as structural components. Ease of manufacturing and availability were important deciding factors for material selection. So, in this hunt for material with low cost and ease, and flexibility in manufacturing, PVC was selected. The standard PVC pipes are readily available, having low cost and low density. The pipes used were of 1-inch internal diameter and 1 5/16 ‘outer diameter. The pipes with 80g/ft. linear density were chosen due to their strength as compared to low density ones.

All the components are designed to be joined with the help of fasteners and rigid ones using chemical fastening techniques. The whole robot can be covered in plastic sheets to protect vital components from paint particles in the air. So, the whole design revolves around minimum running and manufacturing cost, ease in manufacturing, working and operation. The robot is designed to be used as a training robot i.e., designed for people and workers having first interaction with robots. The robot has versatile applications; coating, painting, sorting (pick-and-place), or any other task, with an appropriate end-effector and control system.

4.3 Stress Calculations

As with every mechanical design, ensuring that the product does not fail and cause damage, is essential. For calculating the stress acting upon the robotic manipulator and factor of safety, first, the nature of loading was considered. As the robotic manipulator is constantly changing its shape and location, finding stress profile for every possible option was very tedious. So, to ensure safe design of product, two potential high-stress orientations were identified.

In the first scenario, consider that the robotic manipulator is fully extended and horizontal. In such a state, the manipulator essentially acts as a beam. The assumed beam will have distributed loading due to the weight of the manipulator and a point load at the extreme end, depicting the end-effector. The probable failure can be caused due to bending of the beam. So, to ensure the safety of the product, bending stresses are calculated using equation (4.4). Factor of safety can be determined by calculating Von Misses stresses using equation (4.5) and then using this value in equation (4.6).

$$\sigma = \frac{Mc}{I} \tag{4.4}$$

$$\sigma' = \frac{1}{\sqrt{2}}\sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau^2{}_{xy} + \tau^2{}_{yz} + \tau^2{}_{zx})^2} \tag{4.5}$$

$$n = \frac{S_y}{\sigma'} \tag{4.6}$$

The second probable orientation suspected for failure is when the manipulator is fully extended and is vertical. In such a scenario, the manipulator acts as a column and is susceptible to buckling. The goal once again was to prevent failure and Von Misses Theory was used for the calculations. By using this technique, it was observed that the loads for which the manipulator was being designed, will not result in failure, in both scenarios. For finding the stress distribution along the length of the manipulator, Finite Element Analysis (FEA) was used. The simulation was performed using CREO Simulate.

In order to reduce the required computational power, for performing the simulation, the complex features of manipulator were replaced by a simple prismatic beam. The beam will have a circular cross-section, same as that of linkages of manipulator, having same diameter and net length. Although various materials are involved in the design of manipulator, it is assumed that the analogous beam is composed of PLA support & PVC beam. The results obtained from simulations are: In case of manipulator being fully horizontal and extended, the maximum stress is observed at the base of manipulator i.e., J2 in this case. The distribution of stress is clearly shown in Figure 4-2.

Figure 4-2: Stress for fully extended horizontal manipulator

Similarly, the base is under maximum stress when manipulator is in vertical position. In such a scenario, the stress distribution is shown in Figure 4-3.

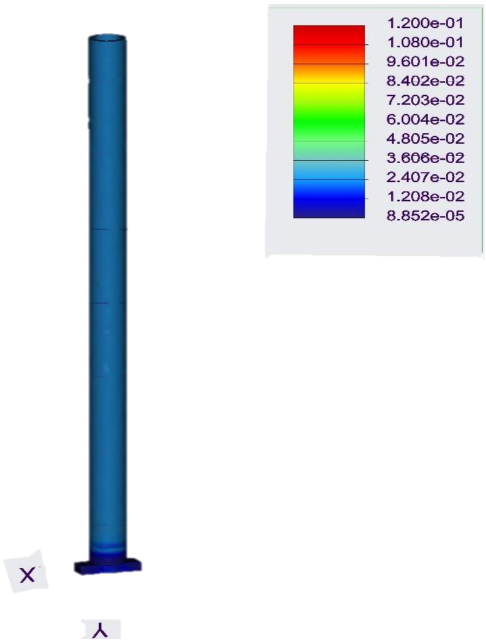


Figure 4-3: Stress distribution for fully extended manipulator

It is clear from the simulations performed, the support of beam i.e., J2 for robotic manipulator must be designed so that it could sustain the stresses acting on it. This was considered in the design stage and hence the final design of manipulator incorporated this particular fact, to prevent failure of the manipulator.

4.4 Control System Working

A modular control system was designed to provide ease in up-gradation and maintenance. Consequently, the control system can be divided into three subsystems namely remote input, driver and motors unit. The first unit is responsible to take user code or Keypad input and encode it into ASCII for Serial Communication with Driver. The Serial Output from the remote unit is decoded in driver and is used to call specific case, which then overtakes the processing operation and sends input to the motor unit. Motor unit works in a close feedback loop and returns a value upon completion of operation. The complete summary of relationship between various components involved in controlling of manipulator is shown below in Figure 4-4.

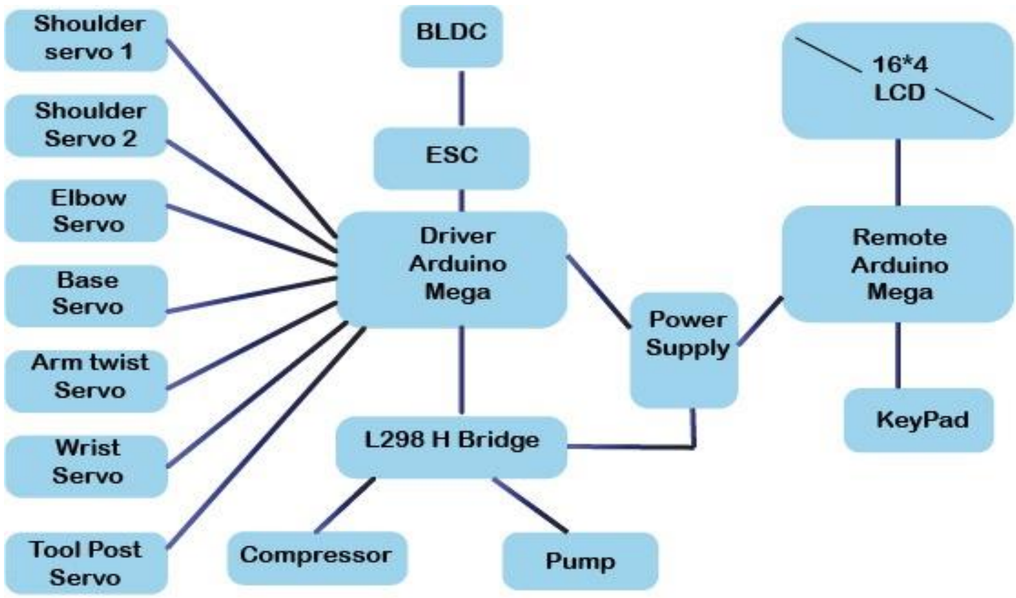


Figure 4-4: Connection scheme for control system

4.4.1 Subsystems

Three Subsystems in which the control system was divided are as follows:

- Remote Input
- Driver
- Motor

Overall, the components that constitute the control system of robotic manipulator are mentioned in Table 4-1.

Table 4-1: Components of control system

Component	Quantity
MG996 R	4
DS3218	3
L298 H Bridge	1
ESC 30A	1
BLDC	1
3*4 key Pad	1
16*4 LCD	1
Arduino Mega	2

Details about subsystems and components involved in operation of each subsystem are:

4.4.1.1 Remote Input Unit

User interactive component was named as Remote Consisting of an Arduino mega with 3*4 Key pad and LCD display and an extended cable for direct input from pc. The data transfer was done by wired Serial communication, having capabilities to be upgraded to wireless RF (Radio Frequency) communication by hardware installation. System was tested for wireless communication and is capable of handling wireless data transmission from remote input unit to driver unit, a stationary unit present at working end. A wired communication option is also provided and is suggested for indoor environment to avoid noise caused by other devices in RF communication. The remote was programed to take custom code and sent it as serial input through pc. The Code was generated to be a combination of 0-9 numbers and (* and #) as special characters. The code was then encoded as serial data, for transmission. In addition to code, the system was also designed to support direct manual input. Direct Manual Input feature was introduced to facilitate user by providing direct manual control of motors for adjustment and zeroing of end-effector. The wiring of Arduino Mega at remote input end was done in the pattern as indicated in Table 4-2.

Table 4-2: Wiring legend for remote input unit

Pin No.	Connection	Pin No.	Connection
Vcc	5V in from power Supply	10	Keypad Column 1
Gnd	To Common Ground	11	Keypad Column 2
1 TX	For serial out	12	Keypad Column 3
9	Keypad row 1	20 SDA	To LCD SDA port
8	Keypad row 2	21 SDL	To LCD SDL Port
7	Keypad row 3	5V	To LCD Power
6	Keypad row 4	GND	To LCD Ground

4.4.1.2 Driver Unit

The control component at manipulator end was named Driver Unit. The driver unit was assigned tasks of controlling all seven servos, controlling speeds and on/off operations of BLDC, compressor and pump using L298 Motor Driver. Driver unit basically consists of Arduino Mega programmed to call pre-defined cases, which then process data and send position information to motors. The main duty of the driver unit is to control motors in accordance with input data and predefined cases. Mega was attached to L298 H-Bridge to control the pump and compressor. L298 not only provided speed control but also functioned as a 12v relay. BLDC is controlled by driver by providing value of speed to ESC (Electronic Speed Controller) which then controls the BLDC output. The wiring scheme is represented below in Table 4-3.

4.4.1.3 Motor Unit

The motor unit consists of 3 closed-loop servos, 4 continuous rotation servos, BLDC, controlled by 30A ESC, & a compressor along with a pump. The motor unit being the only part giving physical output and response, was one of the crucial parts of the control system.

Table 4-3: Wiring legend for driver unit

Pin No.	Connection	Pin No.	Connection
Vcc	5V in from power Supply	8	Arm Twist Servo
Gnd	To Common Ground	7	Wrist Servo
0 RX	For serial in	6	Tool Post Servo

18	Shoulder joint Servo 1	50	Compressor On/Off Switch
19	Shoulder joint Servo 2	51	Pump On/Off Switch
10	Elbow servo	5V	To Power L298
9	Base Servo	52	BLDC Speed Control

The final simplified sketch of manipulator is illustrated below in Figure 4-5.

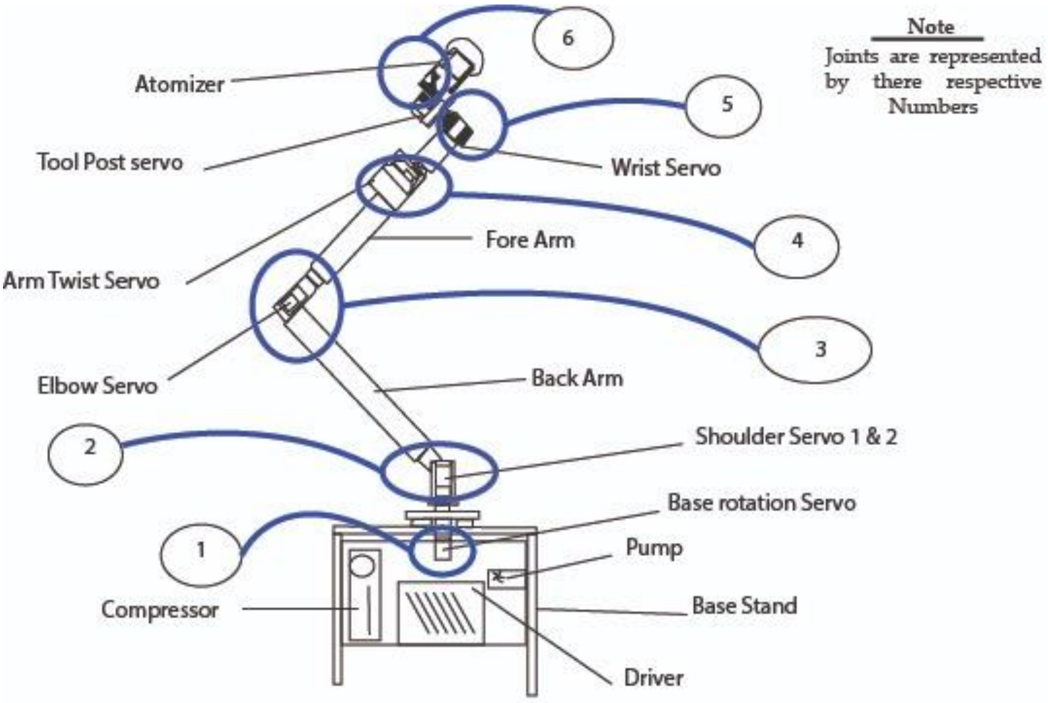


Figure 4-5: Simplified sketch of designed robotic manipulator

4.5 Code

Complete coding of the project was done using Arduino IDE. The logic was developed and two separate codes were written, one for the driver i.e., unit directly controlling motors, and one for the remote input unit, responsible for calculations and sending data to the driver unit, for motion control. The details of algorithm developed for this task are explained below.

4.5.1 Driver Algorithm

The main focus of driver algorithm was to control motion of motors, by defining angular motion values for them. 50 increments were given to position-controlled servos. The tough part was to control continuous rotation servos. This was done by using Pulse Wave Modulation (PWM), a technique to control output motion by mapping the motion of motor with the width of the signal i.e. the amount of time value is high. To achieve precise control of continuous rotation servos, they were fine-tuned to give 50 increments in motion with 100 milliseconds of signal width. Compressor, pump and BLDC were programed to start and shut down in a pattern to make sure no residual paint is left in the atomizer that may get stuck. In starting condition, cone was given head start, followed by paint and air at the end. However, while shutting down, paint is the first one to get cutoff, then air and at last BLDC, making sure all paint from cone is removed, before BLDC shuts down. BLDC speed was set after iteration, to provide smooth operation. BLDC was fine-tuned to ensure homogenous mass transfer from cone to work piece. Delays were added to ensure low data loss and complete input information, before any action, to ensure user safety and safety of equipment itself, preventing overheating due to continuous operation. Driver unit was programed to use the above-described functions on demand by the remote. This demand was received via serial communication, which was first decoded and then acted upon. Serial Input was received using the RX pin of Arduino. The driver unit can also be directly controlled by a computer, via serial input, to operate as a CNC.

4.5.2 Remote Unit Algorithm

Remote was programed to map keypad and values are assigned to keys. The mapped values were encoded as serial output. Serial output was then transmitted by wired communication, using the TX port of Arduino. The entered information, which was being transmitted, could be verified, in real-time, from LCD. For this task LCD library named Liquid_Crystal_Display.h was used [41]. The remote unit is responsible for performing all calculations and then transmitting serial data to the driver unit.

Chapter 5: Fabrication

Fabrication is an essential component of any project, as it serves as a proof of concept. Fabrication is the test of the design’s working, whether the design is just an abstract idea or it is capable of being manufactured and assembled. For this project, following are the major assemblies that needed to be manufactured:

- Robotic Arm
- End Effectors
- Stand

The whole process of fabrication is explained in detail below:

5.1 Robotic Arm

Design & fabrication of robotic arm is the major focus of the project. The robotic arm comprises of different linkages, coupling mechanisms and the housings of drive mechanisms. For the fabrication of linkages, flexible, non-schedule PVC pipes were used. This decision was made as, apart from being light-weight and having relatively better strength, these PVC pipes are economical and readily available. So, instead of manufacturing cylindrical sections, we employed lightweight pipes. A single length of pipe, i.e., 13 ft. of pipe was bought and by using the hand saw, appropriate lengths of linkages were obtained. These linkages are shown below in Figure 5-1. The robot is designed such that these cuttings of pipes serve as a linkage between consecutive manipulator joints.

