Design of a 3-DOF Parallel Mechanism with Shape Memory Alloy Actuators.

by

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Dissertation submitted in partial fulfillment of

the requirements for the

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CERTIFICATION OF APPROVAL

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Approved by,

(T. Nagarajan)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2012.

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD. AZLAN B. ZAMAHARI

ABSTRACT

This research is a study on the application of Shape Memory Alloy (SMA) as actuators in a 3-DOF parallel manipulator. The objectives of the project include the designing process of the 3-DOF manipulator, developing a control mechanism for the SMA actuators and also performing analysis on the finished prototype. The control strategy chosen is using Arduino programmable microcontroller to produce Pulse Width Modulation signal (PWM) which is the most ideal control strategy for a small scale prototype. The SMA actuator design and dimension is also displayed in the discussion section and the SMA wire selected is Flexinol by Dynalloy Inc. The research covers the designing process, modeling and up until the fabrication process of the 3-DOF parallel manipulator.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The importance of robotic and automation in the industry nowadays has driven many researches in the development of the area. In definition, a robot is a machine constructed as an assemblage of joined links so that they can be articulated into desired positions by a programmable controller and precision actuators to perform a variety of task (Keramas, 1999). In this study, a 3 Degree of Freedom (DOF) mechanism (a type of robotic system) with a Shape Memory Alloy (SMA) as the actuators is designed and will be analyzed.

Most robotic links and manipulator are driven by conventional actuators such as hydraulic actuators, pneumatic or even electric motor. Therefore, in this study a Shape Memory Alloy (SMA) is used to replace the conventional actuators on the 3-DOF mechanism. A 3-DOF manipulator is a type of parallel mechanism which according to Inoue, 1985, the end-effector is connected to the base by several parallel chains; in this case the chains are the SMA actuators. With this parallel mechanism, the design will have a high weight to load ratio as compared to a serial mechanism, thus increasing the capabilities in handling heavy load with high acceleration and accuracy.

1.1 Problem Statement

A 3-DOF mechanism can be used to perform several functions. Due to its simplicity, a simple but efficient actuators system is required as the driven mechanism of the device. It can be used as an end-effector or as the arm of machining tools. In the construction sector the SMA actuators can be used to erect pole and beam by attaching it to the beam to be erected.

In order to produce a mechanism with high capabilities, this study is important since most of the robotic mechanisms today are driven by conventional actuators which are bulky, heavy and have limited capabilities. In a motor driven actuator as example, due to its high speed and low torque, a reduction gear system are required to produce the needed torques that are compatible with the motion of the devices (Mavroidis, 2002). As for the SMA actuators, the power input can be manipulated to produce the desired output directly thus increasing the efficiency of the actuators.

1.2 Objectives

The project is aimed to achieve several objectives.

i) To design and develop a 3-DOF manipulator using the SMA wires as the actuators.

ii) To develop a control mechanism for the SMA wires actuators

iii) To achieve practical, efficient and controllable 3-DOF manipulator and to do analysis on the working model.

1.3 Scope of Project

The project will include all the steps in an engineering design process up till the analytical process. It will start with the generation of concept ideas until the evaluation of each concept to determine the most suitable design. Once a design is chosen, the next process is the embodiment of the concept in which the application of software such as AutoCAD$^{©}$ is crucial to ensure the validity of the design. The project will also include the modeling and simulation of the 3 DOF manipulator design.

Since SMA wire actuators are to be used, experiments to determine the control mechanism and performance of the SMA wires should be done to ensure the actuators are applicable in the working prototype. Once the experimental and detailed design is procured, the fabrication of the prototype will commence.

1.4 Significance of the Project

SMA material can be a part of the future in automation and robotics. With the increasing of research in the application of SMA it can be predicted that the design of robotic mechanism will be much simpler but with the same robustness and versatility of today's mechanism.

Some of the examples for the application of SMA actuator is the Micro gripper by Mohamed Alia, 2010. In Figure 1 the SMA micro actuators is activated wirelessly by magnetic field from a radio frequency (RF).

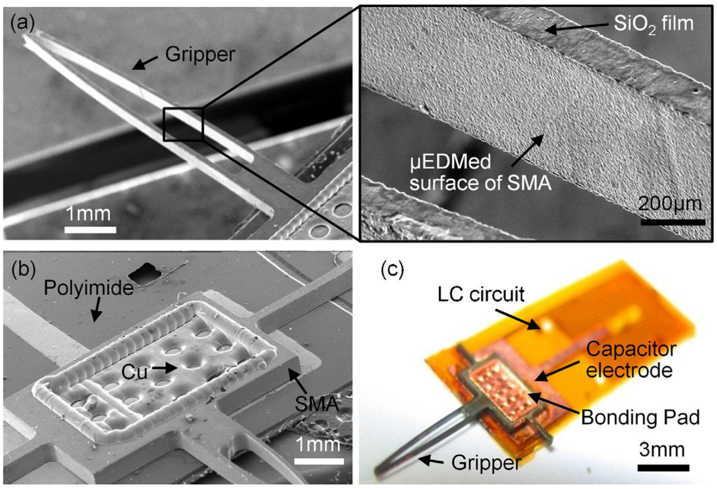


Figure 1: Fabrication results for device-1 (4-mm-long gripper). (a) Gripper beams split using EDM with a close-up showing the inner sidewall of the beam; (b) the SMA pad bonded by electroplated copper; (c) overall shape of a fabricated device (Mohamed Alia, 2010).

Due to its simple design and application, SMA is suitable in the usage of micro sizes equipments such as in the medical sectors where a micro equipment for endoscopic surgery or even in biotechnology field and patient rehabilitation process. Therefore, it is significant to conduct more researches on the application of SMA materials in the robotic and automation sectors as it can bring major improvements in these fields.

CHAPTER 2

LITERATURE REVIEW

2.1 3-DOF Parallel Manipulator with SMA Wire Actuators

A parallel manipulator is a parallel mechanism where the links are replaced with a SMA wires that acts as an actuator. A manipulator connected to the base with spherical joint and actuated by four SMA wires actuator will be designed. Since a spherical joint is used, the manipulator will have 3 degree of freedom. With the use of SMA wires to replace the conventional actuators, a lightweight design could be achieved with the advantages of reduced in weight, simplified modeling of the dynamics, ease of transportation and construction (Darwin, 2010).

Many applications can be adopted with the design of manipulator with cable actuators. Albus (1993) described a cable driven manipulator has the capabilities of manipulation of heavy payloads in the manufacturing sector, where as Oh (2005) stated the application in cargo handling. Several applications in construction of building (Bosscher, 2007) and rehabilitation (Surdilovic, 2004) are also noted.

The application of cable like actuators will also result in several disadvantages. In a research paper by Darwin (2011), cable actuators can only be actuated unilaterally through tension and not compression. Therefore in designing the 3-DOF manipulator, a mechanism to provide a bias force must also be considered to return the manipulator to its original position. Mavroidis (2002) suggested that a bias force can be supplied by stored potential energy (gravity or a spring) or be provided by another SMA actuator working antagonistically.

Therefore, with the references of previous researches, a functional 3-DOF parallel manipulator should be designed by implementing the suggested solutions to overcome the problems that might arise.

2.2 Shape Memory Alloy (SMA) Wire

The first SMA alloy was discovered accidentally in 1932 by a Swedish Physicist by the name of Arne Olander. Arne was astounded by the characteristic of gold (Au) and cadmium (Cd) alloy that plastically deformed when cool and then return to its original form when heated. The phenomenon is known as the shape memory effect (SME) and shape memory alloy (SMA) is any metal alloy that is able to exhibit the SME characteristic (Mavroidis, 2002)

With the founding of other SMA which is much less expensive such as Nitinol©, the interest in the application and research of SMA arises. Nitinol© is a Nickel- Titanium alloy which is famous in the research field due to its characteristic such as less expensive, harmless and easy to control.

In this project, the SMA in the form of Nitinol wires will be used to perform dynamic task which is as an actuator in a 3-DOF parallel manipulator. Figure 2 shows the shifting in the materials crystalline structure between two phases which is martensite and austenite. Changes in temperature and internal stress are the reason behind the SME (Mavroidis, 2002).

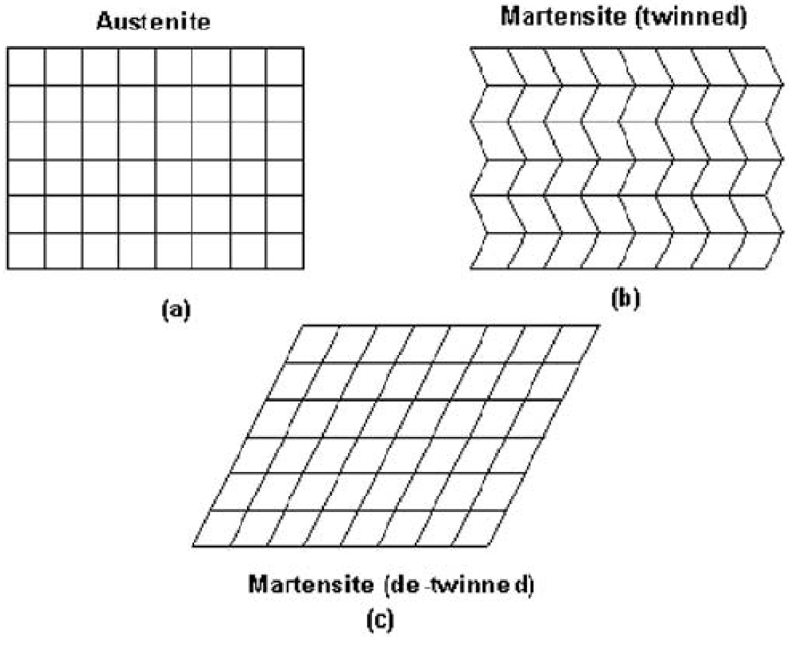


Figure 2: Material crystalline arrangement during the shape memory effect (Mavroidis, 2002). (a) In Austenite phase after heat is applied. (b) In Martensite phase before heat is applied. (c) De-twinned Martensite after the cooling process.

From this characteristic the SMA can be controlled by changing its temperature. There are several ways to provide heat to the SMA and thus provide control of the materials. One technique is Joule heating or heating by electric current. In order to provide more control of the SMA heating, pulse-width modulation (PWM) are the most common method. The main advantage of PWM is the uniform heating of the SMA element which means more control over the actuations of the elements.

Despite the active heating method of using Joule heating, several passive heating are also developed and currently under extensive research. Passive heating reduce the size of the SMA actuator since no wires and batteries to provide power source are required. Some methods used directed beams such as laser (Hafez, 2000) and electron beams (Clements., 2003) to heat the SMA components. In a research by Mohamed Alia (2010), a radio frequency (RF) was utilized as power transfer method to the SMA components as shown in Figure 3. This method is much more efficient compared to other passive heating methods since RF does not affect by any obstruction between the RF emitter and SMA components.

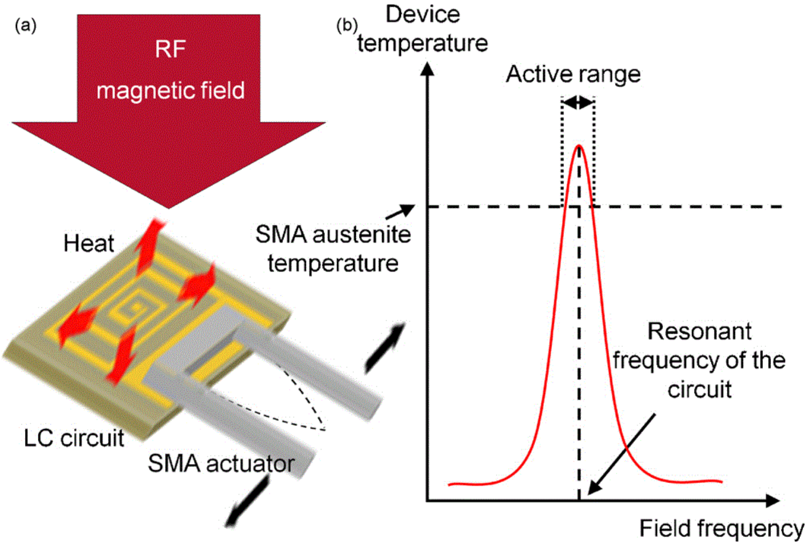


Figure 3: (a) Wirelessly controlled SMA micro gripper and (b) working principle of the device.
Mohamed Alia (2010)

2.3 FLEXINOL® Actuator Wire

Flexinol is a trade name of SMA wire produced by Dynalloy Inc. There are several types of Flexinol with various diameter and properties. Flexinol is a Nickel-Titanium alloy with the capabilities of shape memory effect (SME). Several parameters must be considered in choosing the correct SMA wire for the project. The parameters are namely, cost, wire diameter, activation current supply, temperature and maximum load that can be sustained. Table 1 shows the properties of Flexinol wire that are available with respect to the diameter.

