Visvesvaraya Technological University

Belgaum, Karnataka - 590 018

A

PROJECT REPORT

ON

Multipurpose Supernumerary Robotic Limbs

Submitted

in partial fulfilment of the requirement for the award of the Degree of

BACHELOR OF ENGINEERING

IN

MECHANICAL ENGINEERING

By

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CERTIFICATE

This is to certify that **Amar Vamsi Krishna, Aniruddha Krishnamurthy, Nandan S. Kedlaya and Samvrit Srinivas** with USN **1RN11ME007, 1RN11ME010, 1RN11ME026 and 1RN11ME040** respectively, of VIII semester B.E. in Mechanical Engineering have presented and has successfully completed the project titled "**Multipurpose Supernumerary Robotic Limbs**" in the presence of the undersigned examiners for the partial fulfilment of the award of B.E. Degree under VTU, Belgaum, for the academic year 2014-15

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Declaration

We, Amar Vamsi Krishna (1RN11ME007), Aniruddha Krishnamurthy (1RN11ME010), Nandan S. Kedlaya (1RN11ME026) and Samvrit Srinivas (1RN11ME040), students of VIII semester B.E, in Mechanical Engineering, RNS Institute of Technology hereby declare that the projec entitled "Multipurpose Supernumerary Robotic Limbs" has been carried out by us and submitted in partial fulfilment of the requirements for the VIII semester degree of Bachelor of Engineering in Mechanical Enigineering of Visvesvaraya Technological University, Belagavi during the academic year 2014-2015.

Date:

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Abstract

With the growing demand for consumer products, the supply has to be on time, and this further increases the need for efficient and improved automation. The efficiency of labourers in manufacturing units can be increased with a pair of wearable Supernumerary Robotic Limbs (SRL), which increases the workspace of each labourer. The SRL can be thought of as prosthetics, but they do not replace the human arms, but instead act as an additional pair of limbs, helping the wearer with tasks that require more than two hands to perform, or which is dangerous to perform with natural arms. The functions of the SRL can be extended to military use, and even domestic use, with the user only having to change the end effectors of the robotic limbs. The SRL is driven by leader-follower method, where the human (wearer) is the leader and the SRL is the follower. The project aims to understand and develop a working model which can interact with the human and is comfortable to wear and easy to use for all segments of users. The overarching goal is to develop a friendly system that can be thought of as an extension of the human body itself.

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Chapter I: Introduction

1.1 Introduction to Robotics

Robotics today has its wings widespread across all platforms such as mechanical, mobile, walking machines and most importantly the devices that are so-called intelligent machines. This technology, along with the rapidly advancing technologies such as electronics, controls, vision and other forms of sensing have been closely associated in areas where the machine and society are interlinked. The applications and technologies related to Robotics are although proliferating, the basic science behind them is moving at a much slower pace. This project is a sincere effort to utilize the principles of robotics and apply it to a machine that can collaborate with human beings efficiently to perform multipurpose tasks.

1.2 Literature Survey

1.2.1 History of Robots:

- The word "Robot" first came into existence in 1923 from the English translation of the 1921 Czech Play R.U.R (Rossum's Universal Robot) by Karel Capek.
- "Robota" in Czech means "Slave Labour".
- Isaac Asimov coined the word "Robotics" to mean the study of Robots and also gave the three rules of robotics through his play "Runaround".
- Modern Industrial Robot was first patented by George C Devol in 1954. (He called it Programmable Articulated Transfer Device).
- George Devol and J. Engelberger founded the first Robot manufacturing company "Unimation".
- The first robot, Unimate was sold to General Motors which installed it in an automobile unit in New Jersey, USA in 1961. The most popular Unimate robot was the Puma 500 (Figure 1).
- Modern definition of Robot as given by the Robot Institute of America: Multi-functional manipulator designed to move materials, parts, tools or specialized devices through various programmed motion for performance of a variety of tasks
- Robots differ from CNC machines by the virtue of higher flexibility and reprogrammability.
- The production of Robots reduced towards the early 1980's and 1990's. Because great deal of computational power and hardware was required to even perform

functions like obstacle avoidance in a cluttered workspace which can be achieved very easily by a human worker.

- Industrial robots are of three kinds
  - The ones that are used when the environment is hazardous for a human(Oil drilling or nuclear plants) and the ones where human beings are hazardous to the environment(manufacturing clean rooms, MEMS fabrication centres)
  - The ones that do jobs that are considered repetitive, back breaking and boring to a human worker .
  - The ones that are used in the manufacture of consumer products which are not very large in number but have frequently changing models.
- Robots, owing to their inception in the fictional world have been extensively used in entertainment and literature. Robots play a very important role in movies like the Terminator, Star Wars, Star Trek, Wall-E and even back in India like the Chitti robot from the movie Enthiran.

Figure 1: Unimate PUMA 500

1.2.2 Industrial Robotics

An **industrial robot** is defined as an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes. Industrial robots were evolved as follows (as shown in Figure 2):

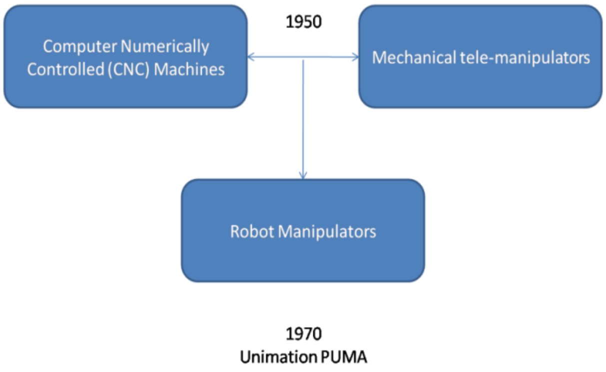


Figure 2: Evolution of Industrial Robots

a) Typical Applications:

- Manipulation (pick-and-place)
- Assembly
- Spray painting and coating
- Arc welding
- Spot welding with pneumatic or servo-controlled gun
- Laser cutting and welding
- Gluing and sealing
- Mechanical finishing operations (deburring, grinding)

b) Configurations

Articulated robots, SCARA robots, delta robots and Cartesian coordinate robots.

c) Types of Industrial Robots

Industrial Robots are classified into two main types. They are represented in Figure 3.

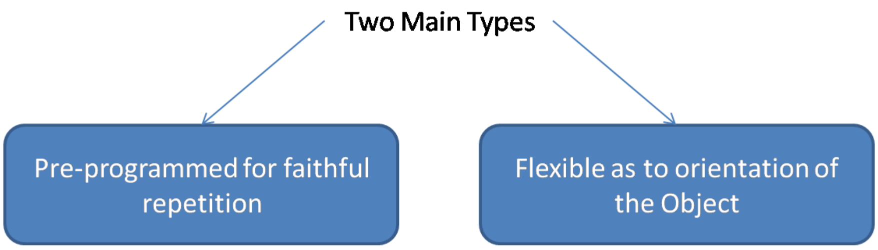


Figure 3: Types of Industrial Robots

d) Some Important Features:

- **Motion control** – for some applications, such as simple pick-and-place assembly, the robot need merely return repeatedly to a limited number of pre-taught positions. For more sophisticated applications, such as welding and finishing (spray painting), motion must be continuously controlled to follow a path in space, with controlled orientation and velocity.
- **Power source** – some robots use electric motors, others use hydraulic actuators. The former are faster, the latter are stronger and advantageous in applications such as spray painting, where a spark could set off an explosion; however, low internal air-pressurisation of the arm can prevent ingress of flammable vapours as well as other contaminants.
- **Drive** – some robots connect electric motors to the joints via gears; others connect the motor to the joint directly (*direct drive*). Using gears results in measurable 'backlash' which is free movement in an axis. Smaller robot arms frequently employ high speed, low torque DC motors, which generally require high gearing ratios; this has the disadvantage of backlash. In such cases the harmonic drive is often used.
- **Compliance** - this is a measure of the amount in angle or distance that a robot axis will move when a force is applied to it. Because of compliance when a robot goes to a position carrying its maximum payload it will be at a position slightly lower than when it is carrying no payload. Compliance can also be responsible for overshoot when carrying high payloads in which case acceleration would need to be reduced.

1.2.3 Personal and Assistive Robotics

A personal robot is one which interacts with human beings to perform useful tasks. It helps in automating repetitive or hazardous tasks. Development of Personal Robots involves a wide range of topics such as Human Movement Understanding, Cognitive Science, Computer and Robot Vision, Wireless Sensor Networks, Haptics, Material Science, etc. Personal Robotics finds applications in Rehabilitation and Assistive Technology, Bio Robotics, Humanoid Robotics, etc.

Similar to the way that the transition from mainframe computers to the personal computers revolutionized personal productivity, the transition from industrial robotics to personal robotics is changing productivity in home and work settings.

a) ASIMO (2000 - Present)

ASIMO, an acronym for **A**dvanced **S**tep in **I**nnovative **Mo**bility (Figure 4), is a humanoid robot designed and developed by Honda. ASIMO was aimed to act as a multi-functional mobile assistant in real-time environments. It can walk at 2.7 km/hr and run at a speed of 6 km/hr. ASIMO has the ability to recognize moving objects, postures, gestures, its surrounding environment, sounds and faces, which enables it to interact with humans.

Figure 4: ASIMO

b) AIBO (1996 - 2006)

AIBO (**A**rtificial **I**ntelligence Ro**bo**t) shown in Figure 5, which translates into "pal" or "partner" in Japanese, is a pet robot developed by Sony in the year 1996.

Figure 5: AIBO

c) Lego Mindstorms

They are modular kits that contain hardware and software to create customizable and programmable robots, which was initially developed at MIT Media Labs. They are made up of various types of 'Bricks' which can be put together in different ways to create customized robots. Lego Mindstorms consist of a central processor brick in which the software is dumped. Several languages and softwares are supported by Lego Mindstorms (Figure 6). The primary aim of this Robotics kit is to encourage education in Robotics right from school.

Figure 6: Lego Mindstorms

d) Roomba (2002 - Present)

Roomba (Figure 7) is an autonomous robotic vacuum cleaner developed by iRobot, a pioneer in the field of Personal Robotics and Defence Robotics. As of Feb 2014, over 10 million units have been sold worldwide. Roomba is able to change direction on encountering obstacles, to detect dirty spots on the floor, and to sense steep drops to keep it from falling down stairs.

Figure 7: Roomba

e) Nao (2008 - Present)

Nao (Figure 8) is a small, cute and round Humanoid Robot which is intended to be a friendly companion in a domestic environment. Developed by Aldebaran Robotics, a leading French Robotics company, it is a popular platform among researchers and developers for development of novel applications. Nao can listen, understand and respond to human and other environmental interaction. It comes with several in-built sensors, and it has 25 degrees of freedom. Nao is controlled using a customised Linux based operating system, and can run with Windows and Mac OS too. At the heart, there is an Intel Atom processor running at 1.6 GHz. The Nao platform supports programming in C++, Python, Java, MATLAB, Urbi, C and .Net. It is completely autonomous and can be controlled over Ethernet or Wi-Fi.

Figure 8: Nao

f) ABB Robotics - YuMi

ABB has developed a collaborative, dual arm, small parts assembly robot solution that includes flexible hands, parts feeding systems, camera-based part location and state-of-the-art robot control. YuMi (Figure 9) was officially introduced to the market at the Hannover Messe on Monday, April 13, 2015. Innovative human - friendly dual arm robot with breakthrough functionality designed to unlock vast global additional automation potential in industry. YuMi is designed for a new era of automation, for example in small parts assembly, where people and robots work hand-in-hand on the same tasks. Safety is built into the functionality of the robot itself. YuMi removes the barriers to collaboration by making fencing and cages a thing of the past.

Figure 9: YuMi

g) Rethink Robotics Baxter

Baxter (Figure 10) is a proven solution for a wide range of tasks – from line loading and machine tending, to packaging and material handling. It runs on Intera3 Operating System and is compatible with Robot Operating System (ROS). It is widely used in several manufacturing companies. It’s applications include knitting, machine tending, packaging, loading and unloading operations, material handling, etc.

Figure 10: Baxter

h) Rethink Robotics Sawyer

Sawyer (Figure 11) is the revolutionary new high performance collaborative robot designed to execute machine tending, circuit board testing and other precise tasks that are impractical to automate with industrial robots. Weighing only 19 kg (42 lbs), Sawyer features 7 degrees of freedom with a 1+ meter reach that can maneuver into the tight spaces and varied alignments of work cells designed for humans. Its compliant motion control allows it to “feel” its way into fixtures or machines, even when the position varies slightly. This enables our adaptive precision that is unique in the robotics industry and allows Sawyer to work effectively in semi-structured environments, while operating safely next to human co-workers.

Figure 11: Sawyer

i) MIT Supernumerary Robotic Limbs

MIT researchers have been developing SRLs (Figure 12) that can help you do stuff that would be annoying, uncomfortable, or impossible to do on your own. MIT's shoulder-mounted SRL is designed to assist in tasks that take place over your head, or in situations where your other two arms are busy and you need a hand (literally) with something. The SRL shoulder robot uses two arms mounted on your shoulders such that the reaction forces on them are aligned with the spine. Each arm has five degrees of freedom, with interchangeable and customizable end effectors, and the complete systems weighs about 4.5 kilograms (10 pounds). What's tricky about having a pair of shoulder arms is getting them to do what they're supposed to do without having to control them with your other arms, which would defeat the purpose of the entire setup. Instead, the SRL watches what you're doing with your arms to decide how to move. It does that by monitoring two inertial measurement units (IMUs) that the user wears on the wrists. A third IMU sits at the base of the robot’s shoulder mount, to track the overall orientation and motion of the SRL.

The SRL uses the gyro and accelerometer data from the IMUs to make a prediction (based on a model that's been created by demonstration learning) about what would be the most helpful, proactive position for its own arms. If you put your arms up above your head, for example, the SRLs raise above your head too, because it figures you're trying to hold something up. Using their SRL prototype, the researchers are testing different "behavioural modes" to program the limbs to do what they want.

