Pneumatic Actuation of a 2-Link Robotic System

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Abstract

In the world of robotics, the interaction between an end-effector and a load is to be made as precise and stable as possible. Various fields of robotics, especially nanorobotics, are still in the testing phase but they demand precision. The investigation of a 2-link pneumatic robotic system, using robotic and electric actuators, will be made. For the sake of representation, the prototype will be made of available materials in the market to fulfil its requirements. An insight into robots explaining the various functions in the human world will be outlined. The aim of the Paper will be to illustrate an appropriate control strategy for a pneumatically-actuated robot. The choice and design of the actuator for the prototype will be explained. The type of piston, directional control valve (DCV) and push-buttons to meet the specifications of the robot will be elucidated. The completion of the prototype will give conclusive results about the operation of the robotic system.

Keywords: Robot, Pneumatic, Linear, Rotary, Actuator

**For correspondences and reprints*

1. INTRODUCTION

Robots are defined as machines that imitate human capabilities like walking talking, picking and placing objects, amongst other functions, for the purpose of lightening the burden of Man. The 21st Century beseeches better precision and coordination in the world of robotics. Complex tasks, such as mining operation, diffusing bombs, factory automation and space exploration, have become dependent on robotic devices. Most of these robots are androids: they are designed to have humanlike body parts to facilitate their work in their respective applications. The use of a 2-link member to represent the human arm is vastly common and the following Paper will investigate the requirements and devices to make the actuation of the two connected limbs function as desired.

The aim of the Research was to model and construct a prototype that will eventually operate using its 2-link arms to approach an object at a point, grab it and place it at another point. Therefore, much investigation is made to study the necessary factors to design a feasible robot that will be paralleled with industrial applications.

Some of the common terms that will be relative to the Research Paper are:

1. Linear actuators: They are components that produce movement in a linear path and will relate physically in the environment in which they are driven. Two most popular linear actuators are single-acting cylinders and double-acting cylinders.
2. Rotary actuators: These devices operate in a circular movement. They are appropriate for "mixing, dumping, intermittent feeding, screw clamping, continuous rotation, turning over, automated transfer, providing constant tension and material handling." (Hydraulics & Pneumatics Magazine, 2012).
3. Degrees of Freedom: It is the independent motions that are allowed to the 2-link body or the number of possible independent relative motions between the pieces of the mechanism (Wikipedia).

Two control systems are usually applied for robots: non-servo and servo:

1. Non-servo control: The non-servo robot is an open-loop control system. No feedback mechanism is used to compare programmed positions to actual positions. A common type of non-servo robot is the "pick-and-place" operation of a robot (Ross, Fardo, Materson, & Towers, 2011).

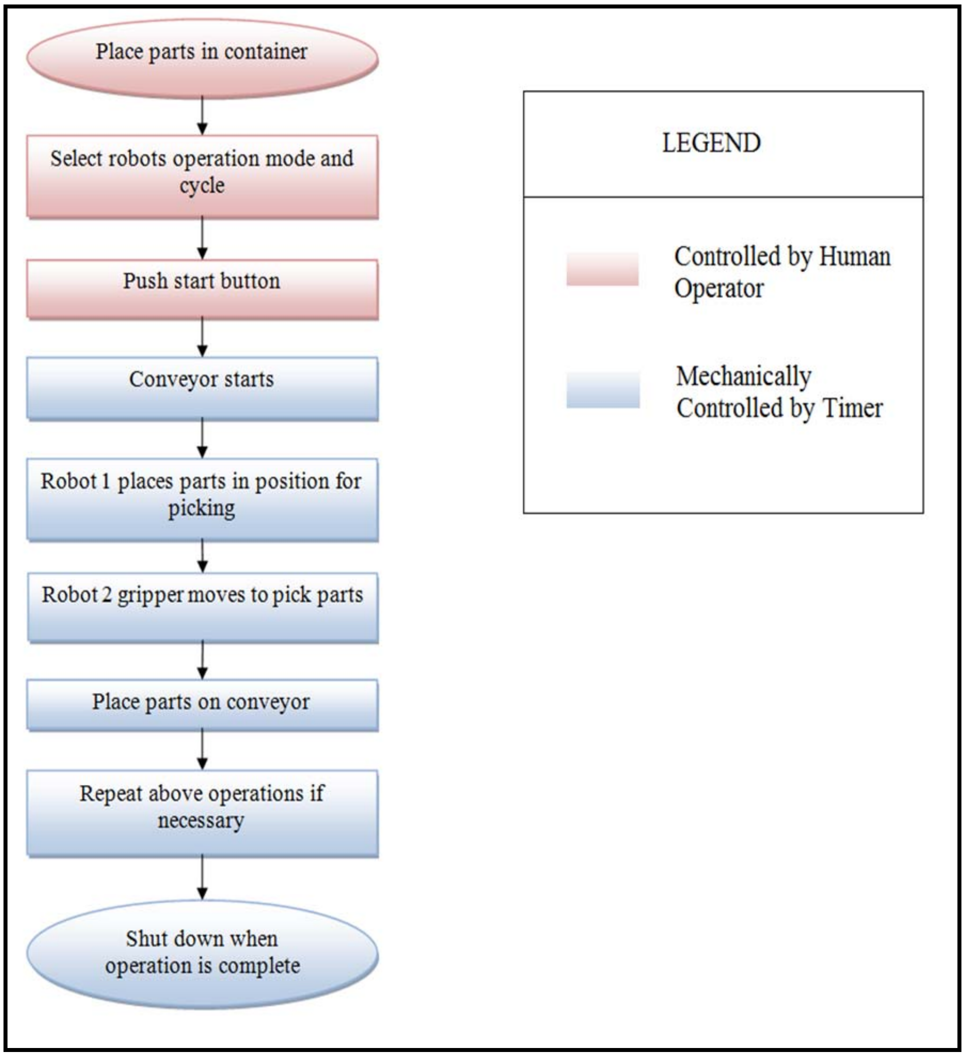


Figure 1: Non-Servo system of an inline Robot cell (Ross, Fardo, Materson, & Towers, 2011)

2. Servo control: Servo robot is a closed-loop control system. The feedback mechanism is used to eliminate the errors between programmed positions and actual positions (Ross, Fardo, Materson, & Towers, 2011).

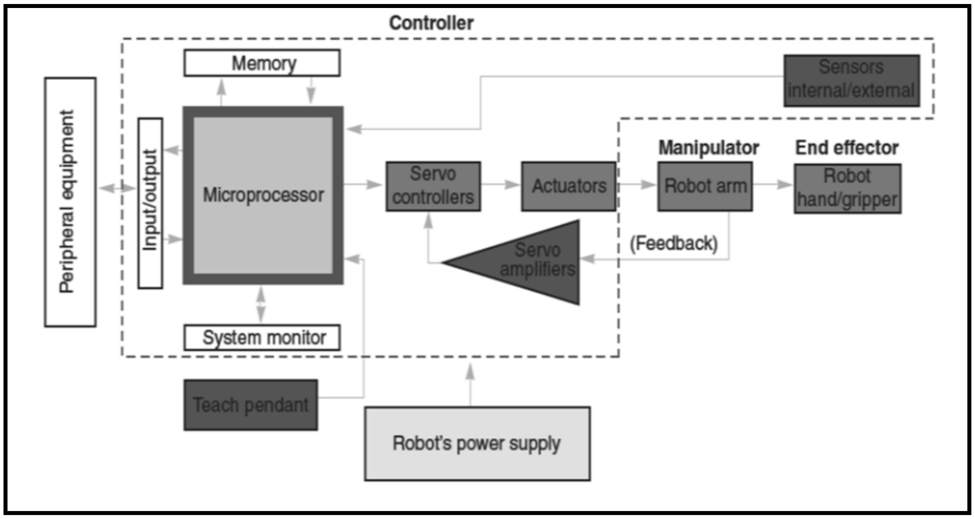


Figure 2: Servo System of a Robot consisting of Feedback (Ross, Fardo, Materson, & Towers, 2011)

In relevance to the current Paper, it has been decided that a non-servo control system would be sufficient to manage the system. Most industrial robots are non-servo ones, although servo controlled system are now the current trend. They are, however, more expensive because additional components, like transducers, are necessary for proper functioning (Ross, Fardo, Materson, & Towers, 2011).

Another factor influencing the type of robot is the choice of either a compliant actuator or a stiff actuator. At an equilibrium position, a robot produces zero force or zero torque (Van Ham, Sugar, Vanderborght, Hollander, & Lefeber, 2009). A compliant actuator permits deviation from that equilibrium position owing to the load it can carry or an external force influencing its position. On the other hand, a stiff actuator does not have a variable position when it is loaded to a weight or experiences an external force, provided that the force does not exceed the load limit. In the case of an industrial robot, the use of a compliant actuator is not needed because industrial applications use stiff systems and they do not engage in confrontation that induces physical damage (Van Ham, Sugar, Vanderborght, Hollander, & Lefeber, 2009). Moreover, variable stiffness actuators are extensively used in robotic prosthetic actuators where the human will essentially feel more comfortable when performing either soft or abrupt movements, thus catering for the healthy condition of the user.

Safety of a pneumatic robot was also investigated whereby the simulation of the collision between a 2-link robot and a human head showed that if there is an amount of passive compliance in a robot, the impact is dependent predominantly by the inertia of the impacting link and not by the entire robot (Van Damme, et al., 2010).