Table 1: Properties of Flexinol Wire with various diameter. (Dynalloy Inc.)

Diameter Size inches (mm)	Resistance ohms/inch (ohms/meter)	Pull Force* pounds (grams)	Approximate** Current for 1 Second Contraction (mA)	Cooling Time 158° F, 70°C "LT" Wire*** (seconds)	Cooling Time 194° F, 90°C "HT" Wire*** (seconds)
0.001 (0.025)	36.2 (1425)	0.02 (8.9)	45	0.18	0.15
0.0015 (0.038)	22.6 (890)	0.04 (20)	55	0.24	0.20
0.002 (0.050)	12.7 (500)	0.08 (36)	85	0.4	0.3
0.003 (0.076)	5.9 (232)	0.18 (80)	150	0.8	0.7
0.004 (0.10)	3.2 (126)	0.31 (143)	200	1.1	0.9
0.005 (0.13)	1.9 (75)	0.49 (223)	320	1.6	1.4
0.006 (0.15)	1.4 (55)	0.71 (321)	410	2.0	1.7
0.008 (0.20)	0.74 (29)	1.26 (570)	660	3.2	2.7
0.010 (0.25)	0.47 (18.5)	1.96 (891)	1050	5.4	4.5
0.012 (0.31)	0.31 (12.2)	2.83 (1280)	1500	8.1	6.8
0.015 (0.38)	0.21 (8.3)	4.42 (2250)	2250	10.5	8.8
0.020 (0.51)	0.11 (4.3)	7.85 (3560)	4000	16.8	14.0

* The pulling force is based on 25,000 psi, which, for many applications, is the maximum safe stress for the wire. However, many applications use higher and lower stress levels.

**The contraction time is directly related to current input. The figures used here are only approximate since room temperatures, air currents, and heat sinking of specific devices varies.

*** Approximate cooling time, at room temperature in static air, using a vertical wire. The last 0.5% of deformation is not used in these approximations. LT = Low Temperature and HT = High Temperature Flexinol® Actuator wire.

From Table 2, the resistance of the wire is represented in Ohms/m. For example, 0.025 mm Flexinol will have the resistivity of 0.0356 Ohm. The pulling force of the Flexinol is tested with a pulling force of 25 kpsi and the result of the pull force provide by the wire are as tabulated in the Table 1. The 25kpsi force is also the maximum safe stress for the Flexinol wire as mentioned by the manufacturer (Technical Characteristics of Flexinol Actuator Wires.).

In terms of movement, the amount of deflection by the Flexinol wire due to the temperature change is called stroke. The stroke of each Flexinol wire usually measured in term of percentage of the wire's total length. As mentioned before, SMA wire can only produce stroke unilaterally, thus a mechanism is needed to produce the bias force. The bias force is exerted on the wire continuously during the cooling of the SMA wire or the austenite phase. It is important in determining the stroke, the recovery time and the amount of deflection of the Flexinol wire.

Table 2: Stroke and Available Force Table. (Technical Characteristics of Flexinol Actuator Wires.)

	Approx. Stroke	0.076mm Wire	0.15mm Wire	0. 25mm Wire
Normal Bias Spring	3%	80g	330g	930g
Dead Weight Bias	4%	80g	330g	930g
Leaf Spring Bias	7%	80g	330g	930g
Right Angle Bias.	14%	20g	83g	232g
Simple Lever	30%	11g	47g	133g
Adjusting Curvature	110%	3g	12g	34g
Clam Shell	100%	3.2g	13g	37g

2.4 Control Strategy

In this project, Joule heating or heating by electric is being chosen as the control method of the SMA wire. In Joule heating, several aspects must be taken into consideration such as current provided max temperature, cycle time cooling time. Basically, the stroke of the SMA wire is due to heating and cooling which means the mechanical cycle is solely depend on the temperature changes. Since the SMA wire is temperature sensitive, there will always a possibility that the wire will overheat. Therefore, a correct power supple must be chosen to avoid overheating of the SMA wire.

One of the control strategies for manipulating the SMA wire is by using Pulse Width Modulator (PWM). A pulse width modulation is the process whereby the power to a device is switched between on and off at certain frequency. The on and off interval is called duty cycle and the duty cycle depends on the resistance within the PWM circuit. From Figure 4, when the circuit resistance is low, the duty cycle is high, high duty cycle means faster heating rate of the SMA wire (Abdul Malik, 2011). With higher heating rate the contraction time will be shorter.

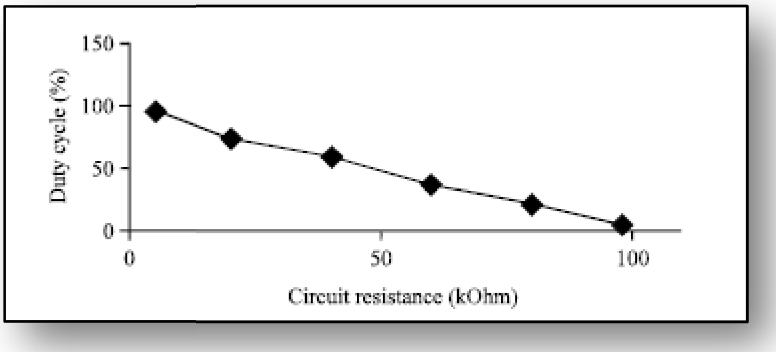


Figure 4: Relations between PWM resistances with duty cycle

(Abdul Malik, 2011).

There are several advantages in the application of PWM as the controller. One of them is the heating in interval. Since the SMA wire is a thermal sensitive, continuous heating might cause overheating thus damaging the crystalline structure of the SMA sire. Heating consist of short pulses will provide heat to the wire evenly and avoiding thermal build up. To provide an efficient PWM controller Loh (2005), suggested a thermocouple should be used to monitor the heating process and eliminate the possibility of overheating entirely. Figure 5 shows the working principle for the controller.

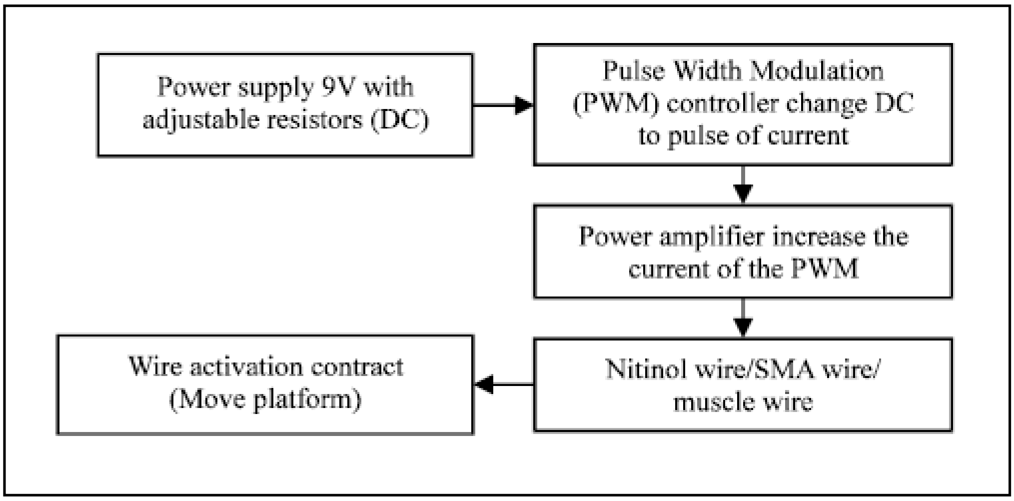


Figure 5: Process flow of PWM control method (Abdul Malik, 2011).

To gain better control of the PWM output, an open-source electronics prototyping platform is used which is Arduino as shown in Figure 6. The Arduino can be used either to receive input from various sensors or even can be used to produced output or in this case to produce PWM signal. The microcontroller can be programmed by using its Arduino programming language. The main advantage of Arduino is a greater control, with correct programming where the activation sequence of each actuator can be program or even its signal intensity.

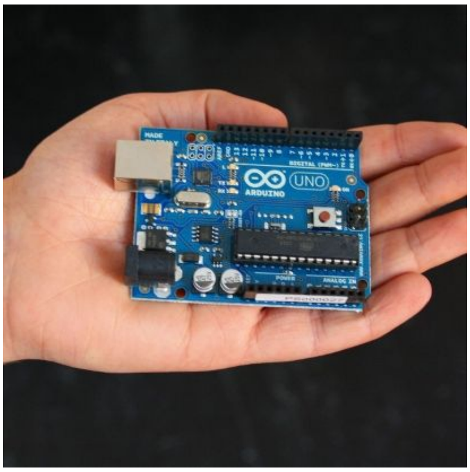


Figure 6: Arduino Uno board, a programmable microcontroller. (Arduino)

2.5 Kinematics

Basically in robotic there are two types of kinematics which known as forward direct kinematics and inverse kinematics. In the direct kinematics the position of any point is calculated given the length and angle of each joint, whereas in inverse kinematics, the length of each link and position is given and the angle of each joint is calculated. The design of the 3-DOF manipulator is inspired by a 4-DOF Cable Driven Parallel Mechanism by (Darwin, 2010). Thus the kinematic mostly resemble the work of (Darwin, 2010).

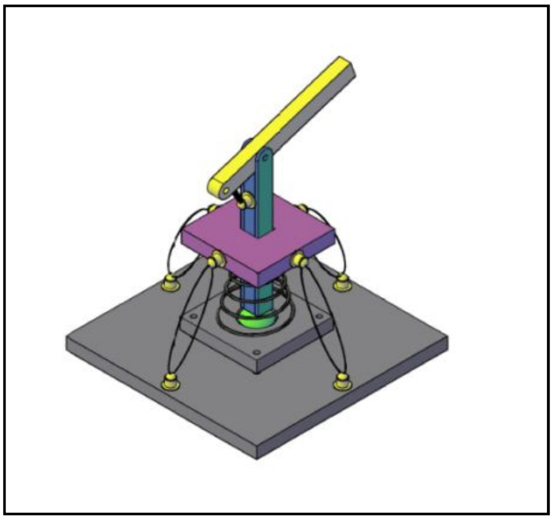


Figure 7: CAD of the 3-DOF manipulator.

The manipulator is designed with two links as shown in Figure 7 above. The first links is constrained by a spherical joint with the base and the second link is connected with the first link by a revolute joint. For the kinematics, Darwin (2010), 4-DOF Cable Driven Parallel Mechanism Kinematics are used as reference in this project. The mathematical modeling of the mechanism can be refer in Figure 8.The lengths of each SMA actuator can be denoted as $l = [l_1\ l_2\ l_3\ l_4\ l_5]^T$, where l_i is the length of cable i. In this design the kinematic relationship is:

Type 1: Actuator connecting from base to link 1.

$$l_i = r_{O_{o1}} + r_{B_i} - r_{A_i} \tag{1}$$

By differential relationship the Jacobian matrix for the system can be denoted as:

$$\dot{\mathrm{l}} = \mathrm{J}\,\dot{\mathrm{q}} \tag{2}$$

And the derivative actuator length is:

$$\dot{l}_i = \hat{\mathrm{l}}_i \cdot \dot{\mathrm{l}}_i \tag{3}$$

Therefore from the relationship of the actuator connection for Type 1, the kinematics is:

$$\dot{l}_i = \begin{bmatrix} A_{\mathrm{il}1} & A_{\mathrm{il}2} & A_{\mathrm{il}3} \end{bmatrix} \begin{bmatrix} {}^{1}\dot{r}_{O_{o1}} \\ {}^{1}\omega_1 \\ {}^{2}\dot{r}_{O_{o2}} \\ {}^{2}\omega_2 \end{bmatrix} \tag{4}$$

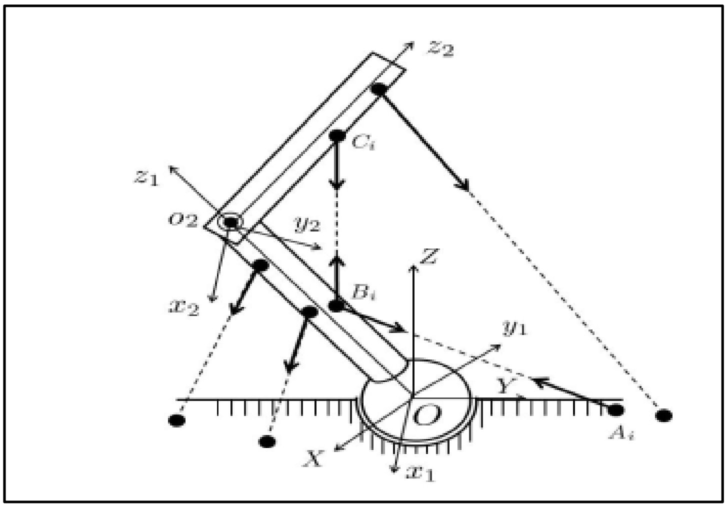


Figure 8: Model of Darwin (2010), 4-DOF Manipulator and its representation.