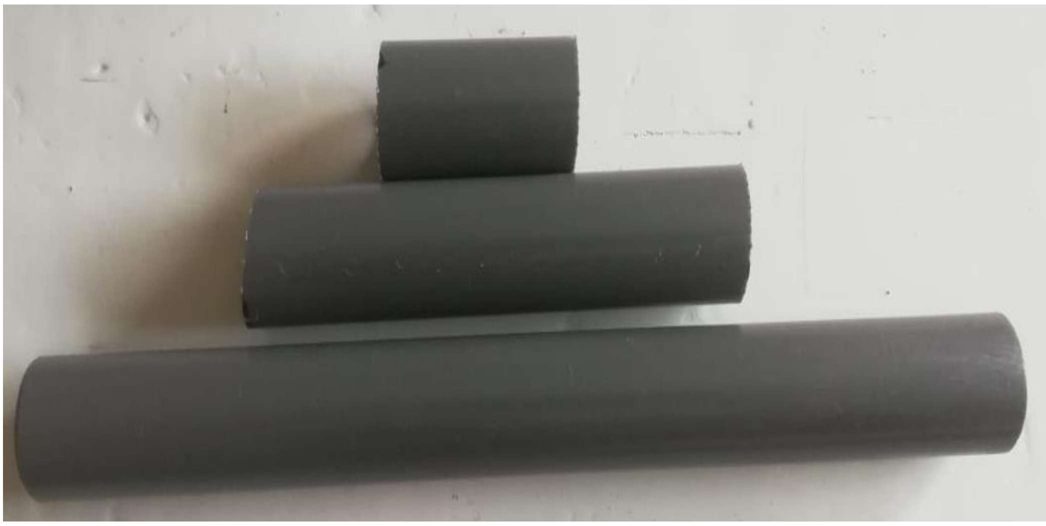


Figure 5-1: PVC Linkages

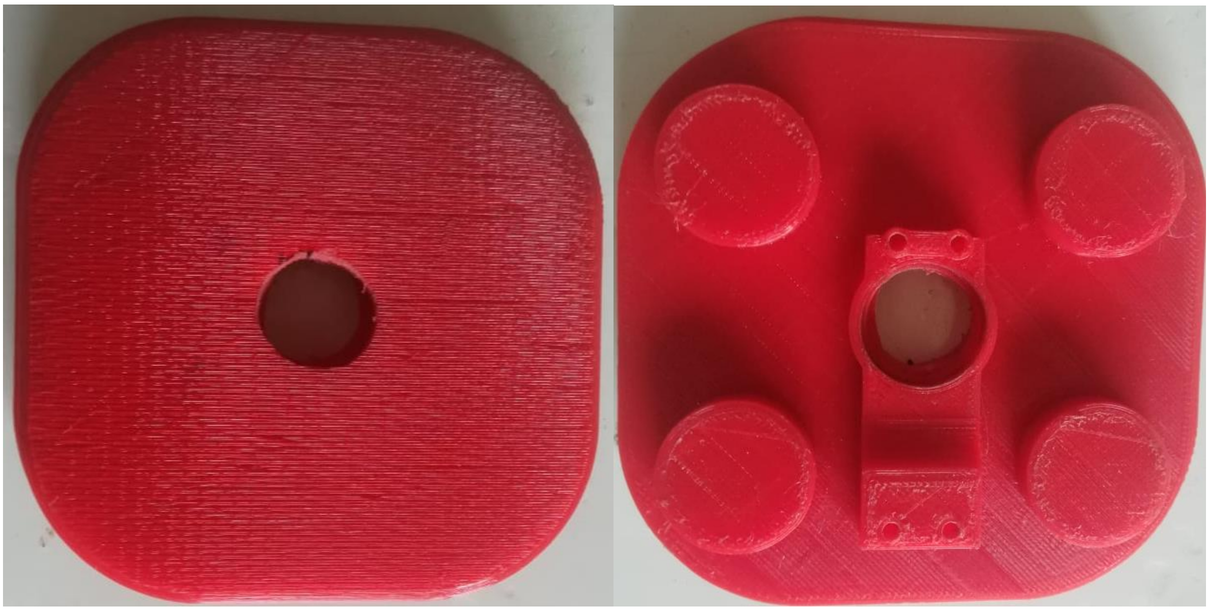


Figure 5-2: Base for the Robotic Manipulator

To serve as a base for the rest of the robot, a base structure was fabricated using 3D printing, as shown in Figure 5-2. PLA was used for printing. The base also houses the base motor, which provides the spanning motion, perpendicular to the vertical axis. Seat for the bearing is also integrated into the part geometry. Halfway through 3D printing the component, the bed of the printer was misaligned and features like non-concentric holes were formed. These issues were rectified at the assembly stages. For achieving the above-mentioned motion, a medium torque servo motor was used. One of the most critical motions for the robotic arm is the up & down motion. The torque requirement for achieving this motion increase dramatically, when the arm is fully extended. So, for this particular motion, a combination of two high-powered servo motors is used. These motors are coupled with a single servo bracket, which assists in transmission of motion to next linkage of arm. These two motors are housed in a part as shown below in Figure 5-3. The base and the housing are coupled together using an aluminum coupling shown below in Figure 5-4. This coupling is manufacturing using lathe and milling machines. The holes are drilled and tapped using M3 taps. This coupling passes through the base and its female part is integrated with the housing of raising assembly. Several components were fabricated to serve as coupling between the servo brackets and the PVC pipes. These components were 3D printed by using PLA. These couplings were designed so as to ensure a snug fit with pipe at one end and the other end is secured to the bracket using M3 screws. Figure 5-5 shows the fabricated coupling.

Figure 5-3: Housing for raising assembly

Figure 5-4: Aluminum coupling

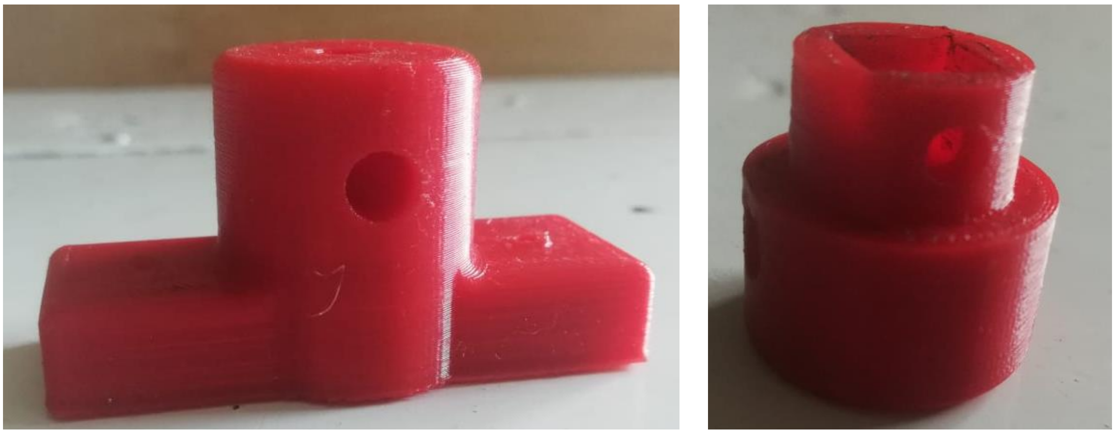


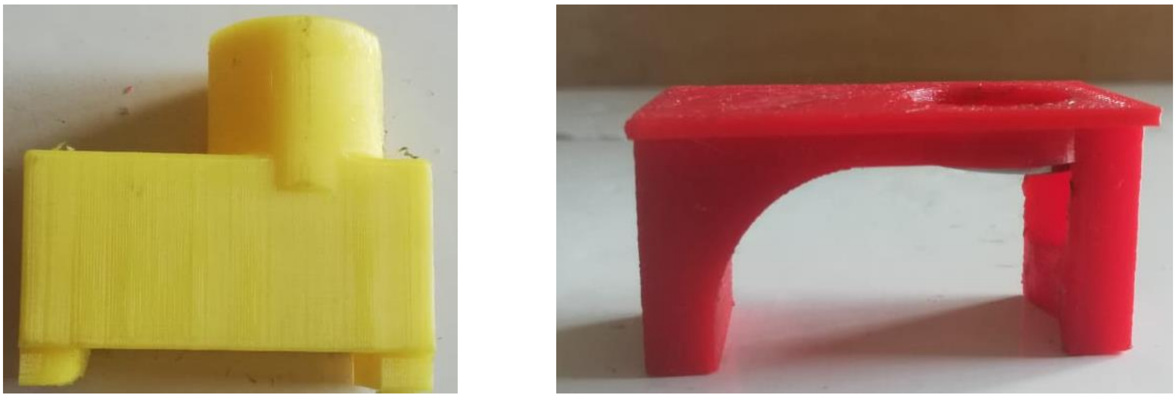
Figure 5-5: Various coupling of robotic arm

For achieving the twist motion of robotic arm, a single medium-torque servo motor is used. The housing of the motor was manufactured using the additive manufacturing technique. Apart from 3D printed components, brackets were also used. The parts used are shown below in Figure 5-6.

During the fabrication of robotic arm, several standardized, off-the-shelf components were used. These components are:

5.1.1 Servo Brackets

Instead of designing everything from the ground up, using standardize readily available parts is a sign of efficient design. In light of this knowledge, standardized servo brackets were brought and utilized. The use of standardized parts results in making the project more economically feasible, along with enhancing the ease of maintenance. The brackets are made up of stainless steel and are shown below in Figure 5-7.



(a) **(b)**

Figure 5-6: Twist assembly housing (a) front (b) back

Figure 5-7: Standard servo brackets

5.1.2 Round Horns

Different types of attachments are generally available with servo motors, to be used for various applications. For this particular scenario, a concentric and low moment arm horn was required. So, special aluminum round horns were obtained from the market and are used. The above-mentioned aluminum coupling was designed and manufactured in accordance with round horn, shown below in Figure 5-8.

5.1.3 Ball Bearing

For reducing the friction at twist joints and span joints, ball bearings were used. For this particular instance, ball bearing 6702 was used. The specifications of the bearing, shown below in Figure 5-9, are

- ID = 15mm
- OD = 21mm
- Width = 4mm
- Double Shielded

Another miniature ball bearing 606, is also placed inside the rotary atomizer assembly. The bearing is used for mounting the paint tube inside the cone, moving with high rpm. The bearing is a single row, 6 mm wide, has 6 mm internal and 17 mm outer diameter.

Figure 5-8: Aluminum round horn for servo motors

Figure 5-9: Ball bearing 6702

5.2 End Effector

Although the designed robotic arm is capable to use multiple types of end-effectors, thanks to the modular attachment design of end effectors, displayed in Figure 5-10, under the scope of this project, only two particular end-effectors were used: paint applicator & universal gripper.

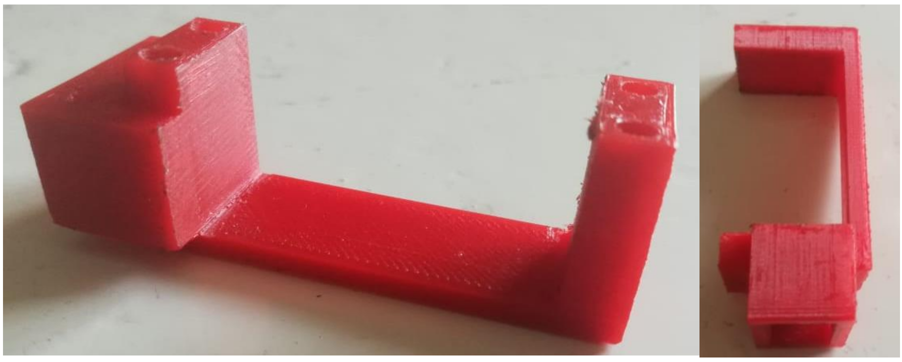


Figure 5-10: Coupling for attaching end-effectors

The details of the end effectors are:

5.2.1 Paint Applicator

As mentioned in Section 2.4, rotary bell atomizer system is ideal for paint applications, using 6 axis robotic manipulator, owing to its high transfer efficiency. The cone of the atomizer is rotated at several thousand revolutions per minute, using a brushless DC motor (BLDC). The paint enters from the bottom and due to high speed, it atomizes when it leaves the cone. The cone housing is designed such that, at the point of paint exit, pressurized air is flown, which serves as the control mechanism for the paint delivery. Higher the air flow rate, more concentrated the paint spot will be on the object and vice versa. The cone housing also contains the BLDC, power transmission systems and air, paint delivery tubes. The assembled rotary bell atomizer end effector is shown below in Figure 5-11.

Figure 5-11: Front view of paint applicator

5.2.2 Universal Gripper

Universal gripper is used for unique ability to handle vast variety of objects. Essentially, it is a granular body with the ability to control air in it. In the absence of air, the granular structure assists in gripping of the object. Then positive pressure is applied, the grains move apart and grip on the object is lost. Manufacturing of end-effector was delayed and hence deferred.

5.3 Platform

Generally, the robots used in industrial settings are mounted on sturdy platforms and their work space is cordoned off. For this project, a sturdy and solid platform was required that would be able to sustain all the stresses and the weight of the manipulator. In addition to it, an appropriate mounting mechanism for robot was required. These requirements were fulfilled by a frame of angle iron, with a Perspex sheet in between, forming a rectangular cuboid, with ground acting as one face. Holes were drilled and tapped, so that the robot could be screwed to the platform. The platform also serves as the housing for the auxiliary systems, required for the end effectors. For example, if the manipulator is being used for paint application, the platform will be able to house the compressor, the paint pump and the storage container, for the paint.

5.4 Electronics

For controlling and powering the robotic manipulator, electronics play an integral role. The detailed electronic components used in the manipulator are discussed below.

5.4.1 Powering Mechanism

For this project, direct-drive system was selected and hence servo motors were opted for. Depending upon the torque required and joint purpose, both high and medium torque servo motors were employed. For high torque application, DS3218, aluminum gear-based, servo motor was used. The motor itself weighs only 60g and has 40 x 20 x 40.5 mm dimensions. The motor has the capability to produce about 19kg/cm of torque. Figure 5-12 depicts the discussed servo motor.

Figure 5-12: High torque servo motor

For nominal torque applications, MG 995, servo motor is used. It has the ability to produce approximately 13kg/cm torque and it only weighs 55g. The dimensions of motor are 40.7×19.7×42.9mm. The motor is shown below in Figure 5-13. For the paint applicator, as discussed above, high rpm is required. For this task, a BLDC was used. Its specifications are A2212 Brush Less DC Motor, 2450KV, and weighing 52 g. In addition to torque and rpm requirements, all the motor selections were made, so that the motors could be operated with same power supply and control circuit.

Figure 5-13: Servo motor installed in its bracket

5.4.2 Control Mechanism

For coordinating the functioning of all onboard electronics, micro-controllers are essential. They serve as the brains of the device. In this particular scenario, Arduino Mega was used as the micro-controller. It was selected due to its more I/O channels. For controller the directions of the servo motors, as well as for controlling the air compressor and paint pump, L298N motor driver is utilized. L298N is essentially an H-bridge combined with a speed controller. The H-bridge is used for changing the direction of rotation, while the other part controls the speed. A typical L298 is shown below in Figure 5-14.