Most Space exploration robots consist of intricately assembled pneumatic actuators. Humanoid robot Robonaut is one of the most dextrous NASA android comprising of two arms and uses various tools to assist Man in Space (NASA).

Figure 3: Humanoid Robot Robonaut from NASA (NASA)

The emergence of robots in the medical domain is now very widespread internationally. The medical field has made tremendous steps in the development of medical robots. Da Vinci, the first heart bypass surgery robot, assisted surgeons in May 1998 (Sandham, 2008).

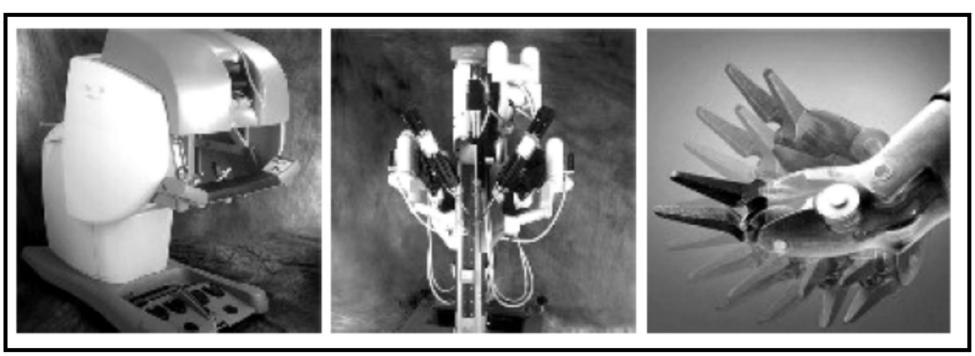


Figure 4: Da Vinci Robot Components (Ortmaier, 2002)

Since then, several replicas of Da Vinci have performed more than two hundred thousand operations worldwide (The Economist, 2012). Another useful medical application of robots is the Minimally Invasive Robotic Surgery (MIRS): 4 mini-incisions are made into the patient's body and surgeons use a robotic system to probe 4 long-instruments into the patient's body for operation. The concept of virtual hospital is created by MIRS whereby a patient is in an operation theatre in a country and that person is being operated by a surgeon who is situated in another country (Ortmaier, 2002).

2. MATERIALS AND METHODS

The preliminary step of the conceptual design in order to choose the appropriate materials and components is to define the working concept of the robot. Just like the PUMA robot (Wikipedia, 2013), the robot will be used for "pick-and-place". The 2-link manipulator will point its robotic end-effector to the right distance to the object, grab it and place it to another point.

The next step is to choose an appropriate rotary actuator. Three types of motor were stated of which only one was to be chosen: a DC motor, a servo motor and a stepper motor. The factors that determined the appropriate motor were its availability, its cost and its ability to manoeuvre the base at the required angle. The DC motor was eliminated because of its inability to control the desired angle. Albeit the servo motor gave a much better precision for the variation of the speed and the degree at which the angle varies, it was also disregarded as the price was too costly. The stepper motor was the appropriate and only choice left where it gave both desirable rotational speed and angle adjustment. Two types of stepper motor were experimented: a unipolar stepper motor and a bipolar stepper motor. During the testing of the unipolar stepper motor of less than a holding torque of 1 $kg.m^2.s^{-2}$ for the prototype, it was found that a more powerful motor was required to rotate the 2-link arm with the piston. A bipolar stepper motor (See **Figure 5**) of holding torque 1.235 $kg.m^2.s^{-2}$ was secondly tested and found to be providing sufficient torque for the overall prototype, hence finalising the appropriate choice of the motor to be used.

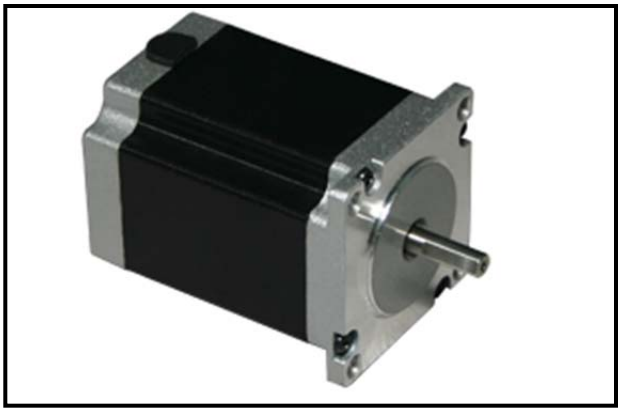
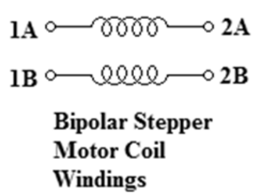


Figure 5: NEMA 23 Bipolar Stepper Motor

In addition to the type of stepper motor used, the switching scheme was important to understand as it gives important details of how to switch the motor for simulation.



S/N	1A	1B	2A	2B
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	1

KEY
1: ON 0: OFF

Figure 6: Coil names and Switching Schemes of Stepper Motor

In order to move in a clockwise direction, the stepper motor has its labelled coils energised in a specific order: 1A, 1B, 2A and 2B. While this is done automatically by the bipolar stepper driver, it is important to be acquainted with the order in which the coils are energised as demonstrated later in the simulation phase.

Moreover, the choice of the pneumatic actuator, the directional control valve and the power sources were to be selected. Since the system is to be both electric and pneumatic in nature, an electro-pneumatic circuit is to be designed. A single-acting cylinder (See **Figure 7**) is used since most industrial applications use single-acting actuator for grippers and it also less costly than double-acting cylinders.

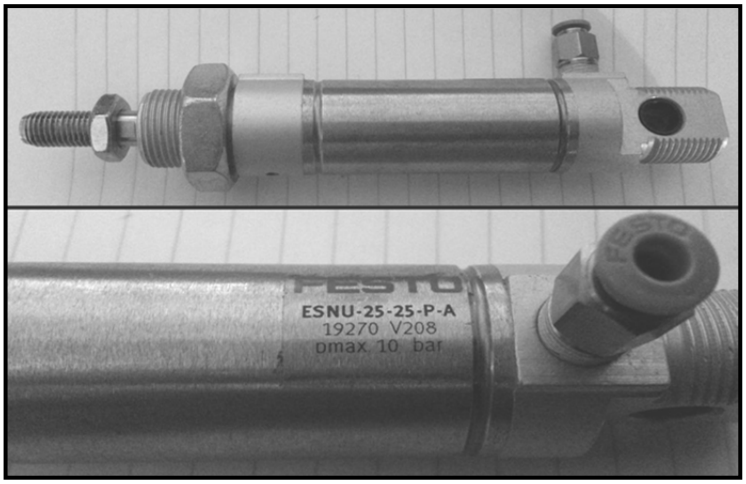


Figure 7: Single acting cylinder with spring-return

A 3/2 way control valve is selected as the DCV (See **Figure 8**) and a 12 V DC coil (See **Figure 9**) with a power rating of 4.12 W is chosen since they are both compatible with the current desired robotic system. The cost of the bipolar stepper motor, the single-acting piston cylinder, the DCV and the DC coil amounted to Rs 10,616.

Figure 8: 3/2 way valve used as DCV

Figure 9: 12V DC coil rated 4.12W

Furthermore, the design of the 2-link member and its base is achieved using the 3D modelling software SketchUp Pro 8. The initial thought process is to have a base of area of 270 mm by 280 mm bolted by 4 screws with a circular motor at the centre (**Figure 10**). The main drawback with the four screws was that it would be destructive to the base.

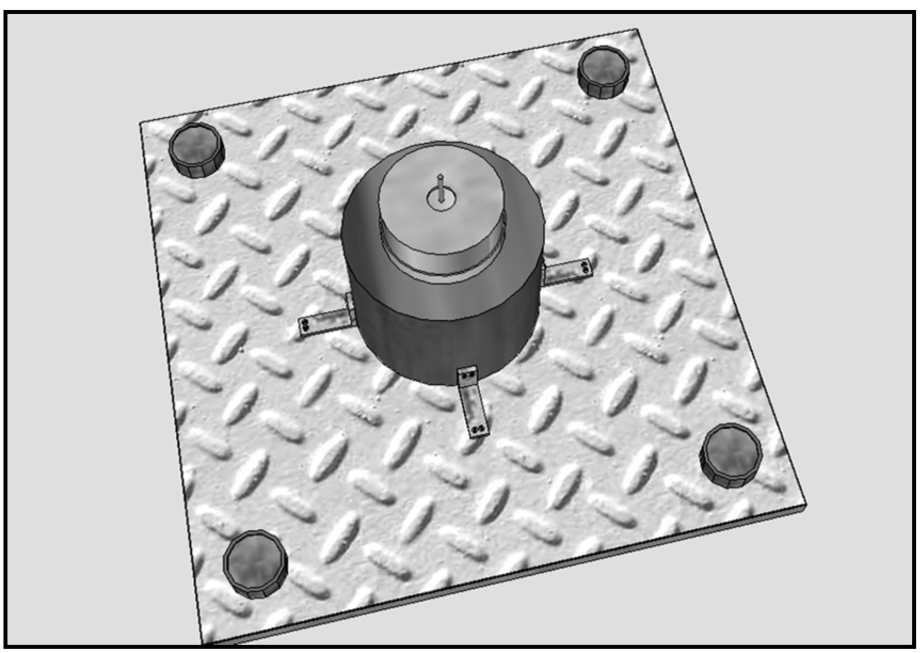


Figure 10: Initial Design of base and Motor at Centre

Instead of four screws, two G-clamps were used to fasten the base as it was non-destructive and it is easier to shift to another location for demonstration purposes.