CHAPTER 3

METHODOLOGY

3.1 Process Flow Diagram

The project will undergo several phases to achieve its objectives. The flow diagram in Figure 9 shows the phases before the completion of the project:

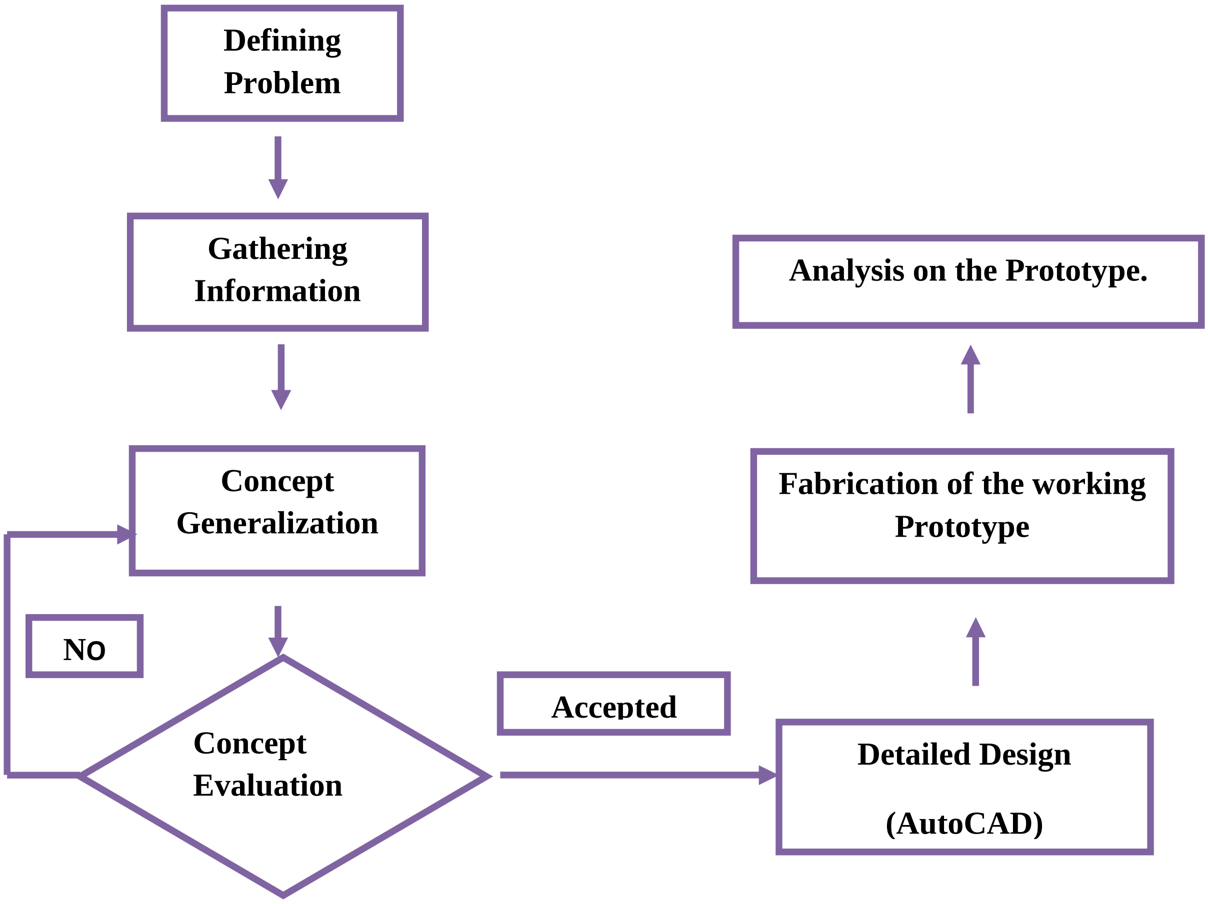


Figure 9: Diagram of the Project Workflow.

Basically there are 2 main phases in this project. The phases are conceptual design phase and embodiment design phases.

3.1.1Conceptual Design

During the study phase several topics was covered to ensure that the project can be carried with full understanding towards the objectives. First is the study of the SMA wire, its properties, specification, application and performance. Secondly, the control strategy for the SMA wire, in this project, PWM is chosen as the control method due to its effectiveness and efficiency. Lastly is the study of the design of the mechanism itself. A proper design must be chosen and tested to achieve the objectives

3.1.2 Embodiment

This phase is the most crucial phase throughout the entire project. During this phase, there were experimentation, detail design and fabrication of the whole prototype. In the detail design software such as AutoCAD used to design the prototype with exact dimension and detail specification. Once the design is finished, experiment is conducted to determine the performance of the SMA wire and to figure out the desired control parameter. Then the fabrication process is commenced and finally the assembly of the components his consist of the manipulator, the SMA actuators and the PWM controller.

3.2 Methodology

3.2.1 Mechanical Works

The main material to be used is Perspex or scientifically known as Polymethyl Methacrylate (PMMA). Perspex is chosen due to its lightweight characteristic and shatter proof compared to conventional plastic. Table 3 shows the steps taken to manufacture the prototype:

Table 3: Table showing the mechanical works involved in this project.

No.	Works Description	Tools/Software.
1	3D Parts design of the manipulator.	AutoCAD 2007/Catia.
2	Assembly of each parts design.	AutoCAD.
3	Cutting of perspex to desired shape.	Laser Cutting machine, Electric Handsaw.
4	Constuction of SMA actuators.	Power Drill, Spherical joints, crimps,screws.
5	Full protoype construction and assembly.	Power Drill, Super glue, bolts and nuts.

3.2.2 Electrical and Programming Works

Since Arduino board is used, there are basically two parts which are the programming parts and the assembly parts. Arduino environment is open source software, thus the programming code to produce the PWM signal can obtained freely in the web, although some alterations are needed to suit the desired output. The works involved in making the controller can be seen in Table 4.

Table 4: Table showing the electrical works involved in this project.

No.	Works Description	Tools/Software.
1	Assembling board and SMA wires	Arduino Board, SMA actuators, jumper wires, resistors, 12V battery.
2	Installing the IDE program.	Computers, Arduino IDE software.
3	Programming of the command	Micro USB Cable, Arduino IDE software.
4	Testing the output	Arduinno Board, SMA actuator.
5	Reprogramming to achieve desired output.	Computers, Arduino IDE software.

3.3 Project Gantt Chart

The Gantt charts in Table 5 and Table 6 exhibit the planned works and milestones for the project. These Gantt chart are important to ensure the project are running smoothly and finished on time.

Table 5: Gantt Chart for FYP 1.

No.	Activities / Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project topic selection.	🟦	🟦						Mid-semester break							
2	Preliminary research work.		🟦	🟦	🟦	🟦										
3	Extended Proposal defense Submission.						🟥									
4	Proposal Defense.									🟦	🟦					
5	Detailed design .											🟦	🟦			
6	Material procurement.													🟦		
7	Interim draft report submission.														🟥	
8	Interim report submission.															🟥

Table 6: Gantt Chart for FYP 2.

No.	Activities / Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Experimentation of SMA Wires.	🟦	🟦	🟦					Mid-semester break								
2	Fabrication process.				🟦	🟦											
3	Analysis of experiment result						🟦	🟦									
4	Progress report submission									🟥							
5	Provide experiment discussion and conclusion									🟦	🟦						
6	Prepare final report											🟦	🟦	🟦			
7	Pre - EDX												🟥				
8	Draft report submission													🟥			
9	Dissertation submission														🟥		
10	Technical paper submission														🟥		
11	Oral Presentation															🟥	
12	Project Dissertation submission																🟥

🟥 - Key milestone

🟦 - Process

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Detail Design

The detail design of the manipulator was performed using AutoCAD 2007 software to produce a 3-Dimension image of the prototype as shown in Figure 10. The design consists of two arms joint together by a revolute joint. The lower arm is then attached to the base by a spherical joint. The lower arm is controlled by four SMA actuators connected from its middle towards the base which will provide 2-DOF motion. The upper arm will also be controlled by a SMA actuator connecting from the lower arm middle to the upper arm middle.

4.1.1 Prototype Design

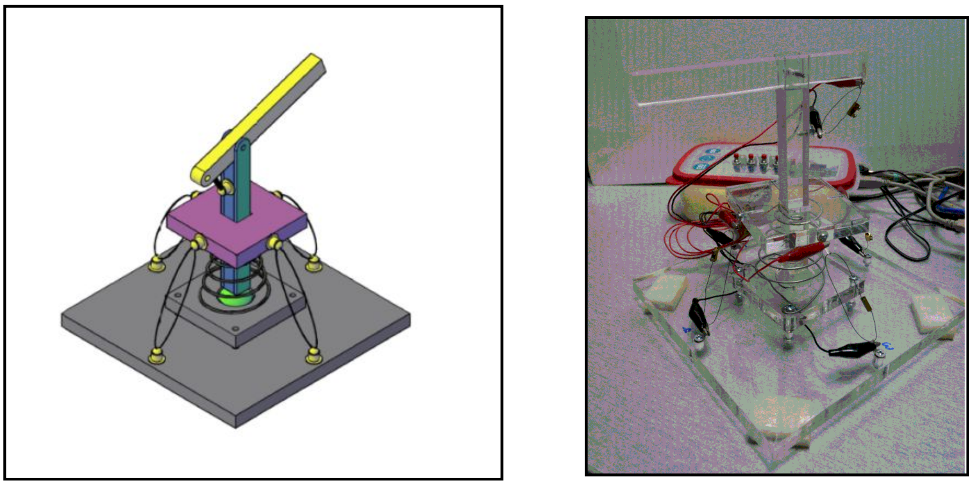


Figure 10: CAD image and the real image of the prototype.

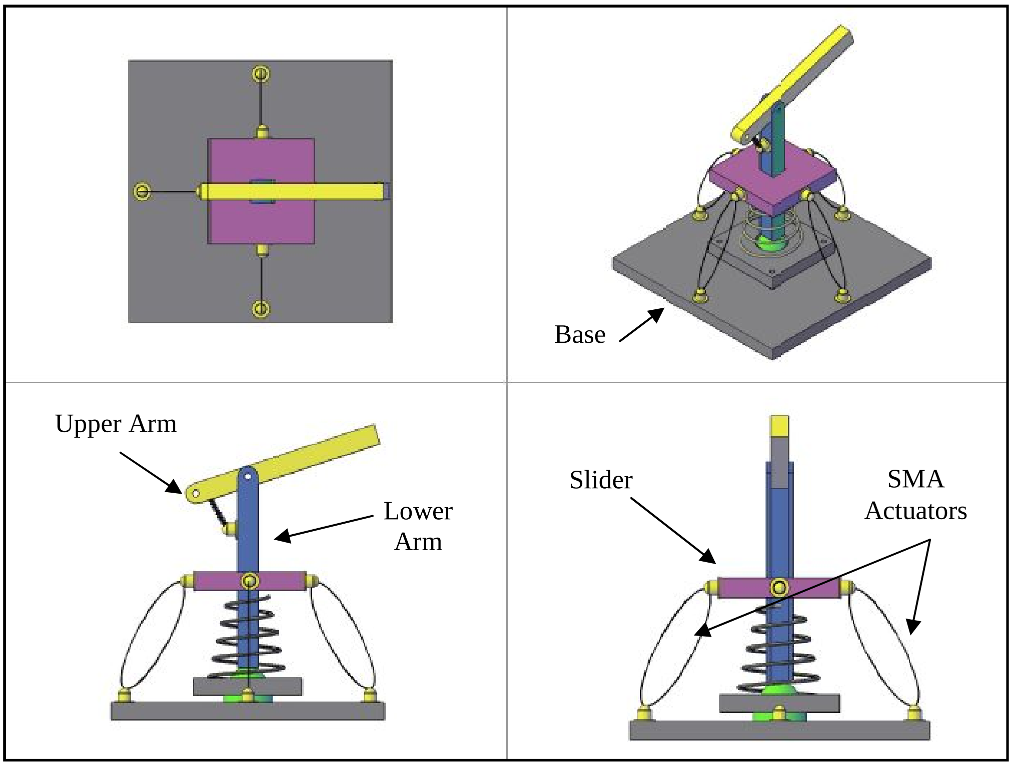


Figure 11: Orthographic View of the prototype.

The prototype is consisting of several main parts such as the base, the lower arm, the upper arm and the slider as shown in Figure 11. All these parts were made by using Polymethyl Methacrylate or commonly known as Perspex. The material is chosen due to its durability and lightweight properties. The detail design of each part can be referred in Appendix 3. Figure 12 and Figure 13 show the images of the complete prototype with the controller box. Figure 14 and Figure 15 shows the close up image of the controller.