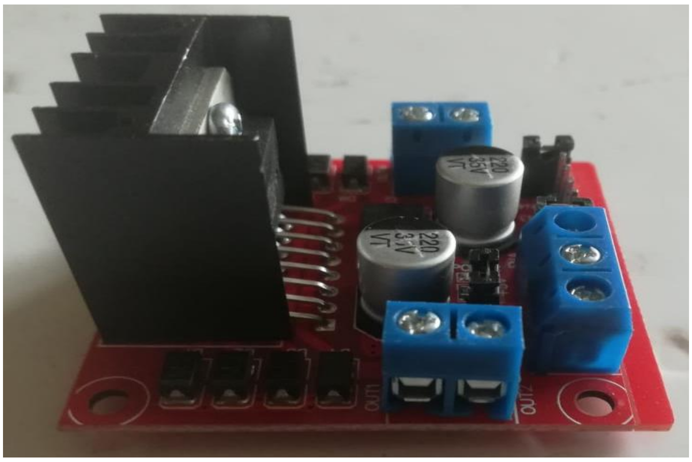


Figure 5-14: L298N motor driver

For achieving the goal, in case of BLDC, an Electronic Speed Controller or ESC is used. Essentially the both L298N and ESC serve the same purpose, but for different types of motors.

Chapter 6: Assembly

Assembly is the final stage of production. It acts as a litmus test for the design and is the indicator of the effort put in by the designer, to ease the assembly of the product. Instead of addressing the whole manipulator as a single assembly, the manipulator was divided into many sub-assemblies, comprising of different linkages and joints. End effectors were considered as separate sub-systems. As mentioned previously in Chapter 5: there were some manufacturing defects detected in 3D printed parts. During the manufacturing stage, due to certain irregularities in the functioning of printer, for example, missing of several layers, misalignment of glass, etc., the parts printed were deviating from the design specifications. For example, in case of base of the manipulator, the through-hole generated in the center was not concentric, rather it had the shape of a warped cylinder. This constituted a major problem, as it affects the proper seating of bearing and power transmission through coupling. Upon careful assessment of the part, it was decided that instead of printing a new part, modification would be done to utilize the base. For achieving the desired shape, careful sanding and filing were done. After several man-hours, the purpose-conforming shape was obtained.

Initially, pieces of angle-iron were welded together using electric-arc welding. The welded pieces formed the basic structure of the platform. This structure was painted to prevent it from corrosion and other environmental effects. Drilling was done so that M10 bolts could be used for holding the Perspex sheet in its place. Afterwards, motor was installed, along with the base of robot. This is the first joint of robotic manipulator, named J1. This complete assembly of the platform is shown in Figure 6-1.

Figure 6-1: Assembled platform and Joint J1

Housing for motors for raising joint was 3D printed in such an orientation that would result in the least support requirement. For installing the motors, these supports needed to be filed and sanding thoroughly, which was achieved using mini-sanding tools and files. Round horn and brackets were attached using the M3 screws. PVC linkage was attached by using press fit. For better securing the linkage and to avoid unnecessary rotation, clamps were used. The assembled joint is shown below in Figure 6-2.

.

Figure 6-2: Joint, J2

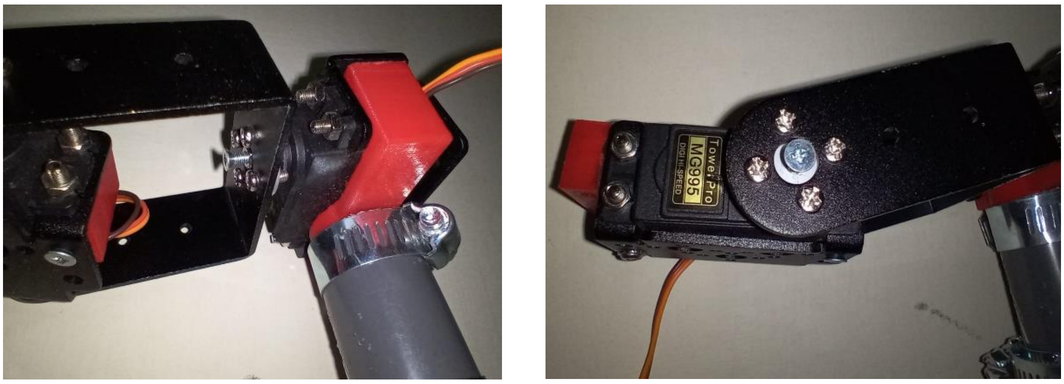
Joint J3, was assembled by attaching the servo brackets with specially designed connectors that would attach the servo motor, operating the joint 3, with the second linkages of robotic manipulator, as shown in Figure 6-3. Once again M3 screws are used for fastening all the various parts of J3 subassembly.

Figure 6-3: Joint J3 fully assembled

Joint 4, the twist subassembly comprises of motor housing and corresponding motion transmission components. Aluminum coupling and bearing are used to connect the motor with the next linkage and to ensure smoothness of motion. The coupling is held in place using an aluminum pin. The subassembly is shown below in Figure 6-4.

Figure 6-4: Joint J4, the twist assembly

Joints 5 & 6 constitute the wrist of robotic manipulator. Servo brackets and, aluminum round horns and servo motors are assembled to form J5 & J6, both are then attached using specially designed part. M3 screws are used as fasteners. The assembled joints are depicted below in Figure 6-5.



(a) **(b)**

Figure 6-5: Joints sub-assembly: (a) J5 (b) J6

The paint applicator end-effector is a self-contained independent painting unit. It comprises of piping for paint & air, paint atomizing system, powering mechanism and final atomized paint delivery system. A BLDC, fastened to the housing, powers the atomizing mechanism, connected to the paint delivery pipe. Atomized paint stream is controlled using pressurized air-stream and at the end atomized paint leaves the sub assembly, ready to be applied anywhere. The assembled paint applicator end-effector is shown in Figure 6-6.

Figure 6-6: Paint applicator

After successful completion of all sub-assemblies, they were integrated to form the final complete assembly. An aluminum pin was used for attaching J1 and platform with J2 and linkage. Consequent sub-assemblies are joined together using clamps, attached to various linkages. Joint J1 assembled on the platform is shown below in Figure 6-7.

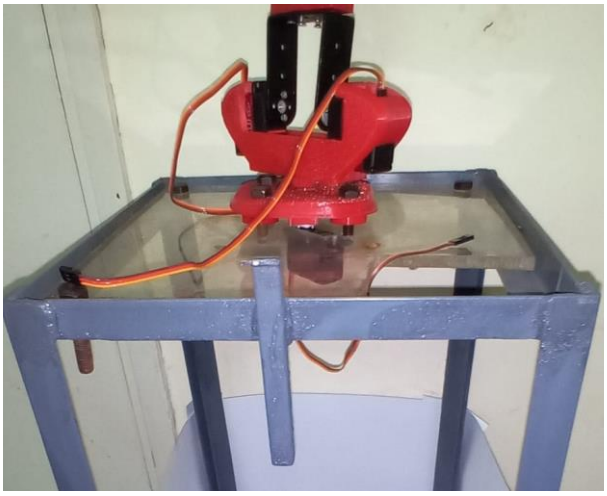


Figure 6-7: J1 mounted on the platform

Air and paint piping is connected to the corresponding delivery system. Pressurized air is supplied using an air compressor which is housed underneath the manipulator platform. Paint is delivered to the applicator using a pump. For this particular purpose, a submersible pump is used, which is submerged inside the paint storage container, also housed beneath the platform. For the supplying power and control mechanism, control circuitry was connected according to the designed controller. Various components of the control system were soldered together. As the factory-provided power and signal cables for servo motors are very short, cable extensions were attached to increase the length. The control and powering mechanism of paint applicator was also attached. BLDC was connected to ESC and the corresponding micro-controller. Paint pump and air compressor were also provided power. I/O interface of control system is shown below in Figure 6-8.

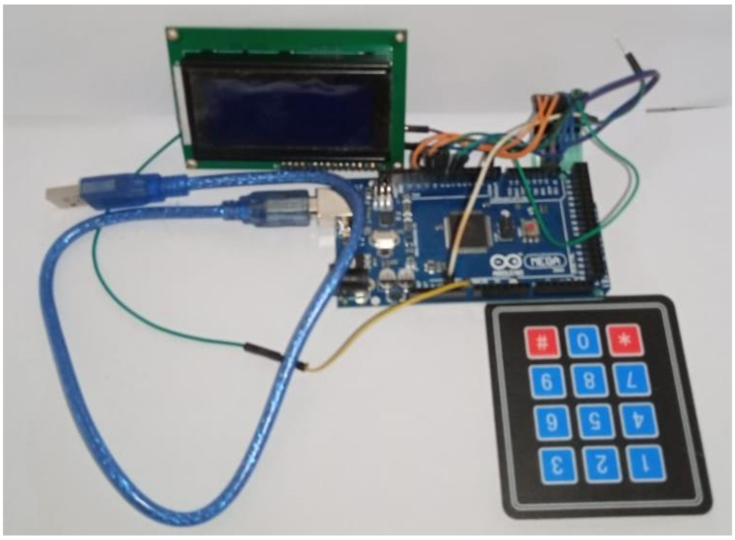


Figure 6-8: Input and output module for the control system

The final fully assembled manipulator, mounted on the platform, along with its auxiliary systems is shown below in Figure 6-9.

Figure 6-9: Robotic manipulator assembly

Chapter 7: Results and Discussion

As described in detail in previous sections, series of steps were undertaken for the completion of the project. After reviewing the requisite literature and studying previous designs of various robots, the design stage was started. Apart from considering multiple technical parameters during the design stage, the ease of assembly and the responsible manufacturing of the robot were also incorporated. Manufacturing was done on the basis of created design and consequently, six axis robotic manipulator was the end product. The electronics and control system were attached and integrated. Numerous test runs were performed for benchmarking of the manufactured product against the designed one.

7.1 Testing

In terms of maneuverability and motion, the robotic manipulator was fully functional. It had the capability to reach any point, in its designated workspace. Although, ideally the joints of six-axis manipulator must be capable of undergoing 360 degrees of rotation, but due to physical constraints, associated with servo motors and mountings, some joints were restricted to 180 degrees of rotation. But this factor can be easily mitigated, while trying to achieve a certain orientation, by using the combination of other joint movements. Overall, the manipulator was capable of operating in a designated 3D space. In terms of speed of manipulator, the motors undergo the rotation at the rate of 50°/ sec, i.e., it would take 7.2s for the motor to complete a full 360-degree rotation. Although as the manipulator was operated in manual input mode, achieving this speed was not possible owing to human factors and time lag associated with detecting, processing and transmitting of signals.

Achieving high repeatability was another desired characteristic of manipulator. To cater to this particular property, servo motors were selected for powering the manipulator. This selection was based on the fact that servo motors are highly precise, owing to miniature gear train gear attached to the motor. Secondly, these motors are free from the step-missing errors that are generally associated with stepper motors. To ensure high repeatability, control system was designed such that it would result in maximum repeatability by reducing the step increment size. A trade-off was made between speed and step increment of servo motors.

Another major accomplishment of manipulator was increased payload-to-manipulator weight ratio. For the designed manipulator, this ratio is around 0.1, owing to the use of lightweight materials. For most modern commercially used robotic manipulators, the ratio is usually less than 0.1. As the manipulator is a scaled-down prototype, the payload capacity is just 150g, while the intrinsic weight of manipulator is around 1500 grams.

While undertaking the project, several challenges were encountered at various stages. At the design stage, the selection of low-density, high-strength material was a difficult task. Apart from mechanical properties to be considered, the ease of manufacturing and type of manufacturing process being used had to be taken into account. Similarly, to incorporate heat rejection and wiring of robot, the design was altered. During manufacturing, various unprecedented circumstances occurred. The parts manufactured were not in compliance with the generally established tolerances used while 3D printing parts. In addition to this, some warped and disoriented parts were produced, due to unprovoked motion of printing bed. In light of sustainable and responsible manufacturing, instead of manufacturing parts from the ground up again, various post-manufacturing techniques were employed for using these components, without comprising the operability. While designing the control system of manipulator, potential losses due to various components, signal noise and losses due to long wires, were some of the challenges that had to be overcome.

7.2 Sustainability of Project

Economics play an integral role in any project. Prior to undertaking any tasks, a monetary analysis is must, as essentially there is a trade-off between economics and utility. Anything can be designed and manufactured, provided sufficient funds are provided. Before starting this project, a brief overview of required financial resources was done and the purpose of project was also considered. As the goal was to provide an economical automation solution, micro-managing was required for achieving maximum value for money, without compromising on essentials. From material selection to motor selection, economics played an important role. To cut down the cost, the use of off-the-shelf standardized parts was encouraged. Similarly, wherever possible, certain refurbished components were utilized. Detailed expenditure on the project is given in the appendix.

Making efforts to conserve the environment and Earth is civic duty of every citizen. To play our part, efforts were done from the very beginning. PLA was used for fabrication of most components, which is a recyclable material and less harmful to environment, as compared to its counterparts. Whenever possible standardized parts were used, to reduce energy and resource wastage to make such components. Many components of robotic manipulator are re-used parts, extracted from discarded products. For example, while making the platform of manipulator, instead of using new angle-iron and Perspex sheet, these things were taken from out of service, discarded projects. Similarly, the power supply was scavenged from an old PC. All these efforts were done to keep the carbon footprint to minimum, while maximizing the recycling and reusing of discarded, out-of-service things. All the endeavors undertaken for completing this project were taken in light of 3 R’s, Reduce, Recycle and Reuse.

The motivation for undertaking this project was to provide a service to society. This robotic manipulator is a scaled-down prototype for robotic manipulator that can be used in an industrial setting. This would provide a cost-effective solution for automation in Small Medium Enterprises (SMEs), which would result in increased output of these units and availability of high-quality, low-cost products to society. In addition, it would provide a safer work environment and prevent repetitive stress-related injuries like Carpel Tunnel Syndrome, etc.

7.3 Safety

Throughout the project, special attention was given to safety. All the safety protocols and guidelines were followed. Designated apparel and safety equipment was used, while fabricating manipulator. Owing to these efforts, the manipulator was manufactured successfully and safely, without any accident.

Chapter 8: Conclusion and Future Recommendations

The idea behind undertaking this project was to create a fully automated robot, capable of performing various functions in an industrial setting, to efficiently manufacture better-finished products, while reducing the human input. The main motivation for pursuing this extensive project was to find a cost-effective solution for the manufacturing sector that can easily automate the production of various items, thereby increasing production efficiency & sustainability. Previous work was studied and various technicalities involved in undertaking the task were determined. After evaluating various types and designs of robots, six axis robotic manipulator was opted as a solution to the problem faced. This selection was driven by the fact that six-axis robots are capable of performing a wide variety of complex maneuvers in 3D space, without compromising the speed and functionality. For ensuring the usage of manipulator for diverse applications, a modular end-effector was selected, which would enable interchangeability among various end-effectors, according to need, at a moment's notice. Prior to divulging into the actual design of manipulator, multiple parameters that impact the end-product were analyzed and carefully selected. Weight of robotic manipulator is an important factor that impacts the overall design process. The goal was to reduce the intrinsic weight of manipulator, while maximizing the payload weight. Secondly, the manipulator had to be designed for a certain workspace, which in return dictated the dimensions of manipulator itself. Appropriate material and motor selection were also crucial for proper functioning of robot. In addition to that, utmost efforts were done to ensure that the manufactured product was in line with Asimov's 3 Laws of Robotics.