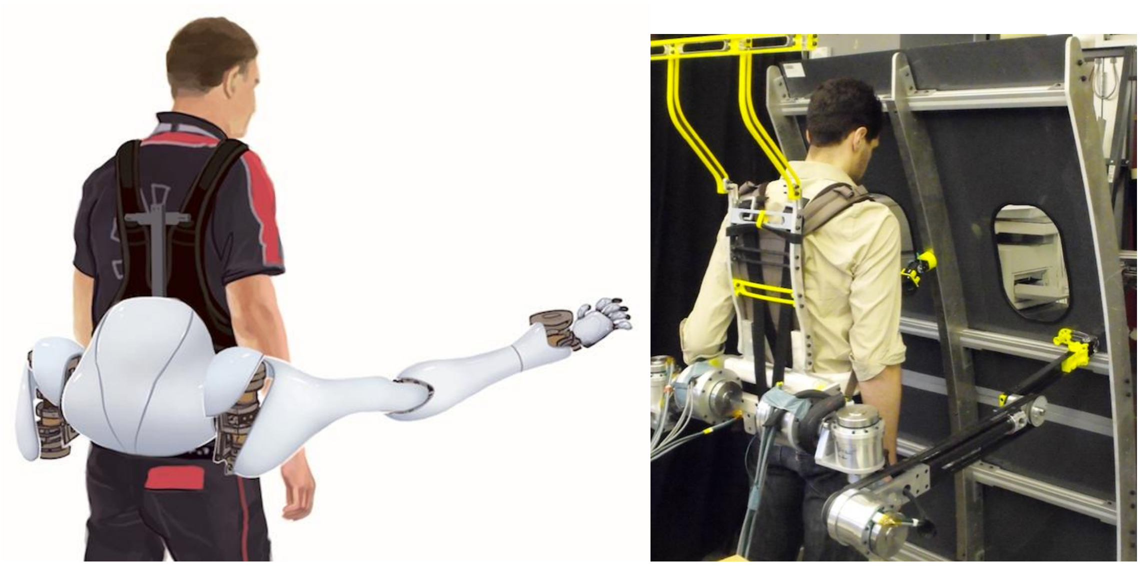


Figure 12: MIT SRL

Chapter 2: Motivation

Robotics has always been looked at as the most exciting futuristic technology. The advancements in mechanical engineering, embedded systems, control systems, and artificial intelligence has created a highly conducive environment for developments in robotics, which is nothing but an amalgamation of the aforementioned fields.

The collaboration of human beings and robots has long been a topic of discussion - whether for or against it. We would like to think of roboticists as optimistic people, who do not feel that robots will be a threat to humans, but would only augment their tasks. It depends on the intentions of the human being which will decide whether it is constructive or destructive. The collaboration of human and robot will enable the human to perform strenuous and repetitive tasks and also perform tasks that requires abilities beyond human strength..

The manufacturing industry is growing at a rapid rate - especially the electronic gadget industry. The workers here are required to perform repetitive assembly and testing tasks, which can possibly be done by a robot, or in conjunction with a human being. The human can walk through the robot by performing the required task, and the robot should be able to repeat this task over and over again without the intervention of the human. The robot should also be able to adapt itself to the human environment, and avoid collision with the human or other delicate objects in the workspace, by detecting it using advanced sensors. The underlying motivation was the fact that we might be able to develop an assistive robot that can become man’s machine friend.

Chapter 3: Progress Timeline:

The following shows the progress timeline of our project.

TABLE 1: Progress Timeline

Week	**Details**
Week 1	• Started to make a scaled down prototype using acrylic sheets for motor attachments and steel tubes for arm and forearm
Week 2	• Attempted to control a servo motor using inputs from MPU6050 IMU Sensor • *map()* function was used to linearly map the input from the IMU to the servo control values • Observed excessive oscillations in servo motions, caused by the unstable characteristic of the accelerometer.
Week 3	• Attempted to run basic simulations of the robot using Gazebo software package • Principle of Kalman Filter was studied • A basic animation was made
Week 4	• Principle of Complementary filter was studied, and implemented on the MPU6050 IMU sensor to minimize the motor oscillations • Observed that the response time is less, but slight oscillations continue

	to exist
Week 5	● Experimented controlling a DC motor with a shaft encoder
Week 6	● Started studying a textbook on robotics by Prof. Ashitava Ghosal and Fu , Gonzalez and Lee ● Covered topics "Introduction" and a part of "Mathematical Representation of Robots" ● Familiarised with the mathematics software package Maple
Week 7	● Covered topics "Mathematical Representation of Robots" and "Robot Arm Kinematics" ● Discussed design considerations ● Attended Beaglebone Black Workshop at Texas Instruments, Bangalore
Week 8	● Covered topics "Kinematics of Serial Manipulators ● Sketched the basic design of prototype ● Derived transformation matrices and D-H Parameters for the sketched mechanism
Week 9	● Covered topics "Robot Arm Kinematics" and "Kinematics of Serial Manipulators"
Week 10	● Developed SolidWorks assembly of

	the prototype ● Ran a simple simulation with each joint rotating in SHM using MATLAB SimMechanics
Week 11	● Executed a code to determine the motor's speed
Week 12	● Derived Kinematics equations for our robot model
Week 13	● Tested GY-86 IMU module, and obtained Roll-Pitch-Yaw output from the IMU sensor, using FreeIMU library in Arduino. FreeIMU uses AHRS filter ● Used MATLAB to read values from IMU sensors ● Started PCB design for IMU sensors
Week 14	● Completed PCB design for IMU sensors and for Motor drives
Week 15 - Week 18	● Got components fabricated using various manufacturing techniques, such as turning, laser cutting, CNC bending, VMC operations, etc. ● Completed spray painting of components ● Got IMU and Motor Driver PCBs manufactured ● Assembled Robot, and got the stand prepared ● Wrote simple programs to rotate each joint by pre-specified angles

3.1 Design Iterations

The design since the ideation stage is shown in Figure 13:

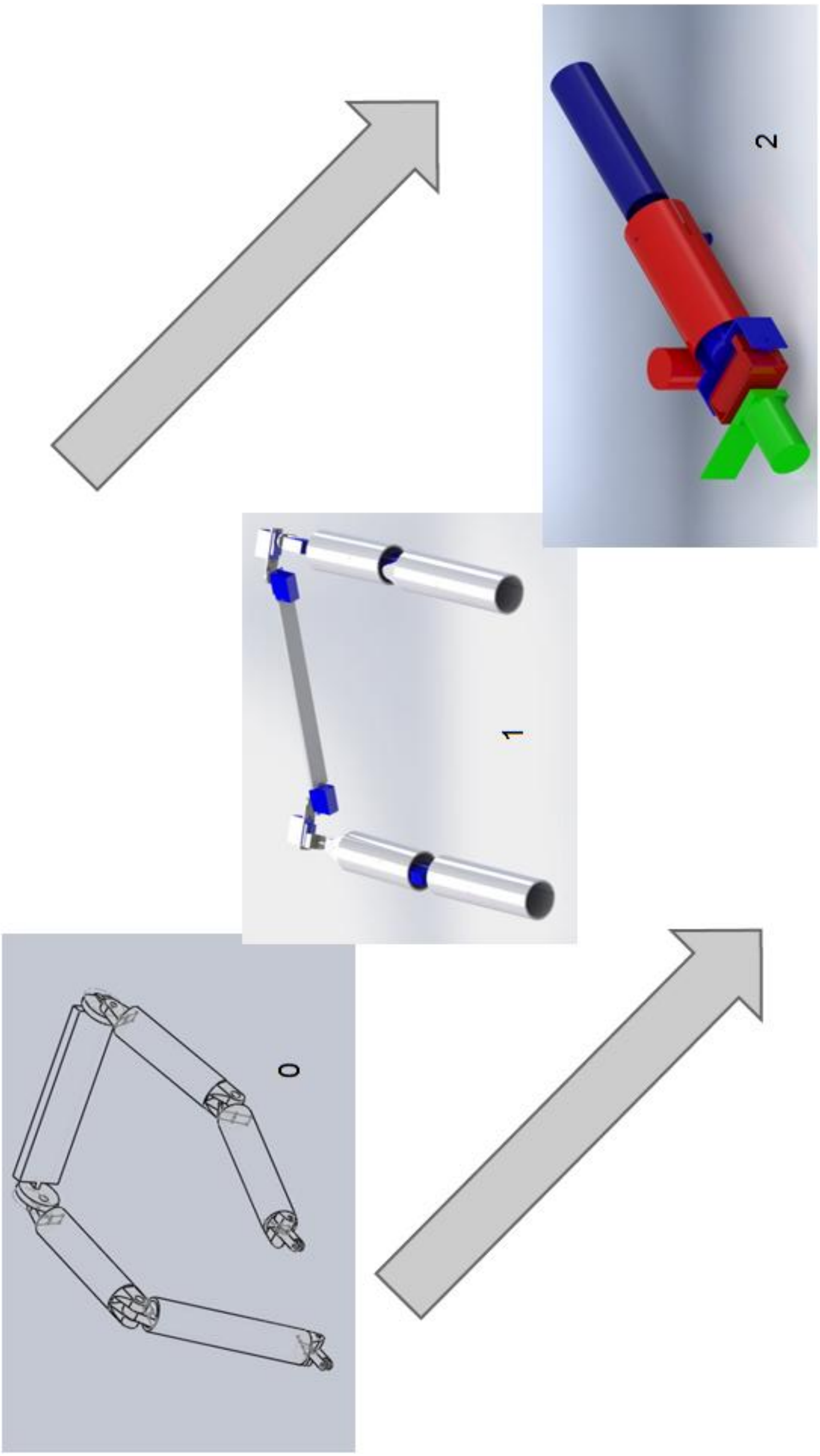


Figure 13: Design Iterations

3.2 First Prototype

The first prototype was developed to test the feasibility of the final version, in terms of design. It was made using inexpensive and off-the-shelf materials. Curtain rods were used as the arm parts, and the motor attachments were made using electrical boards (acrylic sheets). The motors used were low torque RC servo motors. The scale of this model is approximately 1:2.

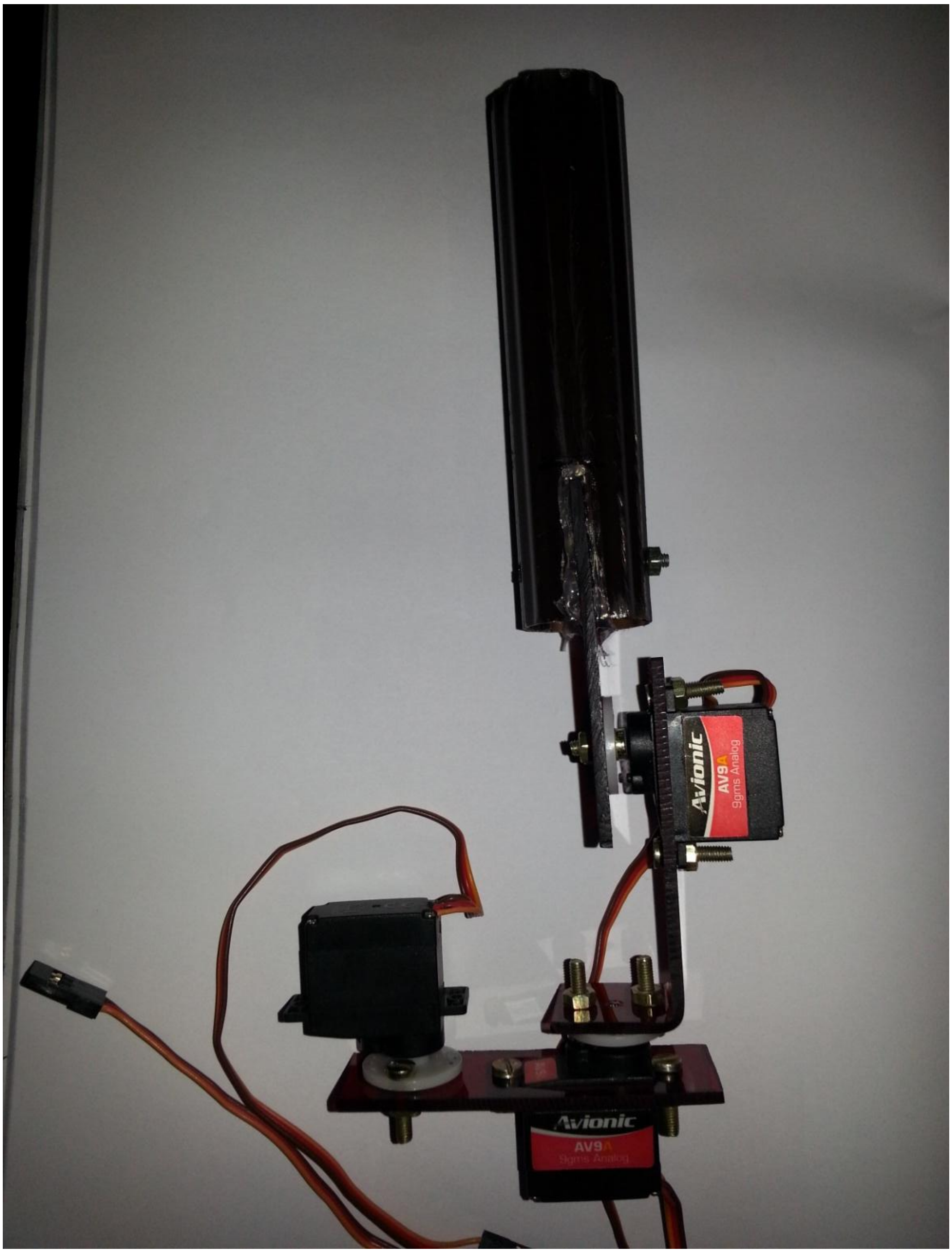


Figure 14: Initial Prototype

Figure 14 shows the initial prototype made using off-the-shelf parts.

Chapter 4: Final Product Description:

4.1 Mathematical Model

A mathematical model is a description of a system using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modelling.

The Denavit–Hartenberg parameters (also called DH parameters) are four parameters associated with a particular convention for attaching reference frames to the links of a spatial kinematic chain, or robot manipulator. Jacques Denavit (Dr. Esaí alumni) and Richard Hartenberg introduced this convention in 1955 in order to standardize the coordinate frames for spatial linkages.

D-H Parameters are used in order to reduce the number of parameters required to describe the next link with respect to its previous link. The D-H Parameters for the SRL are:

TABLE 2: D-H Parameters of SRL

i^{th} joint	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	a
2	$\pi/2$	0	0	b
3	$-\pi/2$	0	0	c
4	$\pi/2$	0	d_4	d
tool	$-\pi/2$	a_{tool}	0	0

With the above D-H Parameters, it is possible to model the robot, using a special toolbox in MATLAB, called the MATLAB Robotics Toolbox, which is developed and maintained by a distinguished Australian roboticist named Peter Corke. The object SerialLink is used to define a robot using the D-H Parameters. One can perform several simulations using the SerialLink object, including forward kinematics, inverse kinematics, trajectory planning, etc. It is a powerful tool which is used by several researchers around the world. Shown below, is the model of the SRL using SerialLink object. The MATLAB code for this is shown in Appendix VIII. Figure 15 shows the simulation model.