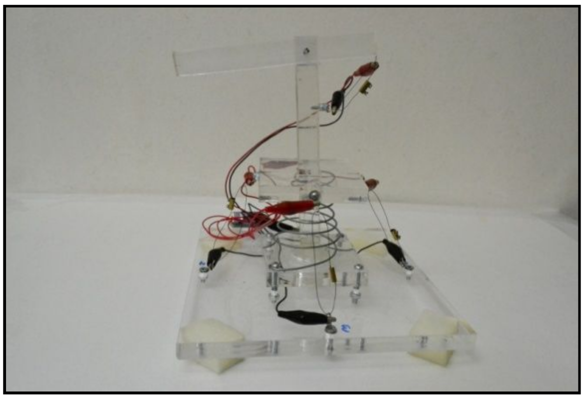


Figure 12: The full image of the prototype.

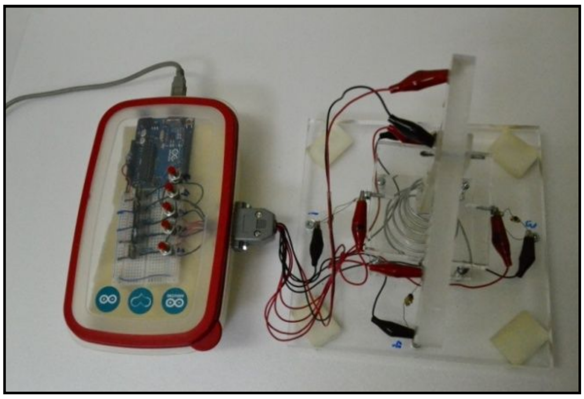


Figure 13: The prototype connected with the controller box.

4.1.2 SMA Actuator

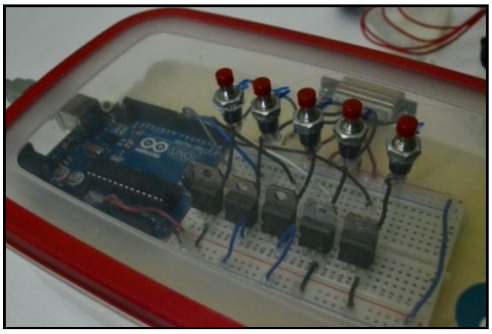


Figure 14: Close up view of the controller box with the Arduino board and the transistor circuit inside. The push buttons above is used to control the signal manually.

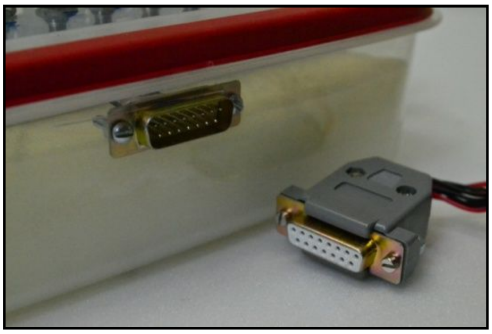


Figure 15: 15 pins connector is used to connect the controller with the actuators

In this research, an SMA wire with diameter of 0.015 inches. is chosen. The design of the actuator as in Figure 16 is a piece of SMA wire, looped together to make an ellipse and anchored at both ends with metal crimps. The actuator is designed to be simple and efficient. Since the SMA wire can provide force unilaterally, therefore a spring is needed to provide bias force and thus allowing the actuator to provide force bilaterally. In the design, the spring is attached in the middle around the first link, and the SMA wire is mechanically attached using crimps to the base and the platform which connects it to the first link. The design has several advantages such as; the SMA wire is suspended freely without any obstruction, thus will further simplify the design.

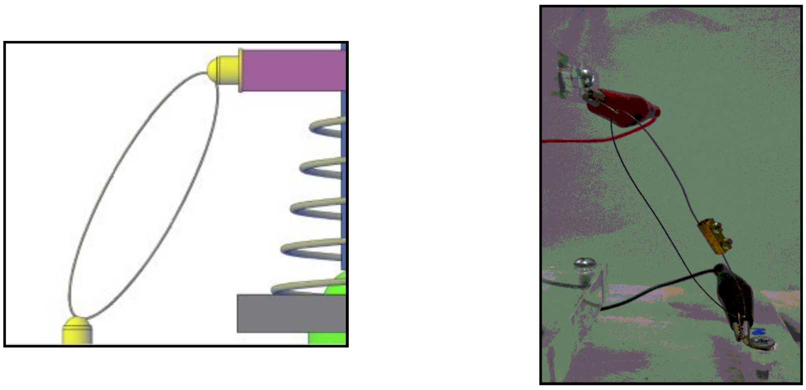


Figure 16: SMA wire attachment to the prototype and the actual image of the actuator with the connectors attached at both ends.

4.2 Controller Circuit

Although the Arduino board is a versatile controller, due to its low current output around 50 mA, it cannot be used directly to provide current to the SMA wire. An additional circuit were made using a TIP120 transistor. The transistor circuit diagram can be referred in Figure 17. By using the transistor, enough current output can be produced to heat the SMA wires. The current provided to the SMA wire is directly from the power source and the output signal from Arduino is used solely to activate the transistor.

The transistor is used as an electronic switch to control another circuit with higher current and voltage output by using the Arduino circuit.

Basically, a transistor has three pins: Collector, Emitter and Base. In this circuit, Arduino output pin is connected to the Base pin, one end of the SMA wire is connected to the power source and the other end is connected to the Collector pin, the Emitter pin is connected to the ground to complete the circuit.

With this arrangement, whenever the Arduino is programmed to send high output to the transistor, it will switches and allows current to flow through the SMA wire and completed the circuit.

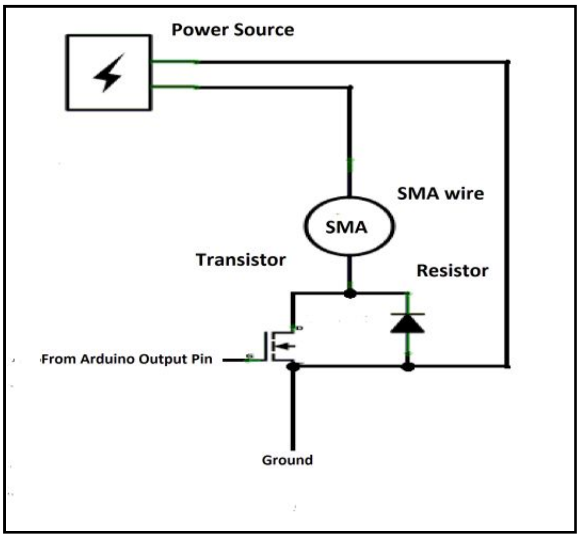


Figure17: Circuit diagram for the transistor circuit.

Five transistor circuits are needed since there are five SMA wire actuators, each transistor circuit for each actuator. A 100 kΩ resister was also used, attached in between Arduino output pin and the transistor Base pin to protect the Arduino board. To provide the power source, an AC-DC adaptor with voltage output ranging from 1.5 to 12 V and maximum current output of 1.0 A was used and connected to the Arduino board. Figure 18 shows the complete transistor circuits connected to the Arduino board.

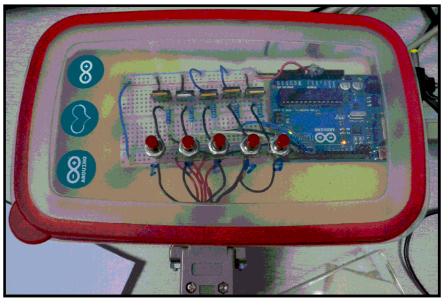
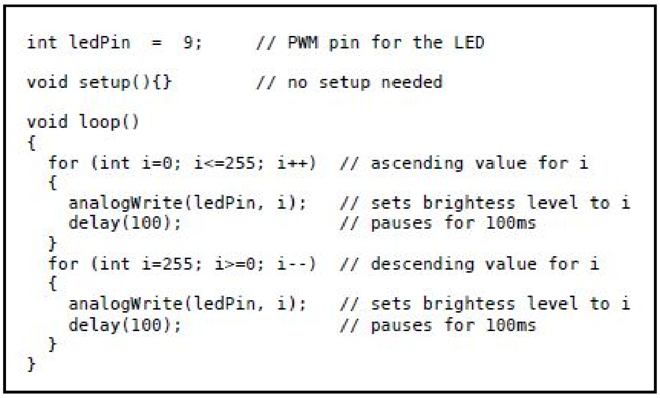


Figure18: Completed controller circuit for the SMA actuators.

4.3 Arduino Uno Programming Code

To control the SMA actuators, the concept of motor controller is used which is a PWM. Arduino can produce fake analog output from a digital output by pulsating the output itself. Figure 19 is an example of programming code to slowly brighten and dims LEDs using loop function. (Evans, 2007)

In the case of SMA actuators controller, there are five actuators thus five output will be required. The code can be programmed to generate pulse according to specific times. Furthermore the sequence of pulse output between each actuator can be preprogrammed in order for the manipulator to perform desired movements. Below is the coding for PWM generation using Arduino (Evans, 2007).



```
int ledPin  =  9;     // PWM pin for the LED

void setup(){}        // no setup needed

void loop()
{
  for (int i=0; i<=255; i++)  // ascending value for i
  {
    analogWrite(ledPin, i);   // sets brightess level to i
    delay(100);               // pauses for 100ms
  }
  for (int i=255; i>=0; i--)  // descending value for i
  {
    analogWrite(ledPin, i);   // sets brightess level to i
    delay(100);               // pauses for 100ms
  }
}
```

Figure19: Example of Arduino codes to generate PWM.

Basically, Arduino programs can be divided into three main parts: structure, values (variables and constants), and functions. Since there are 5 actuators to be controlled, there will be 5 output pins. Each pin is programmed to produce highest output. The capability to receive programme makes Arduino a flexible microcontroller board. The board can be programmed to produce digital or analog (PWM) output. For digital output, the *digitalWrite()* command is used whereas to produce PWM output *analogWrite(*) command is used. However not all output pins are capable of generating analog output. Thus, in the command code, correct pin must be assigned. Figure 20 is an example of the codes to produce digital output:

```
const int transistorPin1 = 2;
const int transistorPin2 = 3;
const int transistorPin3 = 4;
const int transistorPin4 = 5;
const int transistorPin5 = 6;

// connected to the base of the transistor

void setup() {
// set  the transistor pin as output:
pinMode(transistorPin1, OUTPUT);
pinMode(transistorPin2, OUTPUT);
pinMode(transistorPin3, OUTPUT);
pinMode(transistorPin4, OUTPUT);
pinMode(transistorPin5, OUTPUT);
}
void loop() {
digitalWrite(transistorPin1, HIGH);
digitalWrite(transistorPin2, HIGH);
digitalWrite(transistorPin3, HIGH);
digitalWrite(transistorPin4, HIGH);
digitalWrite(transistorPin5, HIGH);
}
```

Figure 20: Example of programming code to produce digital signal.

4.4 Actuator Performance

When the actuator is activated, the SMA wire will shorten and will return to its original state when it is deactivated. Since there are four actuators connected to the first link, it will enable the link to tilt along the X and Y axis. The one actuator attached to both the first link and second link will control the second link motion.

In order to analyse the actuator performance, an experiment was conducted. In this experiment, the actuator links of the finished prototype is used and the control strategy as discussed above is applied. The initial actuator length is recorded as 40 mm which is the length from the first anchored point to second anchored point for the SMA wire actuator. The power source is connected to the Arduino board, and the relationship between the voltage supplied and contraction length and time is observed. The voltage values are depends on the type of power source used, in this case, the AC-DC adapter can only provide voltage value as stated in the Table 7. The contraction time is started when the switch is pushed and stopped, the moment the actuator stop contracting and measured using stopwatch**.** For the contraction time, three values where obtained for each voltage and the average is calculated to ensure the data is reliable. In measuring the contraction length, a ruler were used, and measured manually. For the contraction when 1.5 V is applied, the value is slightly lower due to the human error factor.

Table 7: Table showing results on the performance analysis of the actuator.

