

**DESIGN AND DEVELOPMENT OF SHAPE MEMORY
ALLOY BASED NOVEL ACTUATORS FOR
MINIMALLY INVASIVE SURGERIES**

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Degree of Master of Philosophy

Department of Mechanical Engineering

University of Moratuwa

Sri Lanka

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**Thesis submitted in partial fulfillment of the requirements for the degree of
Master of Philosophy in Mechanical Engineering**

Department of Mechanical Engineering

**University of Moratuwa
Sri Lanka**

January 2022

DECLARATION

I declare that this is my work, and this dissertation does not incorporate without acknowledgment of any material previously submitted for a Degree or Diploma in any other Universities or institutes of higher learning and to the best of my knowledge and believe it does not contain any material previously published or written by another person except where the acknowledgment is made in the text.

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Prof. Y.W.R. Amarasinghe

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ABSTRACT

This work relates to the design and development of Shape Memory Alloy (SMA) based novel actuators for Minimally Invasive Surgeries (MIS). Compared to conventional open surgery, MIS procedures are favorable and developments are possible towards improving the effectiveness of MIS. Handheld slender instruments used in MIS are with limited degrees of freedom achieved using conventional actuation mechanisms which possess disadvantages in handling, durability, and cost.

In this study, an SMA-based approach was considered to improve the operation of an MIS tool effectively. The complex behaviour of SMA led to the investigation of material behaviour before the application-oriented study. SMAs are smart alloys that are capable of remembering a parent shape according to the heat treatment (HT) temperature and aging time providing unique activation temperatures. Commercially available binary SMA material that is known as NiTiNOL was used for the study. NiTiNOL was subjected to different HT conditions and Differential Scanning Calorimetric (DSC) analysis was performed on the resulting material to obtain transformation temperatures. Test results demonstrated the ability to alter activation temperature by varying the HT conditions. Also, the samples were observed under an Optical Microscope (OM) and Scanning Electron Microscope (SEM) to identify morphology and elemental composition by Energy Dispersive X-Ray Spectroscopy (EDX) respectively. Furthermore, an SMA spring actuator element was fabricated using a NiTiNOL wire through a novel fixture to obtain desired spring parameters and geometry. NiTiNOL wire was held in the fixture undergoing a HT at experimented temperatures and aging times. Then, spring actuators were characterized based on maximum attainable force using a specially developed apparatus. A customizable hardware controller and a software interface were developed to set values, monitor temperature, and force output. Using the mentioned apparatus, the controller was validated in both temperature and force feedback controlling modes based on a Proportional-Integral-Derivative (PID) type controller.

Two linear actuators were designed and developed using the characterized spring element. Firstly, an actuator was developed based on external heating using a heated fluid and cooled fluid to heat and cool the spring element, respectively. A novel actuator structure was developed to facilitate the spring element with leak-proof assembly and was used as the drive source of a gripper mechanism. Strain gauge-based force sensing and PID-based force feedback controlling methods were introduced to the gripper assembly. The second approach was utilizing a Joule heating-based method for activation which the passing current generates heat due to the inherent resistance of NiTiNOL resulting in an increment in temperature. The

actuator was characterized in terms of stroke and then introduced to a laparoscopic retractor application to control the flexion-extension motion. A specially developed apparatus and a software interface are used to control parameters and acquire data. Finally, the retractor tool was characterized in terms of stroke.

Key Words: Shape Memory Alloy; Minimally Invasive Surgeries; Differential Scanning Calorimetry; PID Controlling; SMA Spring Actuated Gripper; Laparoscopic Retractor; External Heating; Joule Heating

DEDICATION

I dedicate this dissertation work to my family and my teachers. A special feeling of gratitude to my loving parents, Mr. Rathnasena and Mrs. Malani Weerasooriya and my loving wife Mrs. Thilini de Silva, and my lovely daughter Miheli Aryana, whose words of encouragement and push for tenacity ring in my ears. Finally, I'm grateful for my fellow Sri Lankan citizens who are paying taxes to sustain free education unconditionally.

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LIST OF ABBREVIATIONS

Abbreviation	Description
ADC	Analogue to Digital Converter
ALM	Applied Loading Method
CAD	Computer Aided Design
CCD	Charged Couple Discharge
DAQ	Data Acquisition
DOF	Degree of Freedom
DSC	Differential Scanning Calorimetry
EDX	Energy-Dispersive X-ray
ERM	Electrical Resistance Method
FEA	Finite Element Analysis
FET	Field Effect Transistor
GUI	Graphical User Interface
HTSMA	High Temperature Shape Memory Alloys
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LED	Light Emitting Diode
LIFA	LabVIEW Interface For Arduino
MBD	Multi Body Dynamics
MEMS	Micro Electromechanical Systems
MIS	Minimally Invasive Surgeries
MSMA	Magnetic Shape Memory Alloys
NiTiNOL	Nickel Titanium Naval Ordnance Laboratory

OM	Optical Microscopy
OWSME	One Way Shape Memory Effect
PD	Proportional Derivative
PE	Pseudo Elasticity
PID	Proportional Integral Derivative
PMMA	Poly Methyl Methacrylate
PWM	Pulse Width Modulation
SEM	Scanning Electron Microscope
SMA	Shape Memory Alloy
SME	Shape Memory Effect
SMM	Shape Memory Material
SMP	Shape Memory Polymers
SPS	Samples Per Second
TWSME	Two Way Shape Memory Effect
USB	Universal Serial Bus
VAR	Vacuum consumable Arc
VB	Visual Basic
VGC	Variable Geometry Chevron
VIM	Vacuum Induction Melting
VISA	Virtual Instrument Software Architecture

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Minimally invasive surgery (MIS) provides many advantages to the patients such as minimized surgical trauma, reduced wound complications, shorter hospital stay, and accelerated recovery compared with conventional open surgery. MIS performs within a close space through small access entries of 5-15 mm in size while the surgeon's hands are outside the operative field, and surgical manipulations are performed remotely under visual feedback of a monitor screen. So a loss of tactile feedback, restricted maneuverability and less efficient control of major bleeding could occur in such a procedure. There are several MIS procedures available and one of the main procedures which are known as Laparoscopic surgery is considered in this research and includes operations within the abdominal or pelvic cavities. In such operative procedures, only 4 degrees of freedom are available to surgeons because of the long and slender instruments used. The ergonomics of instrument design is quite limited, and force-feedback is unavailable in manual operations apart from robot-assisted surgeries. A more reliable and predictable engineering approach needs to be there to avoid those difficulties in Laparoscopic surgeries. Most of the Laparoscopic tools consist of miniaturized actuation techniques and in this research, one of the emerging actuator types which can be miniaturized while maintaining the required energy density for the actuation task is considered. The selected actuator type is based on a special material known as Shape Memory Alloy (SMA).

Shape Memory Alloys are a subcategory of Shape Memory Materials (SMMs), which can 'remember' its previous form under an external stimulation namely, thermo-mechanical or magnetic. At the present, there is a trend on SMA applications in Macro (or Miniature) and Micro scales due to their unique properties. Since the key effects of SMA are the Shape memory effect (SME) and Pseudoelasticity, a wide range of applications is possible in many fields. NiTi-based SMAs (NiTiNOL) is much more preferable for MIS because of their excellent biocompatibility with low toxicity and corrosion resistance. Both super elastic and thermal recovery of SMA can provide large deformations and force for robust surgical devices for MIS. NiTiNOL is a non-

ferromagnetic SMA material and can be used as an actuation material for medical devices in MRI-guided surgeries. Devices made of Nitinol can be sterilized by autoclave. Laparoscopic surgery has been the most advanced method of MIS. So SMA-based tools can be purposely designed to overcome the limited degrees of freedom caused by the approach of minimal invasiveness and enable surgeons to achieve complex tasks.