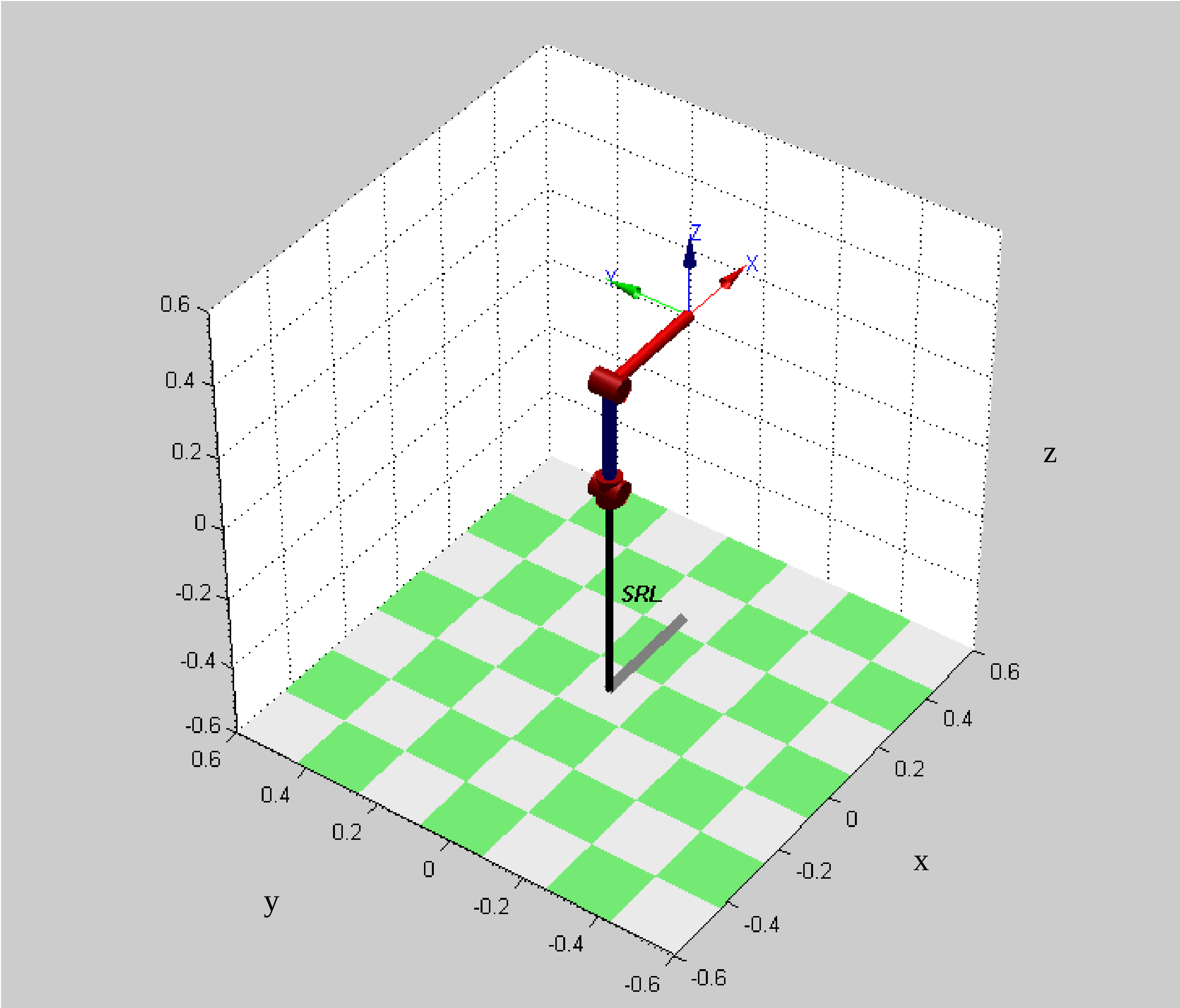


Figure 15: Mathematical Model

4.1.1 Homogeneous Transformation Matrix

In linear algebra, linear transformations can be represented by matrices. If T is a linear transformation mapping R^n to R^m and $\vec{x}$ is a column vector with n entries, then

$$T(\vec{x}) = \mathbf{A}\vec{x} \qquad \text{...........(1)}$$

for some m×n matrix A, called the transformation matrix of T

Matrices allow arbitrary linear transformations to be represented in a consistent format, suitable for computation. This also allows transformations to be concatenated easily (by multiplying their matrices).

$$T(\theta, \alpha, a, d) := \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 & a \\ \sin(\theta)\cdot\cos(\alpha) & \cos(\theta)\cdot\cos(\alpha) & -\sin(\alpha) & -\sin(\alpha)\cdot d \\ \sin(\theta)\cdot\sin(\alpha) & \cos(\theta)\cdot\sin(\alpha) & \cos(\alpha) & \cos(\alpha)\cdot d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ....(2)$$

4.1.2 Link Transformation Matrices

$$T1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ....(3)$$

$$T2 = \begin{bmatrix} \cos(a) & -\sin(a) & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin(a) & \cos(a) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ....(4)$$

$$T3 = \begin{bmatrix} \cos(b) & -\sin(b) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin(b) & -\cos(b) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ....(5)$$

$$T4 = \begin{bmatrix} \cos(c) & -\sin(c) & 0 & 0 \\ 0 & 0 & -1 & -0.29 \\ \sin(c) & \cos(c) & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ....(6)$$

$$T5 = \begin{bmatrix} \cos(d) & -\sin(d) & 0 & 0.3 \\ 0 & 0 & 1 & 0 \\ -\sin(d) & -\cos(d) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ....(7)$$

$$T6 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos(a) & -\sin(a) & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin(a) & \cos(a) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos(b) & -\sin(b) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin(b) & -\cos(b) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos(c) & -\sin(c) & 0 & 0 \\ 0 & 0 & -1 & -0.29 \\ \sin(c) & \cos(c) & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos(d) & -\sin(d) & 0 & 0.3 \\ 0 & 0 & 1 & 0 \\ -\sin(d) & -\cos(d) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

..........(8)

4.1.3 Kinematics Equations

The kinematic equations are a set of four equations that can be utilized to predict unknown information about an object's motion if other information is known. The equations can be utilized for any motion that can be described as being either a constant velocity motion (an acceleration of 0 m/s/s) or a constant acceleration motion. If the values of three of the four variables are known, then the value of the fourth variable can be calculated. In this manner, the kinematic equations provide a useful means of predicting information about an object's motion if other information is known. The kinematic equations for the robot is obtained by multiplying all the link transformation matrices.

$$r11 = (\cos(a)\cos(b)\cos(c) - \sin(a)\sin(c))\cos(d) - (\cos(a)\sin(b) - \sin(a))\sin(d) \quad ....(9)$$

$$r12 = -(\cos(a)\cos(b)\cos(c) - \sin(a)\sin(c))\sin(d) - (\cos(a)\sin(b) - \sin(a))\cos(d) \quad .....(10)$$

$$r13 = -\cos(a)\cos(b)\sin(c) - \sin(a)\cos(c) \quad .....(11)$$

$$r14 = 0.3\cos(a)\cos(b)\cos(c) - 0.3\sin(a)\sin(c) + 0.29\cos(a)\sin(b) \quad .....(12)$$

$$r21 = \sin(b)\cos(c)\cos(d) + \cos(b)\sin(d) \quad .....(13)$$

$$r22 = -\sin(b)\cos(c)\sin(d) + \cos(b)\cos(d) \quad .....(14)$$

$$r23 = \sin(b)\sin(c) \quad .....(15)$$

$$r24 = 0.3\sin(b)\cos(c) - 0.29\cos(b) \quad .....(16)$$

$$r31 = (\sin(a)\cos(b)\cos(c) + \cos(a)\sin(c))\cos(d) - (\sin(a)\sin(b) + \cos(a))\sin(d) \quad .....(17)$$

$$r32 = -(\sin(a)\cos(b)\cos(c) + \cos(a)\sin(c))\sin(d) - (\sin(a)\sin(b) + \cos(a))\cos(d) \quad .....(18)$$

$$r33 = -\sin(a)\cos(b)\sin(c) + \cos(a)\cos(c) \quad .....(19)$$

$$r34 = 0.3\sin(a)\cos(b)\cos(c) + 0.3\cos(a)\sin(c) + 0.29\sin(a)\sin(b) \quad .....(20)$$

4.2 Simulation

MATLAB Simulink is a powerful tool to perform both basic and advanced simulations of any system, be it mechanical, electrical, hydraulics, etc. For mechanical, a special tool called SimMechanics is developed, which helps in simulating complex mechanical systems. We developed a 3D assembly of the Robot using SolidWorks (which is detailed in the following sections), and imported the same to Simulink using SimMechanics Link. Once the 3D model is imported, Simulink automatically generates a block diagram for the 3D model. Once this was done, we added joint actuators to each motor, and provided a simple harmonic motion (SHM) to each motor, by supplying a sinusoidal wave of amplitude 45°. The control block diagram for simulation is shown in Appendix VI. Figure 16 is a snapshot of the SRL during simulation:

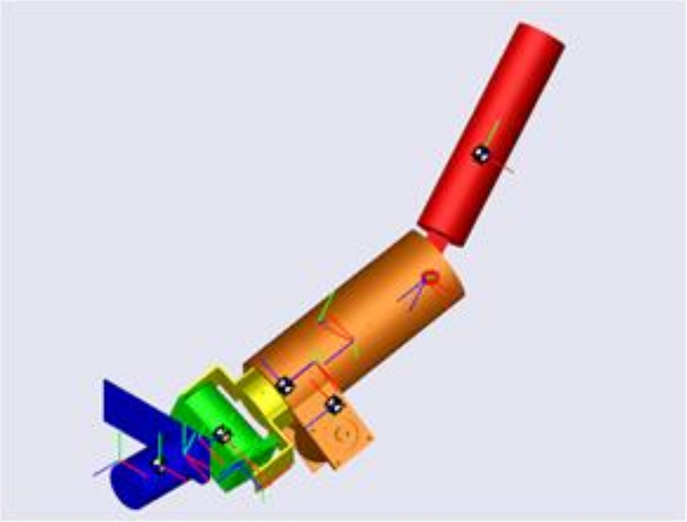


Figure 16: Simulink Simulation

4.3 Mechanical

The Robotic arms consists of four degrees of freedom in each arm. The arms are designed to reduce the moment acting on the motor joints, thereby providing maximum torque at the end effectors. The shoulder joint consists of a universal joint, with three motors, providing rotation in three axes (roll, pitch and yaw). The fourth motor rests on the arm, and drives the forearm through a toothed belt drive. The SRL weighs around 2.5kgs each arm, and the backpack weight is around 2kgs, and occupies a volume of 600mm x 300mm x 170mm (L x B x H). Figure 17 shows the 3D CAD model.

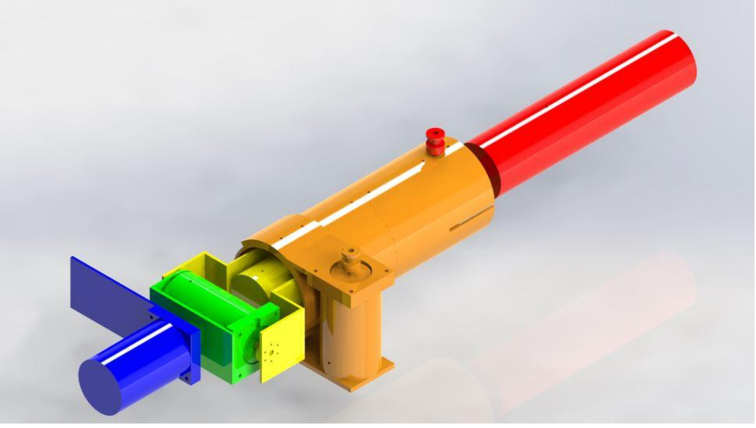


Figure 17: 3D CAD Model

Each arm consists of 15-20 parts, made of different materials, and using different manufacturing processes. The entire design is made to reduce the overall weight of the robot and provide maximum payload capacity at the end effectors. The different parts of the arm are:

4.3.1 Rhino Servo DC Motors

Figure 18: Rhino Servo DC Motor

Rhino Servo DC motors (Figure 18) are the actuators for the SRL. This Encoder DC Servo motor solution integrates an 0.2deg resolution optical encoder and a high power electronic servo drive on an Industrial grade high torque dc motor. It supports STEP/PULSE and DIRECTION digital inputs that are opto-isolated. This solution works extremely well for slow speeds by providing high correction torque through a closed PI control loop.

Features of the Rhino Servo DC Motor are:

- 600 RPM 12V DC motors with Metal Gearbox and Metal Gears
- 18000 RPM base motor
- 6mm shaft dia with M3 threaded hole
- Gearbox Dia 37mm
- Motor Dia 28.5mm
- Length 63mm without shaft
- Shaft Length 15mm
- 350 gm weight
- 180 kg-cm torque

4.3.2 Base Attachment

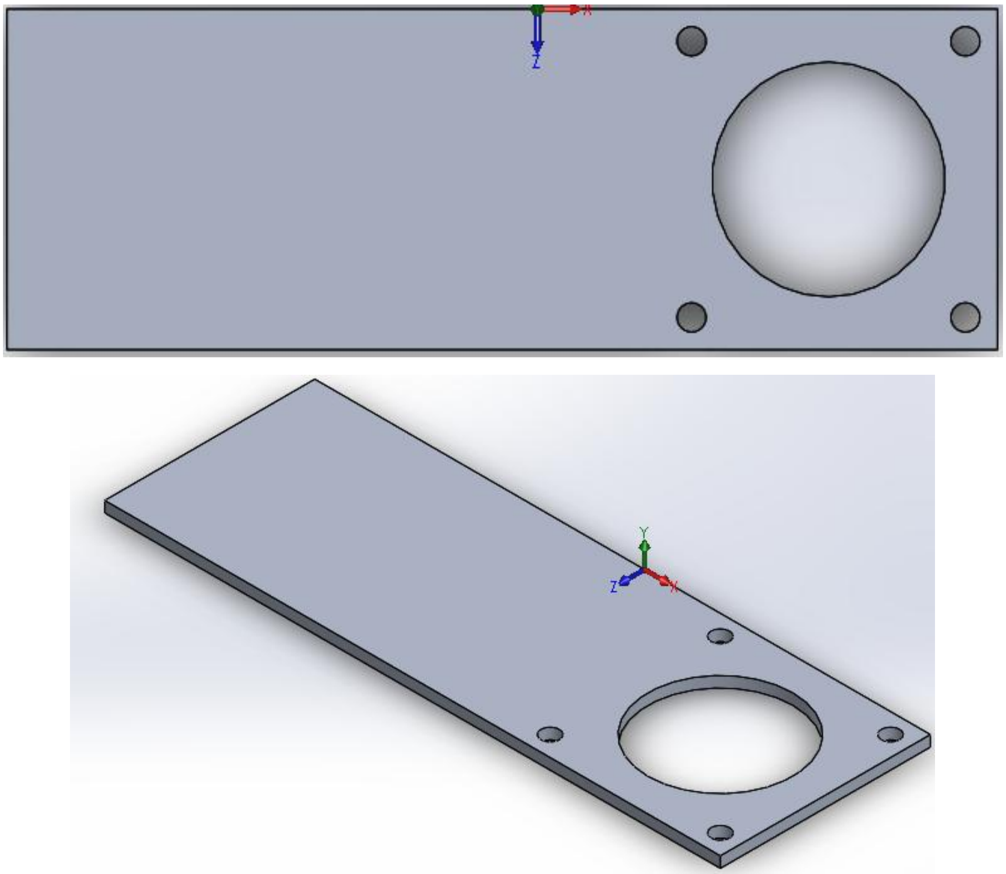


Figure 19: Base Attachment

This fixture (Figure 19) connects the arm assembly to the backpack while supporting the entire weight of it. There is a main motor attached to it which provides the rotation factor for the entire arm.

TABLE 3: Details of Base

Part Name	Base
Material	Aluminium
Quantity	2
Dimensions	L = 170mm, B = 58mm, T= 3mm
Manufacturing Techniques Used	Laser Cutting, Deburring

4.3.3 Arm Component – 1

Figure 20: Arm Component 1

This is the part which forms the outer body of the arm of the robot (Figure 20). It is made using Polypropylene rod, which is turned and bored to the required cylindrical dimensions. The holes and the slots are drilled using a Vertical Milling Machine (VMC).