Voltage (V)	**Contraction (mm)**	**Contraction Percentage (%)**	**Contraction time(s)**			
			1	2	3	Ave.
1.5	4	10	7.81	8.29	7.22	7.77
3.0	5	12.5	4.86	5.08	5.66	5.20
4.5	5	12.5	3.10	4.25	4.54	3.96
6.0	5	12.5	3.85	4.30	3.66	3.94
7.5	5	12.5	3.69	3.78	3.77	3.75
9.0	5	12.5	3.39	3.32	3.55	3.42
12.0	5	12.5	3.11	2.81	2.85	2.92

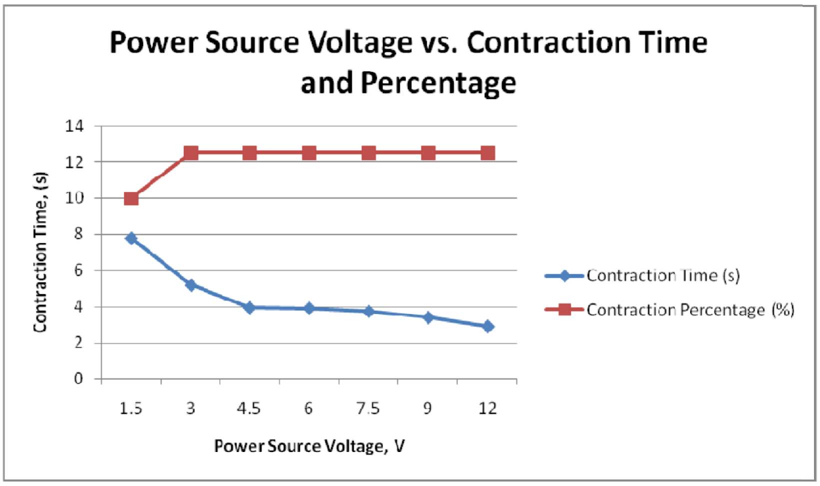
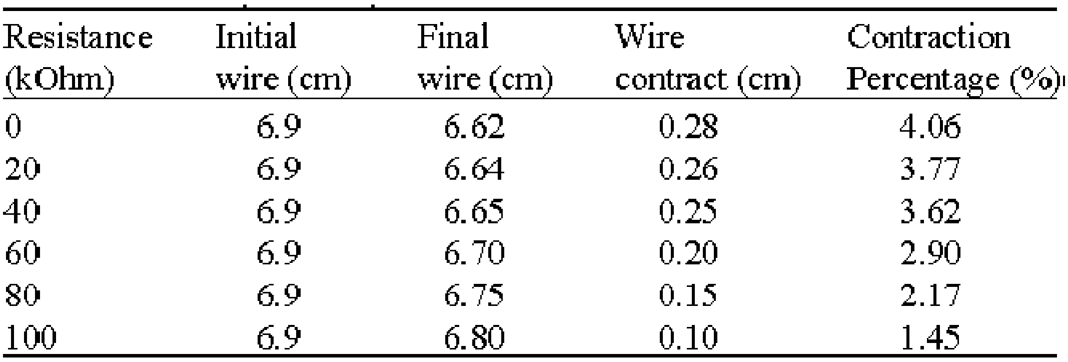


Figure 21: Graph showing the SMA actuator performance against various values of supply voltage.

From Figure 21, it can be concluded that the percentage contraction of each SMA wire are not dependable on the voltage supplies. However, the contraction time is affected by the voltage supply. As the voltage value increased, the contraction time increased, which means a higher voltage will results in faster contraction time. In applying higher voltage in SMA wire, care must be considered as SMA wire voltage limit should not be exceeded. For the 0.015 in SMA wire used in this experiment, an ideal voltage supply is in the range of 7 V to 12 V. Excessive voltage might results in burning out of the SMA wire itself.

Table 8: Results of actuator performance experiment by Abdul Malik (2011).



Resistance (kOhm)	Initial wire (cm)	Final wire (cm)	Wire contract (cm)	Contraction Percentage (%)
0	6.9	6.62	0.28	4.06
20	6.9	6.64	0.26	3.77
40	6.9	6.65	0.25	3.62
60	6.9	6.70	0.20	2.90
80	6.9	6.75	0.15	2.17
100	6.9	6.80	0.10	1.45

From Table 8, an experiment was conducted by Abdul Malik (2011) where an SMA wire was also used as an actuator. We can see that the highest contraction percentage is 4.06 % which is when the circuit resistance is set to 0 Ohm, whereas in the previous experiment, the contraction percentage is 12.5 %. It shows that when the SMA wire is use while in tension, the contraction is smaller compared to a condition without any tension. This can be explained due to the changes in crystalline structure. When the SMA wire is stretched, there is only limited room for the crystalline structure to rearrange themselves due to being stretched, thus resulting in less contraction. However, when the SMA wire is let loose and not being stretched, the crystalline structure have greater room to rearrange.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

The objective of this project is to design, fabricate develop control strategy, and analyse a 3-DOF parallel manipulator using an SMA wire as an actuator. The prototype was successfully fabricated and, the application of the SMA wire to actuate the manipulator is achieved. As the control strategy, Arduino programmable board was chosen as the controller due to its capability to generate various signals and to perform multiple functions. To analyse the actuator performance, an experiment was conducted to assess the capability of proposed actuator design. It is observed that the proposed actuator design is capable in producing more contraction compared to actuator design in the previous work.

For future work, further function of the controller should be studied. Instead of only output generation, input function should be applied too, such as, application of thermocouple in controlling the circuit, thus avoiding overheating of the SMA wire. Further study on the design of the actuator should also be conducted to achieve highly efficient actuator.

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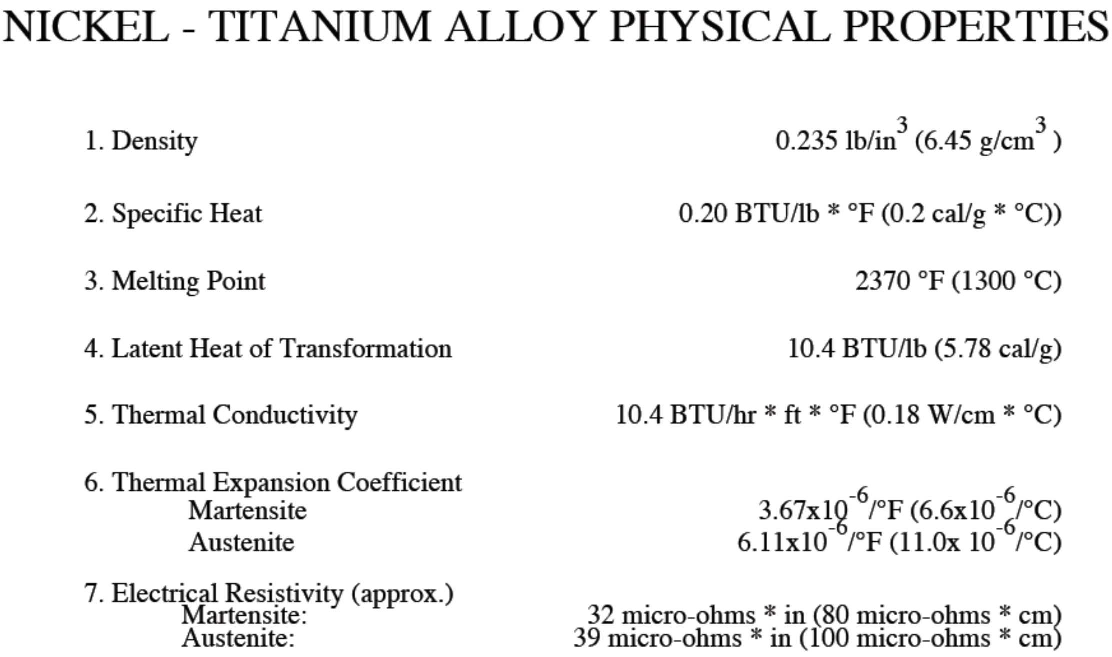
APPENDIX 1

Nickel Titanium Alloy Properties



NICKEL - TITANIUM ALLOY PHYSICAL PROPERTIES

1. Density	0.235 lb/in^3 (6.45 g/cm^3)
2. Specific Heat	0.20 BTU/lb * °F (0.2 cal/g * °C))
3. Melting Point	2370 °F (1300 °C)
4. Latent Heat of Transformation	10.4 BTU/lb (5.78 cal/g)
5. Thermal Conductivity	10.4 BTU/hr * ft * °F (0.18 W/cm * °C)
6. Thermal Expansion Coefficient	
Martensite	3.67×10^{-6}/°F (6.6×10^{-6}/°C)
Austenite	6.11×10^{-6}/°F (11.0×10^{-6}/°C)
7. Electrical Resistivity (approx.)	
Martensite:	32 micro-ohms * in (80 micro-ohms * cm)
Austenite:	39 micro-ohms * in (100 micro-ohms * cm)

APPENDIX 2

Temperature vs. Strain Characteristic for Dynalloy.

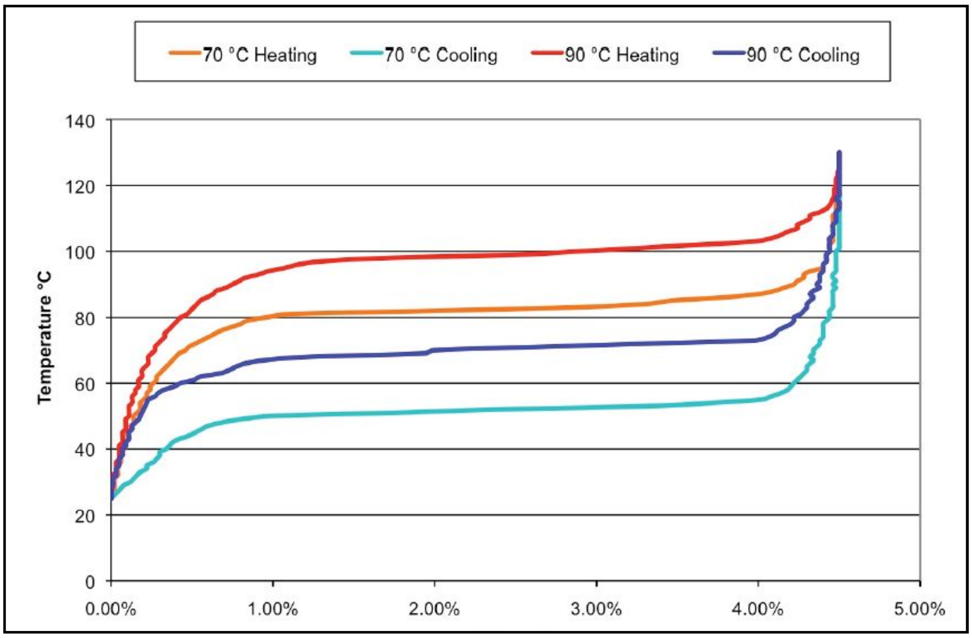


Figure 22: Typical Temperature vs. Strain Characteristics for Dynalloy’s standard 158°F (70°C)

APPENDIX 3

Detail CAD Drawings.

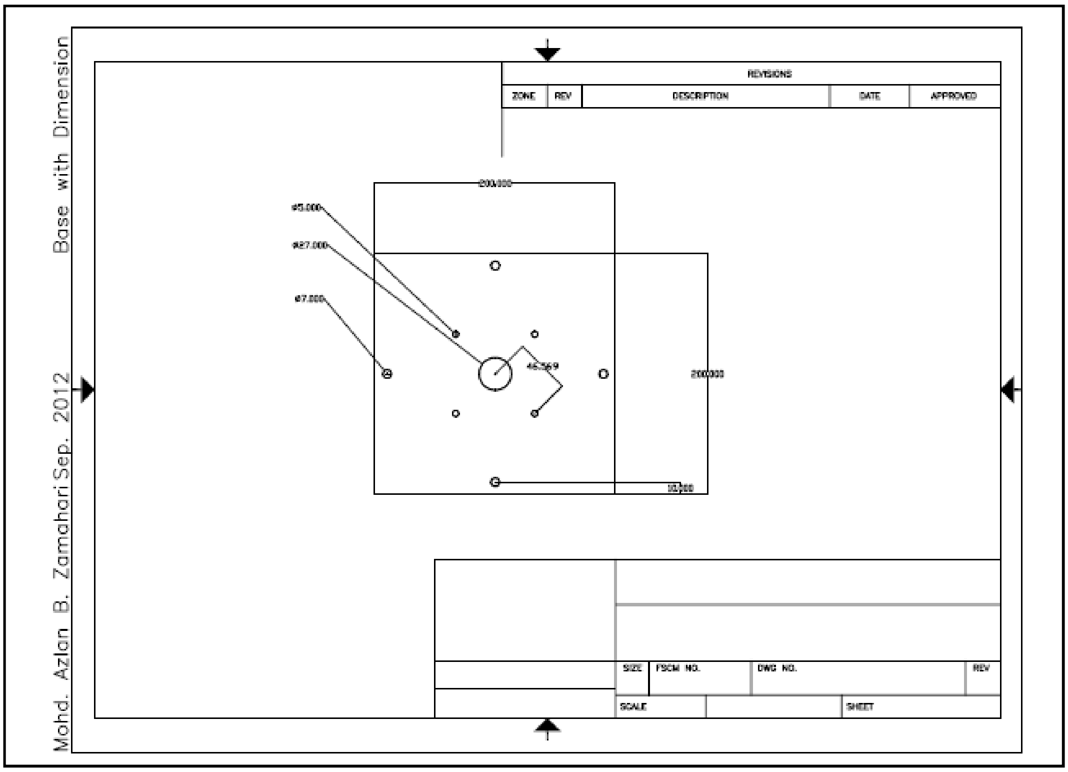


Figure 23: Top view of the Base with dimension.