So, the motivation is to use the properties of NiTiNOL SMA Material for the development of miniaturized actuators for Laparoscopic surgeries. Mainly the flexibility of SMA material provides customization of actuators for different applications in the field. In such a scenario novel actuators could be implemented to replace the existing complex actuation methods and simplify the mechanisms. The SMA-based actuation methods enable redefining the existing surgery tools and improve the working conditions. Also, high energy throughput per unit volume of SMA actuator material will reduce the weight of such handheld surgical tools.

1.2 Objectives and Contribution of the Research

The contribution of the research can be highlighted as the introduction of novel actuation methods which are developed using smart materials (SMA) for MIS surgical tools. The smart material actuation provides solutions for several issues related to existing tool manipulating mechanisms. The improved energy density of the actuation mechanism, reduction of weight, miniaturization capability are several motives in the selection of SMA as the actuation material to replace existing methods. The research introduces SMA-based actuation methods with novel kinematics for tools used in Laparoscopic surgeries and justifies the operation of a Laparoscopic tool through an experimental instrument. Following are the objectives intended to achieve during the research,

- Study on existing actuators for Laparoscopic surgeries and propose suitable dynamic models
- Mathematical modelling of proposed dynamic models and numerical analysis
- 3D modelling, simulation, and Multiphysics analysis of numerically analyzed models and justification
- Design and development of an instrument to prove the concept and validate it in a controlled environment

According to the above-mentioned first point, the existing actuators and their characteristics were studied and new kinematic models which are suitable for the SMA actuators were developed. Those kinematic models were studied in a detailed manner together with kinematic simulations. Secondly, those kinematic models were further analyzed by considering the forces and stress acting on the structures (dynamic modelling). Those dynamic models were simulated through software-based environments. Thirdly those models were incorporated with Finite Element Modelling software and performed Multiphysics analysis. With the details of the Multiphysics modelling the actual working model development was conducted and finally tested the equipment in a controlled environment.

So, the design and development process of the SMA-based novel actuators for the mentioned MIS application was carried out through a special engineering approach as the behaviour of the SMA material is unique. In the preliminary stage, a study had to be done in order to identify the material behaviour and the actuator force outputs. Then justified the developed actuator elements are in the domain of possible force and stroke generation which is compatible with the mentioned application area.

1.3 Methodology

The research was mainly focused on SMA-based novel actuators for MIS tools. The following key points can be taken as the main aspects that explain the concise version of the methodology.

- Conducting a Literature review on SMA, SMA based actuation technologies, MIS
- Study on SMA material to identify characteristics and adaptability to MIS application
- Design, development, and characterization of an SMA based novel actuator element that can satisfy the key requirements of MIS tools
- Integration of the SMA actuator element with a simple tool to validate the performance and controllability
- Redefine the actuation technology of an existing MIS tool by introducing developed SMA based actuation method and validation

1.4 Thesis Organization

Figure 1.1. shows the structure of this research thesis.

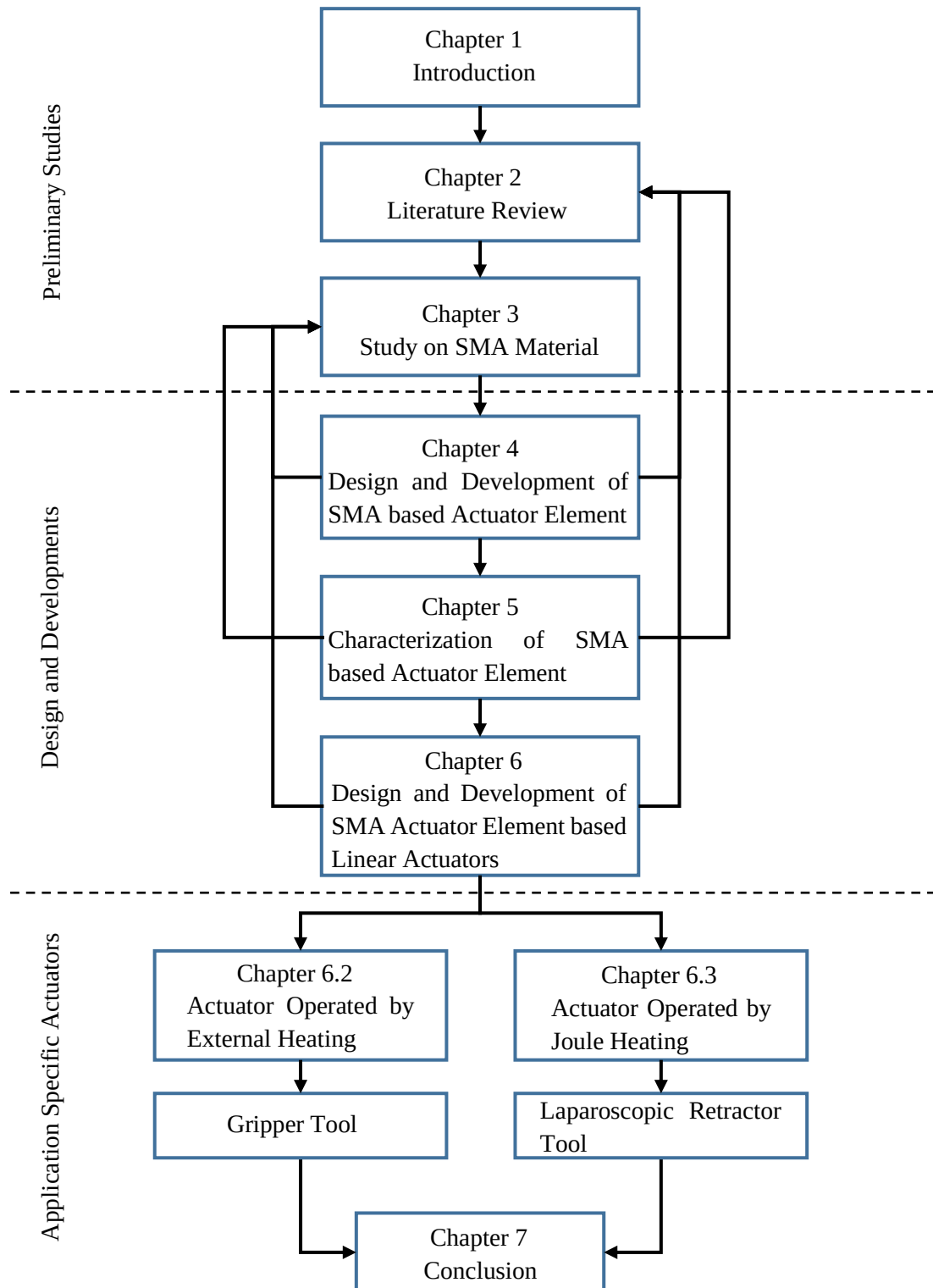


Figure 1.1: Thesis Outline

CHAPTER 2

LITERATURE REVIEW

2.1 Shape Memory Alloy

Shape Memory Alloy (SMA) is a metallic alloy combining at least two elements (binary SMA) in specific weight percentages. They can return to a previously set form (shape) when subjected to a memorization (training) process. The memorization is being done between two main transformation phases namely, Martensite and Austenite which are temperature or magnetic field dependent. The transformation phenomenon between these phases provides the necessary macroscopic changes to the material result in usable deformations and forces. The shape recovery process under external stimulation can be identified as the shape memory effect (SME). Depending upon the nature of the external stimulation, another special property known as Pseudo-elasticity (Super elasticity) can also be seen in this material. The operating principle of this material is fairly simple and identifiable, where the SMAs can easily change their shape by application of an external force and as the temperature of the material increases beyond a certain temperature margin, shape recovery happens to gain its original form. This phenomenon happens in temperature-activated SMA materials. The heating method can either be external heating or internal heating (Joule heating). Hysteresis effect can also be seen in these alloys, which is important in some applications.