TABLE 4: Details of Arm-1

Part Name	Arm-1
Material	Polypropylene
Quantity	2
Dimensions	ID = 93mm, OD = 99mm, Length = 250mm
Manufacturing Techniques Used	Turning, Boring, Drilling, Slotting

4.3.4 Arm Component - 2

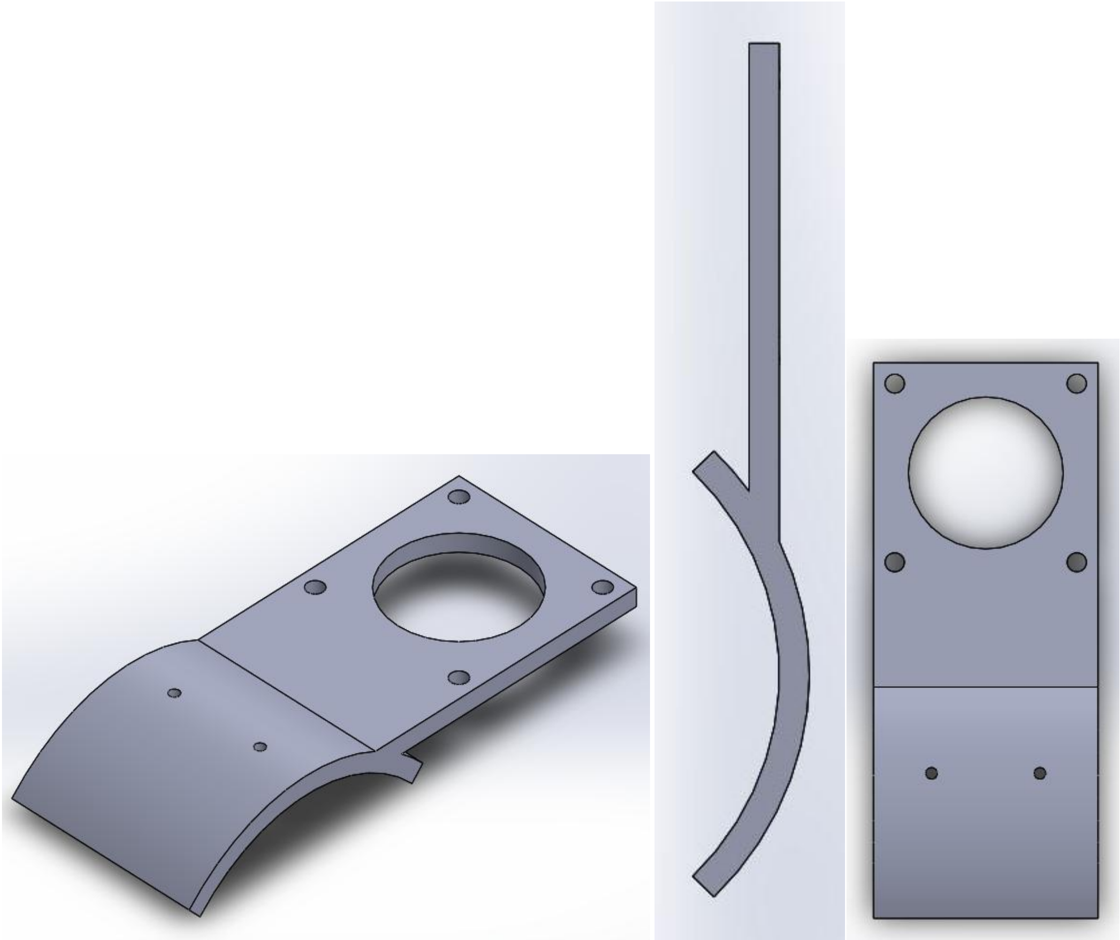


Figure 21: Arm Component 2

This attachment (Figure 21) fixes the fourth motor to the Arm of the robot. It contains four holes to fix the flange of the motor, and has a curved surface with two holes in order to fix it on the outer curved surface of the arm.

TABLE 5: Details of Arm Component - 2

Part Name	Arm Component - 2
Material	Polylactic Acid
Quantity	2
Dimensions	L = 150mm, B = 58mm, T = 5mm
Manufacturing Techniques Used	3D Printing

4.3.5 Arm Component – 3

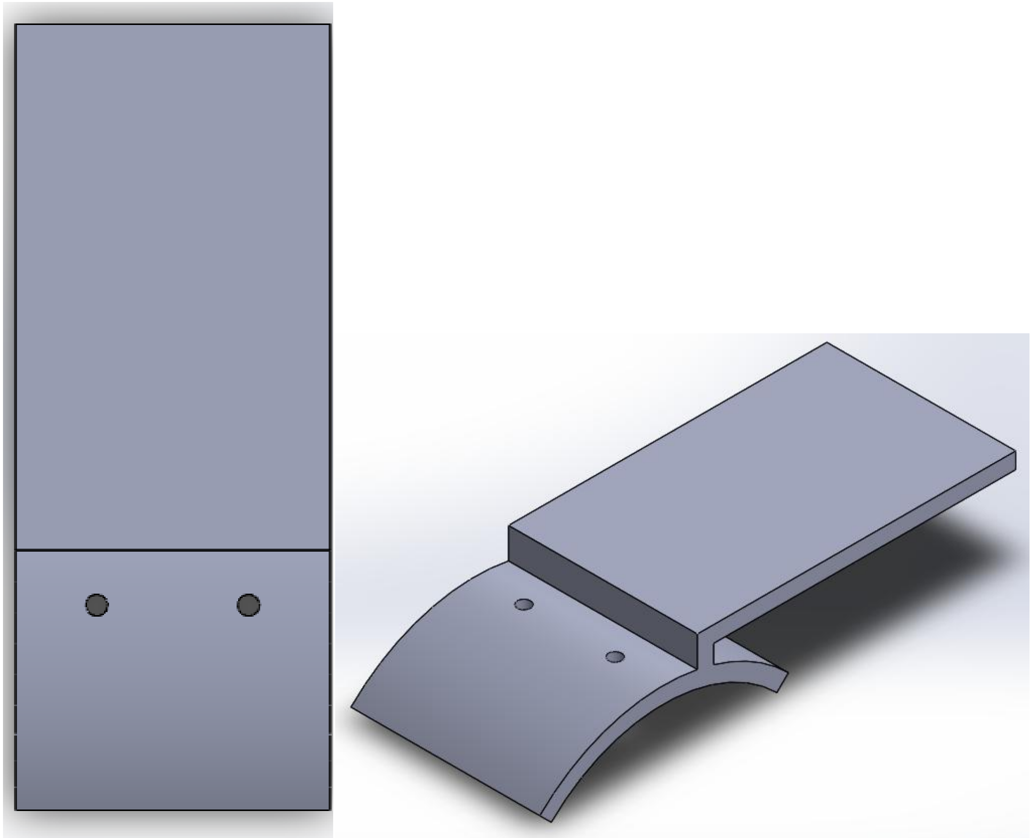


Figure 22: Arm Component 3

This is the part that supports the back of the fourth motor (Figure 22). It has a curved surface with two holes to fasten it to the external face of the arm. There is a small gap between the back of the motor and the attachment, in order to provide slight amount of tolerance.

TABLE 6: Details of Arm Component - 3

Part Name	Arm Component - 3
Material	Polylactic Acid
Quantity	2
Dimensions	L = 145mm, B = 58mm, T = 5mm
Manufacturing Techniques Used	3D Printing

4.3.6 Bracket

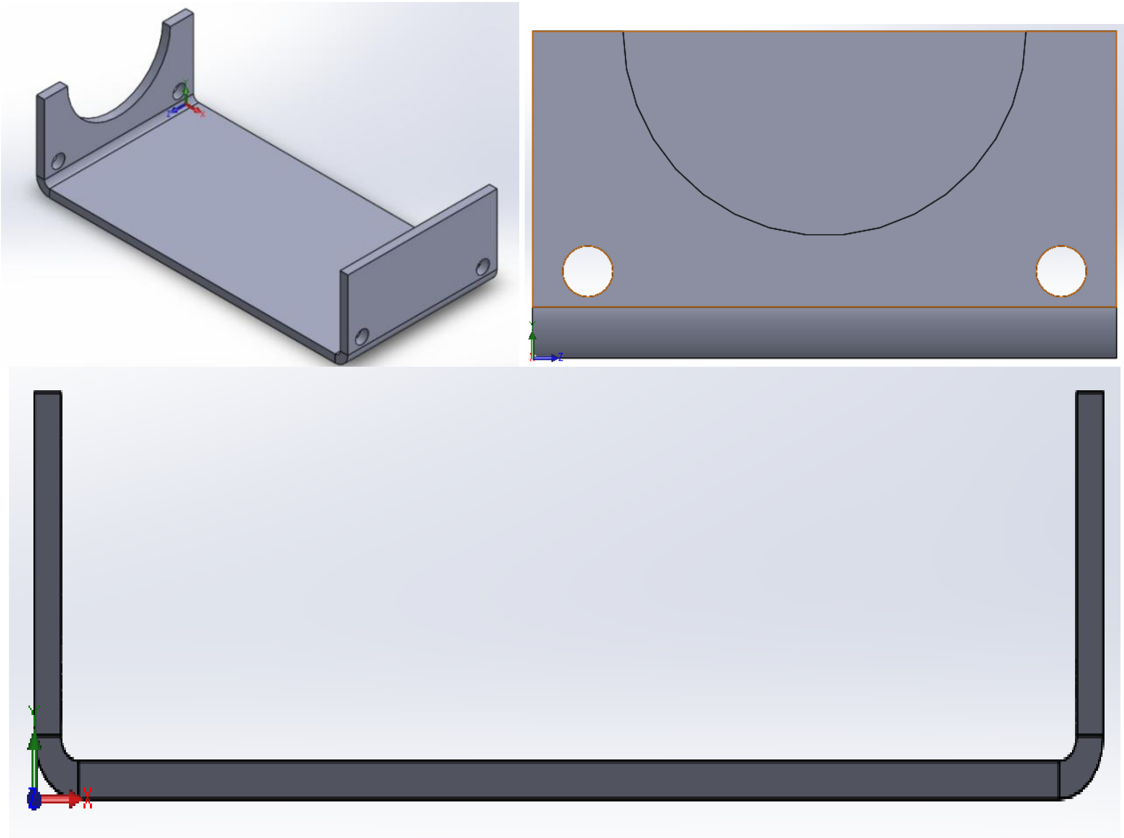


Figure 23: Bracket

This bracket (Figure 23) holds the “Arm Component - 2” and “Arm Component - 3”, with the fourth motor in between. Since the former two components are made out of plastic, and are subjected to tension due to the belt drive, they tend to get distorted. To prevent the two attachments from failure, the bracket is put in place.

TABLE 7: Details of Bracket

Part Name	Bracket
Material	Aluminium
Quantity	2
Dimensions	L = 121mm, B = 58mm, T = 3mm
Manufacturing Techniques Used	Laser Cutting, CNC Bending, Deburring

4.3.7 Arm Component – 4

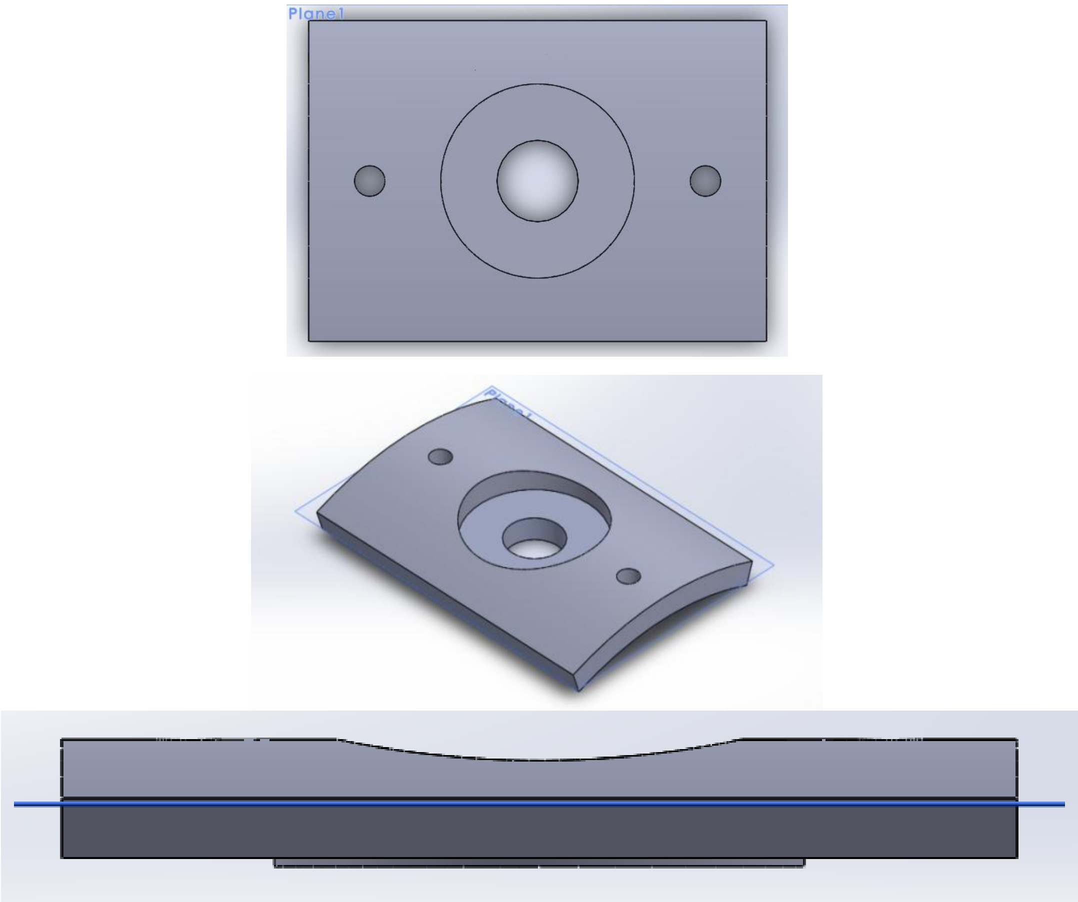


Figure 24: Arm Component 4

This fixture (Figure 24) is fastened to the inner face of the “Arm Component 1” using two screws. Its function is to support the ball bearing and the shaft that rotates the forearm joint.