Two blocks of wood with an arc shape were carved exclusively for the motor's support so that its square-shaped exterior would hold steadily when the 2-link member would rotate (See **Figure 11**). The block sides were of 30 mm by 80 mm and height 18 mm. Screws situated at each extremity of the blocks of the wood were used to fix the motor support sturdily. The initial design was thought to hold the motor in a cylindrical casing (See **Figure 10**) but that design has the drawback of heating the motor over its ambient working temperature of 50˚C since no cooling system has been planned. Additionally, the current design offers versatility if a differently shaped motor is to be installed in case of failure.

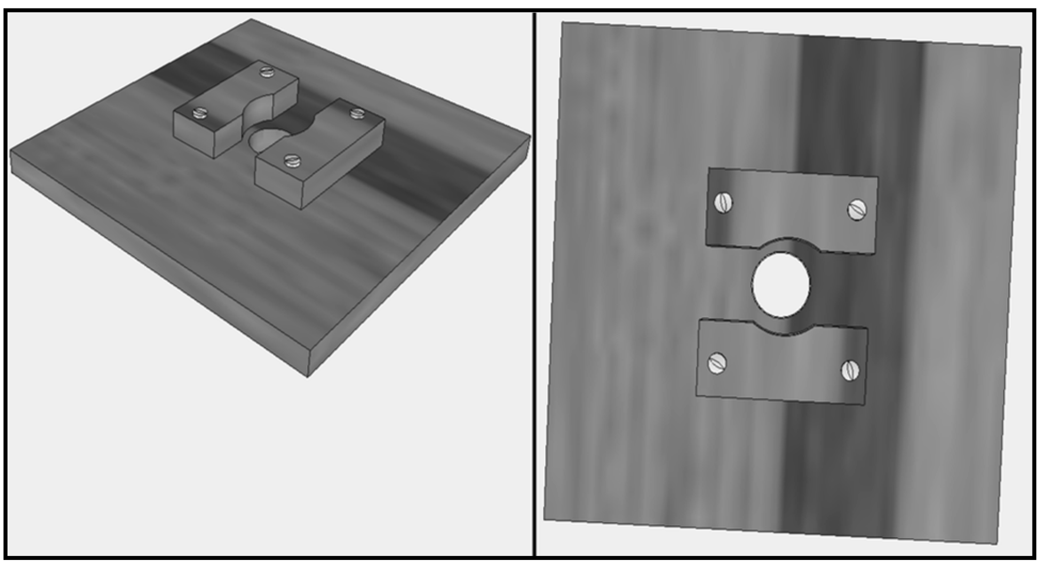


Figure 11: Two blocks of wood for motor (Left). Top View of Model (Right)

The design of the robotic arm is the next step toward building the prototype. The considerations made are cost and type of material suitable to adapt with the motor actuator. The types of material set forth were aluminium, wood or plastic bar. Aluminium was considered as the best choice in terms of type of material since it was light, easily malleable and offered a more appealing look. However, its cost would amount to much more than the available budget and, therefore, it was rejected. On the other hand, wood is easily available at a low price and offers the possibility of being cut or chiselled to any desirable shape. The time taken to work on wood is also quicker and any faulty design can be easily corrected during the implementation and testing phase. Plastic bars were considered as the third choice in case any design with wood was problematic. It was put second to wood as the availability of rigid plastic bars is less than that of wood. Hence, wood was chosen as the final material to construct the 2-link arm. Using SketchUp Pro 8, the accurate and appropriate dimensions of the wood base and the 2-link members are drawn: the arms are labelled as Link A and Link B (See **Figure 12**).

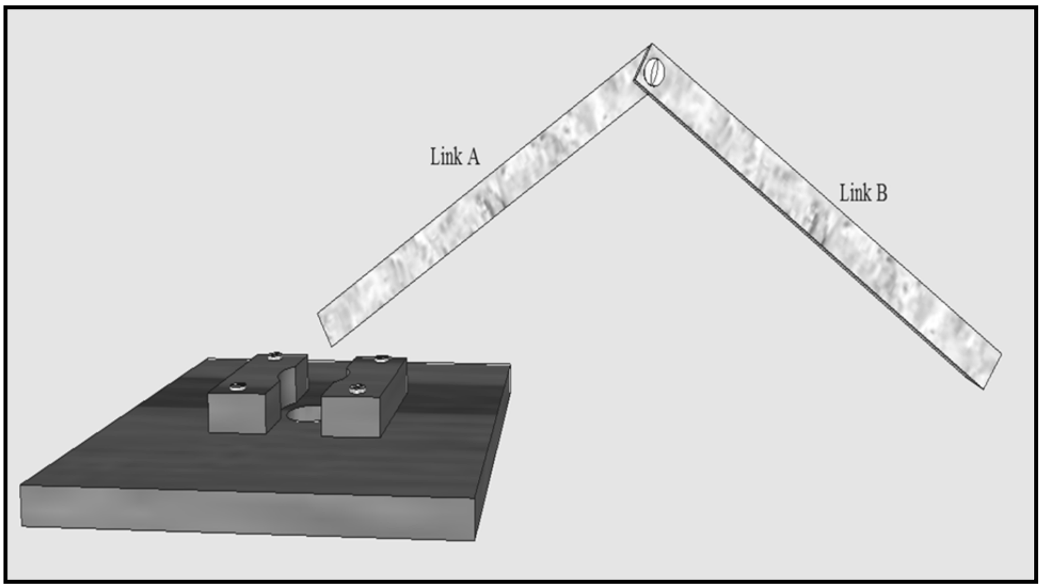


Figure 12: Link A and Link B

The total mass of the link A and link B altogether with the piston rod is not more than 1 kg. The shaping of link A is crucial as it will have to be held by a specially designed connector at the base (See **Figure 14**). It has to be constructed in such a way that is does not cave in under the total weight of the overall robot arm. Link B will hold the piston of mass 0.260 kg and fixed with the help of fasteners. The connector consists of a chrome support over a square-shaped wood and screws fixing the 8 mm motor shaft tightly to the connector (See **Figure 13**).

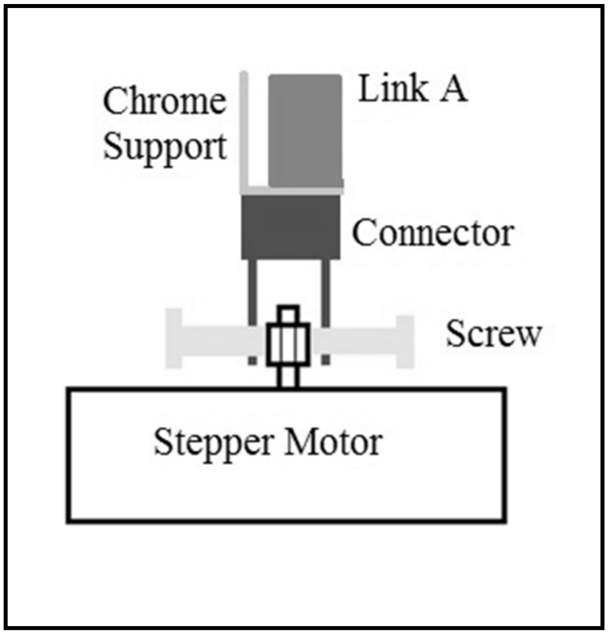


Figure 13: Link A's Connector

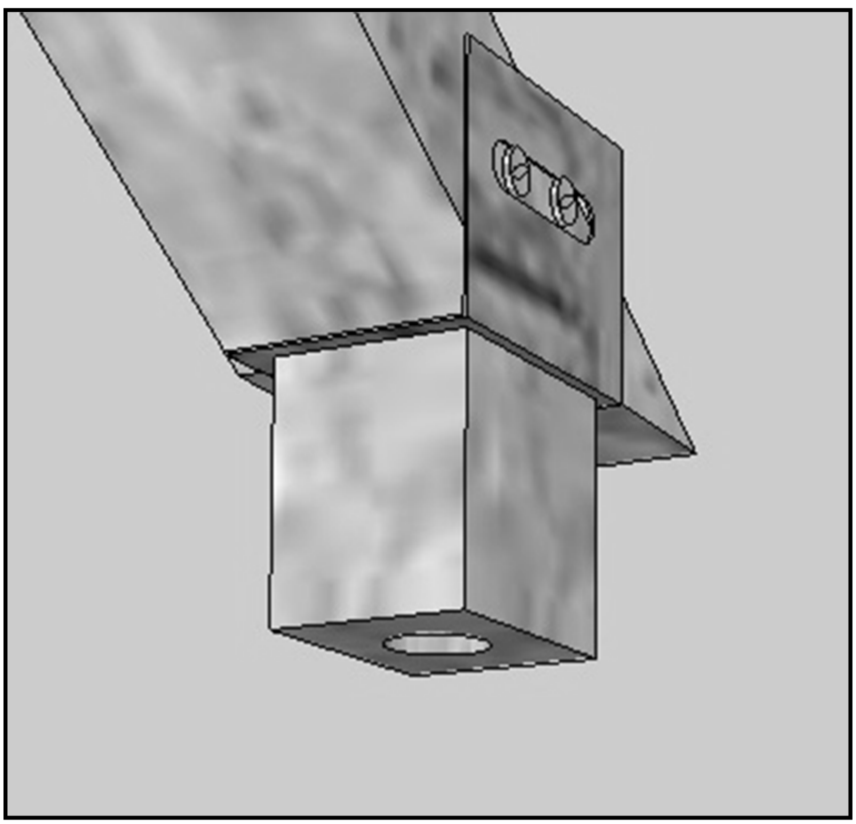


Figure 14: 3-D View of Connector

The overall mechanical design is then assembled via the 3D modelling software (See **Figure 15**).