2.1.1 History and Evolution of SMAs

The discovery of ‘smart alloy’ expands toward the 1930s with the discovery of phase transformation of cadmium - gold (Cd-Au) alloys by Arne Olander [1]. (Figure 2.1.) In the late 1930s, the observation of the Shape Memory Effect (SME) in copper-tin (Cu-Sn) and copper-zinc (Cu-Zn) alloys was done. One of the governing phenomena of SMAs could be identified as the thermo-elastic behaviour of the martensite phase. Many researchers did their studies related to the mentioned fact of SMA around the 1950s [2]. Nickel-titanium (NiTi) is the most important candidate among the SMA family, which is being used in many applications having many advantages.

The groundbreaking discovery was done by William Buehler in 1959 at Naval Ordnance Laboratory [3] and later named the material as NiTiNOL, which abbreviates the main elements and the place of discovery. The potential applications were started after revealing the SME in NiTiNOL material in 1962 by William Buehler and Frederick E. Wang [4]. The discovery of NiTiNOL and its properties led many researchers and industrial experts to simply find solutions for many complex problems. Many application areas were developed around this important discovery [5], [6]. Some of the discovered SMMs are shown in

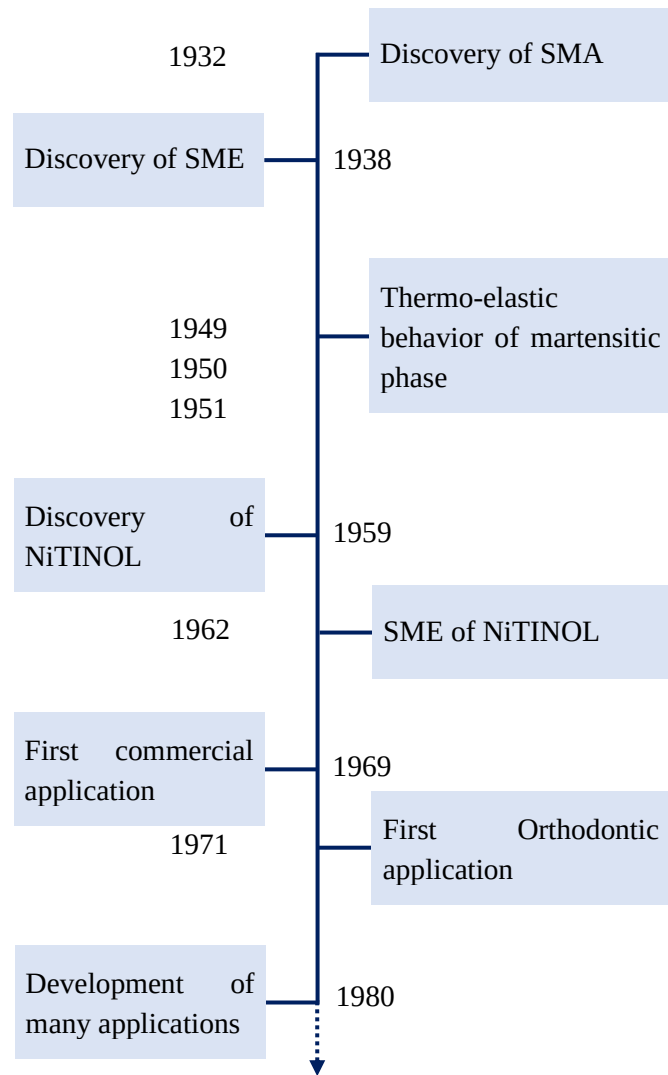


Figure 2.1: History of SMA

(Figure 2.2.). There are Binary, Ternary, and multiple element alloys were developed to exhibit SME under certain external stimulation. Phase-changing characteristics of these materials mainly depend on the composition. A slight change in the composition of the parent element or other elements may cause a recognizable change in the properties. Each of these Fe-based, Cu-based, and NiTi-based SMAs has unique advantages and disadvantages when comparing one another. As an example, FeMnSi exhibits high phase change temperature and hysteresis, which might cause limitations to the applications. Industrial application-related alloys were mainly based on Cu and NiTi. Cu-based SMAs mainly exhibit good resistance to higher temperatures but are poor in low temperatures. NiTi-based SMAs provide a wide area of promising applications in many emerging fields.

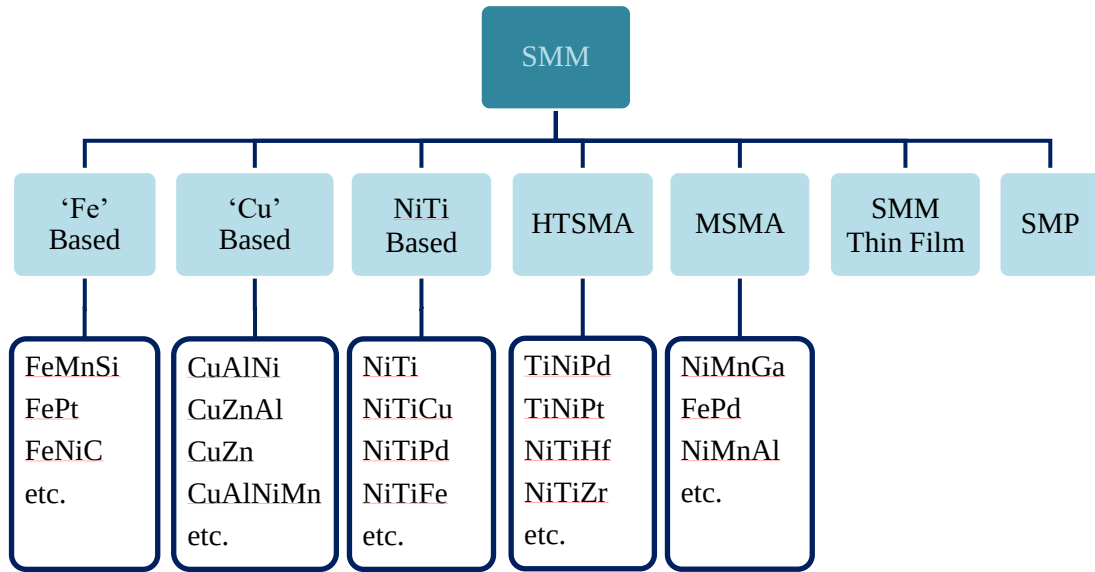


Figure 2.2: Types of SMM

One particular field could be identified as biomedical engineering, where the special property of biocompatibility of NiTi is needed. Scientists have developed SMAs operated in extreme high temperatures (HTSMA) and they are very difficult to process as well as to train. Results in adding additional cost to the application. One of the other operating methods of SMA other than the heating effect could be identified as Magnetism. These Magnetic SMAs (MSMA) could operate at very high frequencies. The MSMAs are somewhat brittle and can only be operated at low temperatures. Thin-film SMAs are also available in the Micro-Electromechanical Systems (MEMS) for actuator developments. Inherent properties and advantages Shape Memory Polymers (SMP) play a major role in engineering applications.