TABLE 8: Details of Arm Component - 4

Part Name	Arm Component - 4
Material	Polylactic Acid
Quantity	4
Dimensions	L = 45mm, B = 25mm, T = 3mm
Manufacturing Techniques Used	3D Printing

4.3.8 Attachment – 1

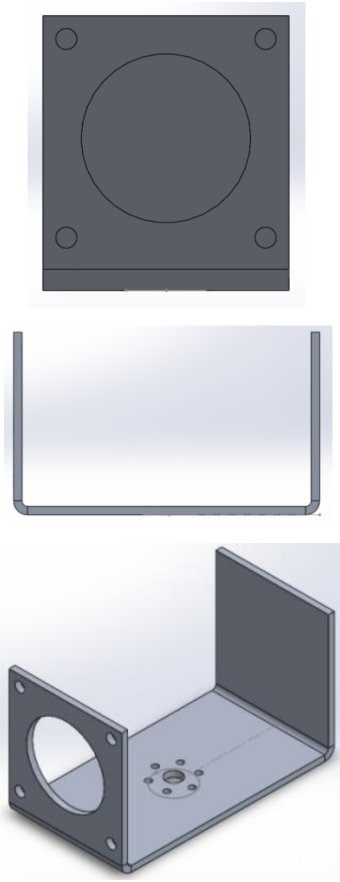


Figure 25: Attachment 1

This part (Figure 25) is attached to the first motor, and supports the second motor. It connects the first motor and the second motor to rest of the arm assembly. This contributes to the roll motion of the shoulder joint.

TABLE 9: Details of Attachment - 1

Part Name	Attachment - 1
Material	Aluminium
Quantity	2
Dimensions	L = 110mm, B = 58mm, T = 3mm
Manufacturing Techniques Used	Laser Cutting, CNC Bending, Deburring

4.3.9 Attachment – 2

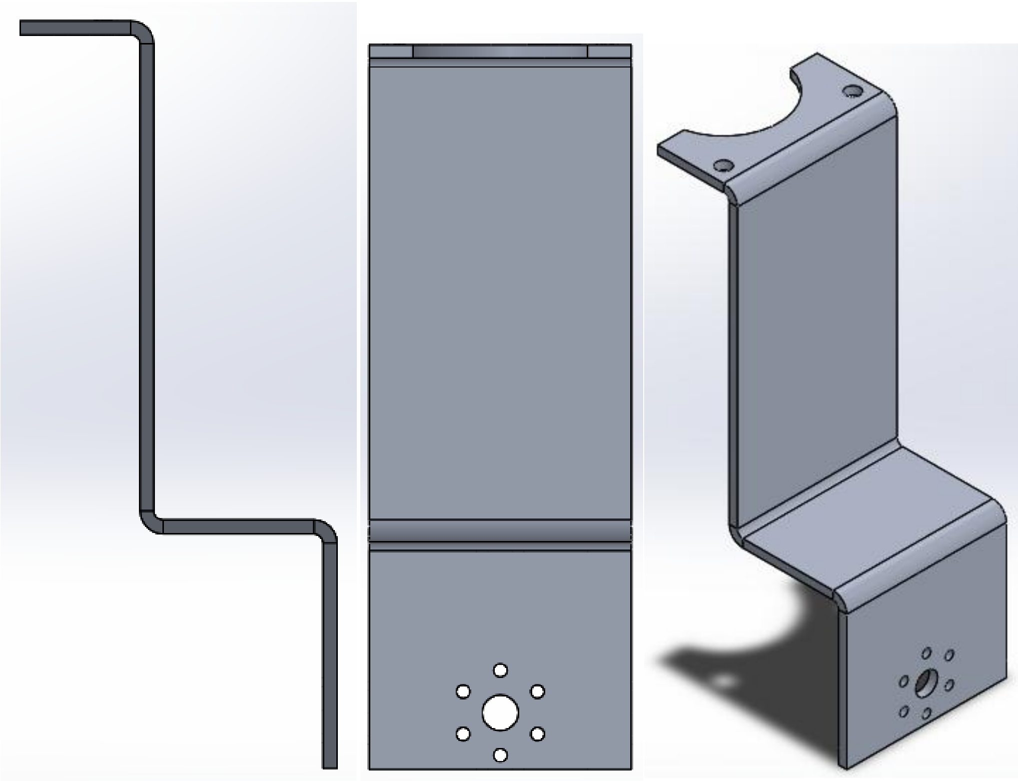


Figure 26: Attachment 2

This fixture (Figure 26) supports the third motor and is fixed to "Attachment 1". This contributes to the pitch rotation of the arm. The identical part fixed to the opposite side of the third motor provides support to the motor, by distributing its weight.

TABLE 10: Details of Attachment - 2

Part Name	Attachment - 2
Material	Aluminium
Quantity	4
Dimensions	H = 165mm, W = 58mm, T = 3mm
Manufacturing Techniques Used	Laser Cutting, CNC Bending, Deburring

4.3.10 Attachment – 3

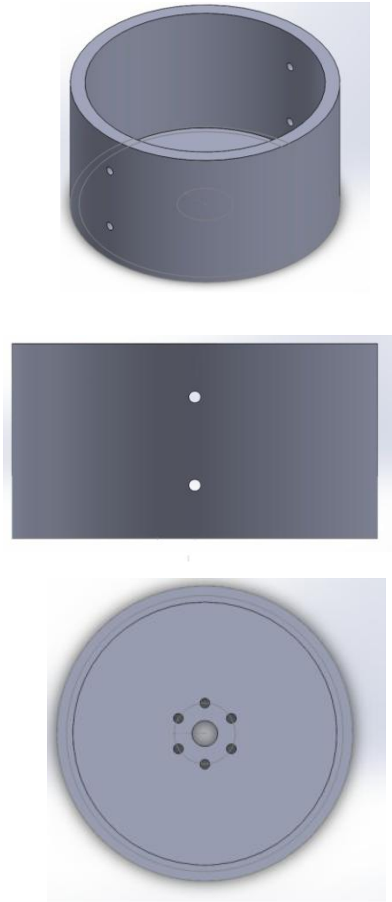


Figure 27: Attachment 3

This attachment (Figure 27) is fixed inside the hollow part the outer body of the robot . The function of this part is to link the third motor to the arm, so that the arm rotates with it. It has four holes in order to fix it to the outer body. The third motor is fixed to this attachment.

TABLE 11: Details of Attachment - 3

Part Name	Attachment - 3
Material	Polypropylene
Quantity	2
Dimensions	ID=97mm, OD=92mm, Length=48mm
Manufacturing Technique Used	Turning, Boring and Drilling

4.3.11 Forearm-1

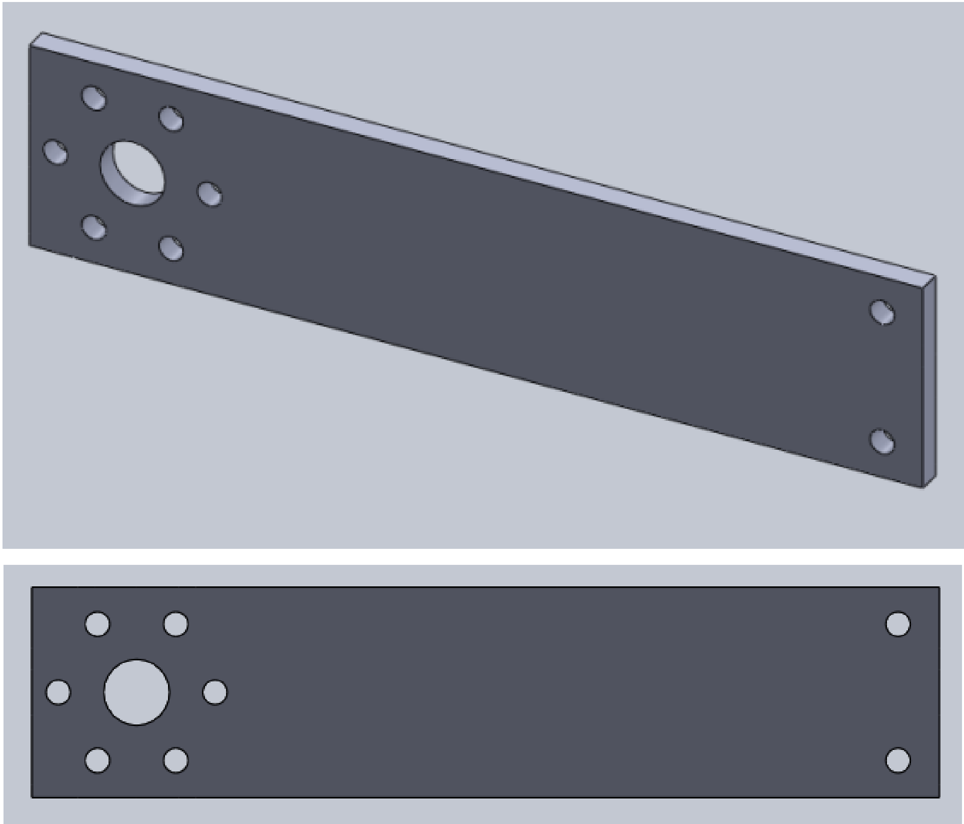


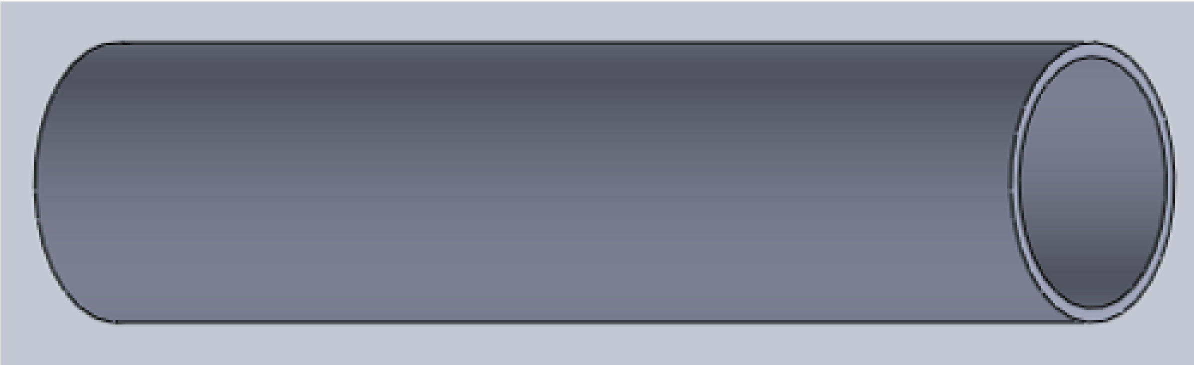
Figure 28: Forearm 1

This linkage (Figure 28) is mounted on the shaft that is driven by Motor-4. The other end of this link is connected to the forearm. It moves within the slot cut in the arm body.

TABLE 12: Details of Forearm Component - 1

Part Name	Forearm - 1
Material	Aluminium
Quantity	2
Dimensions	Length=110mm, Breadth=25mm, Thickness=3mm
Manufacturing Technique Used	Laser Cutting, CNC Bending, Deburring

4.3.12 Forearm-2



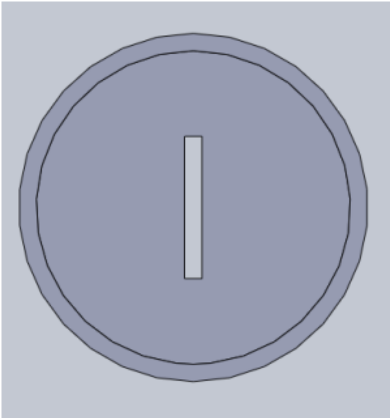


Figure 29: Forearm 2

This is another outer body structure (Figure 29). It is connected to the rest of the assembly through “forearm-1”. There is a provision to attach an end effector at the end of the forearm.

TABLE 13: Details of Forearm Component - 2

Part Name	Forearm-2
Material	Aluminium
Quantity	2
Dimensions	ID=57mm, OD=60mm, Length=250mm
Manufacturing Technique Used	Turning and Boring

4.3.13 Hub

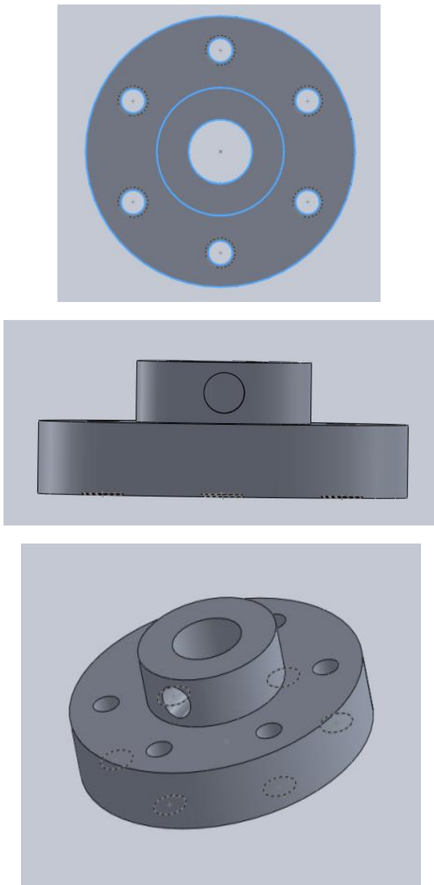


Figure 30: Hub

A hub (Figure 30) is used to mount a motor to the brackets or shafts. It consists of six holes through which screws or bolts can be used for fastening.

TABLE 14: Details of Hub

Part Name	Hub
Material	Aluminium
Quantity	6x2=12
Dimensions	ID=12mm, OD=25mm
Manufacturing Technique Used	Turning and Drilling

4.3.14 Pulley

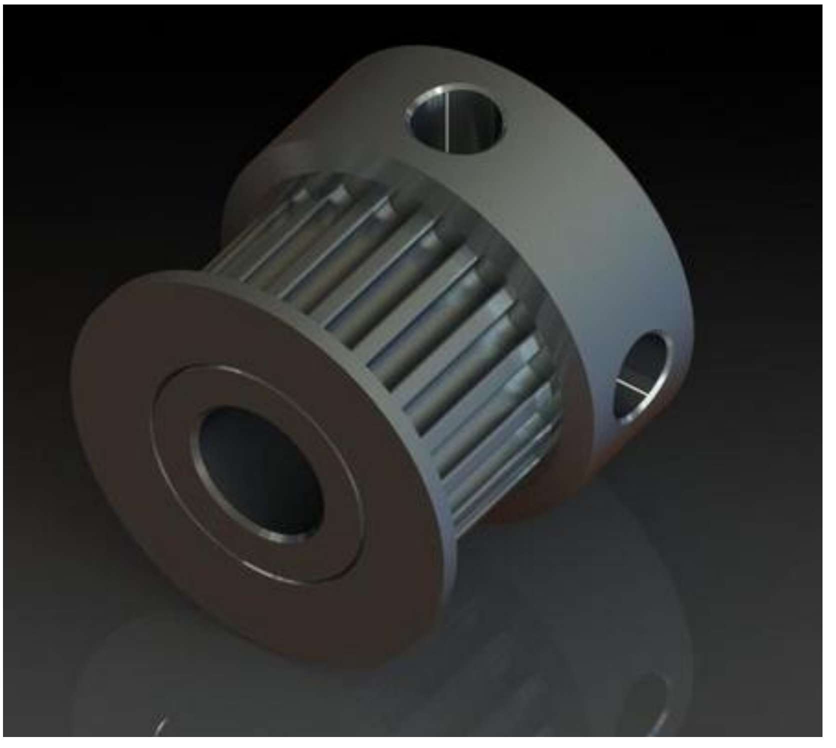


Figure 31: Timing Pulley

A toothed belt drive (Figure 31) is used for transmitting the power from motor 4 to the forearm. A set of two toothed pulleys are used for this purpose, one mounted on the motor and the other mounted axially on the driven shaft of the forearm.