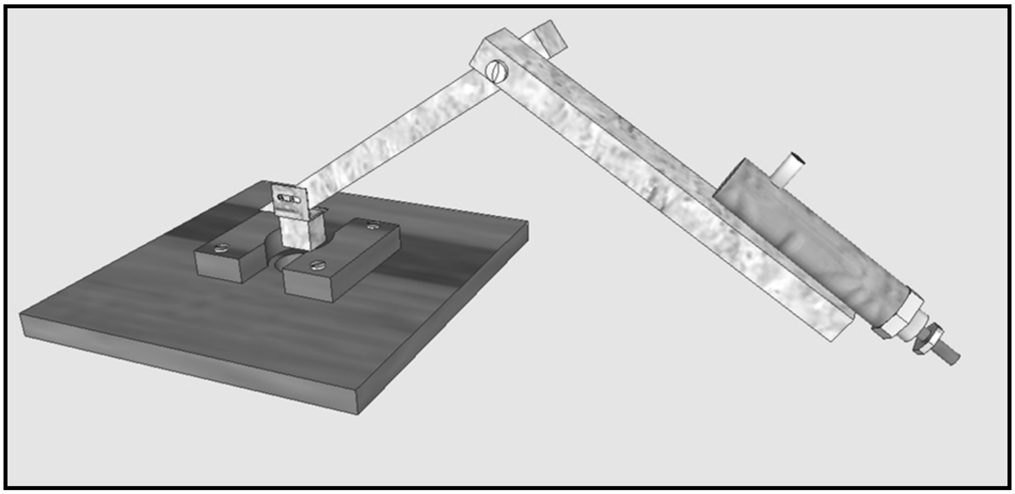


Figure 15: Full Mechanical Design

The mechanical design now having been completed, the following step involves writing a program and then gathering the appropriate equipment for the electrical design to merge with the mechanical part. It is desired that when a push button is pressed, the robotic arm turns toward the object via the stepper motor with the gripper opened. Upon reaching the desired angle, the gripper closes on the object and then returns to its initial position to place the object. The pneumatic piston represents the gripper: an extended position represents an open gripper and a retracted position represents a closed gripper.

The types of input and output are defined to allocate the number of ports and to choose the appropriate microprocessor. One type of output is defined for the bipolar stepper motor, one type of output is distinct to the control of the piston ON or OFF state and one input type is identified for the start of the operation. The allocation for the number of peripheral ports to the microprocessor is 5: 1 input port for the start push button, 3 output ports for the stepper motor and 1 output for the piston cylinder. PIC16F877A is chosen as the appropriate microcontroller having known the desired amount of ports. It has the advantages of being widely available and has a reasonable cost of $4. The programming language used to program the microcontroller is MikroBasic. The appropriate codes are written to satisfy the operation of the microcontroller: a push-button will start the motion of picking, the piston is actuated, the motor starts after a brief delay, the turning motion will proceed over a specific degree of rotation, the piston retracts and the robot returns to its initial position after a brief delay.

Now that the programming sequence has been written and compiled successfully, the electrical circuit is to be put together. It has been divided into three parts: circuit of the microprocessor PIC16F877A, circuit of the bipolar stepper motor and the circuit of the piston cylinder.

The first circuit is that of the microcontroller PIC16F877A whereby each port is defined according to the function it has to obey. The overall circuit is then designed from each port that has been allocated (See **Figure 17**).

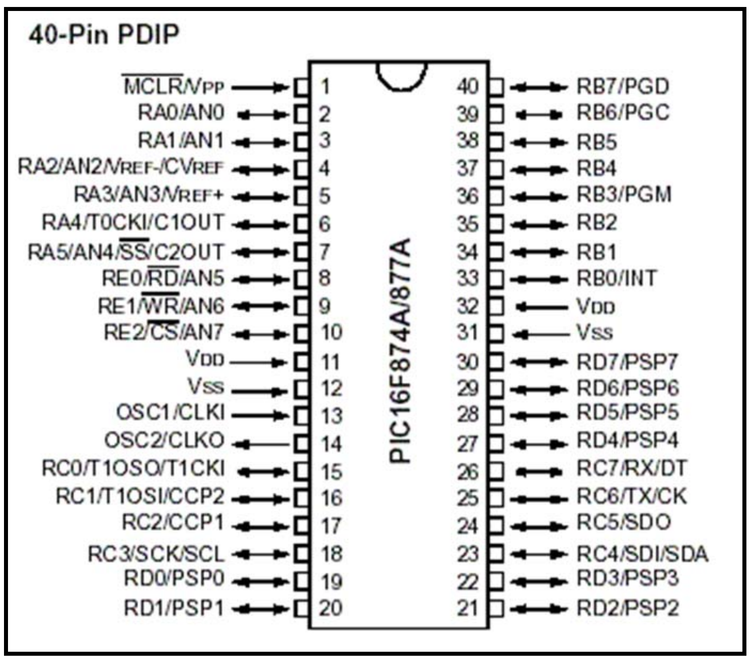


Figure 16: Pin Diagram of microcontroller PIC16F877A

The ports 33 to 35 are the output ports B that will switch the stepper motor.
The port 37 is the output port B that will turn ON/OFF the piston.

The port 2 and 3 are the inputs from port A which will be the push-buttons.
The port 1 will have a memory clear push-button to reset the operation.

The ports 11 and 32 are powered to the 5V supply.
The ports 12 and 31 are grounded.
The ports 13 and 14 are connected to an oscillator of 20.0 MHz with capacitors C2 and C3 in parallel to the oscillator.

The first security step taken is that all grounds are joined together to avoid different ground levels. Also, the appropriate pull-down resistors are connected to port A and the pull-up resistors are installed for the Master Clear (port 1) to settle the voltage level to their expected value.

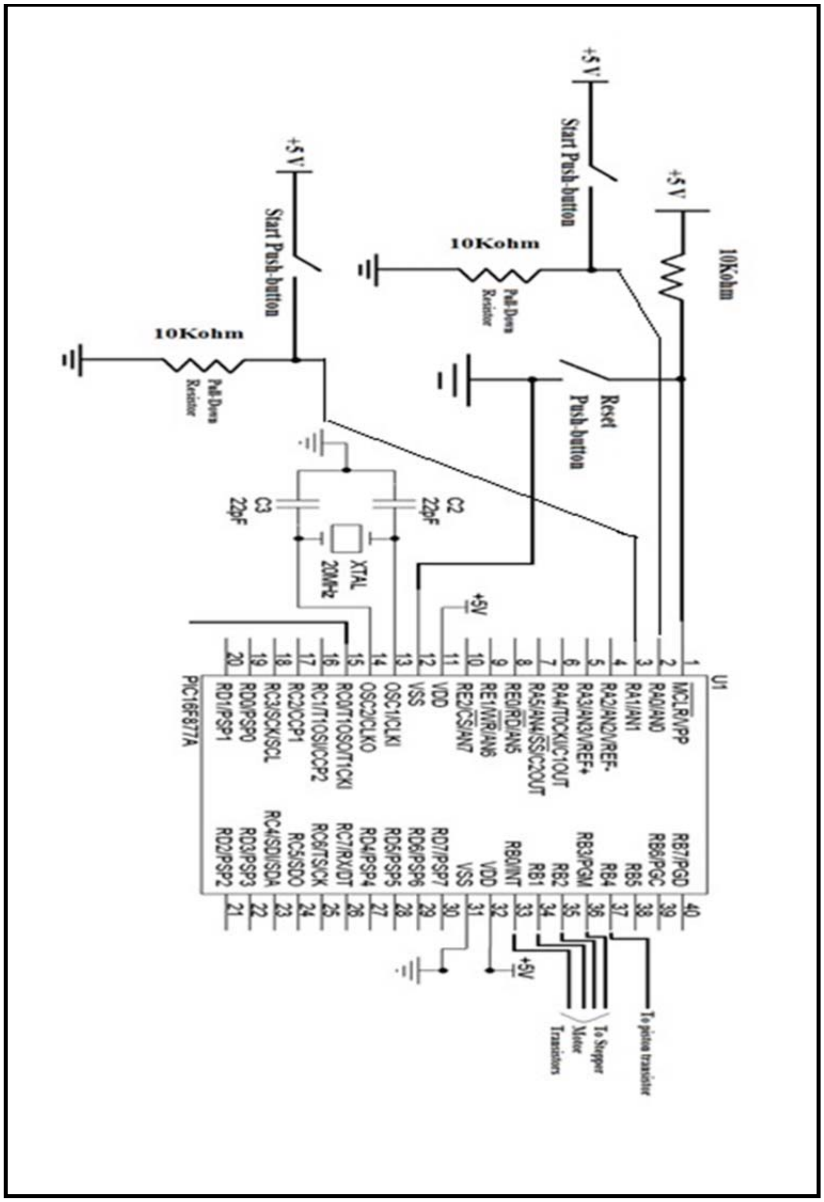


Figure 17: Full circuit Diagram for Microcontroller

The second circuit design is that of the bipolar stepper motor driver (See **Figure 18**).