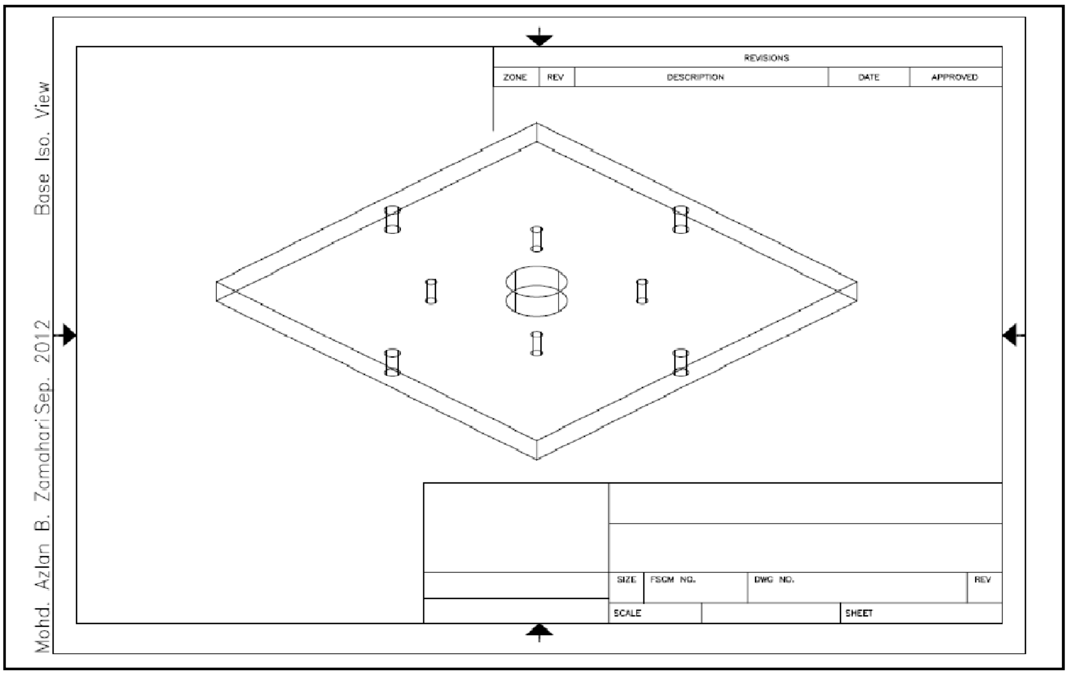


Figure 24: Isometric view of the Base.

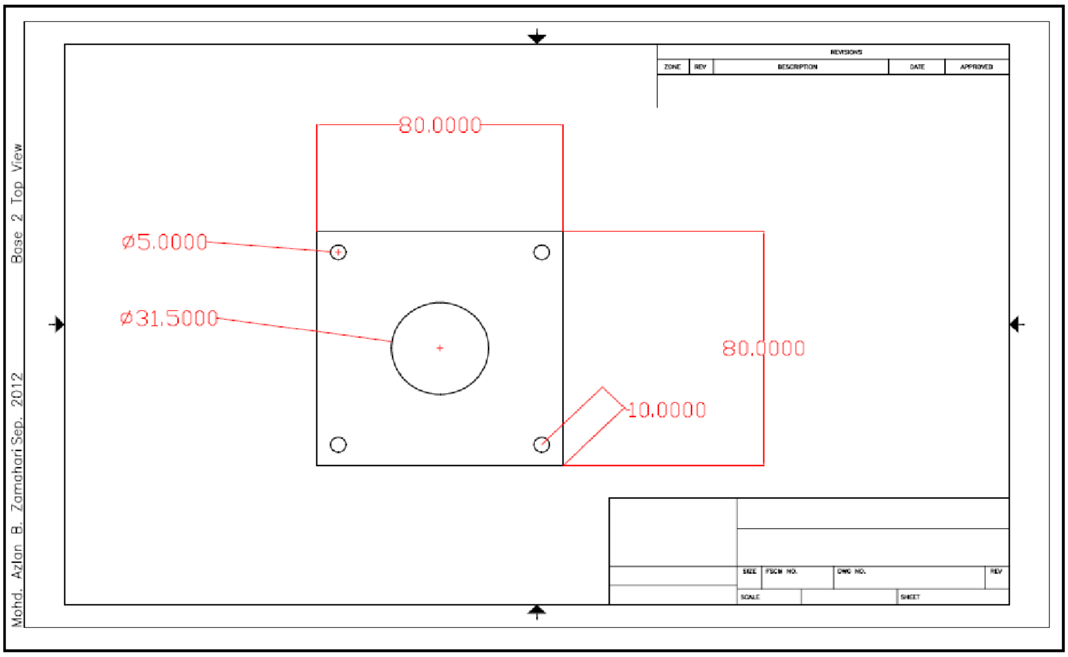


Figure 25: Top view of the Base 2 with dimension.

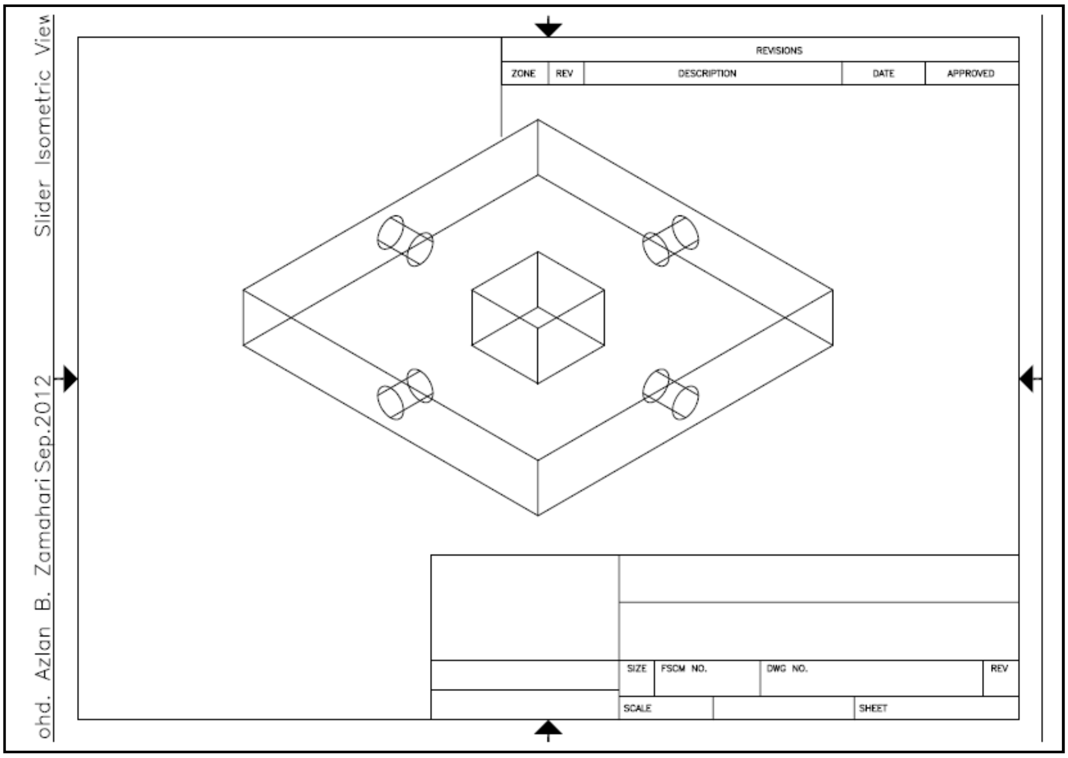


Figure 26: Isometric view of the Slider part.

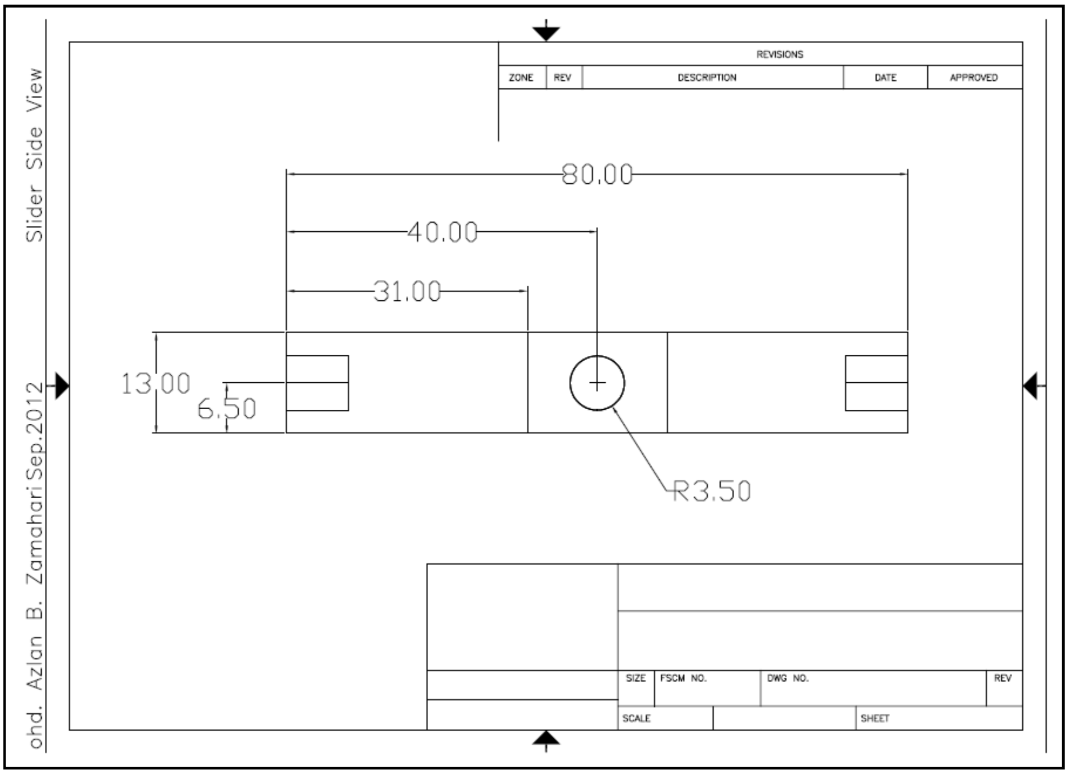


Figure 27: Side view of the Slider part with dimension.

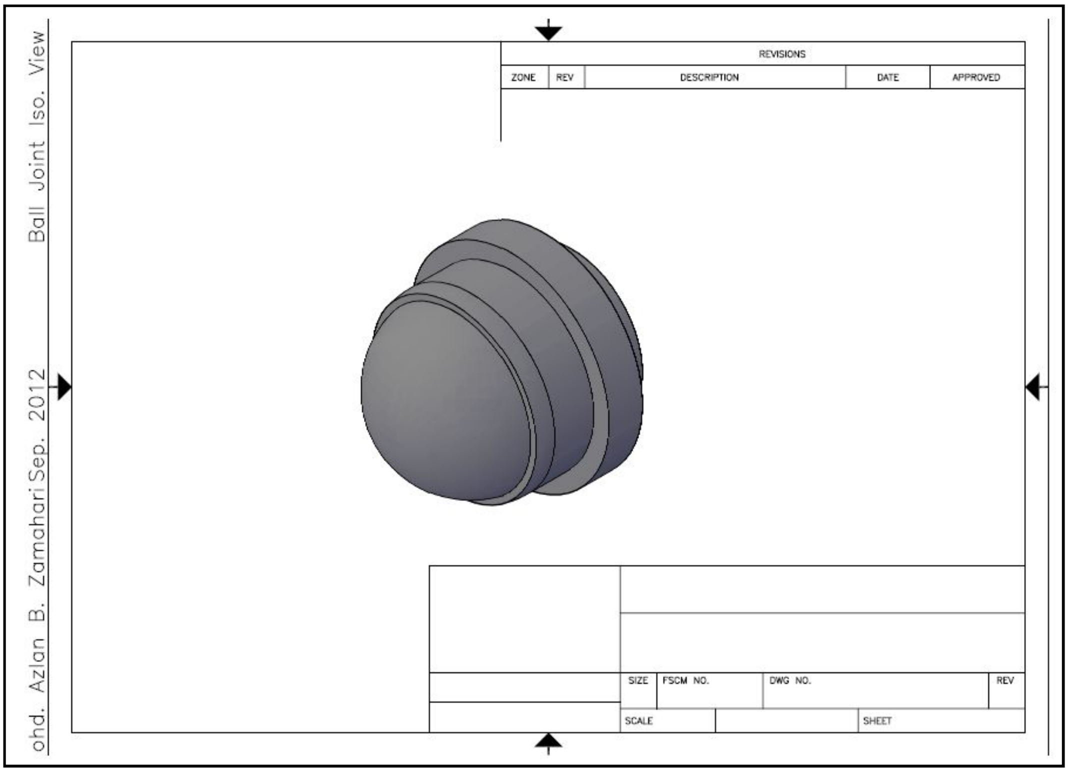


Figure 28: Isometric view of the Ball joint part.