Using basic geometry, relationship between work volume, the dimensions of linkages of manipulator and the size of work cube was found. Using these relationships, for a pre-defined work volume, the dimensions of linkages were calculated, using Mathcad. Afterwards, the CAD of manipulator and auxiliary systems were made, using Creo Parametric. This stage of project was work-intensive, owing to iterative design methodology that was opted for. Simultaneously, the control system of manipulator was designed. The control system was divided into three sub-units, based on their functionality. Remote input unit was used as user interface, enabling operator to enter commands using this module. The driver unit processed the input and forwarded the signal to respective destination. Servo and other motors, that provided the output, were part of motor unit. Using FEA, Creo Simulate was used to find the stress distributions along the length of manipulator, in different orientations and design iterations were made to prevent any kind of failure. Paint applicator was designed on the principle of rotary atomizer. For pick-and-place applications, a universal gripper was designed, capable of handling items having diverse geometries.

Various manufacturing processes were used for fabrication of manipulator. For some parts, made up of PLA, Additive Manufacturing was done. This decision was made due to the small size of parts and the ability of additive manufacturing techniques to produce near-net-shape parts. 3D printing of parts was performed using Craftbot XL. For aluminum components, conventional machining processes like turning and milling were performed. To increase ease of maintenance, several off-the-shelf components were also used. Tapping, filling, drilling and soldering were some of the tasks involved during the assembly of manipulator. Code for controlling the manipulator was written and uploaded to microprocessor, creating a stand-alone control system. Overall, a prototype of an automated robot, to be used in industrial setting, was created. Modular design and six-axis of motion resulted in achieving high maneuverability, for diverse applications. Control system was also made for efficient operation of manipulator. Two end-effectors, paint applicator and universal gripper were also designed.

8.1 Future recommendations

For further reducing the weight of manipulator, PVC linkages can be replaced by low-density polymers like ABS and PLA, etc. Similarly, the servo brackets used in various joints, are made from steel. These can also be replaced by lightweight materials. Instead of using three separate joints for achieving wrist motion, ABENICS (Active Ball Joint Mechanisms) can be used, which will result in more compact wrist, capable of working in stringent space constraints. The payload capacity of manipulator can be increased by employing higher torque motors.

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Appendix A: Arduino Code

For Driver Unit

```
#include <LiquidCrystal_I2C.h>

#include<Servo.h>

#include<Wire.h>

int inByte;

char key;

int posl = 0;//servo

int posr = 180;

int pose = 0;


//int motor5pin1 = 18;

Servo servo_18;

Servo servo_19;

Servo servo_10;

Servo servo_9;

Servo servo_8;

Servo servo_7;

Servo servo_6;

Servo servo_52;


LiquidCrystal_I2C lcd(0x27,16,4);

int LED = 13;


void setup()
```

```
{
Serial.begin(9600);
  lcd.begin(16, 2);
  pinMode(50,OUTPUT);
pinMode(51,OUTPUT);
  // Print a message to the LCD.
  lcd.print("loading..2");
  Serial.print("loading..2");
  servo_18.attach(11, 500, 2500);
  servo_19.attach(13 , 500, 2500);
    servo_9.attach(9);//continues
    servo_8.attach(8);//continues
  servo_7.attach(7);
  servo_52.attach(52);//BLDC inpput to ESC
   servo_6.attach(6);//continues
    servo_10.attach(10, 500, 2500);//servos

  servo_18.write(posl);
    servo_19.write(posr);
  servo_10.write(pose);

pinMode(LED, OUTPUT);

}
void loop()
{
if (Serial.available() > 0)
```

```
{
inByte = Serial.read();
Serial.print(inByte);
  key = inByte;
lcd.setCursor(0, 1);
  // print the number of seconds since reset:
lcd.print(key);
switch (inByte)

{
case '1':
digitalWrite(LED,HIGH);
Serial.println("PRESS 1 SERVO 10 ");
  if (pose<=180){
  pose = pose+5;
   // tell servo to go to position in variable 'pos'
    servo_10.write(pose);

    // wait 15 ms for servo to reach the position
    delay(20);}
break;
case '4':
digitalWrite(LED,LOW);
Serial.println("PRESS 4 SERVO 10 ");
  if (pose>= 0){
    pose=pose-5;
    // tell servo to go to position in variable 'pos'
```

```
    servo_10.write(pose);
    // wait 15 ms for servo to reach the position
    delay(20); // Wait for 15 millisecond(s)
  }
break;
case 'M'://*8*88888888888********8EXTRA
digitalWrite(50, LOW);//pump
delay(5000);
servo_52.write(0);//bldc stops
Serial.println("BLDC STOP");
delay(5000);
digitalWrite(51, LOW);//compressor
Serial.println("Compressor and Pump shut down");
break;
case 'N'://*8*88888888888********8EXTRA
servo_52.write(100);//bldc stops
Serial.println("BLDC STart");
delay(5000);
digitalWrite(50, HIGH);//pump
delay(5000);
digitalWrite(51, HIGH);//compressor
Serial.println("Compressor and Pump Start");
break;
case '7':
  if (posl<=180){
  posl = posl+5;
    posr =180-posl;// tell servo to go to position in variable 'pos'
```

```
    servo_18.write(posl);

    servo_19.write(posr);

    Serial.println("PRESS 7 SERVO18-19 ");

    // wait 15 ms for servo to reach the position

    delay(20);}

    break;

/*digitalWrite(motor5pin1, LOW);

digitalWrite(motor5pin2, HIGH);

Serial.println("claw OPEN");

delay(1000);

digitalWrite(motor5pin1, LOW);

digitalWrite(motor5pin2, LOW);

break;*/

case '*':

  if (posl>= 0){

    posl=posl-5;

    posr=180-posl;

    // tell servo to go to position in variable 'pos'

    servo_18.write(posl);

      servo_19.write(posr);

      Serial.println("PRESS * SERVO18-19 ");

    // wait 15 ms for servo to reach the position

    delay(20); // Wait for 15 millisecond(s)

  }

    break;

/*digitalWrite(motor5pin1, HIGH);

digitalWrite(motor5pin2, LOW);
```

```
Serial.println("CLAW CLOSE");
delay(1000);
digitalWrite(motor5pin1, LOW);
digitalWrite(motor5pin2, LOW);
break;*/
case '0':
  Serial.println(" PRESS 0 sent 0 Rotaing CW ");
                servo_9.write(0);
               delay(100);
                servo_9.write(90);
break;
case '#':
  Serial.println(" PRESS # sent 180 Rotaing CCW ");
                servo_9.write(180);
                delay(100);
                servo_9.write(90);
break;
case '8':
 Serial.println(" PRESS 8 sent 0 Rotaing CW ");
                servo_8.write(0);
               delay(100);
                servo_8.write(90);
break;
case '9'://....................................................to be decided
 Serial.println(" PRESS 9 sent 180 Rotaing CCW ");
                servo_8.write(180);
                delay(100);
```

```
        servo_8.write(90);
break;
case '2':
Serial.println(" PRESS 2 sent 180 Rotaing CCW ");
        servo_7.write(180);
        delay(100);
        servo_7.write(90);
break;
case '5':///*****EXTRA
Serial.println(" PRESS 5 sent 0 Rotaing CW ");
        servo_7.write(0);
       delay(100);
        servo_7.write(90);
break;
case '3':
Serial.println(" PRESS 3 sent 0 Rotaing CW ");
        servo_6.write(0);
       delay(100);
        servo_6.write(90);
break;
case '6':
Serial.println(" PRESS 6 sent 180 Rotaing CCW ");
        servo_6.write(180);
        delay(100);
        servo_6.write(90);
break;
}
```

```
}}
```

For Remote Unit

```
#include <LiquidCrystal_I2C.h>


#include <Wire.h>


#include <Keypad.h>
const byte ROWS = 4;
const byte COLS = 3;
LiquidCrystal_I2C lcd(0x27,16,4);
float x , d,E,U;
char hexaKeys[ROWS][COLS] = {
  {'1', '2', '3'},
  {'4', '5', '6'},
  {'7', '8', '9'},
  {'*', '0', '#'}
};
char mystr[ROWS][COLS] = {
  {1, 2, 3},
  {4, 5, 6},
  {7, 8, 9},
  {E , 0, U}
};
byte rowPins[ROWS] = {9, 8, 7, 6};
byte colPins[COLS] = {10, 11, 12};
```

```
Keypad customKeypad = Keypad(makeKeymap(hexaKeys), rowPins, colPins, ROWS, COLS);
char hexaKey [4];//serial comunication
void setup(){
  Serial.begin(9600);
  lcd.init();
  lcd.backlight();
  lcd.print("six axis ");
  lcd.setCursor(0, 1);
  lcd.print("manioulator ");
  lcd.setCursor( 0 , 2);
  lcd.print("Initializing");

  lcd.noDisplay();



}
void loop(){



  char customKey = customKeypad.getKey();
  if (customKey){

     lcd.setCursor(0,1);
  lcd.print("Six axis ");
  lcd.setCursor(0,1);
  lcd.print("manipulator ");
   lcd.setCursor(0,2);
```

```
  lcd.print("motor = ");// Print a message to the LCD.



    lcd.print(customKey);
    Serial.print(customKey);
  Serial.write(customKey); //Write the serial data
  }
}
```

Appendix B: Mathcad Code

A sample code used for finding the workspace is given below:

$$Ri \equiv 1$$

$$Ro \equiv 2$$

$$Vb := \frac{4}{3} \cdot \pi \cdot Ro^3 - \frac{4}{3} \cdot \pi \cdot Ri^3 = 29.322$$

$$b \equiv Ro^2 - Ri^2 = 3$$

Guess Values

$$a := 0$$

$$x := 0$$

Constraints

$$5 \cdot a^2 + 4 \cdot a \cdot \sqrt{\left(Ri^2 - a^2\right)} - b = -3$$

$$x - \sqrt{\left(Ri^2 - a^2\right)} = -1$$

Solver

$$sol := \mathbf{find}(a, x) = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

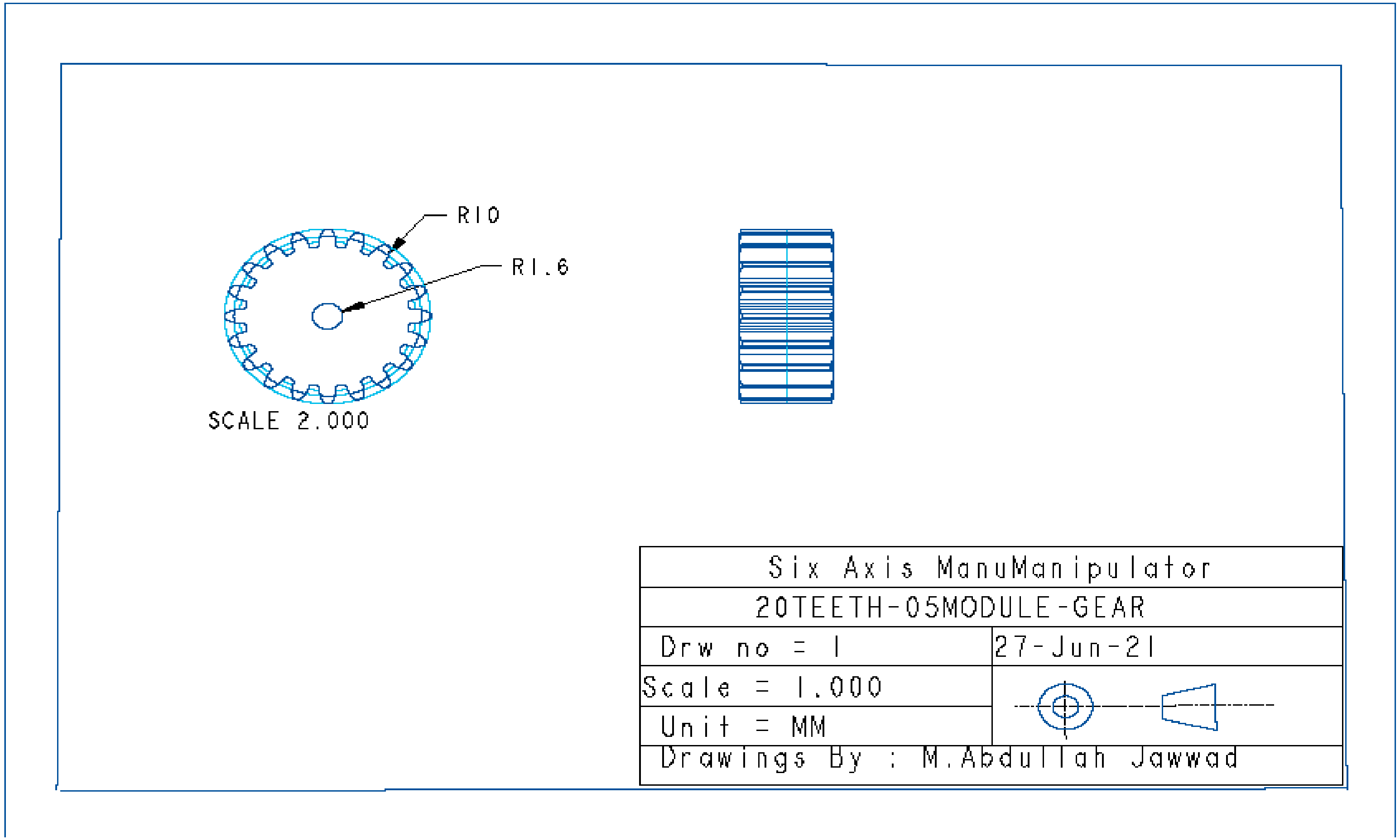
Appendix C: Cost Breakdown

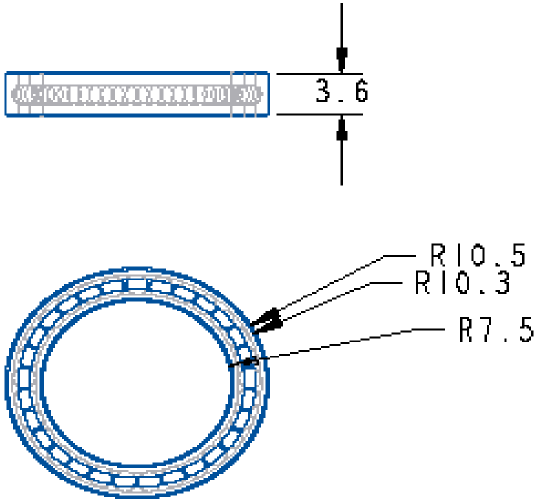
The cost breakdown of items procured for manufacturing of six axis robotic manipulator are given below in Table A- 1..