2.1.2 Micro-structure of SMA and Phase Transformation Phenomenon

The microstructure of the SMA plays an important role in discovered properties of SMAs. The crystallographic structure is changing according to the external stimulation such as applied temperature, stress for thermal SMA, and magnetic field if the material is MSMA. The main crystallographic structures that can be seen in the SMA material are Austenite, Martensite, and Rhombic (R-phase) structure. In thermal SMAs, austenite is considered as the high-temperature phase or the parent phase which is having a cubic crystal structure and Martensite is the low-temperature phase exhibiting monoclinic crystal structure. Martensite is the phase that has low stiffness compared with the parent phase. So, the material could be easily deformable at low

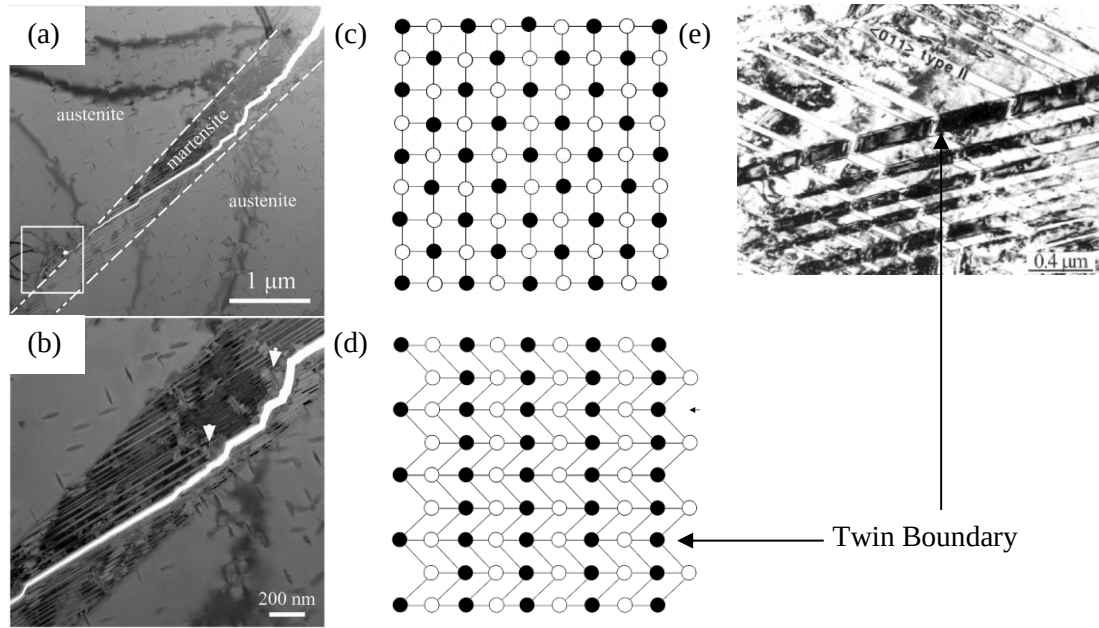


Figure 2.3: Micro-structure of SMA **(a)** Presence of Austenite and Martensite Phases; **(b)** Detwinned Martensite; **(c)** 2-D Representation of Austenite; **(d)** 2-D Representation of Twinned Martensite; **(e)** Presence of Twin Boundary

temperatures and as heated beyond a certain temperature, it could recover its deformed shape by changing its structure to austenite. This effect is known as the Shape Memory Effect (SME) which is a usable property of SMA material. If the material is heated beyond a certain temperature without deforming, then it would still become austenite at the microscopic level exhibiting no change in macroscopic level. If the heated material is subjected to deformation, it would deform by forming stress-induced martensite, and releasing the applied deformation force may cause the material to come to its previous macroscopic shape by becoming austenite. This phenomenon is known as the pseudoelasticity (PE) or super-elastic effect of SMA. Cooling down the material would lead to forming Martensite, which is stable at low temperatures.

Figure 2.3. (a),(b) [7], [8] depict two Bright Field micrograph images of NiTi-based SMA alloy showing the parent austenite phase and the martensite phase. The Austenite phase has a body-centered symmetry (Figure 2.3. (c)) and is referred to as a B2 structure that is cubic in 3D. This cubic structure has Ti atoms at the vertices and Ni atoms at the center of the cube. B2 structure only has one distinct structure. This structure only exists at a range above a specific temperature.

Martensite has a monoclinic structure and exhibits twin boundaries at low temperatures without application of initial deformation stress (Figure 2.3. (d), (e)).

Depending upon the applied stress detwinning happens by displacement of twin boundaries. Cooling the material below a certain temperature, austenite converts to martensite by a displacive athermal transformation [9]. When this happens under no stress conditions, any macroscopic change cannot be seen in the material. It's because of the accommodation by twinning. Martensite could be formed when the material is in the austenite phase by being subjected to external stress above a critical stress level. This is known as stress-induced martensite. The difference between martensite and stress-induced martensite is the number of available variants within the lattice structure. Variants are known as energy equivalent configurations available when self-accommodation happens within the crystal structure. Stress-induced martensite has only one variant while self-accommodated martensite has many.

The R-phase appears in between austenite and martensite phases when the transformation occurs by the varying temperature of the material. Compared to the larger hysteresis of austenite-martensite transformation, R-phase transformation has a small hysteresis which is suitable for low thermal hysteresis and low strain applications. R-phase exists as a Rhombohedral lattice structure. Within the operating temperature range of SMA, the above-discussed phases exist. When the temperature of the material is increasing, a diffusionless solid-solid transformation occurs from martensite (M) to austenite (A) and it is known as forward transformation. Decreasing the temperature of the material causes the reverse transformation from austenite to martensite without showing any macroscopic change. Within the operating temperature range, four characteristic temperatures of SMA can be identified namely [10],

M_f - martensite finish temperature	(i.e.: the temperature at which material fully converted to martensite)
M_s - martensite start temperature	(i.e.: the temperature at which starts the formation of martensite)
A_s - austenite start temperature	(i.e.: the temperature at which starts the formation of austenite)
A_f - austenite finish temperature	(i.e.: the temperature at which material fully converted to austenite)