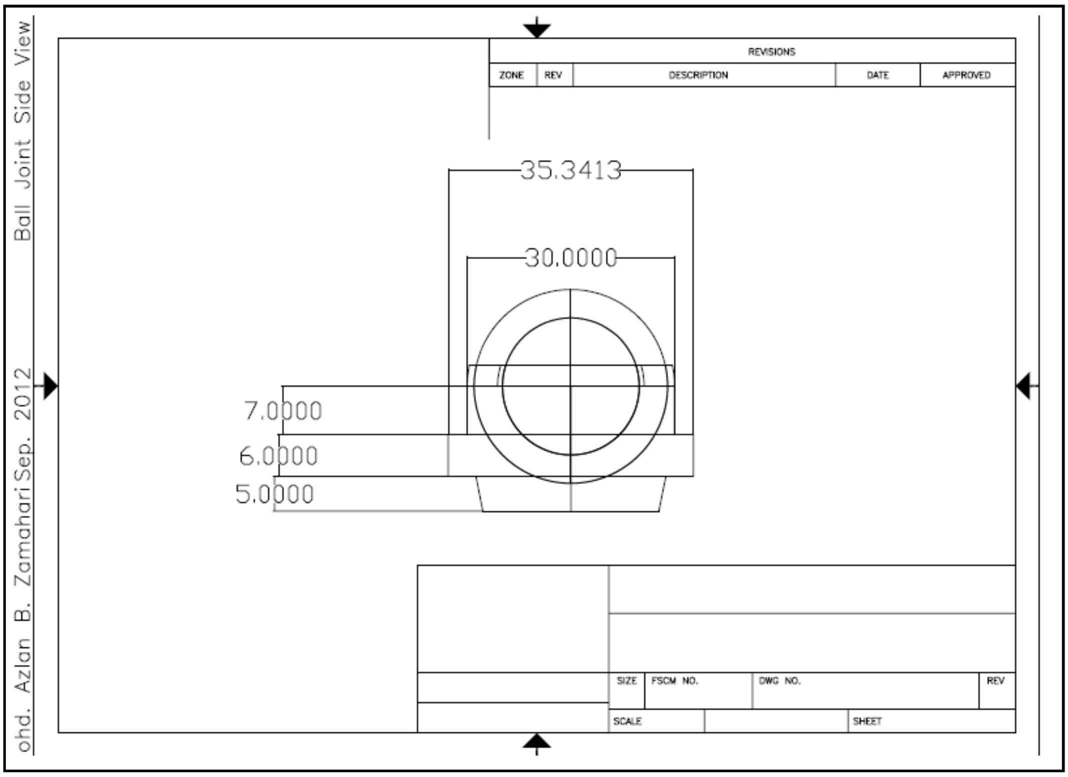


Figure 29: Side view of the Ball joint part with dimension.

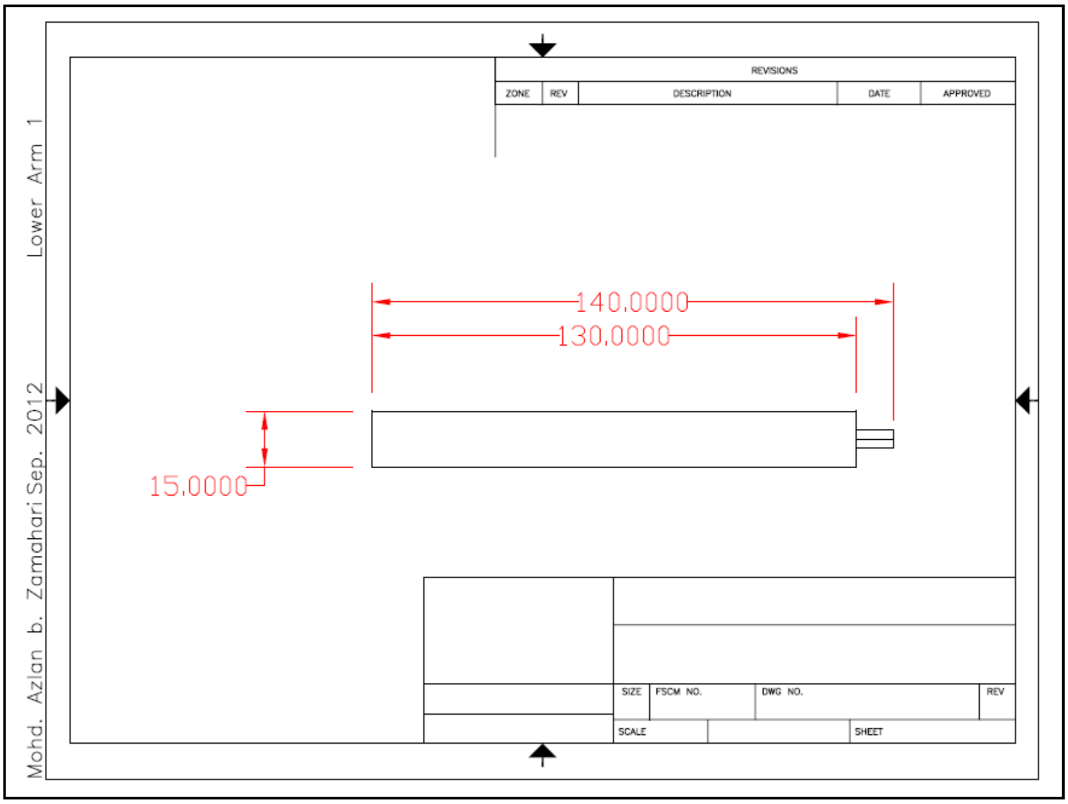


Figure 30: Side view of the Lower Arm 1 part with dimension.

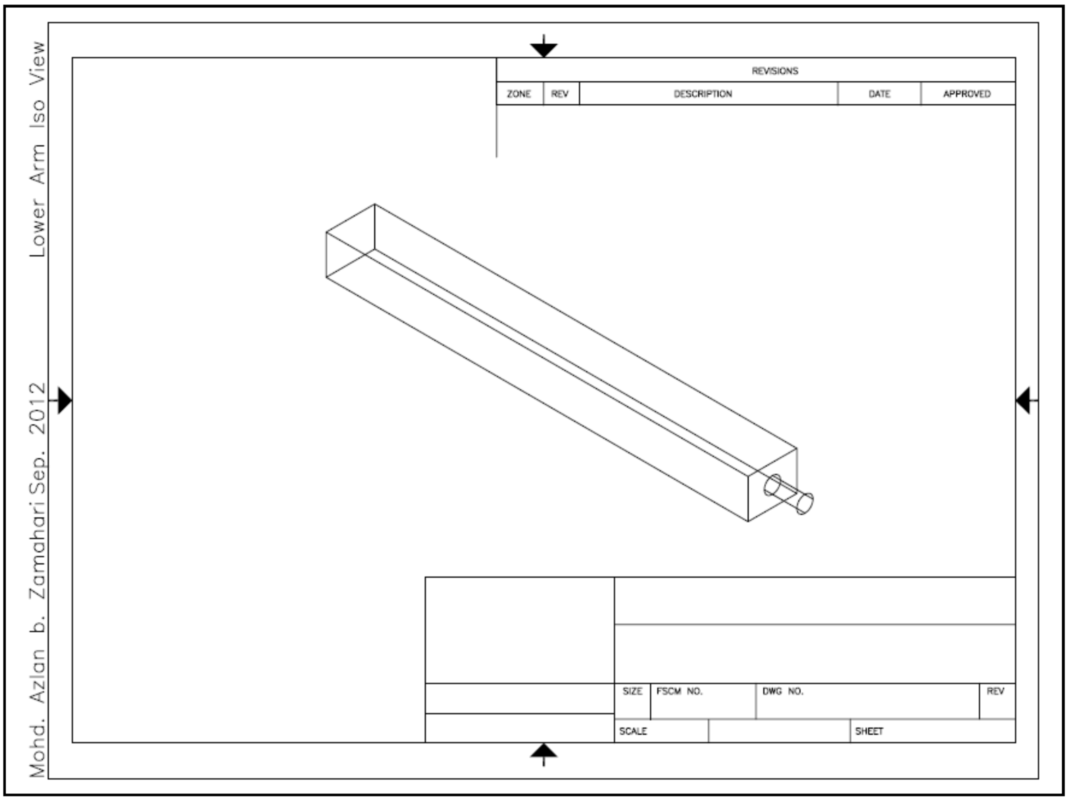


Figure 31: Isometric view f the Lower Arm 1 part.

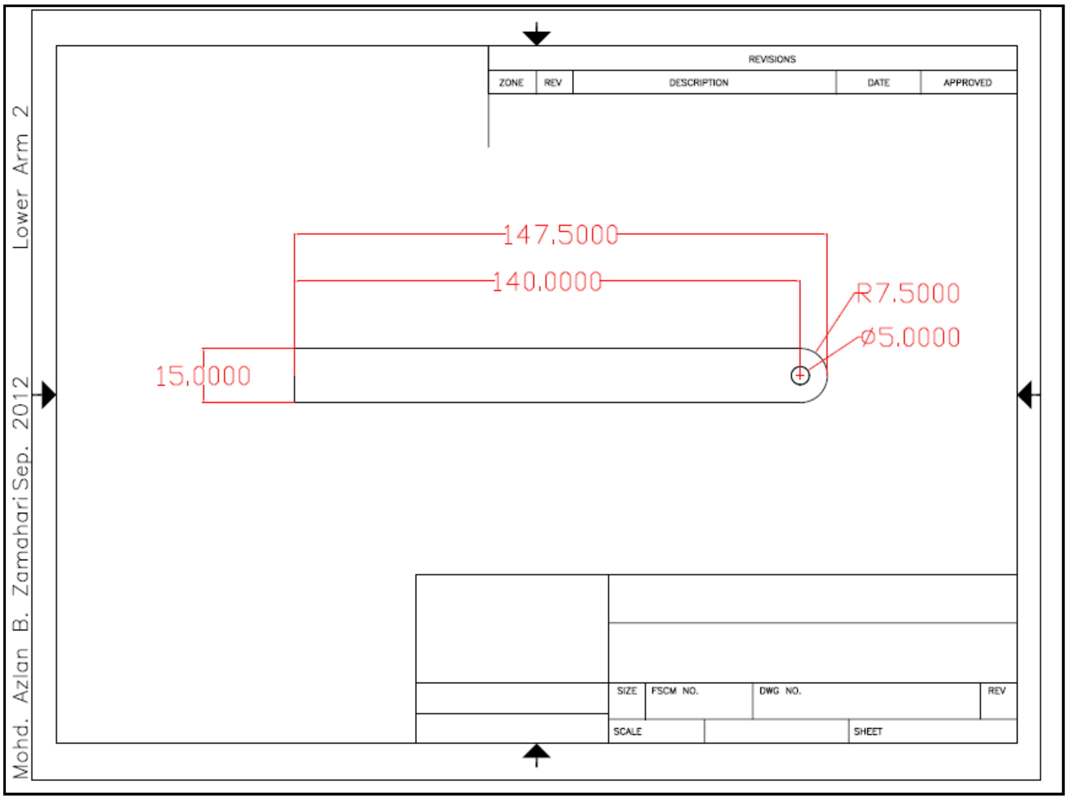


Figure 32: Side view of Lower Arm 2 part with dimension.