Table A- 1: The cost breakdown of procured items

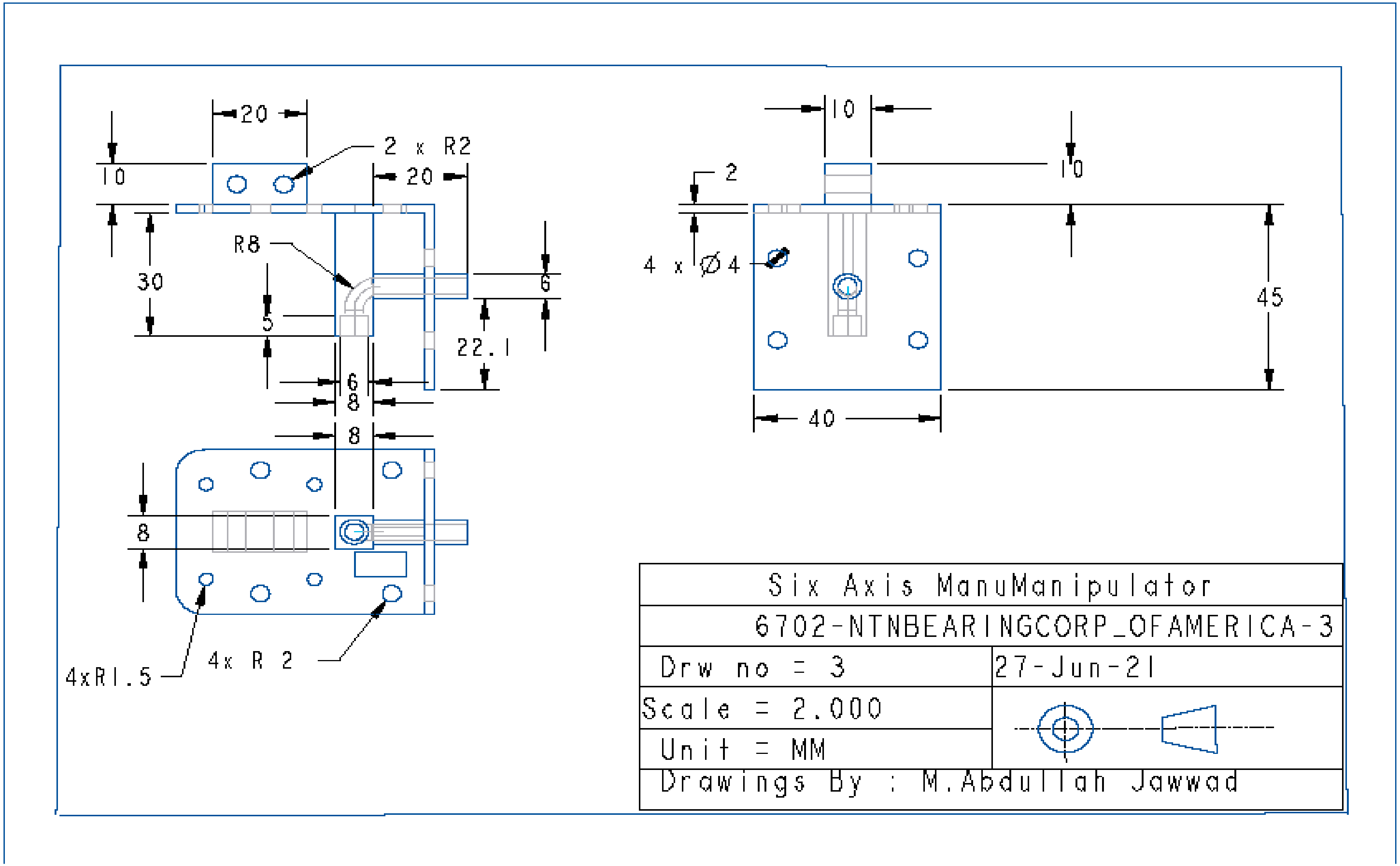
Sr. No.	Item	Quantity	Unit Price
1	Servo Brackets	4	400
2	MG995 (Low Torque Servo Motors)	4	750
3	Arduino Mega	2	1480
4	Brushless DC Motor A2212	1	730
5	Electronic Speed Controller (30A)	1	750
6	Air Compressor (12V DC, 12A, 150 Psi)	1	4000
7	Rubber Tube ½”	1	150
8	Rubber Tube ¾”	1	250
9	606 Bearing	1	50
10	Servo Metal Round Mount	7	840
11	DS 3218 (High Torque Servo Motors)	3	2800
12	Ellen Bolts	46	10
13	LCD 16 x 5	1	500
14	I2C Module	1	150
15	Key Pad	1	150
16	Header Male	4	10
17	UPVC Pipe 1”	1	500
18	Ball Bearing 6702	2	450
19	PVC Pipe 1”	1	250
		Total	**Rs. 25,700/-**

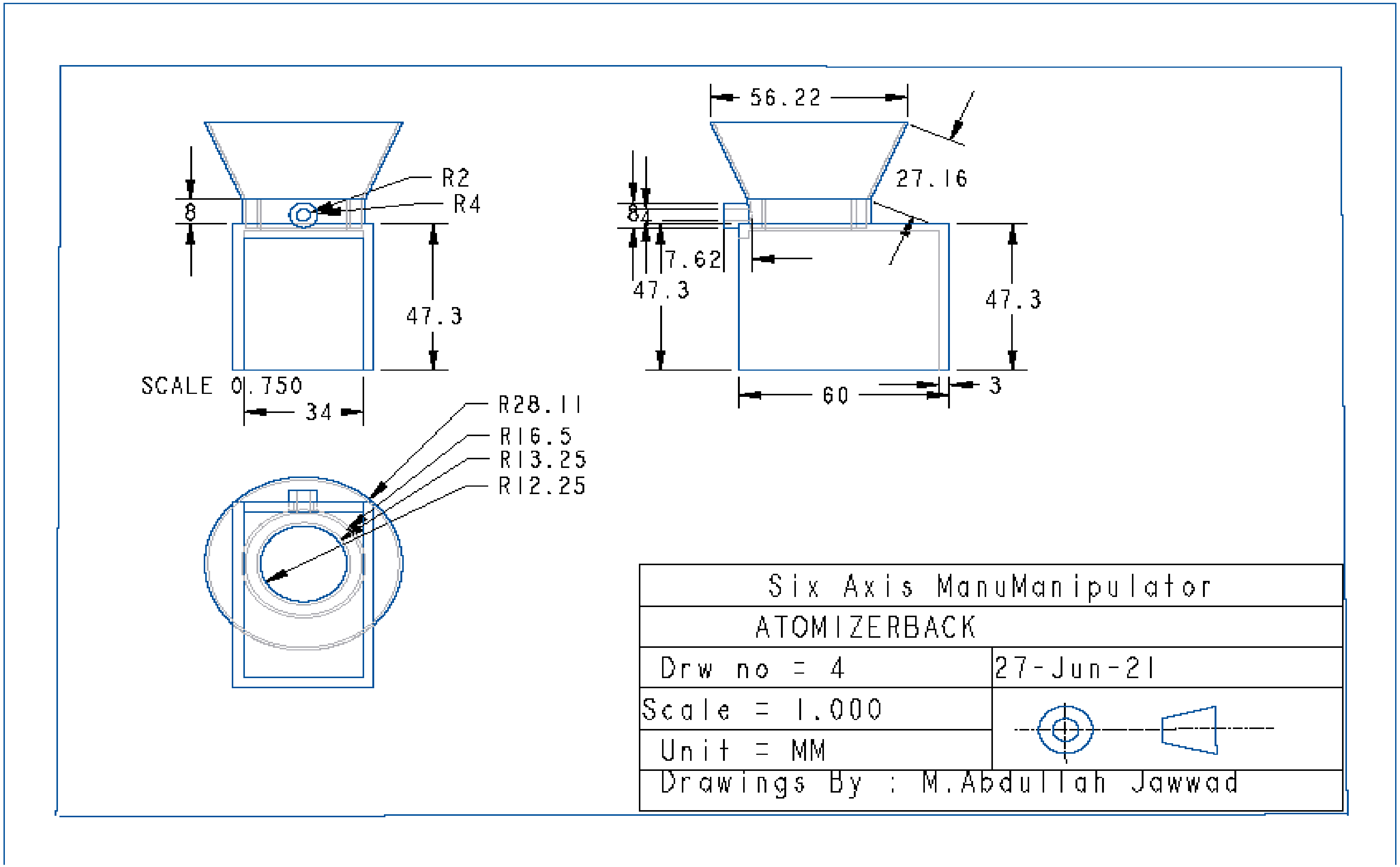
Appendix D Drawings



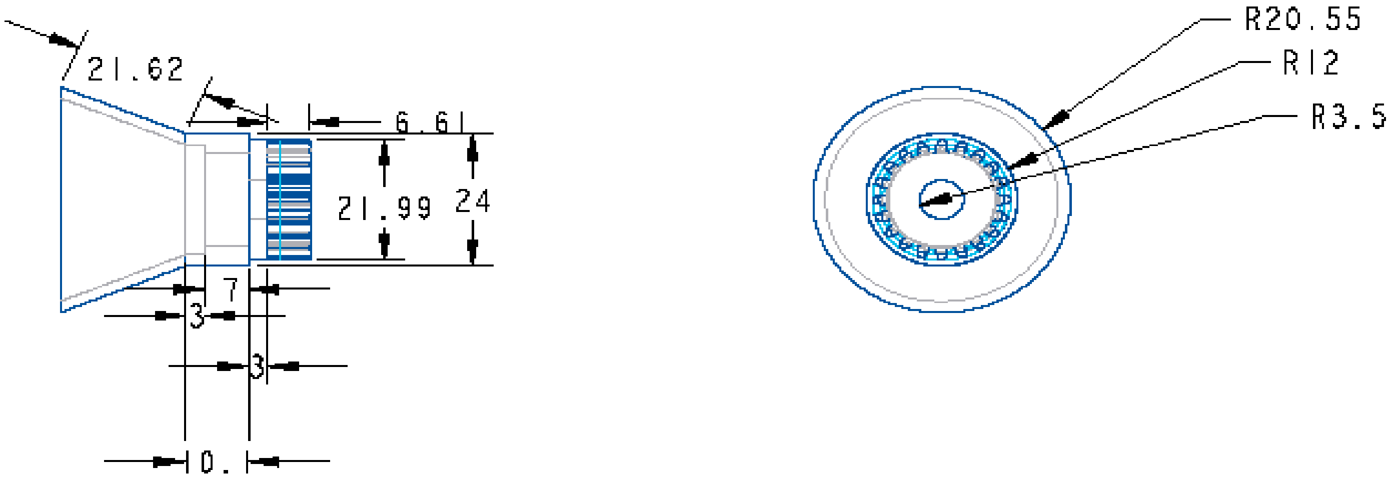


Six Axis ManuManipulator	
6702-NTNBEARINGCORP_OFAMERICA-3	
Drw no = 2	27-Jun-21
Scale = 2.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

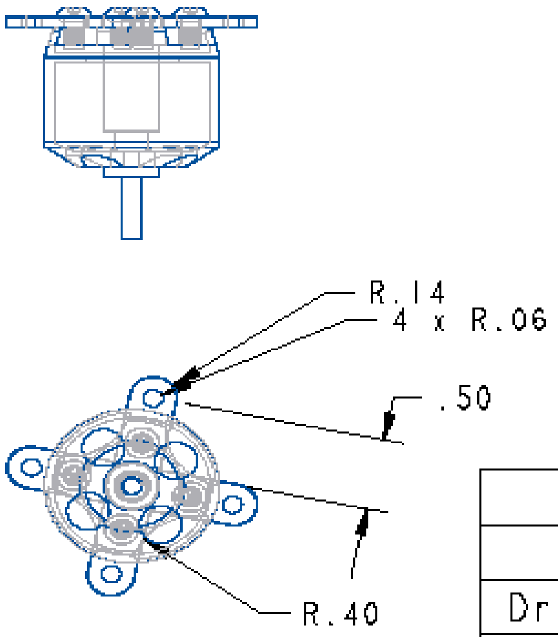

20
2 x R2
10
20
R8
30
5
6
22.1
6
8
8
8
4xR1.5
4x R 2
10
10
2
4 x Ø4
45
40
Six Axis ManuManipulator
6702-NTNBEARINGCORP_OFAMERICA-3
Drw no = 3
27-Jun-21
Scale = 2.000
Unit = MM
Drawings By : M.Abdullah Jawwad



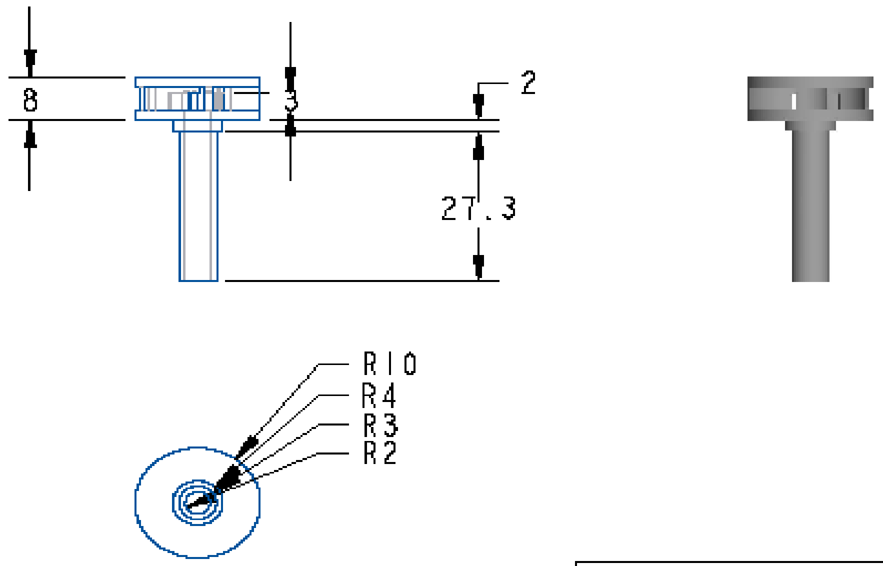
56.22
27.16
R2
R4
8
47.3
8
4
7.62
47.3
47.3
SCALE 0.750
34
60
3
R28.11
R16.5
R13.25
R12.25
Six Axis ManuManipulator
ATOMIZERBACK
Drw no = 4
27-Jun-21
Scale = 1.000
Unit = MM
Drawings By : M.Abdullah Jawwad



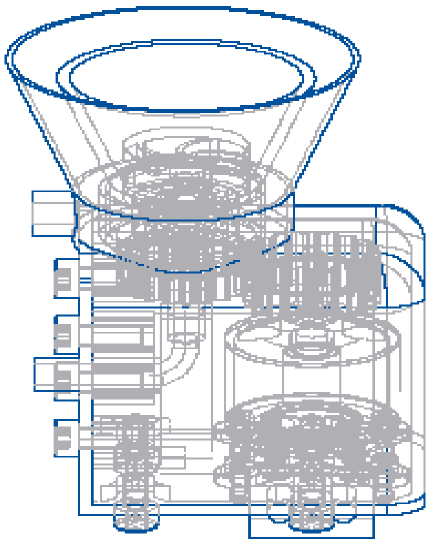
Six Axis ManuManipulator	
ATOMIZERFRONT	
Drw no = 5	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	



Six Axis ManuManipulator	
MOTOR-ASM	
Drw no = 6	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