The "Ground", "Clock Ground", "Clockwise Ground" and "Ground Enable" will be grounded (0 V).
The "Motor Supply" will be connected to a voltage range between 6 – 12 V.
"1A", "2A", "1B" and "2B" will be connected to the appropriate motor coils.

The “Clock (Square Pulse)” will be connected to a square-wave pulse generated by the microprocessor.

The “Clockwise +” is connected to the microprocessor. It determines the clockwise rotation when given the signal. Another push-button is installed to the “Clockwise +” if the microprocessor fails to deliver its signal.

The “Enable +” is connected to the microprocessor. When it receives a signal of 0 V, it enables the driver.

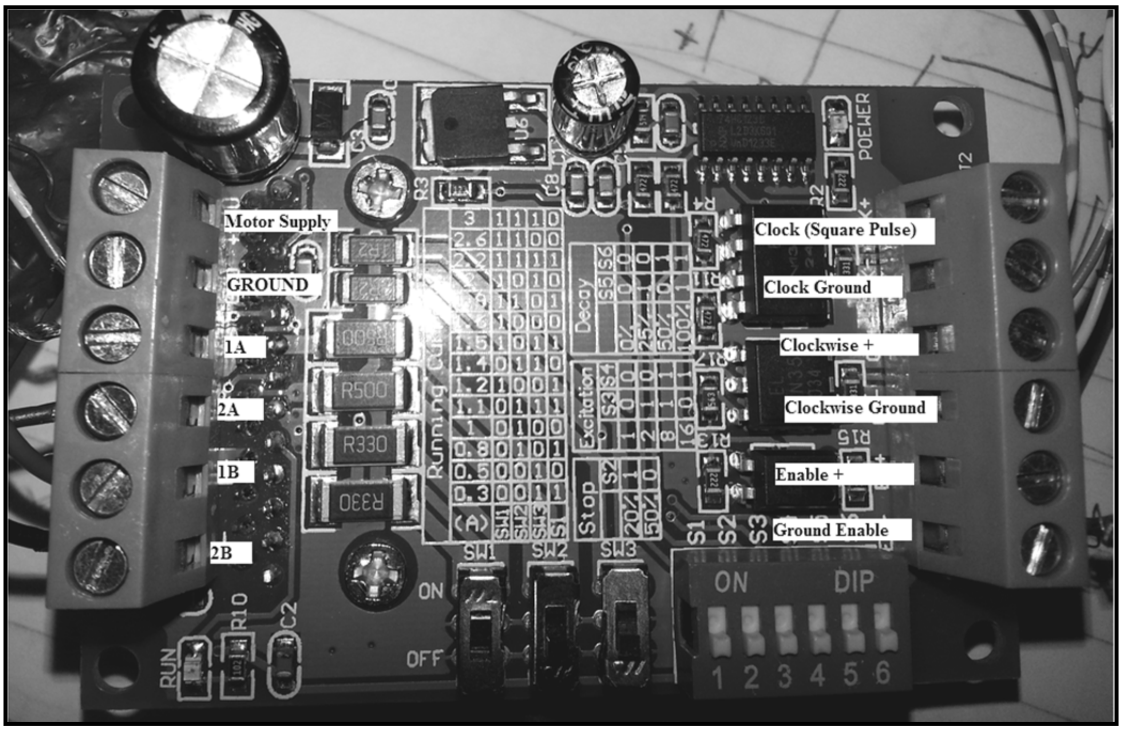


Figure 18: Bipolar Stepper Motor Driver

The third and final circuit involves that of the DCV coil (See **Figure 19**).

The circuit connections for the DCV coil linking it to the piston cylinder are made using a transistor TIP122. The Base of the transistor will be receiving signal from the microprocessor, hence it is connected to a 1 kΩ resistor to prevent an overflow of current. The Emitter is grounded. The Collector is connected to the negative side of the coil and the 12 V will be supplied to the positive side of the coil from the DC voltage source. A diode is connected in parallel to the coil to drain out the back EMF generated by the coil; hence, protecting the coil.

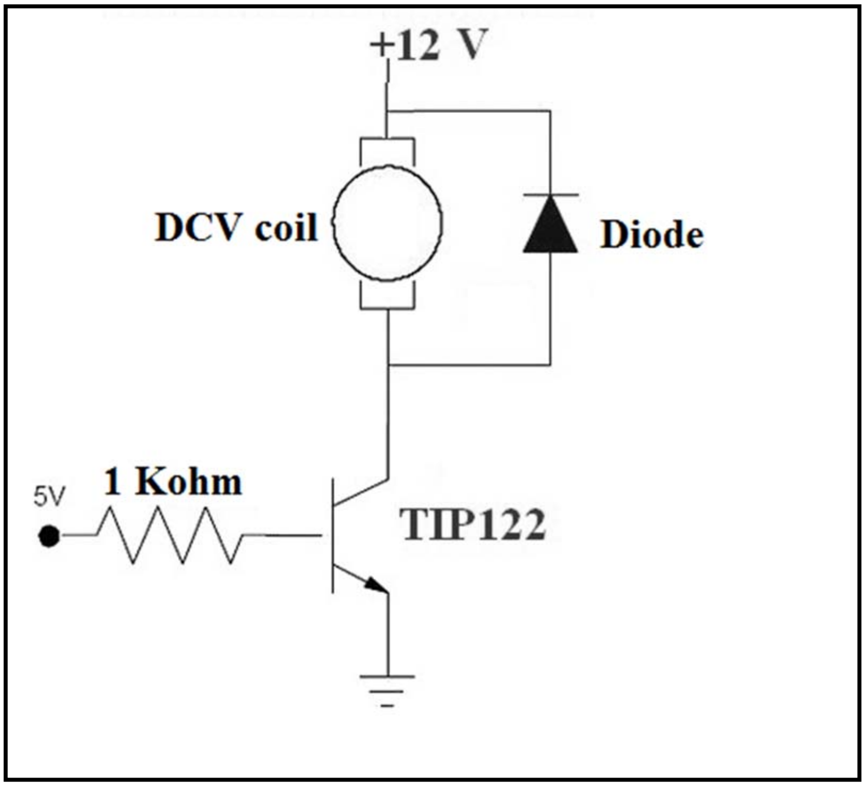


Figure 19: DCV coil Circuit

The third and final circuit is the electro-pneumatic circuit of the piston and solenoid (See **Figure 20**).

Solenoid Y1 will be actuated when a signal is sent to the DCV coil. Since the piston and the DCV are spring-returned, the return stroke of the electro-pneumatic circuit will be effected immediately after the signal to solenoid Y1 is ended.

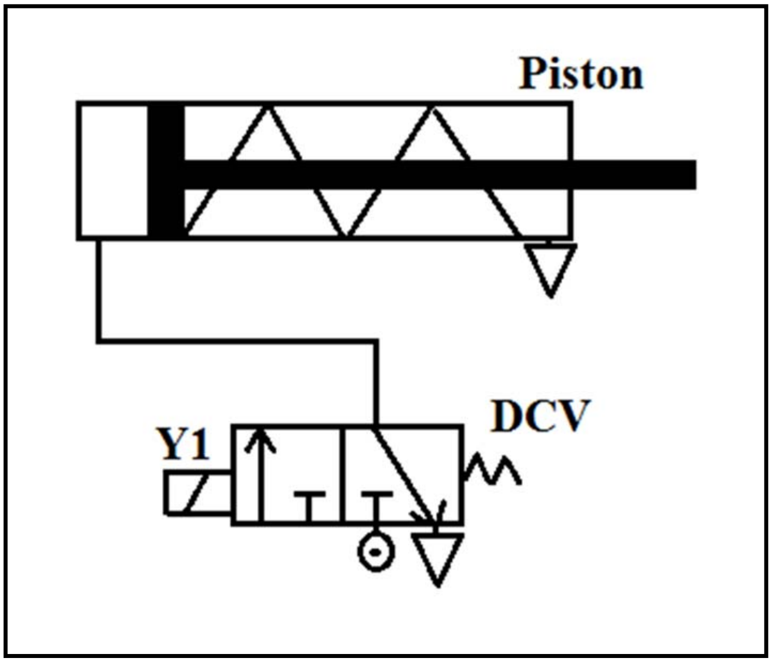


Figure 20: Electro-pneumatic Circuit

Before the testing phase of the mechanical and electrical part of the prototype with the microprocessor, a simulation of the stepper motor turning phase was initiated. The simulation process ensured that the ports sent or received the proper signal and turned the stepper motor accordingly. The program used was PIC Simulator IDE v6.65 as it was available at the University of Mauritius laboratory (See **Figure 21**). The initial part of the programming involved setting the ports from analog to digital. Setting the ports to digital input/output meant that switches could be used to activate the signal. Analog ports were not used because they are redundant in this case and, also, because the use of switches could not have been used through analog ports. The rest of the programming codes involved statements that made the rotation of the robot correspond to the desired degrees of clockwise/counter-clockwise rotation and piston extension/retraction as mentioned earlier.