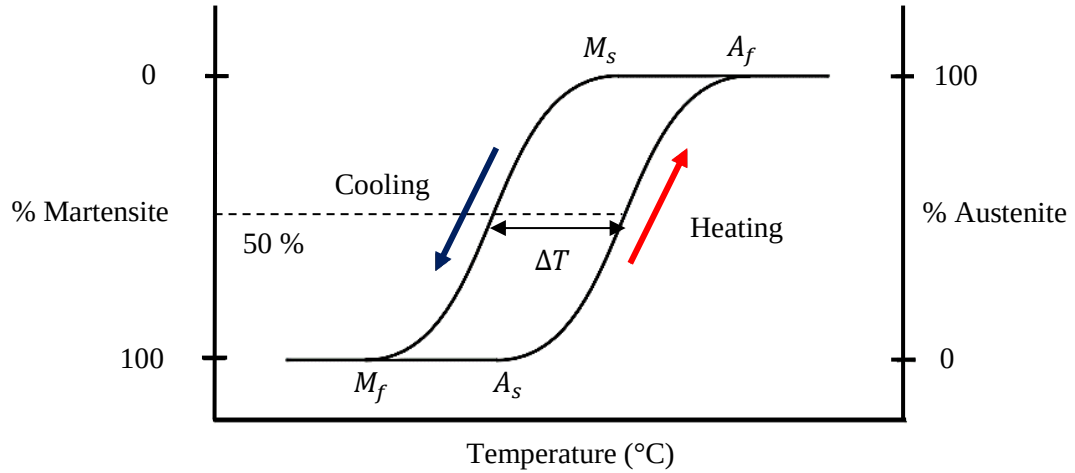
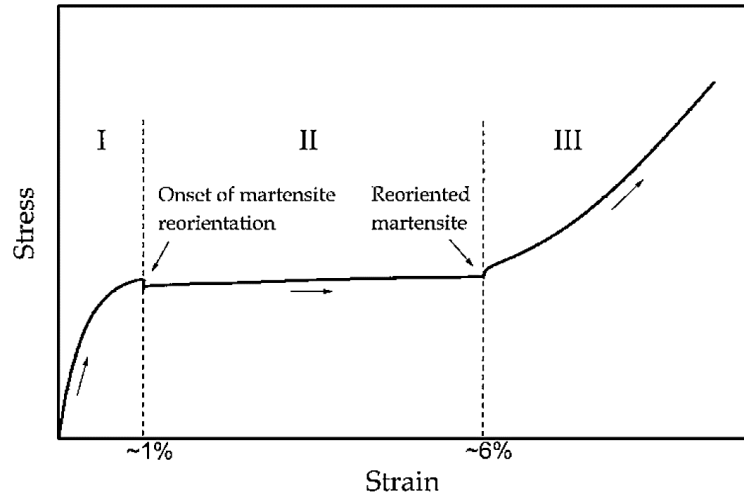


Figure 2.4: Phase Percentage Variation with Applied Temperature

SMA below the M_f consists of 100% martensite. As the temperature is increased gradually with zero applied stress to the material, at A_s the first appearance of austenite happens. When the temperature reaches A_f , the last observable martensite will disappear, and the material becomes fully austenite. In the case of cooling the material, martensite appears at M_s temperature and converts to 100% at M_f . The temperature range between M_f and A_f is identified as the characteristic temperature range of the material. The operating temperature range has to be selected according to the applied stress range and based on the zero-stress characteristic temperature range [10]. Figure 2.4. explains the phase variation with respect to the temperature applied to the material. There is an inherent hysteresis behaviour incorporated with SMA materials and should take into account in applications. The hysteresis effect changes according to the alloying elements and element composition [9].

2.1.3 Properties of SMA

Properties of SMA material are important as they behave differently from other alloys. Without the application of any external stress to the SMA material, varying temperature along the characteristic temperature range would cause micro-structure to alter between austenite and martensite phases without any macroscopic change. Micro-structure changes between twinned martensite and austenite. Application of stress on the SMA material at a temperature below M_f would exhibit a stress-strain relationship as depicted in Figure 2.5. [11].



Region I : The elastic accommodation of martensite twins

Region II : Reorientation of martensite variants

Region III : Elastic deformation of fully reoriented martensite followed by a plastic

Figure 2.5: Stress-Strain Relationship of SMA below Martensite Finish Temperature

After releasing the stress, which is applied up to Region III can be recovered by heating the material beyond A_f . This is identified as the Shape Memory Effect (SME) of SMA material. Upon applying stress to the material at a temperature below M_f , the martensite undergoes detwinning and the strain will remain after releasing the stress (Figure 2.6. (a)). This strain recovers when the material temperature rises above A_f , reverting to the initial macroscopic shape. Cooling of material will lead to form twinned martensite.

Heating the material above A_f will make the material behave elastically upon applied stress. When heated above A_f , SMA is in the austenitic phase, and applying stress will form stress-induced martensite (Figure 2.6. (c)) and exhibit a strain, upon

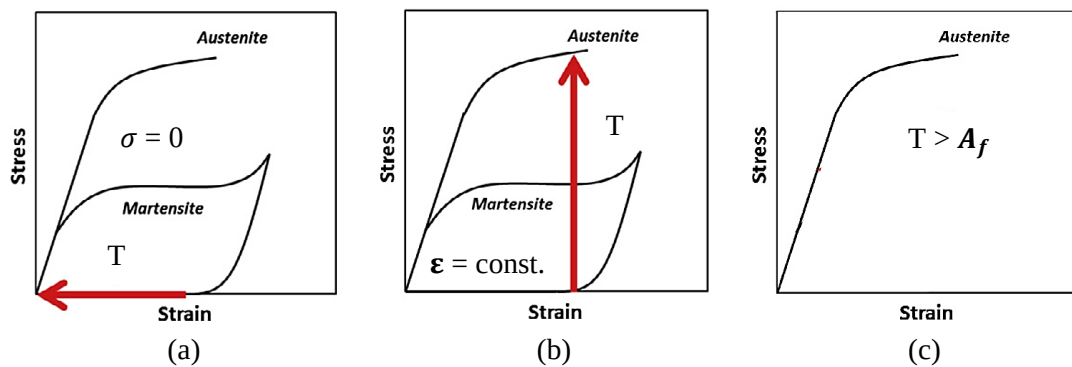


Figure 2.6: Usable Properties of SMA (a) SME; (b) Constrained Recovery; (c) Pseudo-elasticity (PE)

releasing the stress it will revert to the austenite phase by recovering the strain. This property is known as Pseudo-elasticity (PE). If the material is deformed by external stress and maintained the strain while increasing the temperature above transition temperature will lead to considerable force generation (Figure 2.6. (b)). This is known as constrained recovery [6]. The Figure 2.7. shows three-dimensional characteristic behaviour of SMA material explaining SME and PE [12].

Shape Memory Effect

SMA material exhibits permanent deformation due to the application of external force. The material can recover its initial shape upon heating beyond A_f temperature. Immediate cooling does not cause deformation unless an external load is applied. Such behaviour is identified as One-way Shape Memory Effect (OWSME) and is indicated in Figure 2.7. by 0–5–0 path. In addition to the OWSME, if the shape change happens upon cooling at the zero-load condition, it is known as the Two-way Shape Memory Effect (TWSME) and identified in Figure 2.7. by 2–5–2 path.