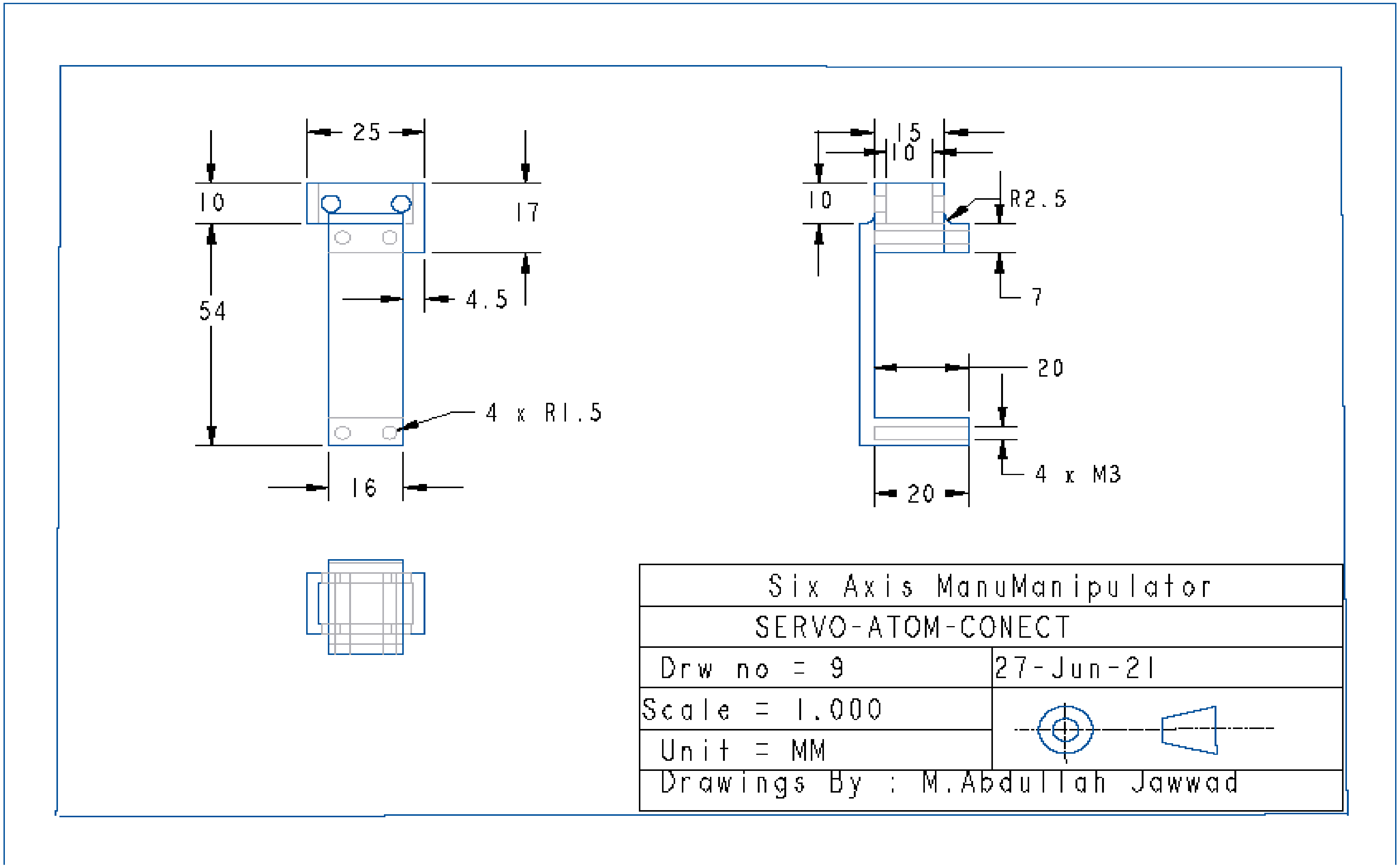


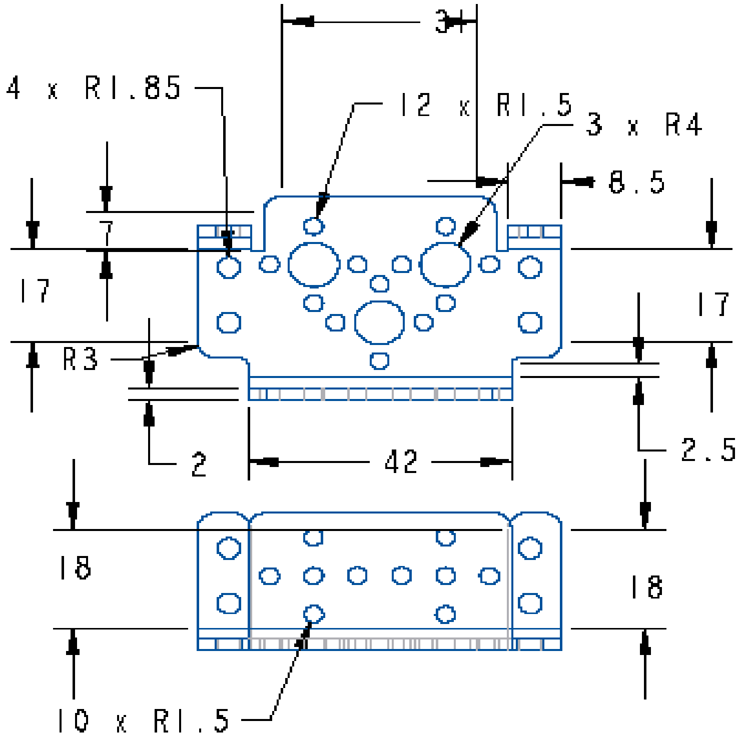
Six Axis ManuManipulator	
PAINTTUBE	
Drw no = 7	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

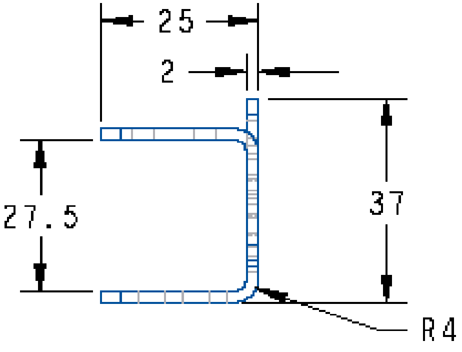


SCALE 1.000

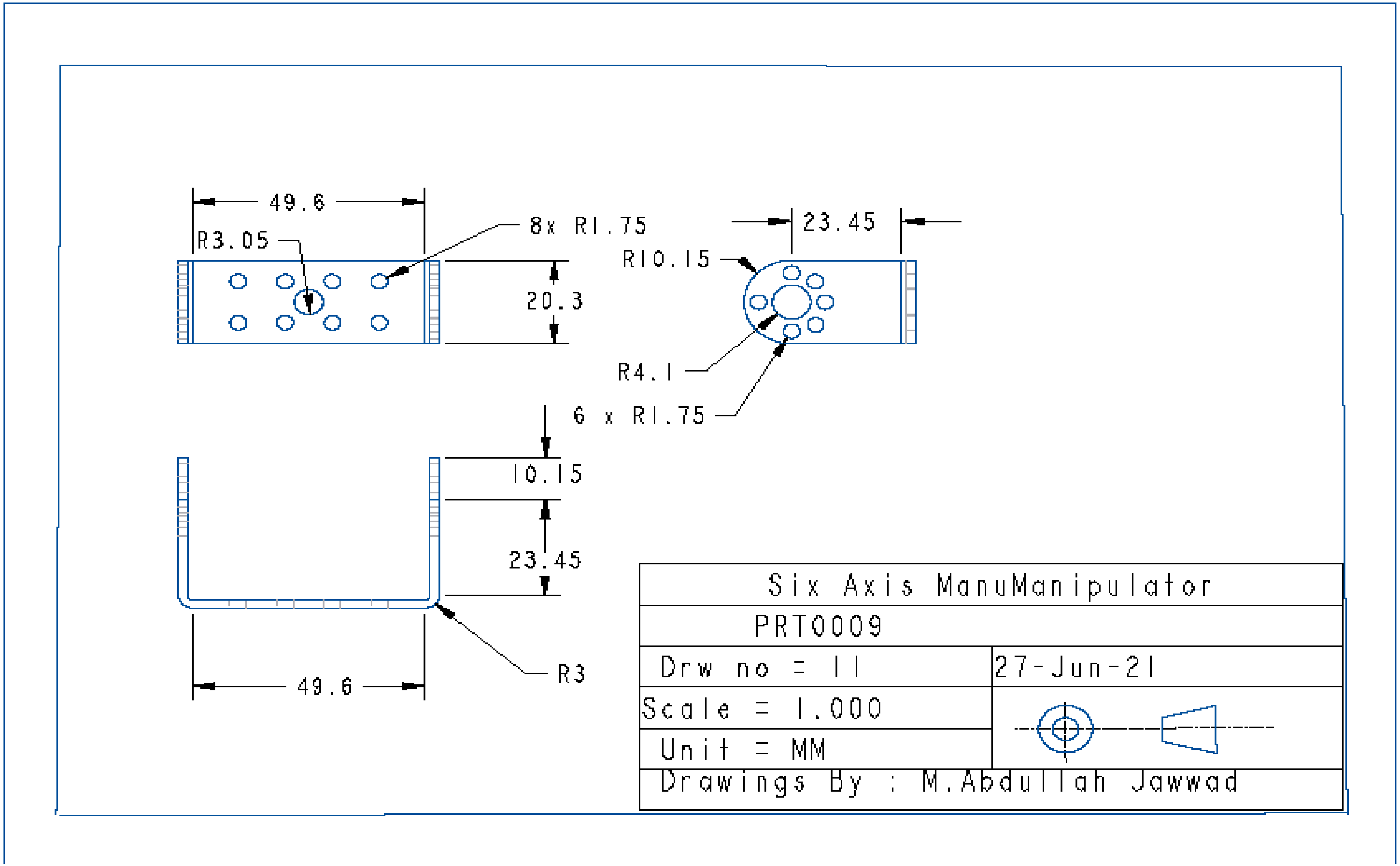
Six Axis ManuManipulator	
ATOMIZER_ASEMBLY	
Drw no = 8	27-Jun-21
Scale = 0.500	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

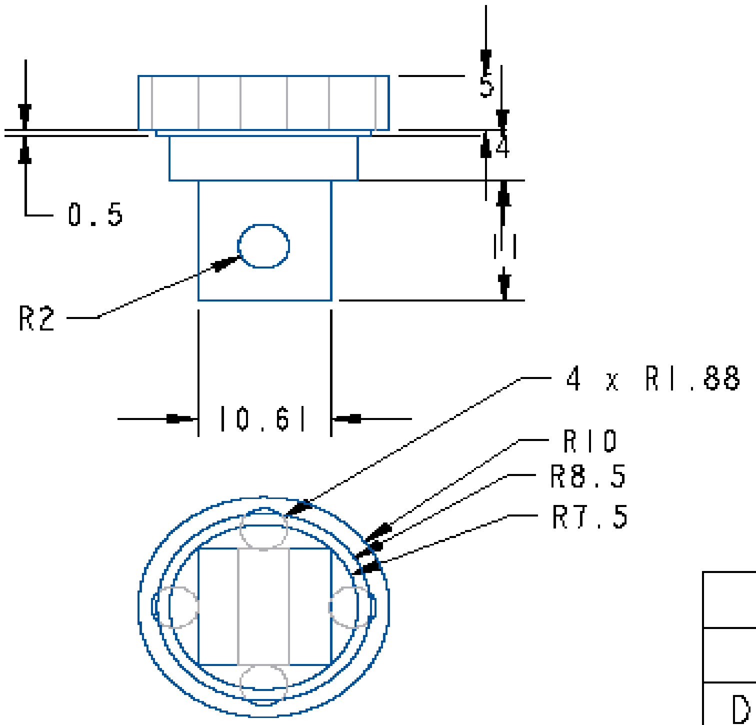

25
10
17
54
4.5
4 x R1.5
16
15
10
10
R2.5
7
20
20
4 x M3
Six Axis ManuManipulator
SERVO-ATOM-CONECT
Drw no = 9
27-Jun-21
Scale = 1.000
Unit = MM
Drawings By : M.Abdullah Jawwad

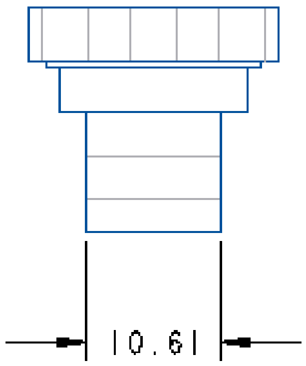




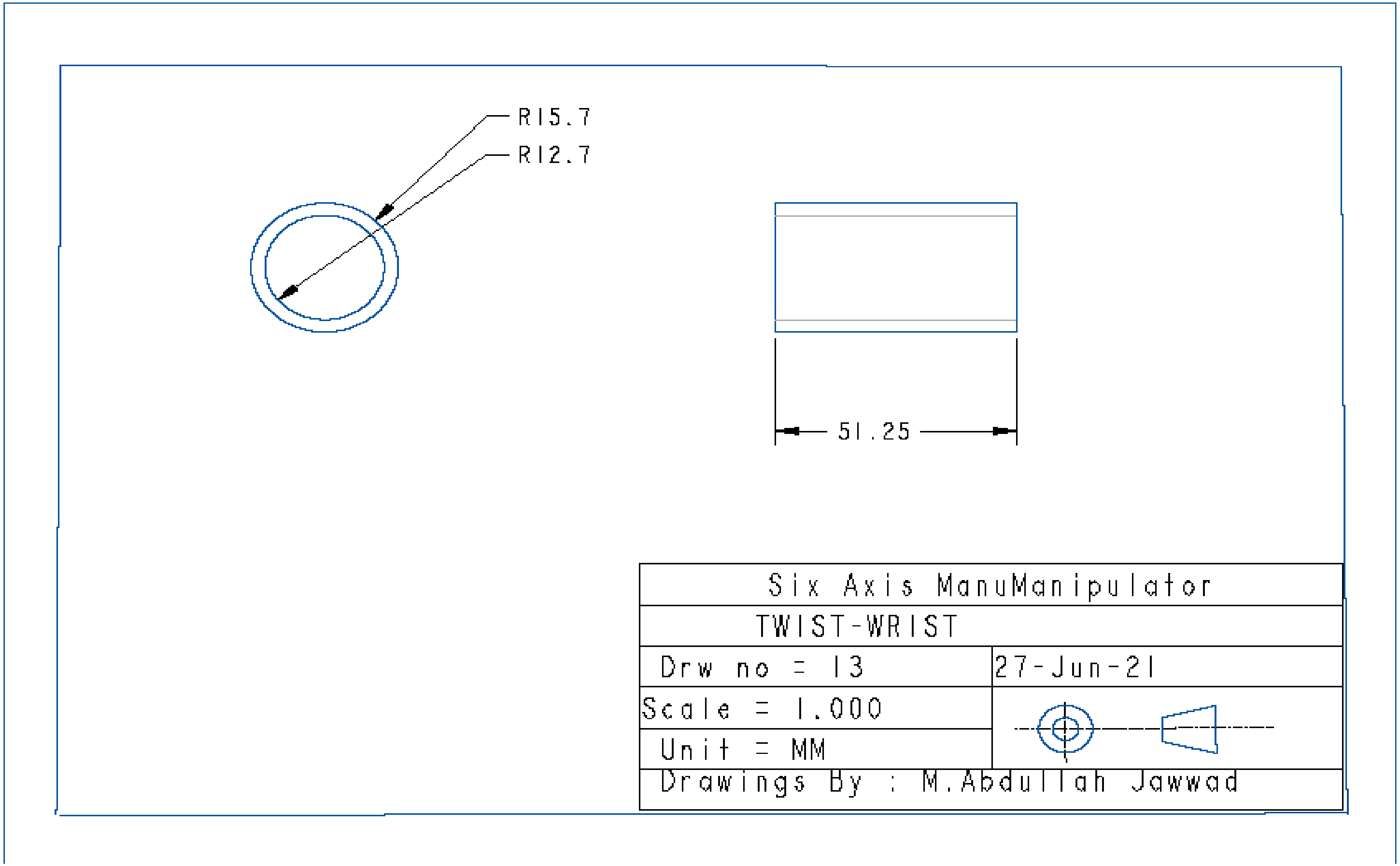
Six Axis ManuManipulator	
SERVO_BRACKET_-_UNIVERSAL_V10_1	
Drw no = 10	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