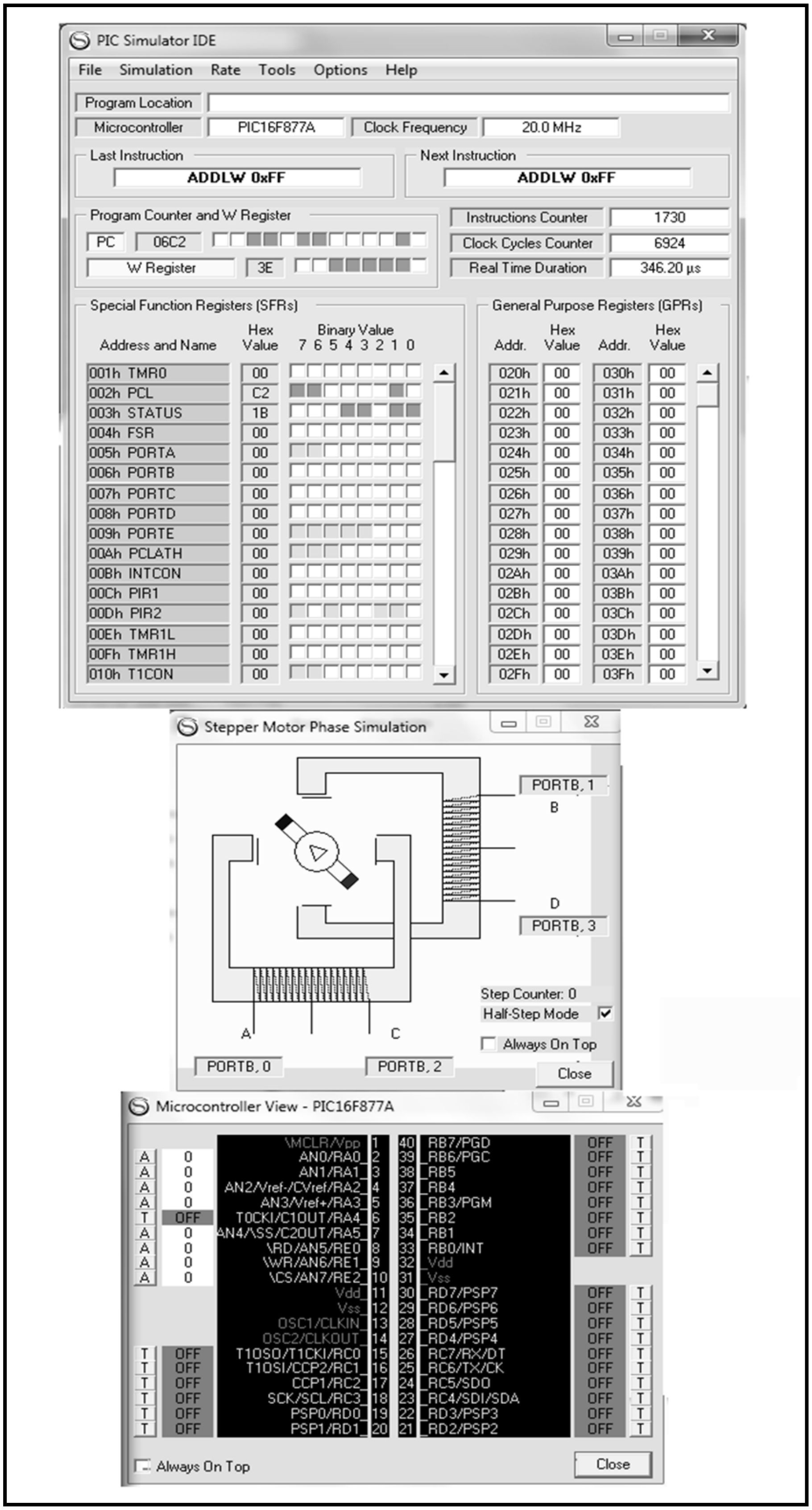


Figure 21: Simulation of Program

The building of the prototype was started with the conception of the 2-link arms. As decided in the “Mechanical Design”, two pieces of soft wood were cut to the appropriate dimensions of Link A and Link B. The advantages of soft wood were that it was very light and could withstand the weight of the piston. Black adhesive wallpaper was used to cover the wood for three reasons: it is aesthetically more appealing, it is waterproof and it protects the wood from external damage.

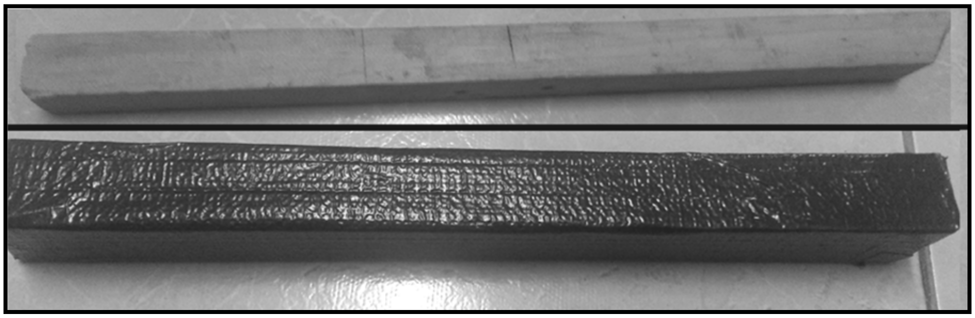


Figure 22: Before (Top) and After (Below)

The next step was to construct the connector and the base (See **Figure 23**). The two curved pieces of wood were placed on a square flat base. The connector was constructed as depicted by the 3D model. The overall wooden components of the model were covered with the black adhesive wallpaper (See **Figure 24**).

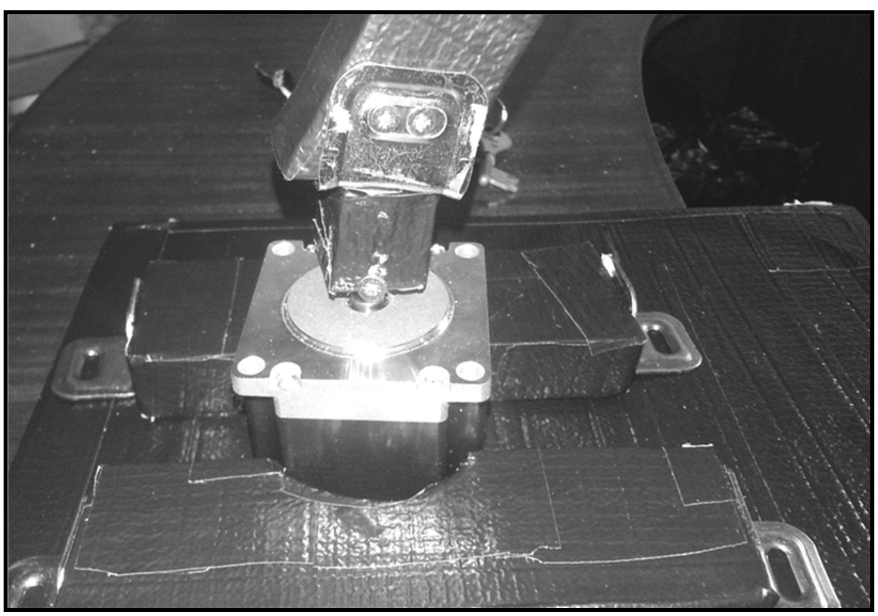


Figure 23: Connector bonding the Motor and Link A

Figure 24: Final building up of Prototype

3. RESULTS

After the piston was installed on the arms, the connecting wires were placed to the DCV coil and jumper wires placed on two breadboards to carry out the testing. With the bipolar stepper driver, the bipolar stepper motor gave a better precision and faster angular velocity was obtained. The 2-link arm turned according to the program, out of which the mandatory calculations were done.

The Torque Calculations that was required is shown below:
Torque, T = Force x Perpendicular Distance
T = (0.3(9.81) x 0.15) + (0.15(9.81) x 0.07)
T= 0.544 Nm
Hence, required torque = 0.544 Nm

Maximum Torque of the bipolar stepper motor was obtained from the datasheet = 1.235 Nm.

Calculated torque provided by the supply:

V = 6.3 V and I = 0.4 A.

From basic equations (Assuming limited friction and negligible power loss):

$P = IV$

$P = T\,\omega$

Where, $\omega = 2\pi f = 2\pi/T$

T = Time taken to complete one revolution = 2.3 s.

Hence, $\omega = 2\pi * 1/(2..3) = 2.73$ rad/s

Calculated torque = $P/(\omega) = IV/(\omega) = 1.10$ Nm

The Piston Calculations can also be made. The piston uses 4 bar pressure from the compressor and 12 V was supplied to the relay. It must be noted that the signal for actuation of either the motor or the piston was initiated by a push button but controlled by the PIC16F877A. The maximum mass that can be allowed to be picked up by the motor can be calculated.