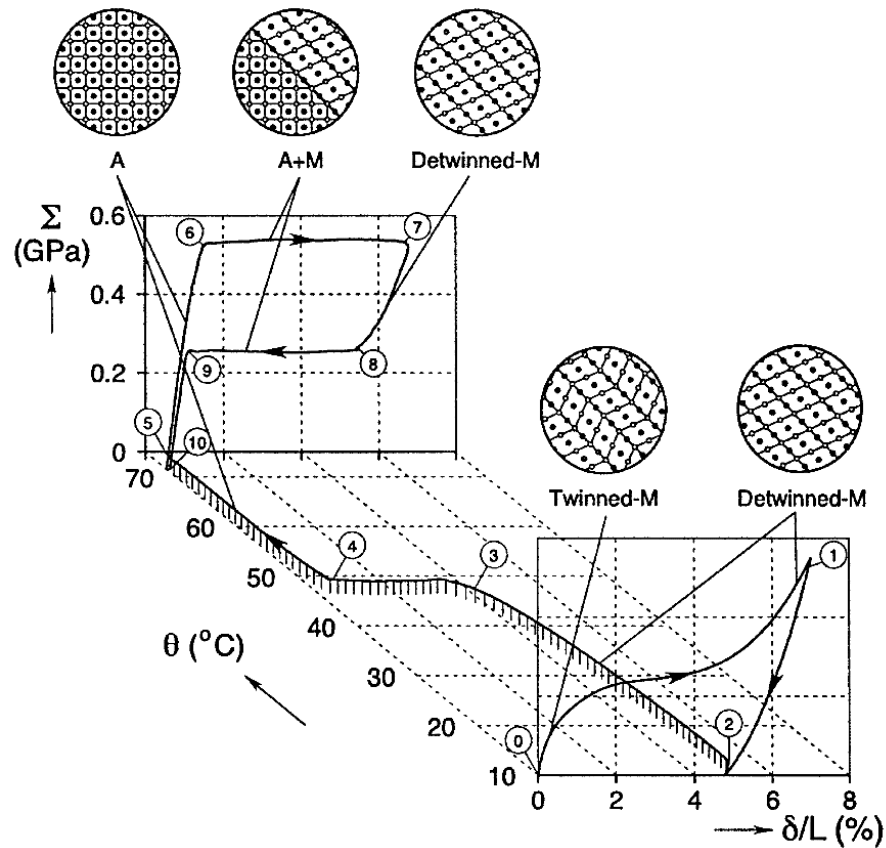


Figure 2.7: SME (0 — 5); PE (5 — 10)

Pseudo-Elasticity

When the temperature of SMA material is maintained beyond its A_f , upon application of load, the material deforms due to the formation of stress-induced martensite. Upon unloading, the material regains its initial shape without showing any permanent deformation. This effect is known as the Pseudoelasticity of SMA material, and this can be shown in Figure 2.7. by 5–10 path.

Hysteresis

Hysteresis is defined as the temperature difference (ΔT) between the points at which the material is in 50% of Martensite upon cooling and 50% Austenite upon heating would occur as seen in Figure 2.4. This property is important for specific applications. Low hysteresis is needed for fast actuation purposes in robotic applications and large hysteresis is important where the application requires to remember the trained shape in between expanded temperature range such as pipe joining applications.

2.1.4 Commercially Available SMA Material

In the commercial market, there are various forms of SMA material available for different applications. Those can be listed down as Wires, Plates, Billets, Rods, Tubes, and Sheets. Figure 2.8. shows the mentioned types [13]. These available forms are fabricated by Ingots made through Vacuum Induction Melting (VIM), Vacuum

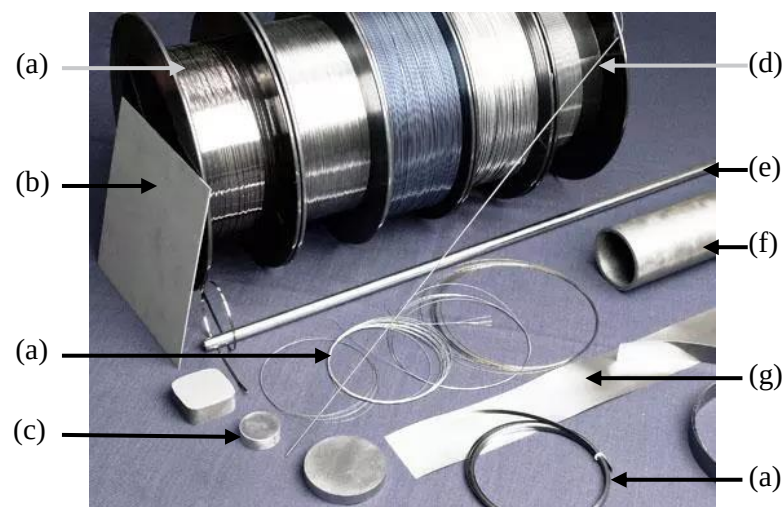


Figure 2.8: Commercial Types of SMA (a) Wires; (b) Plates; (c) Billets; (d) Superelastic Wires; (e) Rods; (f) Tubes; (g) Sheets

Consumable Arc Melting (VAR), and VIM/VAR double melt process. Each ingot processing technique has its concerns according to the SMA material composition. Ingots are then forged and rolled into a slab or bar at elevated temperatures. SMA wires are produced by the die drawing process. Billets and tubes are formed by extrusion [14].

2.1.5 Fatigue Nature of SMAs

The Fatigue nature of a material is defined as the alterations in mechanical or functional properties due to an exertion of cyclic loads during longer periods. There are two types of fatigue failure of SMA alloys as depicted in Figure 2.9. The SMAs are mostly utilized to develop solid-state actuators, accompanied by a unique design and promising power density. A clear knowledge of fatigue behavior is important for a reliable design of SMA actuators. The fatigue nature associated with the SMA material is known as functional or thermomechanical fatigue as the actuation is done by thermal activation of the material. Because the material performs mechanical work against the external load under heating cycles and in turn hinders the properties due to the fatigue phenomenon. Also under constant temperature, SMA exhibits mechanical fatigue upon cyclic loading of the material. Mechanical fatigue happens by the microstructural damage accumulation during cyclic loading. In mechanical fatigue, SMAs subjected to high cyclic loadings could be failed a similar way to other engineering materials, but SMAs exhibit different properties in different temperature ranges compared with the normal engineering materials.

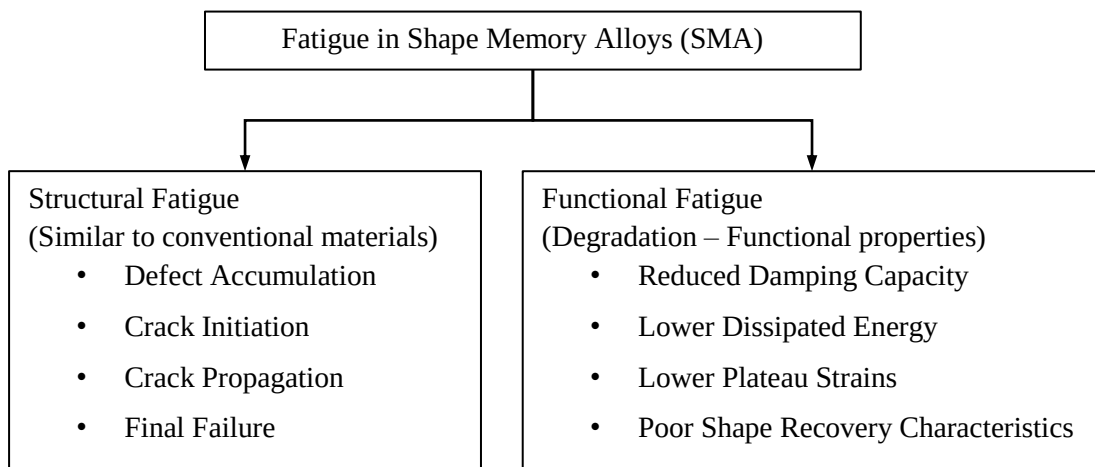


Figure 2.9: Classification of Fatigue Behavior of SMA

Characteristic Stress-Strain Tests to Evaluate Functional Fatigue

Several researchers were conducted functional fatigue tests for different modes under which an actuator is supposed to operate. Those are constant stress, Constant strain, Constant-stress with limited strain, and Variable stress-strain (Figure 2.10. [15]).