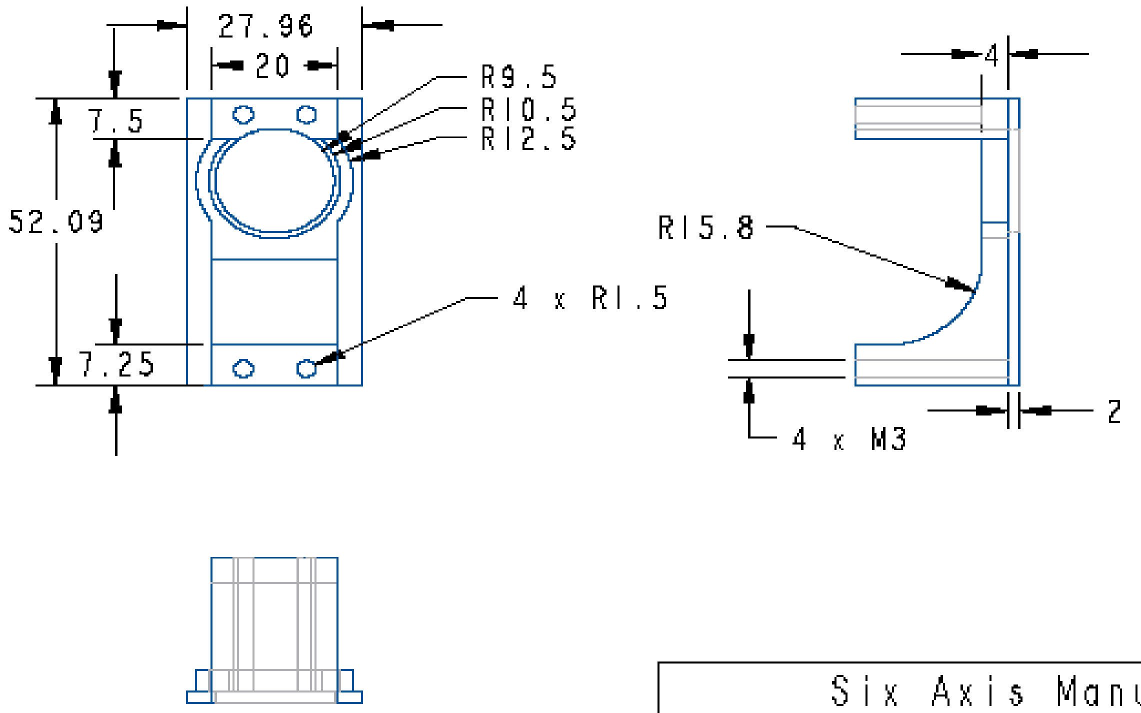

49.6
R3.05
8x R1.75
20.3
23.45
R10.15
R4.1
6 x R1.75
10.15
23.45
R3
49.6
Six Axis ManuManipulator
PRT0009
Drw no = 11
27-Jun-21
Scale = 1.000
Unit = MM
Drawings By : M.Abdullah Jawwad



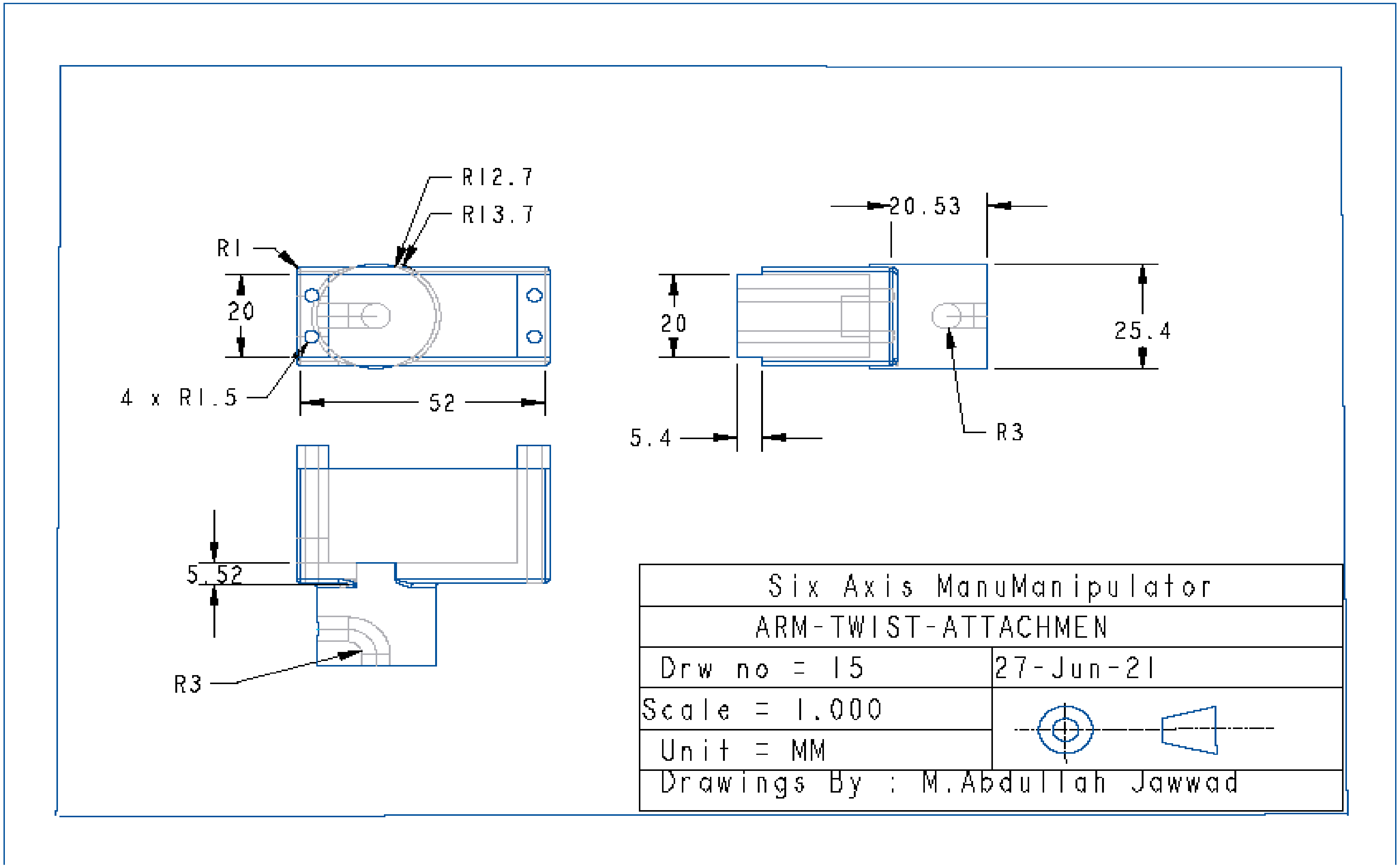


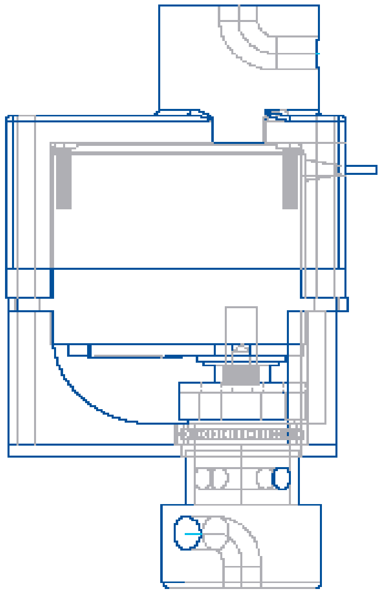
Six Axis ManuManipulator	
TWIST-SERVO-CONECTOR	
Drw no = 12	27-Jun-21
Scale = 2.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	


R15.7
R12.7
51.25
Six Axis ManuManipulator
TWIST-WRIST
Drw no = 13
27-Jun-21
Scale = 1.000
Unit = MM
Drawings By : M.Abdullah Jawwad



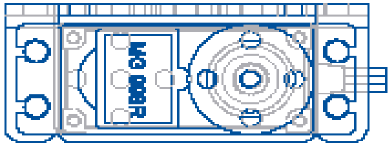
Six Axis ManuManipulator	
TWIST-BEARING-HOLDER	
Drw no = 14	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

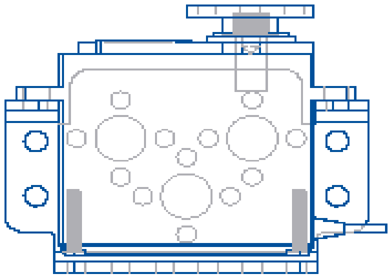

R12.7
R13.7
R1
20
4 x R1.5
52
20.53
20
25.4
5.4
R3
5.52
R3
Six Axis ManuManipulator
ARM-TWIST-ATTACHMEN
Drw no = 15
27-Jun-21
Scale = 1.000
Unit = MM
Drawings By : M.Abdullah Jawwad

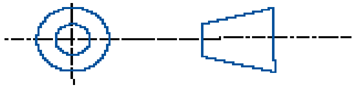


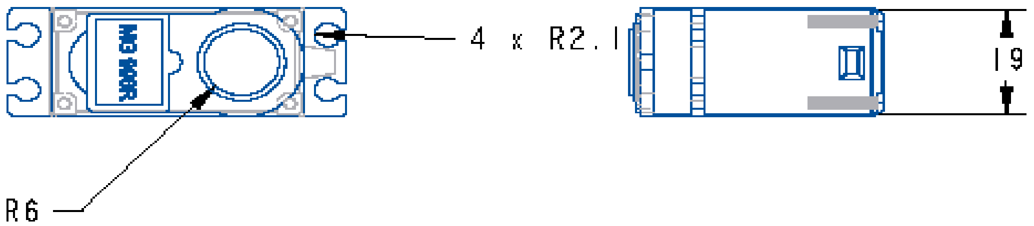
SCALE 1.000

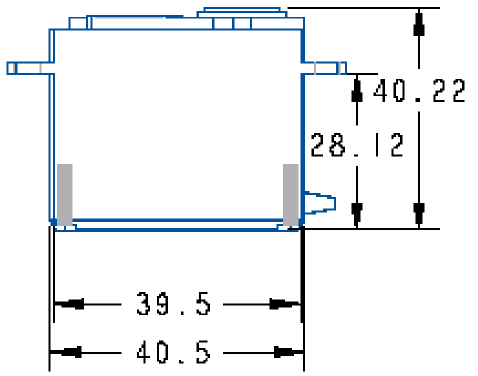
Six Axis ManuManipulator	
ARM-TWIST-ASSEMBLY_	
Drw no = 16	27-Jun-21
Scale = 0.500	
Unit = MM	
Drawings By : M.Abdullah Jawwad	



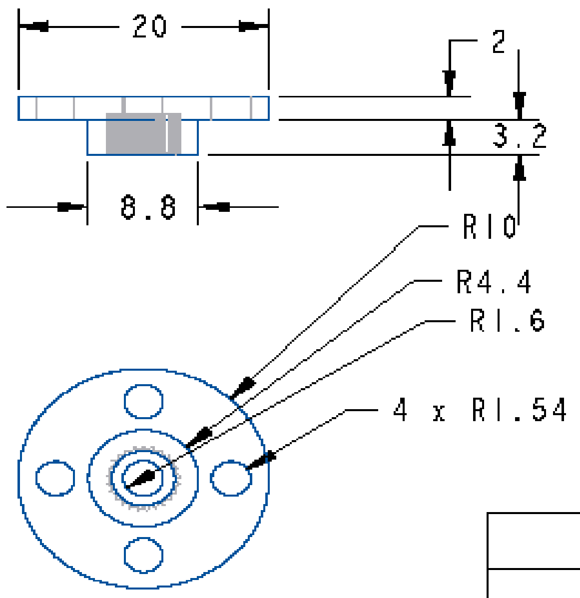


Six Axis ManuManipulator	
ASM0006	
Drw no = 17	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