TABLE 15: Details of Pulley

Part Name	Pulley
Material	Aluminium
Quantity	2
Dimensions	Pitch=10 xl, Width=12mm, Diameter=20mm

4.3.14 Shaft

Figure 32: Driven Shaft

A shaft as shown above (Figure 32) is supported by two bearings in the arm. This shaft is driven by the motor-4 by a timing belt (toothed belt drive). The part “forearm -1” links the shaft and the forearm.

TABLE 16: Details of Shaft Component

Part Name	Shaft
Material	Aluminium
Quantity	2
Dimensions	Pitch=10XL, Width=12mm, Diameter=20mm
Manufacturing Technique used	Drilling and External Threading

4.3.15 Timing Belt

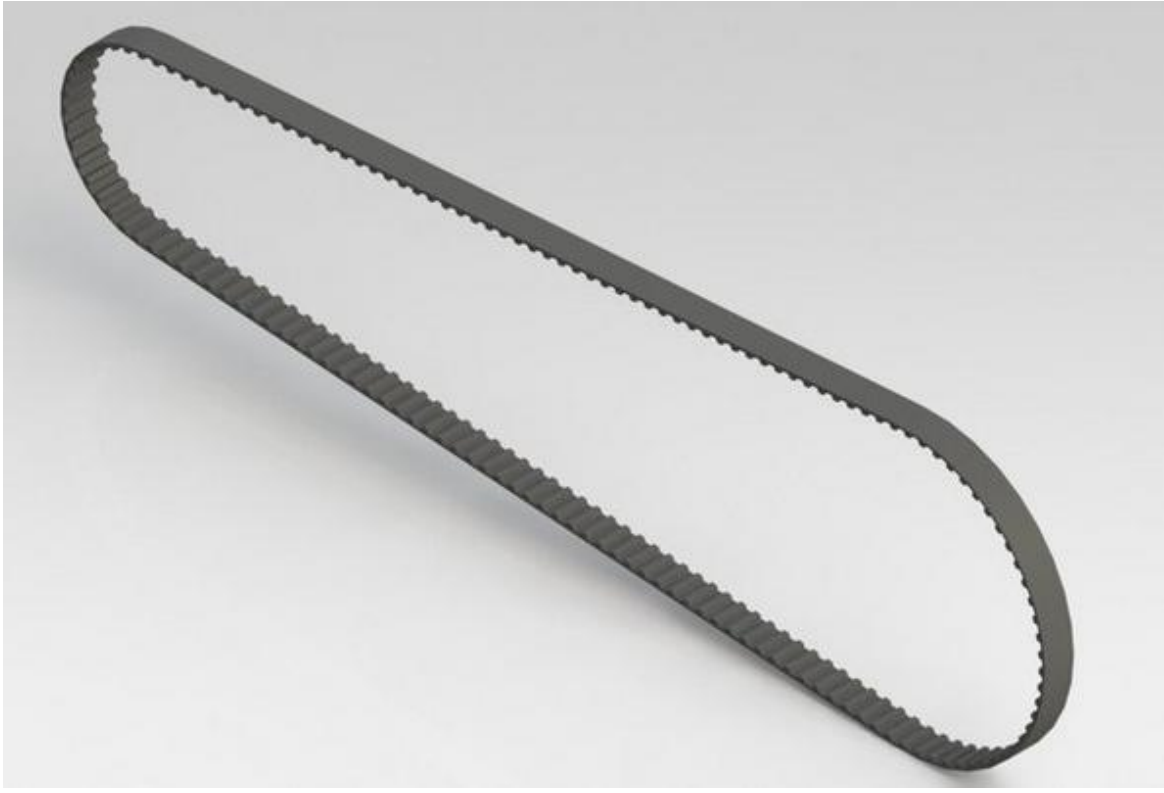


Figure 33: Driving Belt

A timing belt (Figure 33) is a belt which has teeth on the its inner surface. These teeth mesh with the teeth in the pulley to create a positive drive.

TABLE 17: Details of Timing Belt

Part Name	Timing belt
Material	Rubber
Quantity	2
Dimensions	Pitch=10XL, Width=12mm, Length= 15 inches

4.3.16 Manufacturing Processes Used

a) Laser Cutting

Laser cutting (Figure 34) is a technology that uses a laser to cut materials, and is typically used for industrial manufacturing applications, but is also starting to be used by schools, small businesses, and hobbyists. Laser cutting works by directing the output of a high-power laser most commonly through optics. The laser optics and CNC (computer numerical control) are used to direct the material or the laser beam generated. A typical commercial laser for cutting materials would involve a motion control system to follow a CNC or G-code of the pattern to be cut onto the material. The focused laser beam is directed at the material, which then either melts, burns, vaporizes away, or is blown away by a jet of gas, leaving an edge with a high-quality surface finish. Industrial laser cutters are used to cut flat-sheet material as well as structural and piping materials.

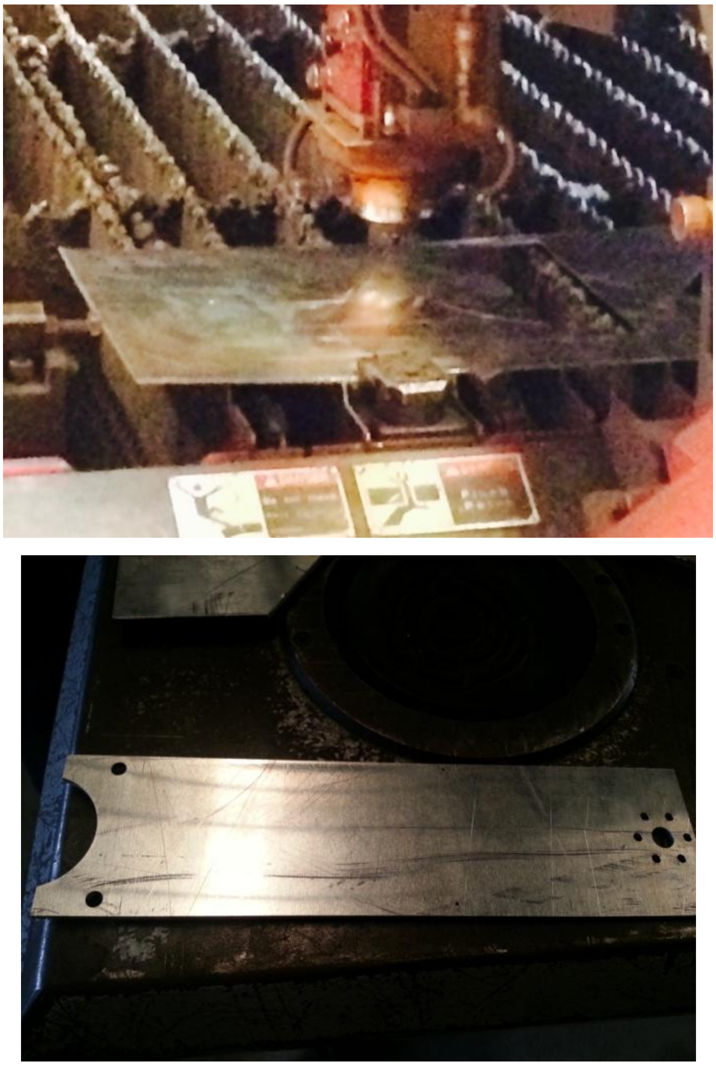


Figure 34: Laser Cutting

b) CNC Bending

A bending machine (Figure 35) is a forming machine tool (DIN 8586). Its purpose is to assemble a bend on a workpiece. A bends is manufactured by using a bending tool during a linear or rotating move. The detailed classification can be done with the help of the kinematics. (M. Weck, p. 112). Recent CNC bending machines are developed for high flexibility and low setup times. Those machines are able to bend single pieces as well as small batches with the same precision and efficiency as series-produced parts in an economical way.

Figure 35: CNC Bending

c) Lathe Turning and Boring

Turning is a engineering machining process in which a cutting tool, typically a non-rotary tool bit, describes a helical tool path by moving more or less linearly while the workpiece rotates (Figure 36). The tool's axes of movement may be literally a straight line, or they may be along some set of curves or angles, but they are essentially linear (in the nonmathematical sense). Usually the term "turning" is reserved for the generation of *external* surfaces by this cutting action, whereas this same essential cutting action when applied to *internal* surfaces (that is, holes, of one kind or another) is called "boring". Thus the phrase "turning and boring" categorizes the larger family of (essentially similar) processes. The cutting of faces on the workpiece (that is, surfaces perpendicular to its rotating axis), whether with a turning or boring tool, is called "facing", and may be lumped into either category as a subset.

Figure 36: Turning

d) 3D Printing

3D printing (or additive manufacturing, AM) is any of various processes used to make a three-dimensional object. In 3D printing, additive processes are used, in which successive layers of material are laid down under computer control. These objects can be of almost any shape or geometry, and are produced from a 3D model or other electronic data source. A 3D printer is a type of industrial robot. 3D printing in the term's original sense refers to processes that sequentially deposit material onto a powder bed with inkjet printer heads. More recently the meaning of the term has expanded to encompass a wider variety of techniques such as extrusion and sintering based processes. Technical standards generally use the term *additive manufacturing* for this broader sense. A Picture of the process is shown in Figure 37.

Figure 37: 3D Printing

4.4 Electrical

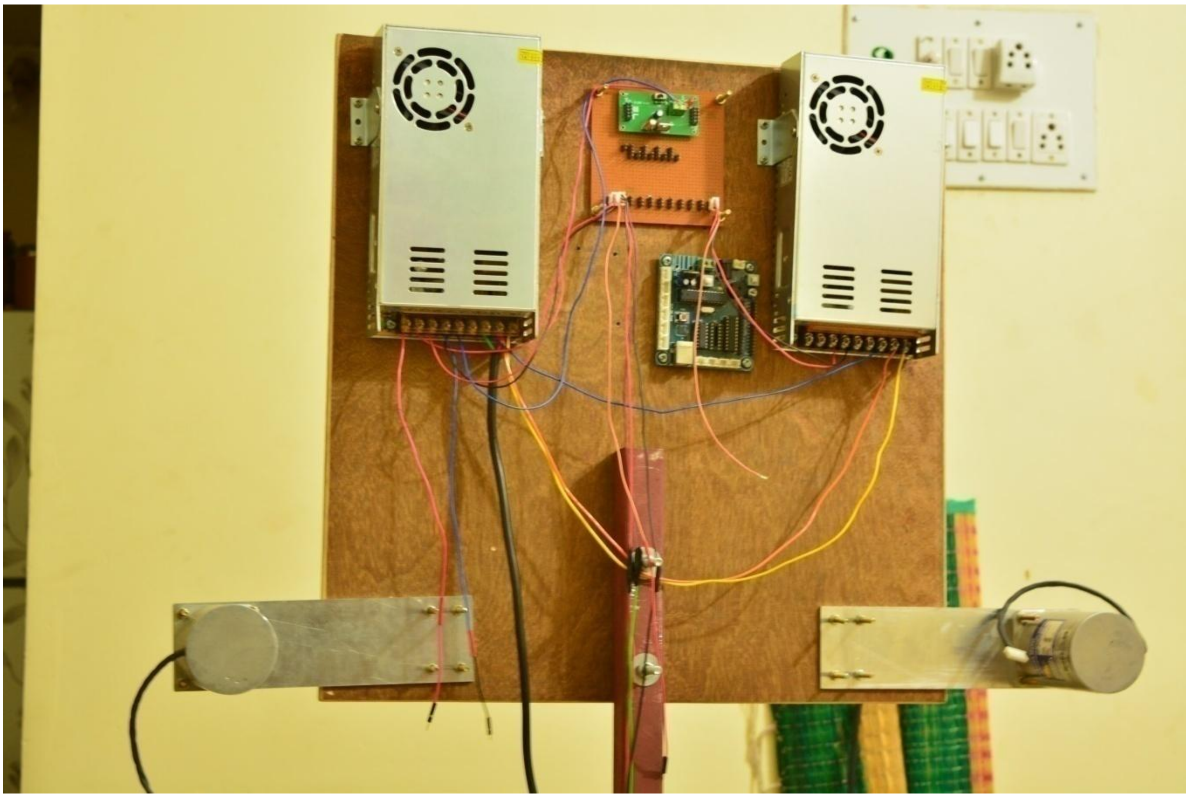


Figure 38: Electrical Design

The average power rating required to run each motor is 12V 5A. The main power is drawn from external power source of 220V AC which is converted to 12V 30A DC using SMPS (Switch Mode Power Supply). Two such SMPS are connected in parallel to get 12V 60A output, so as to sufficiently power eight motors. The microcontrollers, however, require maximum 5V. Hence, a voltage regulator is used to dissipate the excess power.

4.4.1 Important Components

a) Switched Mode Power Supply (SMPS)

A switched-mode power supply (switching-mode power supply, switch-mode power supply, SMPS, or switcher) is an electronic power supply that incorporates a switching regulator to convert electrical power efficiently. Like other power supplies, an SMPS transfers power from a source, like mains power, to a load, such as a personal computer, while converting voltage and current characteristics. Unlike a linear power supply, the pass transistor of a switching-mode supply continually switches between low-dissipation, full-on and full-off states, and spends very little time in the high dissipation transitions, which minimizes wasted energy. Ideally, a switched-mode power supply dissipates no power. Voltage regulation is achieved by varying the ratio of on-to-off time. In contrast, a linear power supply regulates the output voltage by continually dissipating power in the pass transistor. This higher power conversion efficiency is an important advantage of a switched-mode power supply. Switched-mode power supplies may also be substantially smaller and lighter than a linear supply due to the smaller transformer size and weight.

b) Voltage Regulator Board

The wireless modules require a maximum of 3.3V. Hence, the voltage from 12V must be reduced to 3.3V in order to safeguard the wireless modules. Hence, a 3.3V voltage regulator breakout board is used to provide 3.3V to the wireless modules.

4.5 Electronics

4.5.1 PCB Design - Inertial Measurement Unit

The Inertial Measurement Unit (IMU) Sensor, the GY-86 module, communicates with the microcontroller using I2C protocol. For this, appropriate connections are to be given to the microcontroller, so that it can read the values from the sensor effectively. The PCB schematic for this is shown in Appendix IX.