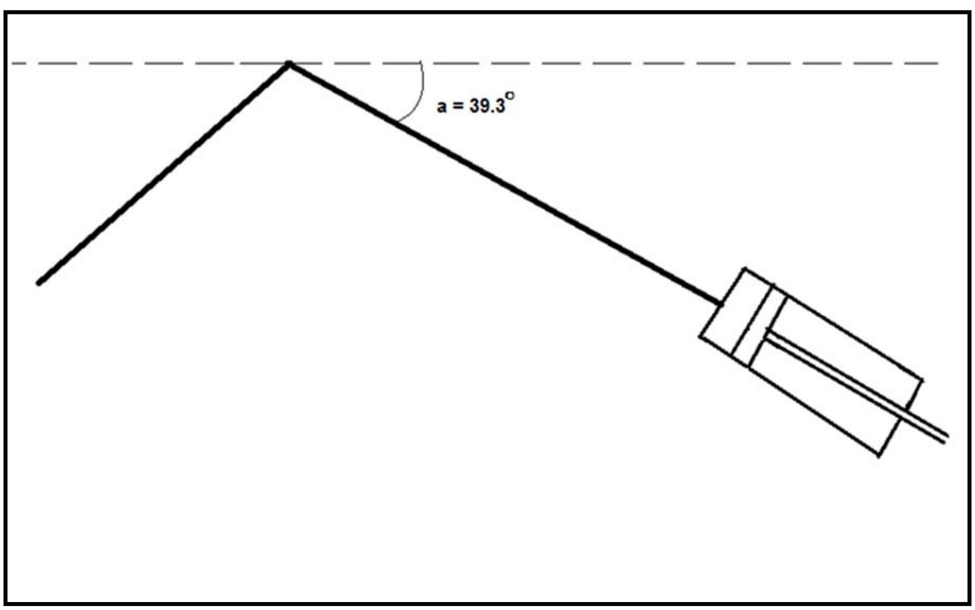


Figure 25: 2-D diagram for Piston Calculations

Assuming the angle "a" and the applied pressure of 4 bar remain constant throughout the whole testing phase, the maximum allowed weight of the object picked up for both extension and retraction can be known.

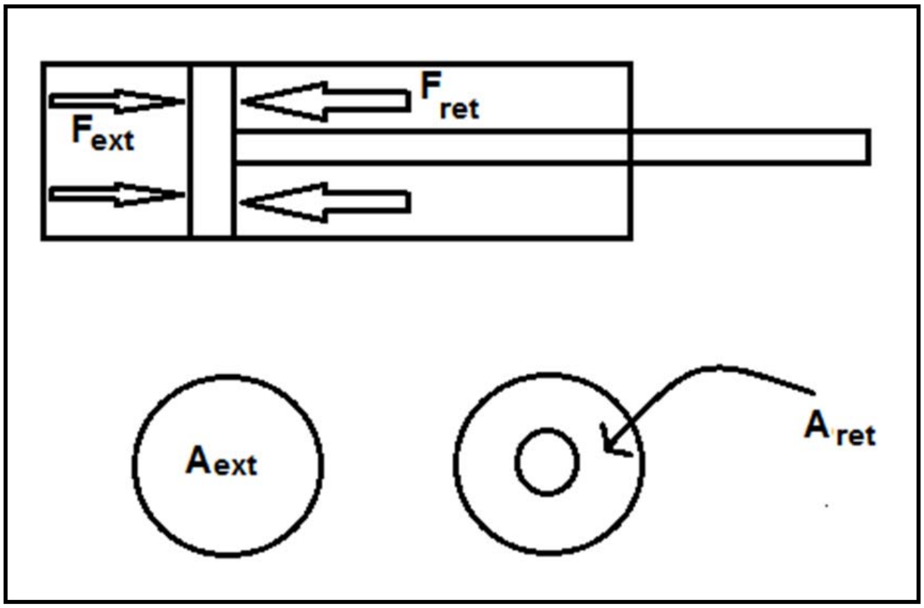


Figure 26: Direction of Forces and Effective Area on which force is applied

Let F_{ext} be Force due to extension.

Let F_{ret} be Force due to retraction.

Let F_R be Resultant force.

Let A_{ext} be Area on which air is applied for extension.

Let A_{ret} be Area on which air is applied for retraction.

Let r_b be Radius of cylinder bore

Let r_p be Radius of piston rod

Since we already know that r_p = 4 mm and r_b = 12 mm, the respective areas of extension and retraction can be calculated.

$A = \pi(r)^2$

$A_{ext} = \pi(r_b^{2)} = \pi\ (0.012)^2 = 4.524e\text{-}4\ m^2$

$A_{ret} = \pi(r_b^2 - r_p^2) = \pi\ (0.012^2 - 0.004^2) = 4.021e\text{-}4\ m^2$

Using the areas calculated and the applied pressure of 4 bar, the force of extension and retraction can be calculated:

$P = (F_{ext/ret})/(A_{ext/ret})$

$F_{ext} = 4e5 * 4.524e-4 = 181.0$ N
$F_{ret} = 4e5 * 4.021e-4 = 160.8$ N

F_{ext} and F_{ret} are the forces provided by the source of the pneumatic compressor.

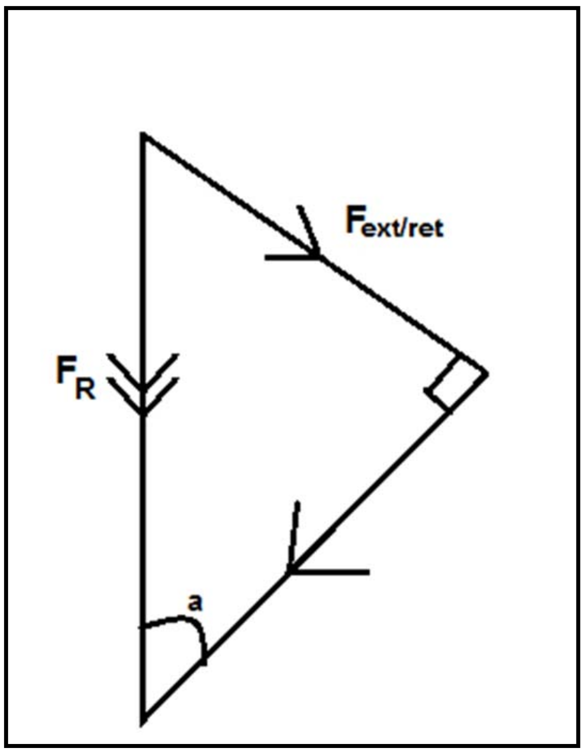


Figure 27: Triangle of Forces

Using **Figure 27**, the resultant force (that is, the weight of the object), can be calculated.

Since a = 39.3º and $F_{ext/ret}$ has been calculated, the force F_R can be determined using simple trigonometry.

sin a = sin 39.3º = 0.53435

$(F_{ext/ret})/(F_R) = \sin a$

$F_R = (F_{ext/ret}) * \sin a$

$F_R = (F_{ext})/\sin a = 181.0/0.53435 = 285.7$ N

Or $F_R = (F_{ret})/\sin a = 160.8/0.53435 = 254.0$ N

Masses allowed = F_R/g , where g is acceleration due to gravity.

= 285.7/9.81 or 254.0/9.81

= 29.1 kg or 25.9 kg

4. DISCUSSION

From the torque calculations, it was found that the bipolar stepper motor provided 1.10 Nm torque to rotate the whole robotic arm without any hindrance.

From the Piston Calculations, it was found that two masses were obtained: 29.1 kg and 25.9 kg for extension and retraction respectively. Assuming that a motor of infinite holding torque is available, the maximum allowable mass of object that can be lifted by the piston is 25.9 kg. This is because any mass greater than 25.9 kg will cause failure of the gripper to hang on the object.

For any further work, supplementary improvements can be made. While the project was designed to be as precise as possible, the limited time allocated was handled wisely to reach the achievable goals and was only in sight to make it work. The final conclusion is not the end but it is rather the beginning of a new opening since more work can be done by taking reference to the different sections. Therefore, the prototype’s design and applications leave much room to additional improvements:

1. Sensors and limit switches can be placed to improve the piston reaction.
2. Aluminium can be used to make the mechanical part more robust.
3. A more powerful motor can be implemented to rotate the metallic arm.
4. Proximity sensors can be included to avoid collision.

5. While this project was targeted mainly for a general use in industrial applications, a more specific use of the robot can be explored.

Furthermore, a better system can be designed for the connector. A proposed solution that can be implemented for future work is detailed as follows.