In the constant-stress tests, the SMA elements experience variable strains with respect to the prescribed stresses, applied by constant loads. The constant-stress test is equivalent for an actuator recovered by a constant force under zero external load such as positioning devices. In the constant-strain test, the SMA elements experience variable stress due to prescribed strains. A material constrained at two ends can be considered as an example for this scenario. The results dictate the amount of strain that is applied to the material initially. In the constant-stress test with limited maximum strain, the material elements experience a variable strain due to prescribed stress where the maximum possible strain is limited by an external restrain. The results depend on the applied stress and the maximum strain. In the variable stress-strain test, the material element experiences a linear change of stress and strain, as the stress increases during strain recovery, and the maximum strain is limited by an external restrain. This is equivalent to an SMA actuator element that is recovered by another SMA element and

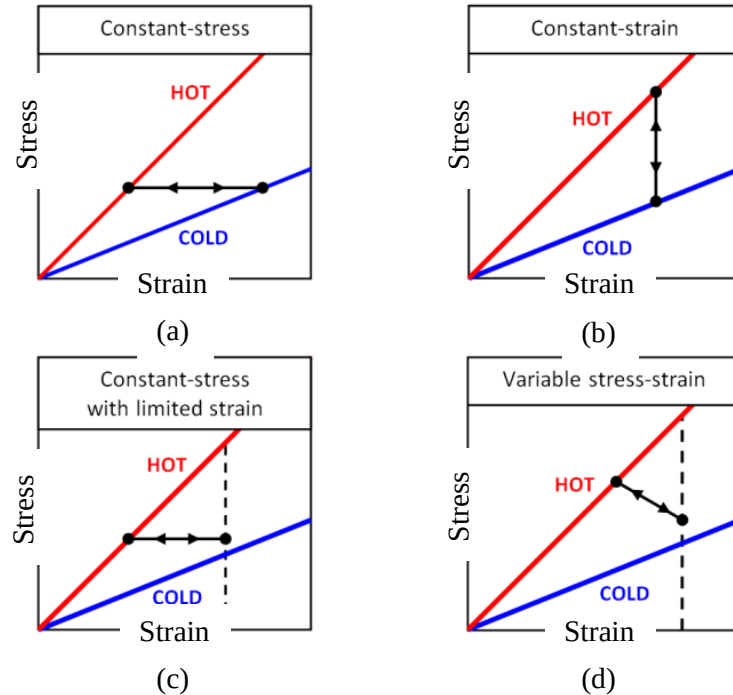


Figure 2.10: Fatigue Tests **(a)** Constant-stress; **(b)** Constant-strain; **(c)** Constant-stress with Limited Strain; **(d)** Variable Stress-strain

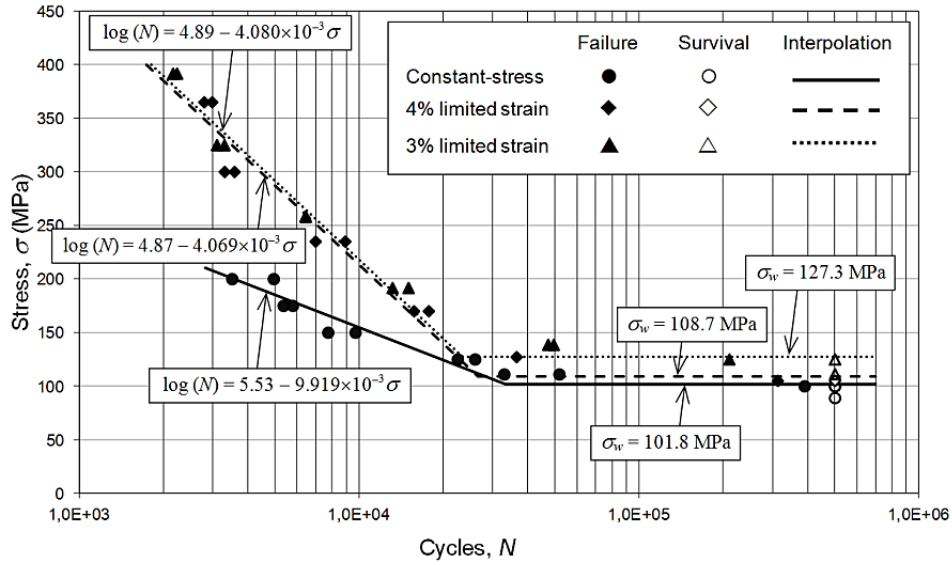


Figure 2.11: Wohler's diagram with the fatigue results for the constant-stress tests and the tests at constant stress with limited maximum strain (3% and 4%)

works between hard stops. The results depend on the stress-strain slope, maximum strain, and the initial stress at the maximum strain. Figure 2.11 [15]. shows a typical Wohler diagram showcasing the results obtained through some of the above-mentioned tests. The placement of the data points related to the experiments is in Figure 2.11. at the horizontal part of Wohler's diagram shows the presence of a true fatigue limit of the material subjected to constant-stress conditions, for both limited and unlimited maximum strains [15].

Figure 2.12. (a) and (b) [16] exhibit results related to a typical behavior of NiTi spring actuators loaded in tension Figure 2.12. (a) shows displacement–temperature curves obtained after achieving first, second, and thousandth actuation cycles. The change of positions x_A and x_M (as defined in Figure 2.12. (c)) related to the high and low temperatures are shown as a function of the cycle number in Figure 2.12. (b). The actuator spring suffers irreversible plastic deformation during the first 100 cycles in both phases: the spring elongates and x_M and x_A get decreased. Finally, the effect saturates, and from that instance x_M and x_A are almost stable. The working displacement Δ however increases during the first 100 cycles, because the decrease of x_M is stronger than that of x_A . The results are shown in Figure 2.12. illustrative for thermal cycling experiments undergone with springs under different loads and heat treatment conditions [16].