Board Layout

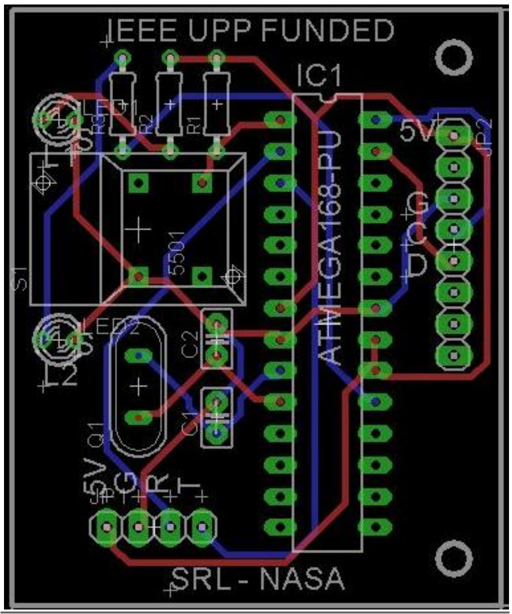


Figure 39: IMU Board Layout

TABLE 18: IMU PCB Components List

Sl. No.	Component	Quantity
1	Atmega328P-PU	1
2	Reset Switch	1
3	Crystal	1
4	22 picoFarad Capacitors	2
5	10 microFarad Capacitors	2
6	220 ohm resistors	2
7	Female Headers	8
8	Male Headers	3
9	LEDs	2

4.5.2 PCB Design - Motor Driver

Each motor is driven by a microcontroller. The motors are to be given commands to rotate, which are similar to G-Codes. The commands are to be given using Serial Communication. The master microcontroller transmits a series of rotation commands to each motor driver wirelessly. Hence, the function of each motor driver PCB is to receive the commands from a wireless receiver through SPI protocol, and then send the same codes to the motor using Serial communication. The PCB schematic for this is shown in Appendix X.

Board Layout

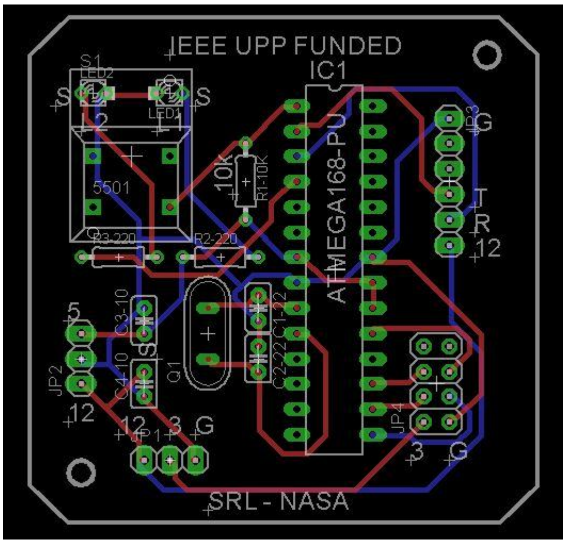


Figure 40: Motor Driver Board Layout

TABLE 19: Motor Driver PCB Components List

Sl. No.	Component	Quantity
1	Atmega328P-PU	1
2	Reset Switch	1
3	Crystal	1
4	22 picoFarad Capacitors	2
5	10 microFarad Capacitors	2
6	220 ohm resistors	2
7	10k ohm resistor	1
8	Male Headers	9
9	Female Headers	8
10	Voltage Regulator	1

4.5.3 Important Components

a) Atmega328P-PU - Microcontroller

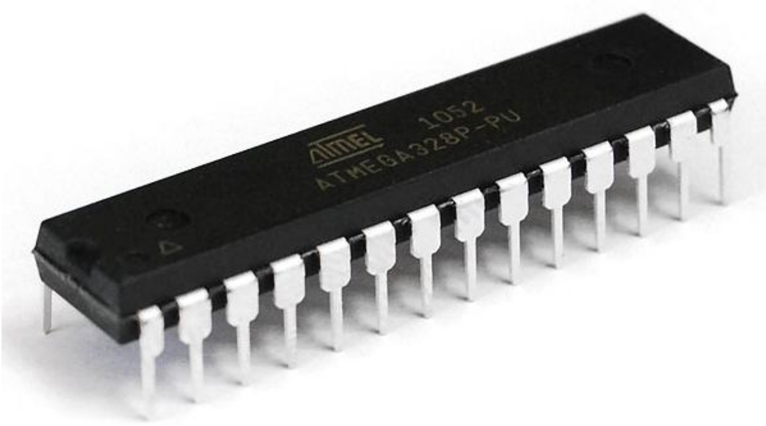


Figure 41: Atmega328P-PU Microcontroller

Manufacturer: Atmel

The high-performance Atmel picoPower 8-bit AVR RISC-based microcontroller combines 32KB ISP flash memory with read-while-write capabilities, 1024B EEPROM, 2KB SRAM, 23 general purpose I/O lines, 32 general purpose working registers, three flexible timer/counters with compare modes, internal and external interrupts, serial programmable USART, a byte-oriented 2-wire serial interface, SPI serial port, a 6-channel 10-bit A/D converter (8-channels in TQFP and QFN/MLF packages), programmable watchdog timer with internal oscillator, and five software selectable power saving modes. The device operates between 1.8-5.5 volts.

b) NRF24L01 - Wireless Modules

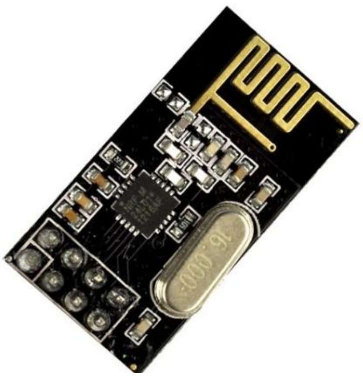


Figure 42: NRF24L01 Wireless Module

Manufacturer: Nordic Semiconductors

The nRF24L01 is a highly integrated, ultra low power (ULP) 2Mbps RF transceiver IC for the 2.4GHz ISM (Industrial, Scientific and Medical) band. With peak RX/TX currents lower than 14mA, a sub µA power down mode, advanced power management, and a 1.9 to 3.6V supply range, the nRF24L01 provides a true ULP solution enabling months to years of battery lifetime when running on coin cells or AA/AAA batteries. The Enhanced ShockBurst™ hardware protocol accelerator additionally offloads time critical protocol functions from the application microcontroller enabling the implementation of advanced and robust wireless connectivity with low cost 3rd-party microcontrollers. The nRF24L01 integrates a complete 2.4GHz RF transceiver, RF synthesizer, and baseband logic including the Enhanced ShockBurst™ hardware protocol accelerator supporting a high-speed SPI interface for the application controller. No external loop filter, resonators, or VCO varactor diodes are required, only a low cost ±60ppm crystal, matching circuitry, and antenna.

c) GY-86 IMU - Sensor

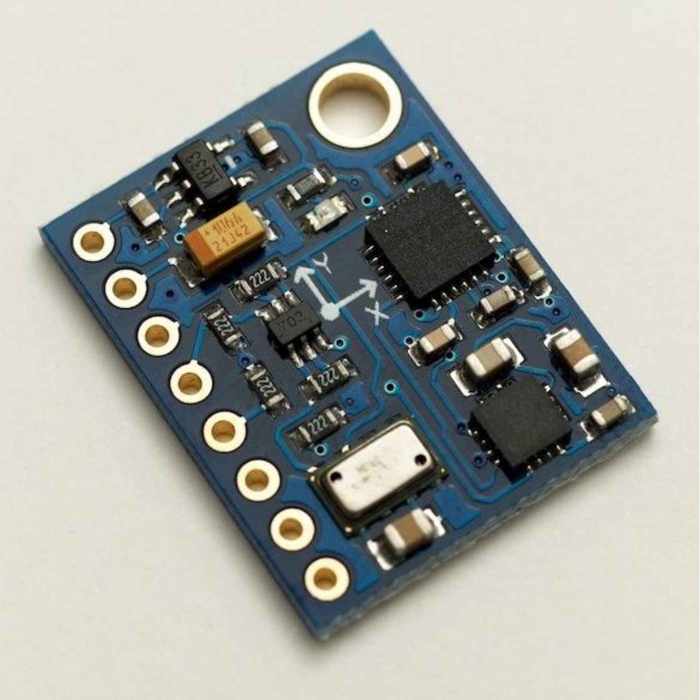


Figure 43: GY-86 IMU Sensor

GY-86 Module is 10 DOF Inertial Measurement Unit, that consists of four sub-components:

1. MS5611 Barometer
2. HMC5883L Magnetometer
3. MPU6050 Accelerometer + Gyroscope

It is used to measure the rotational tilt and angular velocity of any object to which it is attached.

4.6 Computer Programming

4.6.1 Initial Prototype

The initial prototype consisted of just one microcontroller for the entire arm, and its function was only to read the IMU sensor values, perform simple mapping functions, and feed the roll pitch values to the respective servo motors. We used a simple Arduino program, which is shown in Appendix I.

The limitation of the above code was that it did not provide for sensor fusion of the MPU6050 IMU, which resulted in instability of the robotic system. Hence, we tried different sensor fusion algorithms, such as the complementary filter and the AHRS filter. The complementary filter failed for unknown reasons, whereas the AHRS filter algorithm worked fine. The AHRS algorithm comes built-in with the FreeIMU Library, which is developed by Fabio Varesano. The FreeIMU code is shown in Appendix II. The FreeIMU code has not yet been tested on the robot.

4.6.2 Final Prototype

Subsequently, we started working on the final prototype, for which we needed to analyse the DC servo motor we were to use, in terms of angular velocity and acceleration. Although the speed is specified as 10 RPM in the motor datasheet, in practical situations, it will be lesser than 10 RPM. Hence, the speed for standard payload was to be calculated. For this, a plot of position vs time was required. Hence, we used MATLAB to repeatedly read the values from the optical encoder, and plotted it against time. This MATLAB code is shown in Appendix III. After obtaining the plot, we can calculate the rotational velocity, and hence calculate how much time the motor takes to rotate by a certain degree. Using this, we were able to calculate the time delay for rotation of every motor, for different motion patterns, such as “Hi” gestures, and the like.

The Rhino Servo DC motor is controlled by sending commands similar to G-codes, through serial communication protocol by a microcontroller. But a microcontroller can handle only one serial communication device, which makes it impossible to interface all the motors to a master controller directly. Hence, each motor is to be connected to a custom made Printed Circuit Board with a microcontroller. It becomes advantageous to send commands to these individual microcontrollers wirelessly, as it can be controlled remotely, and it also helps in reducing the number of wires and tangling of wires. Using the NRF24L01 wireless modules, we wrote a program at the transmitting end and the receiving end to transmit and receive a set of strings to each motor. This code is shown in Appendix IV and Appendix V respectively.

For simple demonstration, we have pre-programmed each motor to follow a specified trajectory, such as “Hi”. The codes for the different motors in each arm is shown in Appendix VI.

In the next page, the final prototype has been shown.

4.7 Look of the Current Version of SRL

Chapter 5: Scope for Research and Further Advancements

The concept of Supernumerary Robotic Limbs is relatively a new innovation in the field of Robotics. Though researchers are doing some incredible breakthroughs in this technology, it is still in the primitive stage of research.

Because of this, there aren't any readily available spare parts for the Robot. Every small part has to be customized and fabricated according to the required specifications. This gives the designers of this technology a certain responsibility. The designers have the freedom to create the standards of this very futuristic technology.

We suggest these possible future advancements for the existing model of the Supernumerary Robotic Limbs.

- Mechanical Design
    - A more robust design: The current project is in its first prototype stage. The components can be designed for better tolerances and shape.
    - A centralized gear box: All the four motors of each arm can be enclosed within a centralized gearbox and power can be transmitted through various links and drives.
    - Better materials for the body: The body elements are currently fabricated from Polypropylene (PP) plastic and Acrylonitrile Butadiene Styrene (ABS) plastic. They do not posses good mechanical properties like toughness, strength, ductility or wear resistance. Usage of better materials will give better results.
    - Use of mechanical stops and vibration dampers: Using mechanical stops to ensure smooth motion. Dampers can be used to absorb the sound and vibration created by the movement of the arms.
- Control Design
    - Currently the project works on an open loop control. A closed loop control with feedback can be implemented.
    - Algorithms like AHRS or Kalman Filter can be used to fuse and condition the data received from the IMU sensors.
- Electronics
    - A centralized processing unit on a single board where all the motors can be controlled.
    - Using more powerful controller which can give a better bandwidth.

- Provision of expansion ports.

Our current project performs functions or rather follows trajectories that are pre programmed into the controller unit.

We are currently improving upon this design. Our next design would be a leader follower. Where the wearer can perform actions are sensed using the IMU sensors, and then these actions are replicated by the actuators. The actions can be either stored or replicated in real time.

There are a lot of avenues for further research in our projects. The following are a few that we suggest

- Newer innovative path planning algorithms.
- Trajectory control and optimum path traversing.
- Design of modular customized end effectors.
- Testing of new sensors
- 3D mapping of the environment and responding to the changes automatically
- Testing of newer materials
- Optimum shape design for the arms and other parts
- Fabricating the arm to work in specific environments like radioactive conditions, inside a nuclear power plant, at elevated temperatures, handling of cryogenic materials etc

Chapter 6: Applications

The Supernumerary Robotic Limbs can be put to use in any situation that requires more than two natural arms. Listed below are some of the examples of situations where the SRL can be beneficial:

- When a heavy metal slab is to be welded to a vertical wall, the SRL can hold the slab at the required position, and the human can use the welding tool to weld the slab at the desired spots
- When a control box is to be wired, the human can focus on positioning the wires, and the SRL can come in and affix the wires.
- The SRL can be used for performing repair operations in space stations, such as the Indian Space Station.
- In manufacturing assembly lines, it can be used to perform two operations simultaneously
- It can be used by chefs in busy hotels
- It can be used as an ambulatory assistance for disabled people
- Any other operations that cannot be fully automated

Appendices

Appendix I - Motor Roll Pitch Yaw Test

```
##include <Servo.h>
#include <Wire.h>
#include <I2Cdev.h>
#include <MPU6050.h>
MPU6050 mpu;
int16_t ax, ay, az;
int16_t gx, gy, gz;
Servo myservo1, myservo2,myservo3;
int val;
int prevVal;

void setup()
{
  Wire.begin();
  Serial.begin(38400);
  Serial.println("Initialize MPU");
  mpu.initialize();
  myservo1.attach(9);
  myservo2.attach(10);
  mydervo3.attach(11);
  Serial.println(mpu.testConnection() ? "Connected" : "Connection failed");
}

void loop()
{
  mpu.getMotion6(&ax, &ay, &az, &gx, &gy, &gz);
  ax = map(ax, -17000, 17000, 0, 179);
  ay = map(ay, -17000, 17000, 0, 179);
  az = map(az, -17000, 17000, 0, 179);
  if (val != prevVal)
```

```
    Serial.println(val);
    mydervo1.write(ax);
    myservo2.write(ay);
    myservo3.write(az);
    delay(50);
}
```

Appendix II - FreeIMU Sensor fusion using AHRS

```
#include <ADXL345.h>
#include <bma180.h>
#include <HMC58X3.h>
#include <ITG3200.h>
#include <MS561101BA.h>
#include <I2Cdev.h>
#include <MPU60X0.h>
#include <EEPROM.h>
//#define DEBUG
#include "DebugUtils.h"
#include "CommunicationUtils.h"
#include "FreeIMU.h"
#include <Wire.h>
#include <SPI.h>
int raw_values[9];
//char str[512];
float ypr[3]; // yaw pitch roll
float val[9];

// Set the FreeIMU object
FreeIMU my3IMU = FreeIMU();

void setup() {
  Serial.begin(115200);
  Wire.begin();

  delay(5);
  my3IMU.init(); // the parameter enable or disable fast mode
  delay(5);
}
```

```
void loop() {
  my3IMU.getYawPitchRoll(ypr);
  Serial.print("Yaw: ");
  Serial.print(ypr[0]);
  Serial.print(" Pitch: ");
  Serial.print(ypr[1]);
  Serial.print(" Roll: ");
  Serial.print(ypr[2]);
  Serial.println("");
  delay(10);
}
```