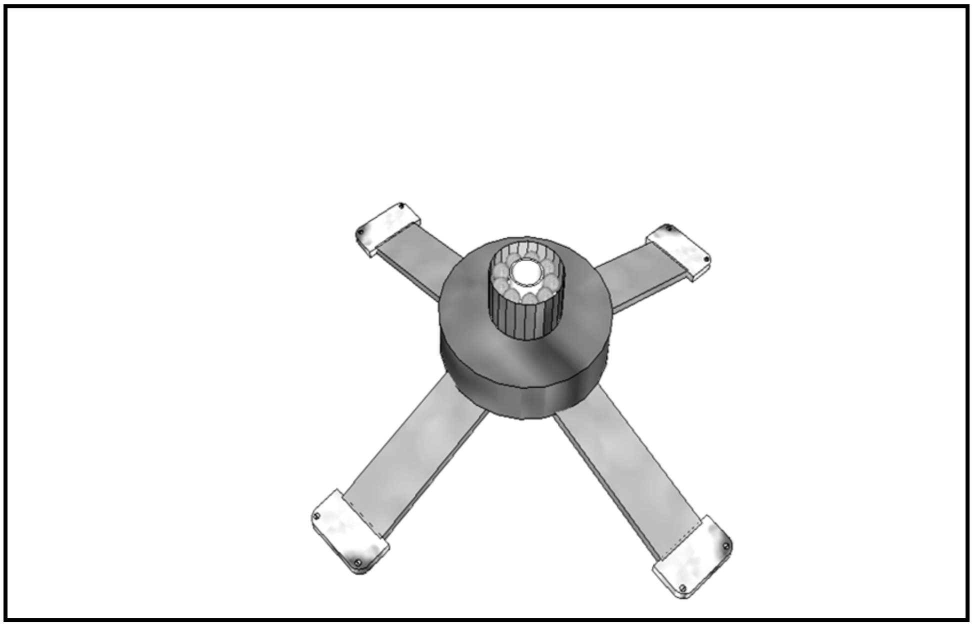


Figure 28: Proposed design for improved base and rotary connector

The redesigning of the connector eliminates the current base and the current connector making them become a single component as shown in **Figure 28**. Four supports are fixed onto a level surface using screws. Ball bearings are added to the new connector to provide smoother rotation.

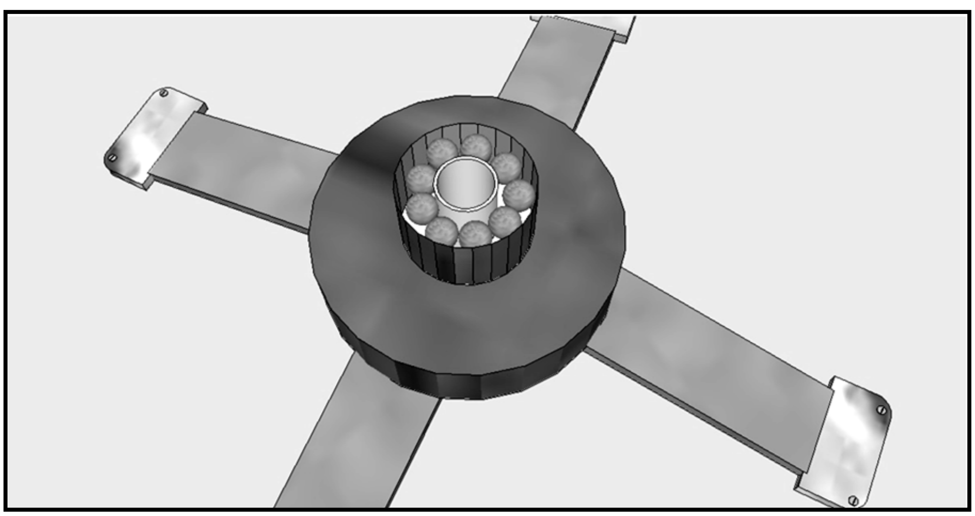


Figure 29: Ball bearings to provide a more robust connector

The ball bearings are placed in between the larger cylinder and the middle cylinder. The former will remain stationary while the latter will rotate with the bearings which must be greased to prevent wear over several uses. To further improve the rotation, an air bearing system can be used: a pneumatically powered moving system where air is driven into middle cylinder to provide a near-frictionless rotation (Hovair). The advantage of using such a method is that the lubricant can be added to the lubricator system of the pneumatic compressor to avoid manual greasing of the bearings.

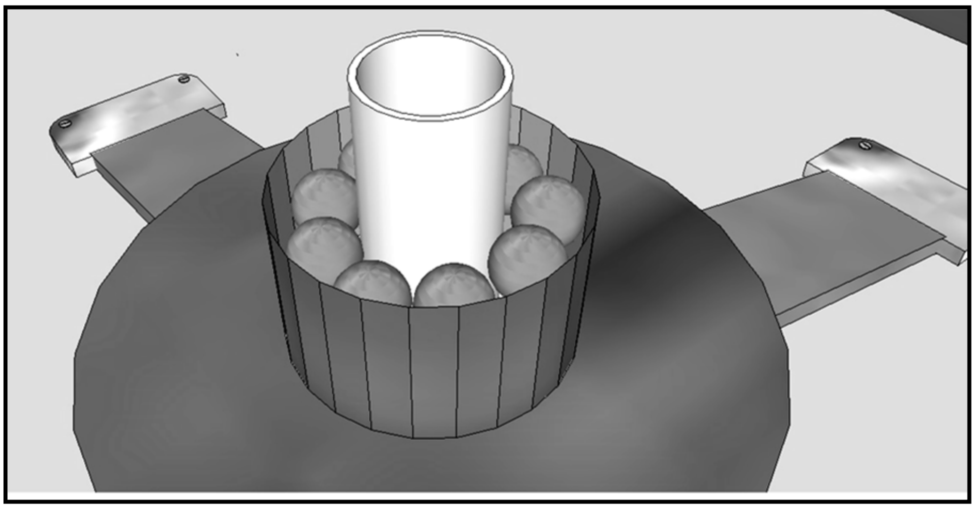


Figure 30: Elongated cylinder for Allocation of Motor's Shaft

The motor is placed underneath the large cylinder. The motor shaft is inserted into the white elongated cylinder (See **Figure 30**). Screws are used to fixed the Link A to the white shaft, thus giving a better support for the 2-link arms (See **Figure 31**).

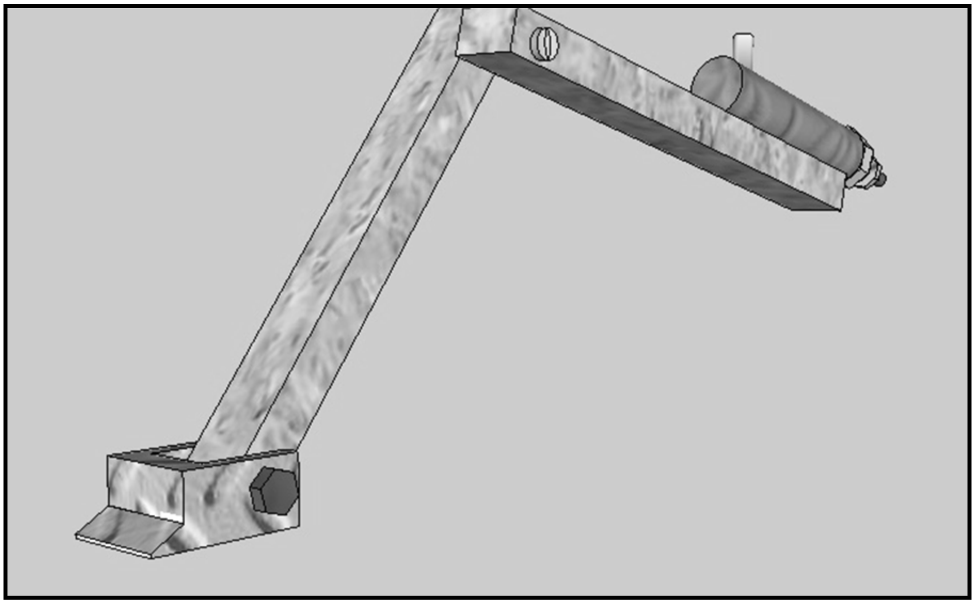


Figure 31: Screws fixing motor shaft to Link A

An overall comparison of the current design and the proposed mechanical is given in **Figure 32**. The suggested mechanical design is observed to occupy a drastically reduced space. Moreover, the material used is aluminium which is sturdier than wood.

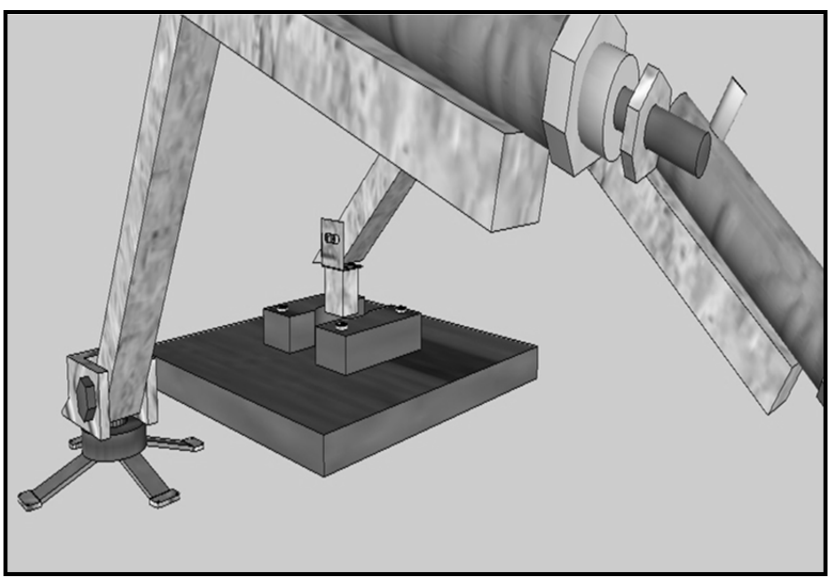


Figure 32: Comparison of current design (Right) and proposed design (Left)

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