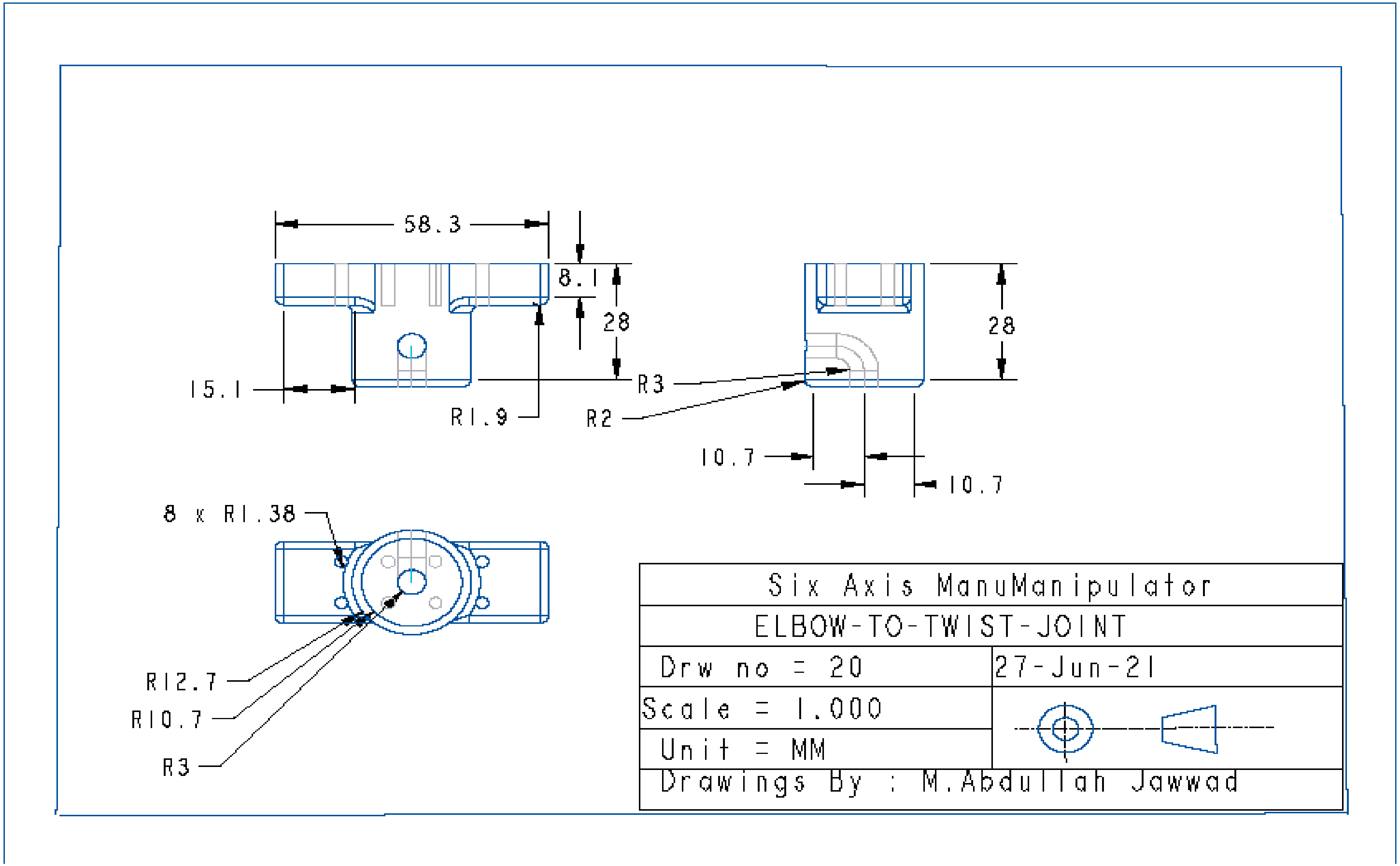


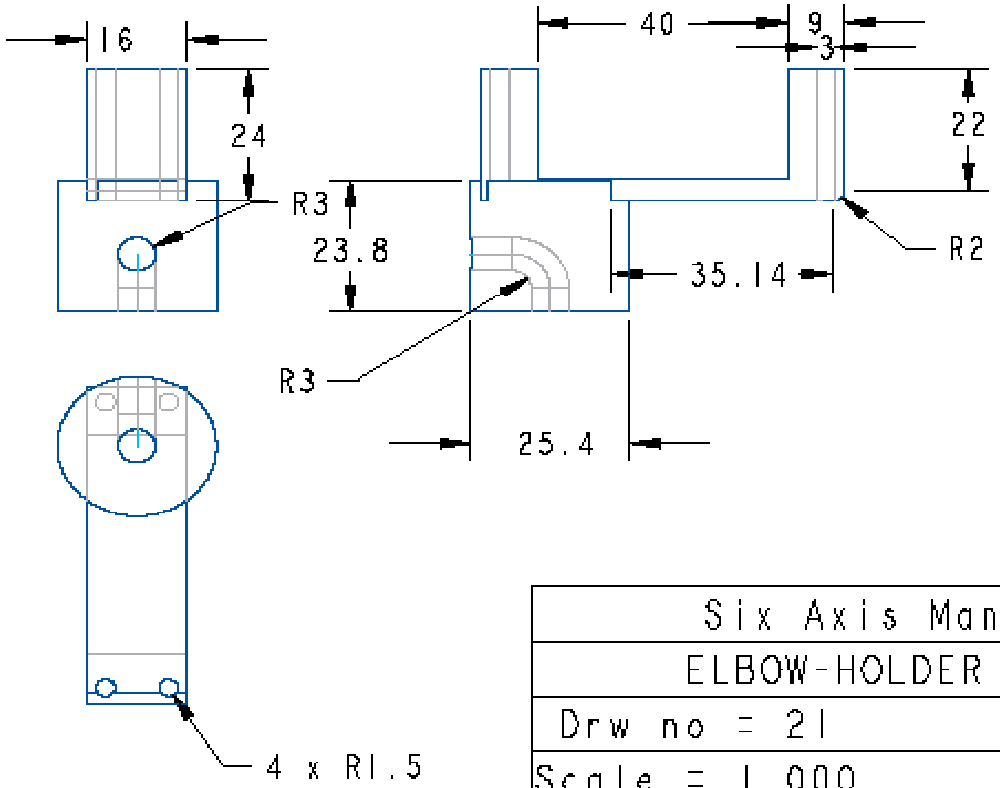


Six Axis ManuManipulator	
BODY2	
Drw no = 18	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

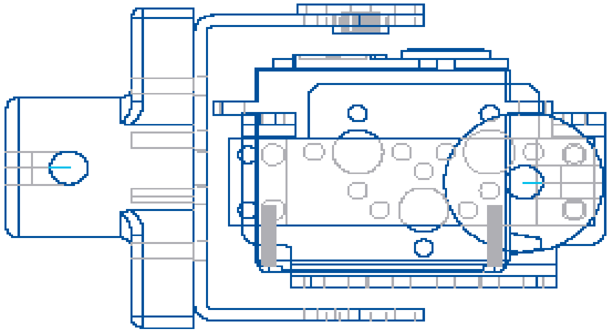


Six Axis ManuManipulator	
SERVO_DISE_V1_1_2	
Drw no = 19	27-Jun-21
Scale = 2.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

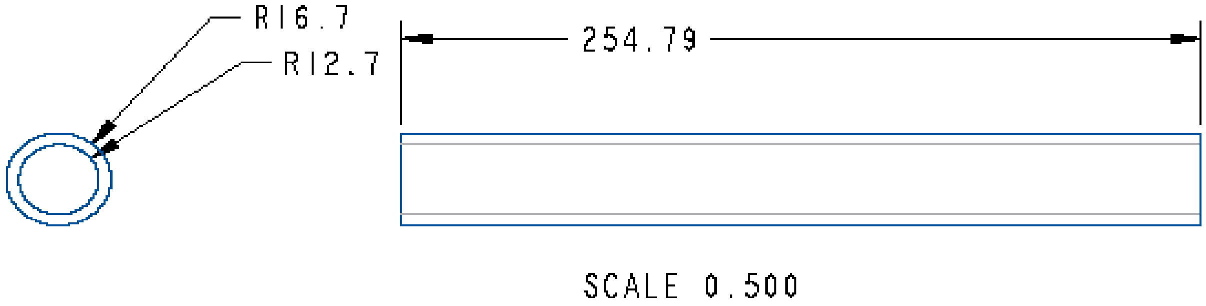

58.3
8.1
28
28
15.1
R1.9
R3
R2
10.7
10.7
8 x R1.38
R12.7
R10.7
R3
Six Axis ManuManipulator
ELBOW-TO-TWIST-JOINT
Drw no = 20
27-Jun-21
Scale = 1.000
Unit = MM
Drawings By : M.Abdullah Jawwad



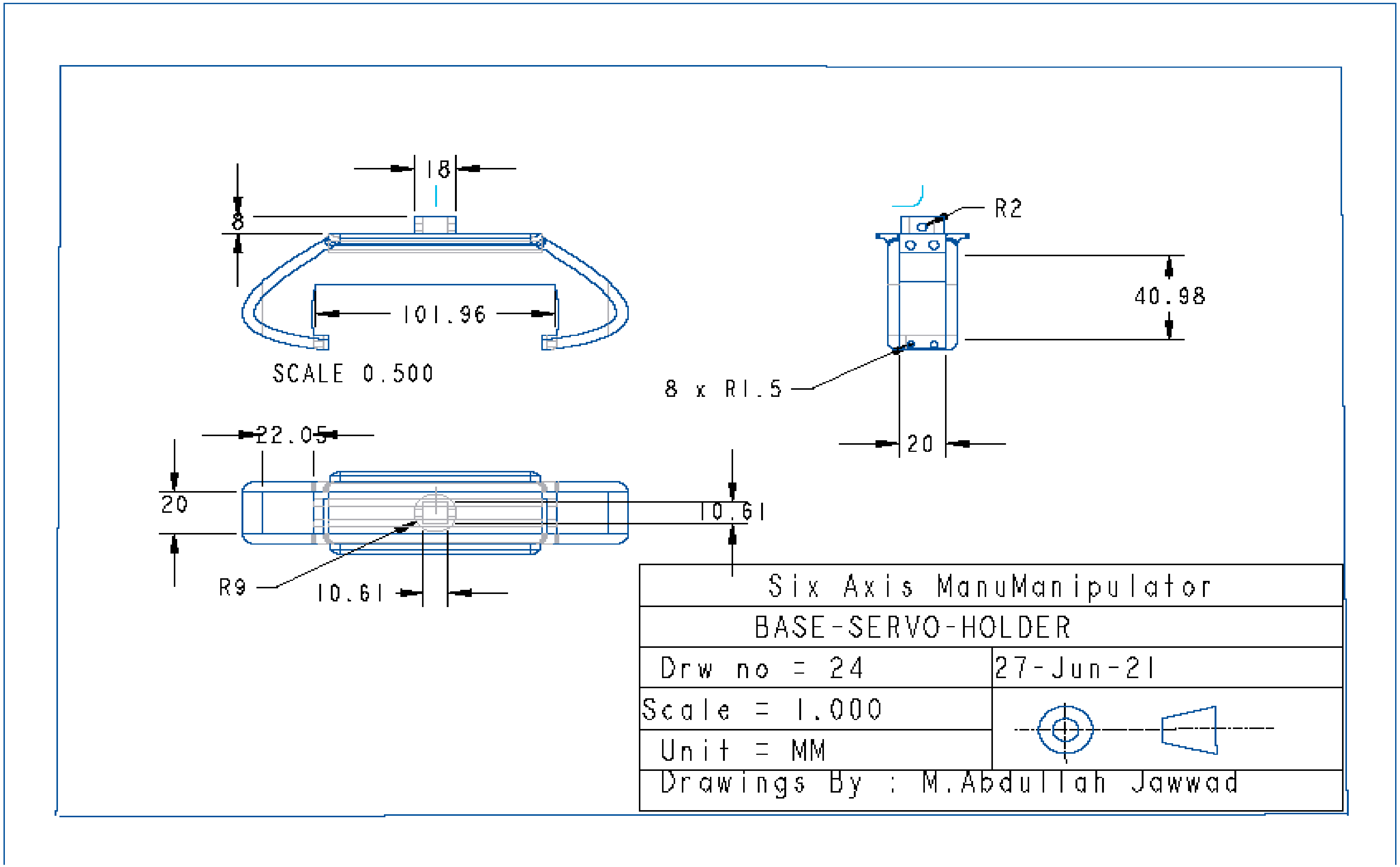
Six Axis ManuManipulator	
ELBOW-HOLDER	
Drw no = 21	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

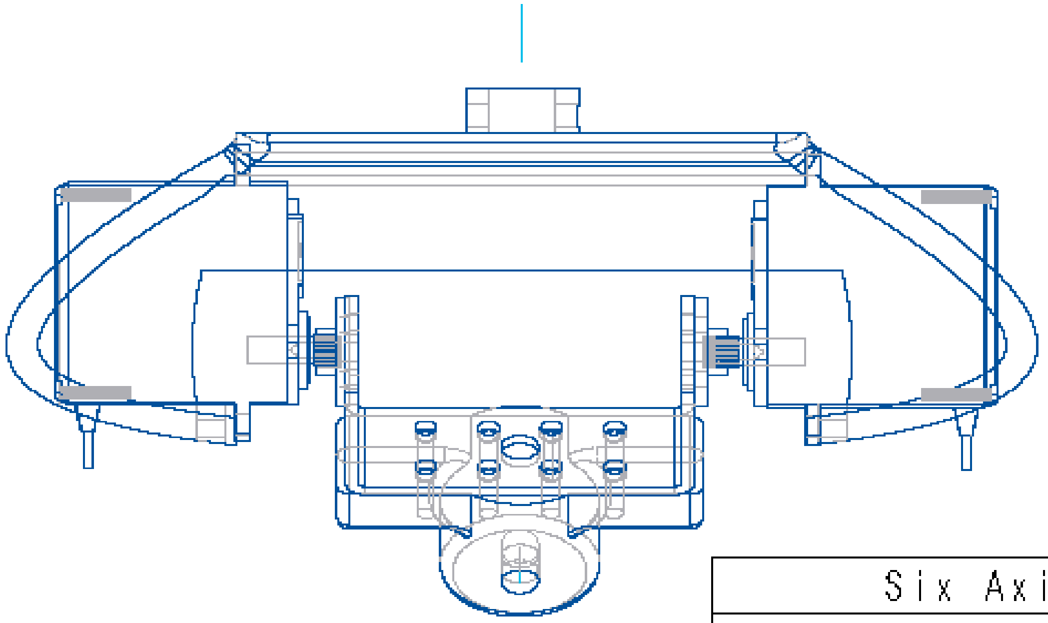


Six Axis ManuManipulator	
ELBOW-ASSEMBLY_	
Drw no = 22	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

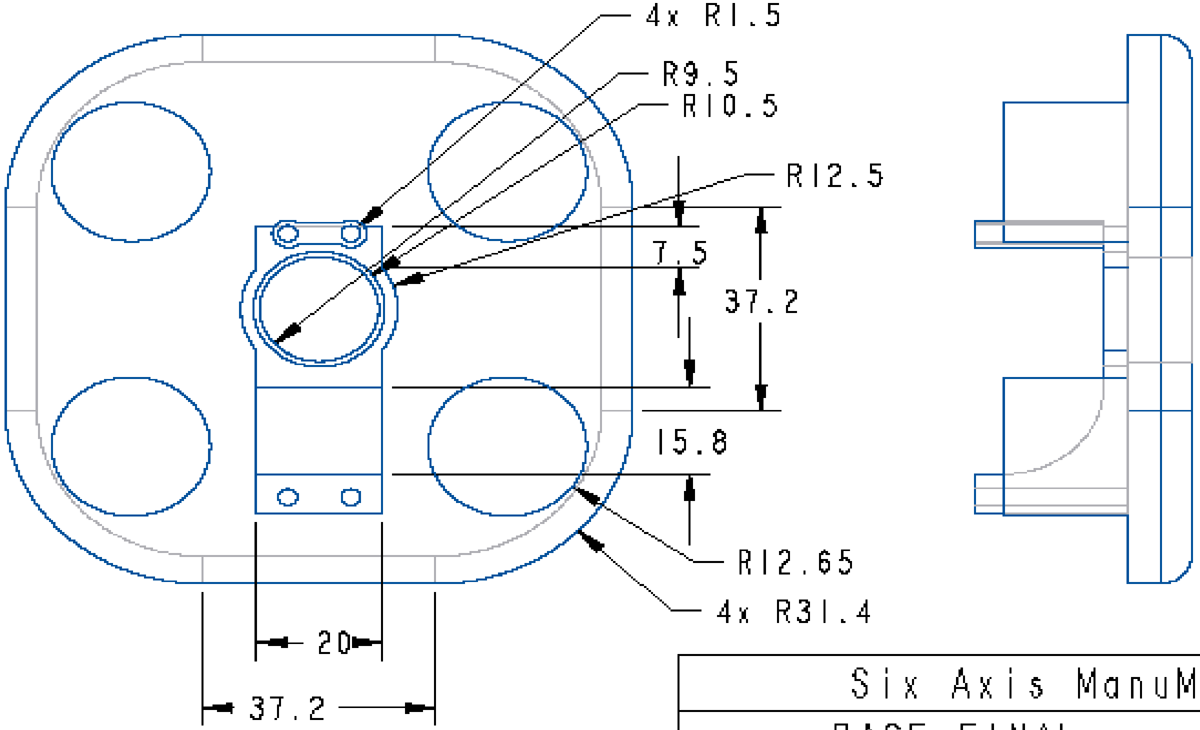


Six Axis ManuManipulator	
BOTTOM-ELBOM-ROD	
Drw no = 23	27-Jun-21
Scale = 0.250	
Unit = MM	
Drawings By : M.Abdullah Jawwad	

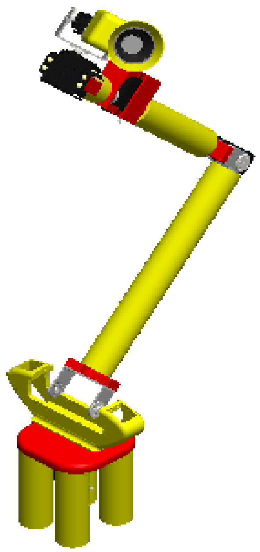

18
8
101.96
SCALE 0.500
R2
40.98
8 x R1.5
20
22.05
20
10.61
R9
10.61
Six Axis ManuManipulator
BASE-SERVO-HOLDER
Drw no = 24
27-Jun-21
Scale = 1.000
Unit = MM
Drawings By : M.Abdullah Jawwad



Six Axis ManuManipulator	
BOTTOM-ROT-ASSEMBLY_	
Drw no = 25	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	



Six Axis ManuManipulator	
BASE-FINAL	
Drw no = 26	27-Jun-21
Scale = 1.000	
Unit = MM	
Drawings By : M.Abdullah Jawwad	



SCALE 0.200

Six Axis ManuManipulator	
COMPLETE-ASSEMBLY	
Drw no = 27	27-Jun-21
Scale = 0.083	
Unit = MM	
Drawings By : M.Abdullah Jawwad	