Appendix III - Motor Analysis

```
s = serial('COM3');
s.Terminator = 'CR';
fopen(s);

a = 1800;
string = int2str(a);
string = strcat('G',string);

while s.BytesAvailable > 2
    junk = fscanf(s);
    disp(junk);
end

fprintf(s,'P0');
fprintf(s,'M255');
fprintf(s,string);

t1 = clock();

x = 0;
y = 0;
t = 0;
count = 0;

str='';

while count < a

    while s.BytesAvailable > 2
        junk = fscanf(s);
        disp(junk);
    end

    fprintf(s,'P');

    str = fscanf(s);
    disp(str);

    str1 = strsplit(str,'P');
    val = str1(1,2);
    count = str2double(val);
    y(end+1) = 0.2*count;

    t2 = clock();
    t(end+1) = etime(t2,t1);
end

dy = diff(y);
dt = diff(t);
ddy = diff(dy);
ddt = diff(dt);

vel = dy/dt;
accel = ddy/ddt;
```

```
subplot(1,3,1);
plot(t,y);
title('Position');

subplot(1,3,2);
plot(t(1:end-1),vel);
title('Velocity');

subplot(1,3,3);
plot(t(1:end-2),accel);
title('Acceleration');

pause(1);

fclose(s);
clear all;
```

Appendix IV - Wireless Transmitter

```
#include <SPI.h>
#include <nRF24L01.h>
#include <RF24.h>
#include <RF24_config.h>

/*
This sketch sends a string to a corresponding Arduino
with nrf24 attached.  It appends a specific value
(2 in this case) to the end to signify the end of the
message.
*/

char msg[1];
RF24 radio(9,10);
const uint64_t pipe = 0xE8E8F0F0E1LL;
void setup(void){
  Serial.begin(9600);
  radio.begin();
  radio.openWritingPipe(pipe);}
void loop(void){
  String theMessage = "Hello there!";
  int messageSize = theMessage.length();
  radio.powerUp();
  delay(1);
  for (int i = 0; i < messageSize; i++) {
    int charToSend[1];
    charToSend[0] = theMessage.charAt(i);
    radio.write(charToSend,1);
  }
//send the 'terminate string' value...
  msg[0] = '\n';
```

```
  radio.write(msg,1);
/*delay sending for a short period of time.  radio.powerDown()/radio.powerupp
//with a delay in between have worked well for this purpose(just using delay seems to
//interrupt the transmission start). However, this method could still be improved
as I still get the first character 'cut-off' sometimes. I have a 'checksum' function
on the receiver to verify the message was successfully sent.
*/
  radio.powerDown();
  delay(1000);
  radio.powerUp();
}
```

Appendix V - Wireless Receiver

```
#include <nRF24L01.h>
#include <RF24.h>
#include <RF24_config.h>
#include <SPI.h>

/*
This sketch receives strings from sending unit via nrf24
and prints them out via serial.  The sketch waits until
it receives a specific value (2 in this case), then it
prints the complete message and clears the message buffer.
*/

int msg[1];
RF24 radio(9,10);
const uint64_t pipe = 0xE8E8F0F0E1LL;
int lastmsg = 1;
String theMessage = "";
void setup(void){
  Serial.begin(9600);
  radio.begin();
  radio.openReadingPipe(1,pipe);
  radio.startListening();
}
void loop(void){
  if (radio.available()){
    bool done = false;
      done = radio.read(msg, 1);
      char theChar = msg[0];
      if (msg[0] != '\n'){
        theMessage.concat(theChar);
        }
```

```
      else
       {
         Serial.println(theMessage);
         theMessage= "";
       }

    }
  }
```

Appendix VI - “Hi” Gesture Control

Motor 1

```
void setup()
{
 Serial.begin(9600);
 delay(5000);
 Serial.println("P0");
 delay(500);
}

void loop()
{
 Serial.println("G450");
 delay(11000);
 Serial.println("G0");
 delay(6000);
}
```

Motor 3

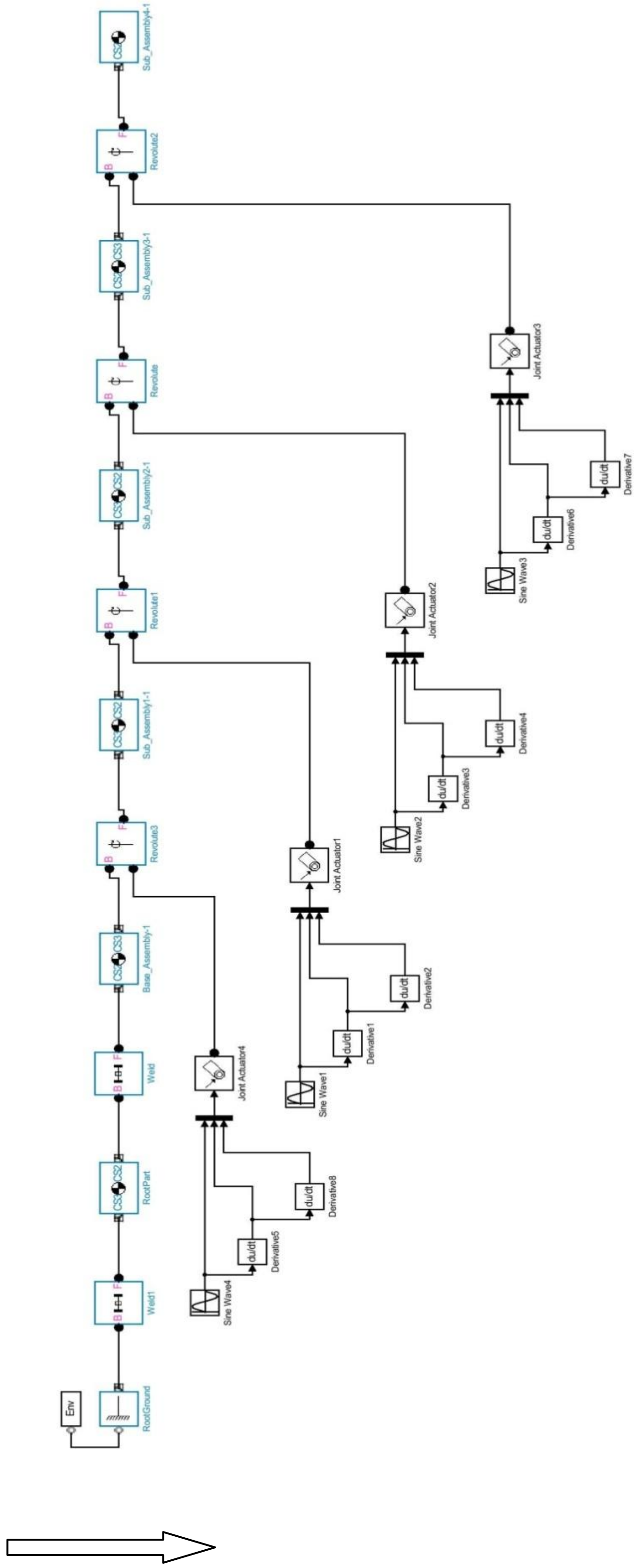
```
void setup()
{
 Serial.begin(9600);
 delay(5000);
 Serial.println("P0");
 delay(500);
}

void loop()
{
 Serial.println("G450");
 delay(11000);
 Serial.println("G0");
```

```
 delay(6000);
}
```

Motor 4

```
void setup()
{
  Serial.begin(9600);
  delay(5000);
  Serial.println("P0");
  delay(500);
}

void loop()
{
 delay(2500);
 Serial.println("G470");
 delay(2000);
 Serial.println("G0");
 delay(2000);
 Serial.println("G470");
 delay(2000);
 Serial.println("G0");
 delay(8200);
}
```

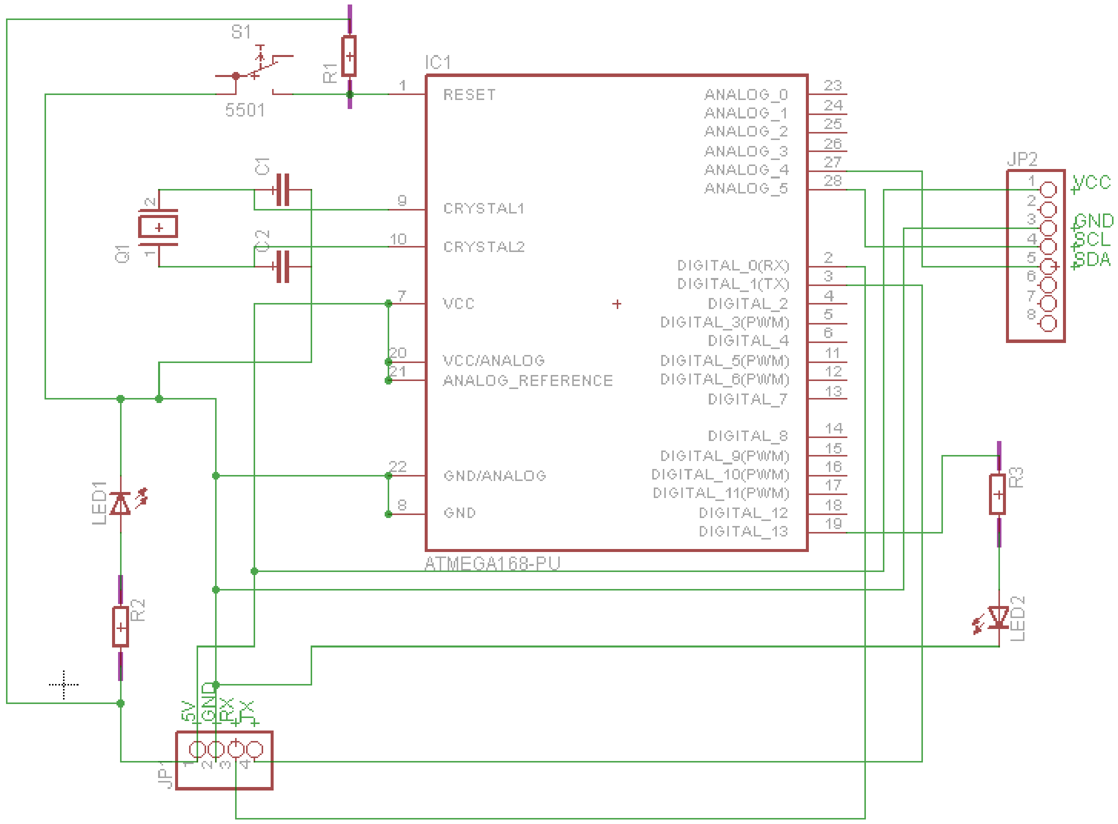
Appendix VII – Control Block Diagram



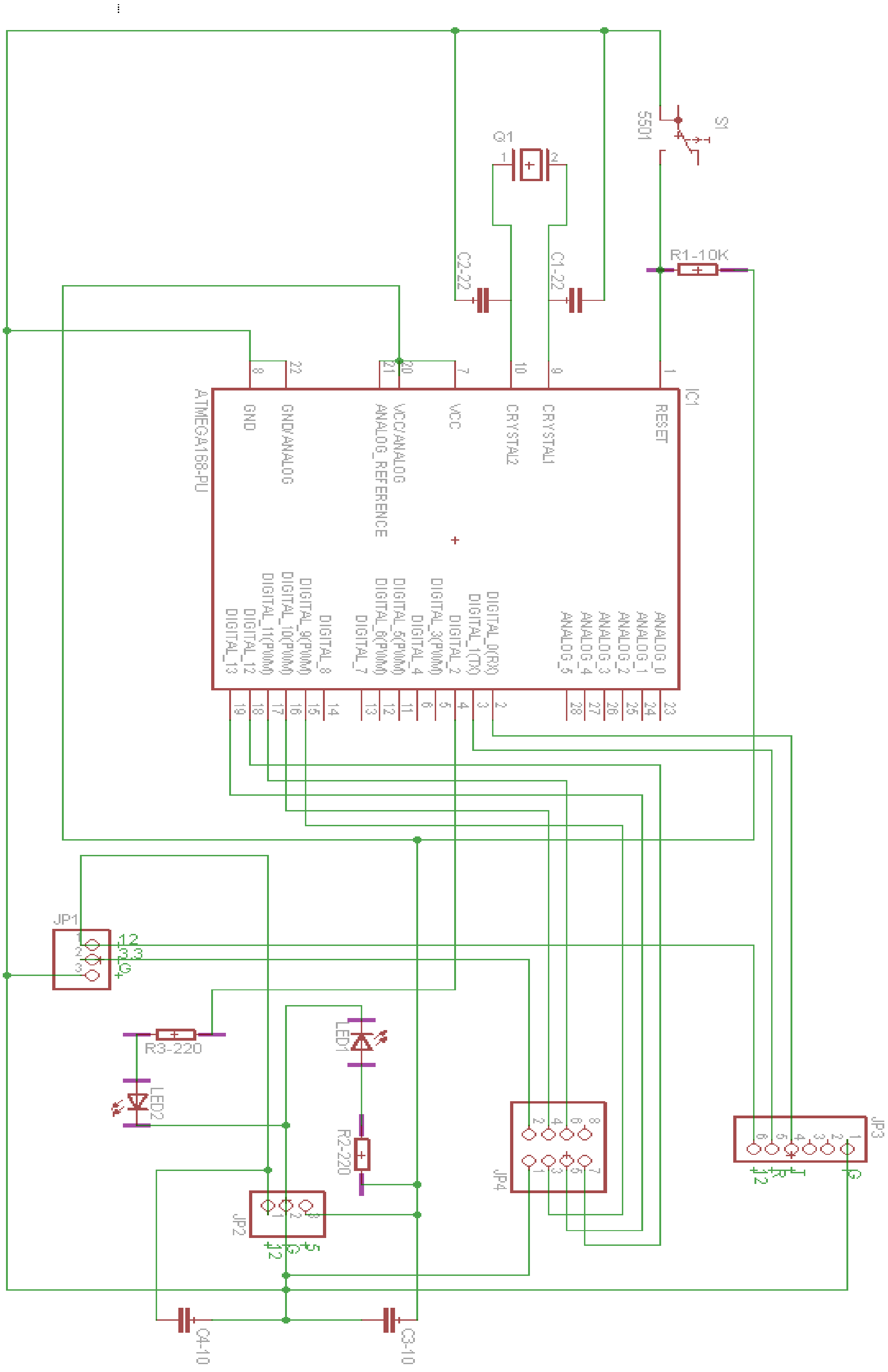
Appendix VIII – MATLAB SerialLink

```
clc;
clear all;
close all;

l(1) = Link([0 0 0 0]);
l(2) = Link([0 0 0 pi/2]);
l(3) = Link([0 0 0 -pi/2]);
l(4) = Link([0 0.29 0 pi/2]);
l(5) = Link([0 0 0.3 -pi/2]);


r = SerialLink(l, 'name', 'SRL');


r.plot([0 0 0 0 0]);
```

Appendix IX – IMU PCB Schematic



Appendix X – Motor Driver PCB Schematic



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