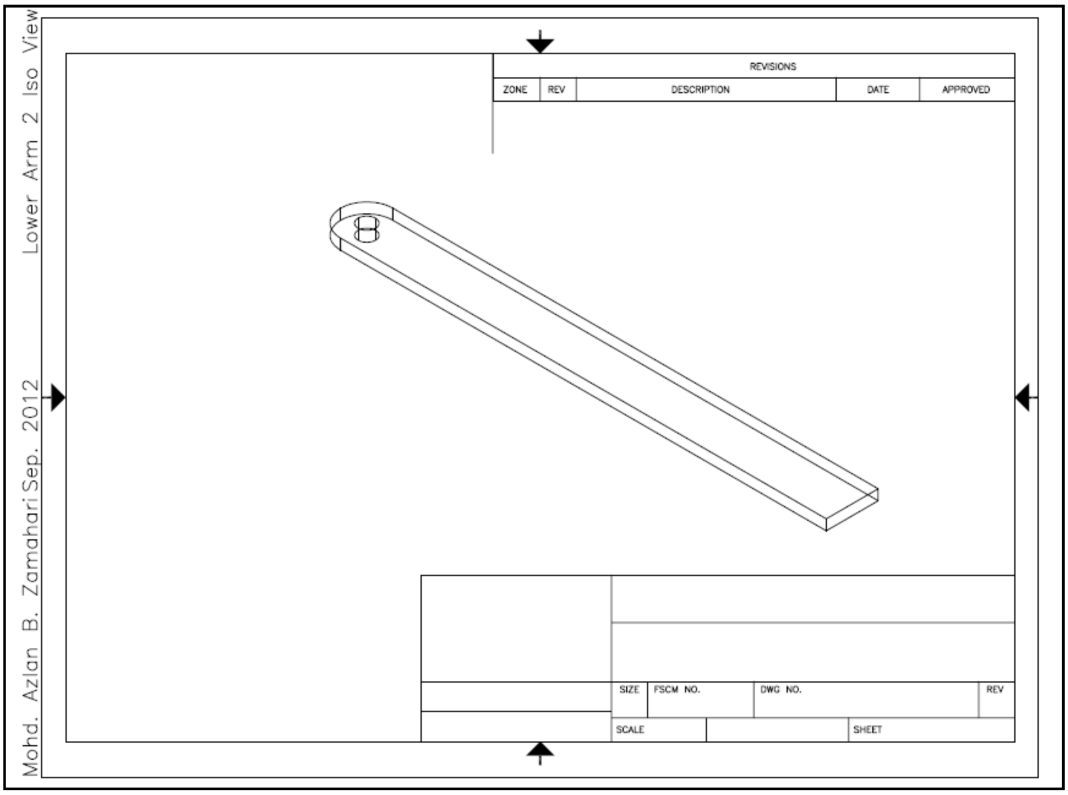


Figure 33: Isometric view of Lower Arm 2 part.

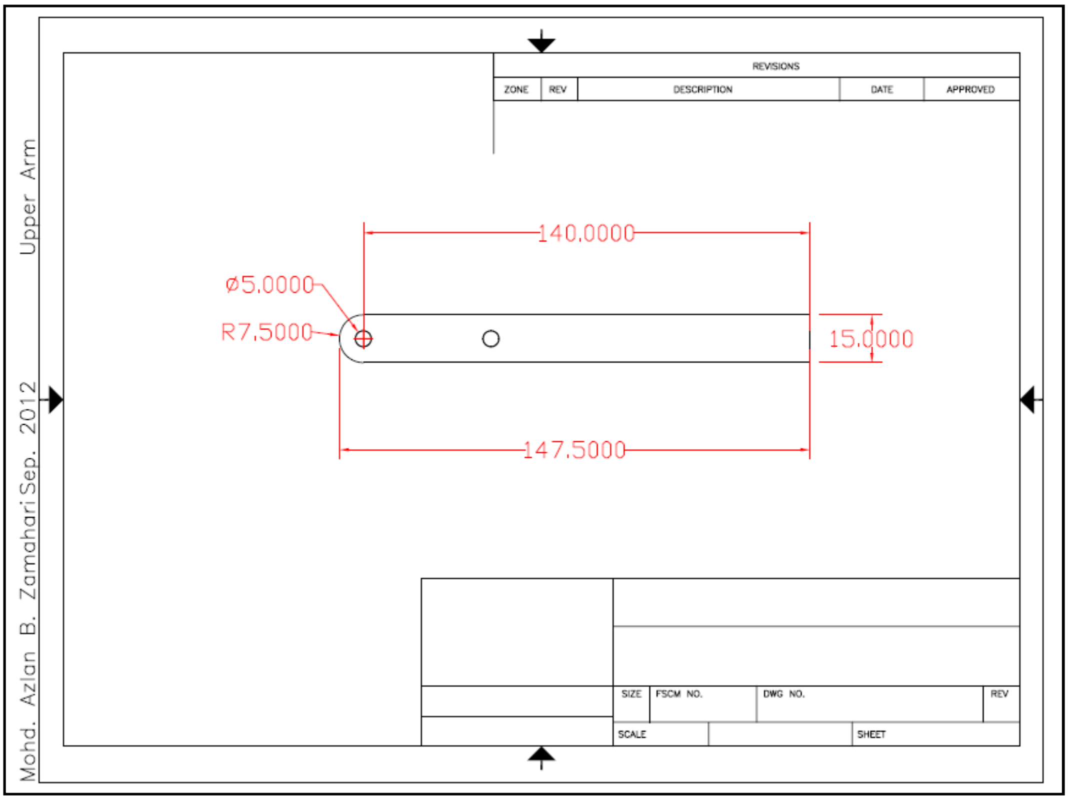


Figure 34: Side view of Upper Arm part with dimension.

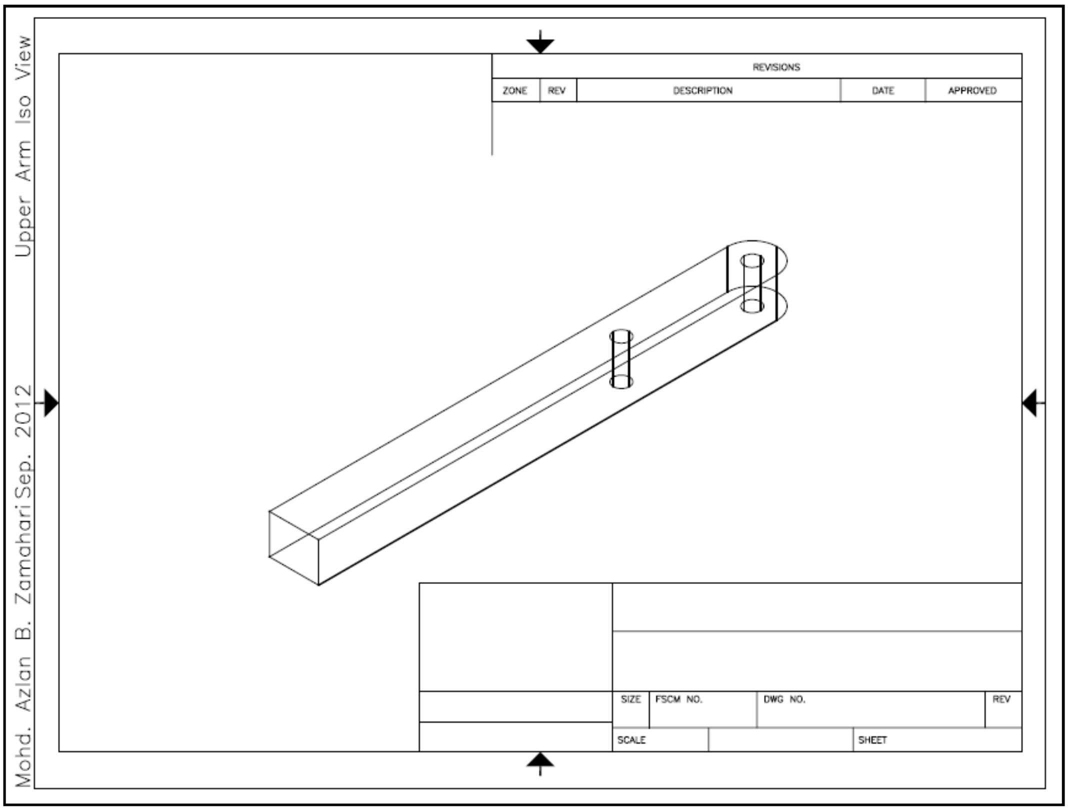


Figure 35: Isometric view of Upper Arm part.

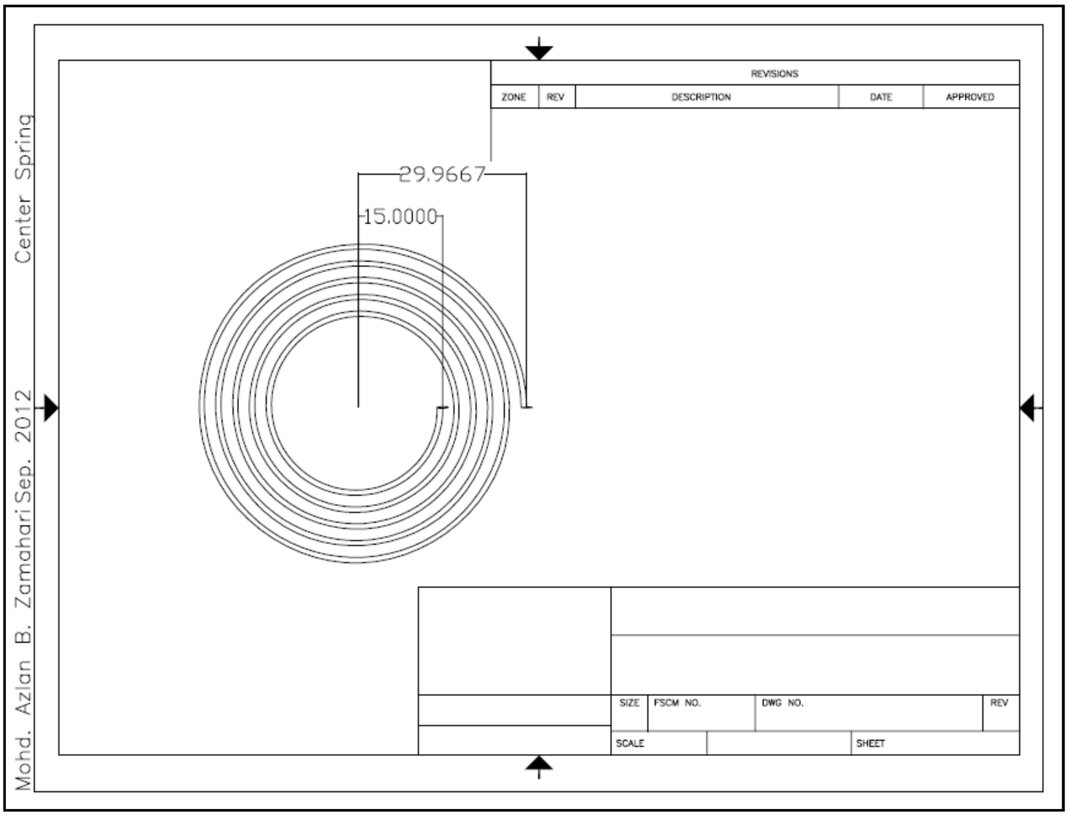


Figure 36: Top view of the spring with dimension.

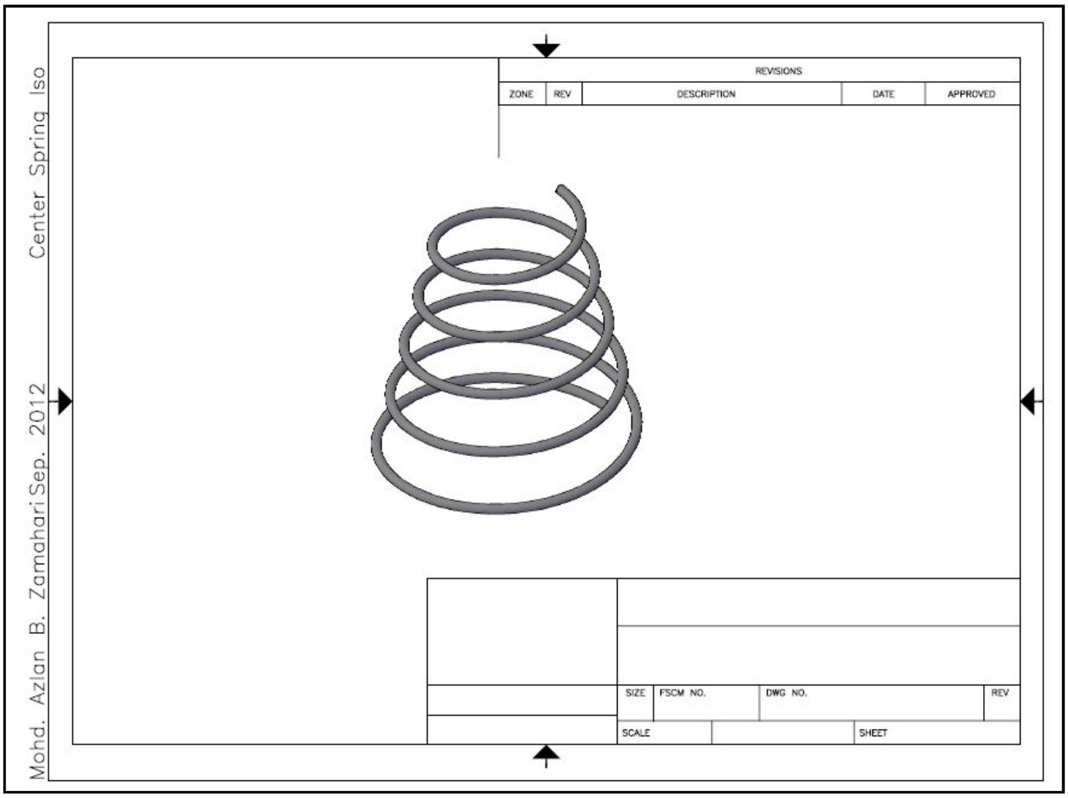


Figure 37: Isometric view of the spring.