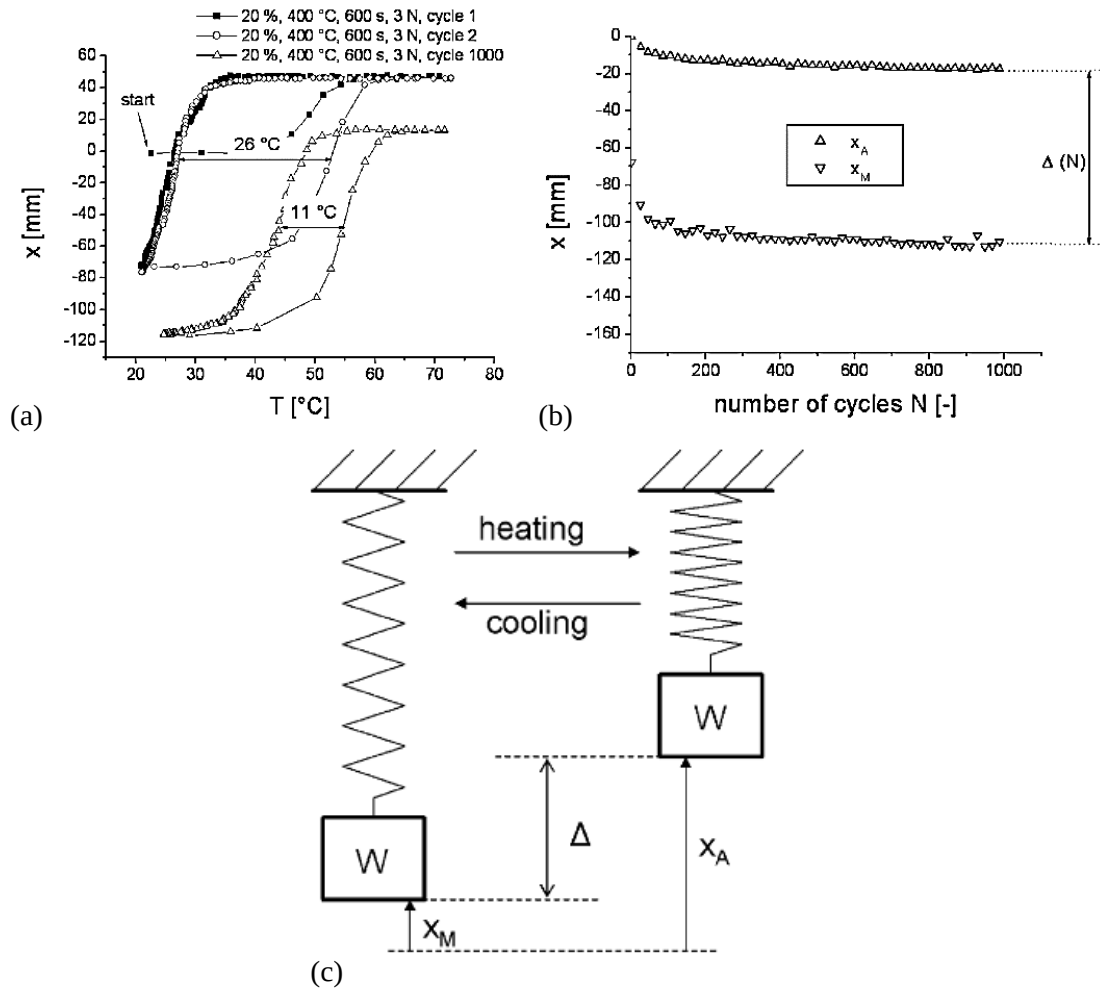


Figure 2.12: Change in spring geometry throughout the thermal cycling with an end load of 3 N. **(a)** Displacement–temperature hysteresis in the first, second and thousandth cycle; **(b)** Positions x_A and x_M as a function of the numbers of cycles; **(c)** Schematic Representation of Spring Actuator Testing under Constant Stress

Following Table 2.1. shows a list of applications where SMA is applied and the number of cycles before degradation of the property it possesses.

Table 2.1: SMA Applications, Underlying SMEs, and Expected Fatigue Lives N_f

Application	SME	Expected fatigue lives N_f
Thermal valve	1WE	10^4
Positioning	2WE	10^5
Robot gripper	2WE	10^6
Orthodontic wire	PE	10^5
Stents	PE	10^8
Damping, internal friction	PE	10^8

The initiation and growth of surface cracks are the governing factors for the structural fatigue of pseudo-elastic SMAs. The formation of surface cracks and subsequent crack growth dictates the fatigue damage accumulation, and it has been shown that crack growth in martensite is slower than in austenite and that stress-induced formation of martensite reduces crack growth rates. Because the stress-induced transformation of martensite limits the crack propagation, pseudoelastic SMAs are damage tolerant.

2.1.6 General Applications of SMA Materials

The unique nature of NiTi SMAs has led to new innovative applications in the aerospace, automotive, automation and control, appliance, energy, chemical processing, heating and ventilation, safety and security, and electronics (MEMS devices) industries. Table 2.2. [6] summarizes a few of these application areas where the SMA actuators can be applied.

There are many more application areas apart from the ones presented in Table 2.2. are available and the interest is growing in using SMAs. The integration of SMA may be a novel application or a simplification of existing simplification, or a substitution. There are several commercially feasible mas-producing application areas such as eyeglass frames [17], mobile-phone antennas, and underwire brassiere though the percentage of commercially promising SMA applications is yet considered to be considerably low. Figure 2.13. [17] shows a few application areas of SMA.

Table 2.2: Applications Areas for SMA Actuation and Examples

Automotive	Aerospace	Robotic	Biomedical
Radiators	Stabilizers	Crawling robots	Braces
Fan clutches	Vortex generators	Flying robots	Catheters
Brakes	Flap edges	Rolling robots	Scopes
Tyres	Spars	Humanoid robots	Suture
Sunroofs	Engine nozzles	Actuators	Valves
Petrol caps	Landing gears	Sensors	Spinal spacers
Airbags	Hydraulic lines	Endoscopic robots	Muscles

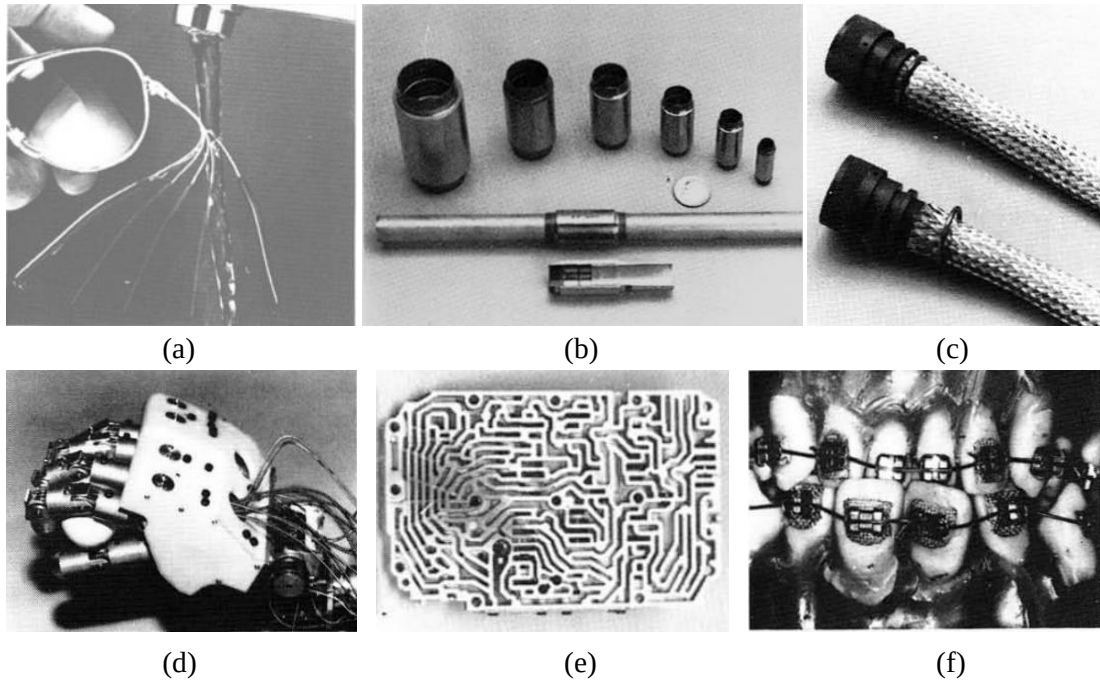


Figure 2.13: Applications of SMA **(a)** Eye Glass Frames; **(b)** Hydraulic Couplings; **(c)** SMA Fasteners; **(d)** Robotic Hand; **(e)** Automatic Transmission Valves; **(f)** Orthodontics

2.2 SMA Based Actuators

The application of SMA varies from smart structures, actuators to sensors. SMAs' attractive morphing capabilities are the key aspect to developing active and adaptive structures. The mechanical simplicity and compactness of the SMA-based actuators significantly reduce the size and the weight of the actuators and it is the major driving component in automobile applications in terms of cost. This subsection presents actuators developed using SMA materials.

2.2.1 Types of Actuators and Operation

SMA-based actuators can be categorized into macro-scale actuators and micro-scale actuators. Macro-scale actuators described in the above application areas are summarized as follows.

Considering typical robotic applications which are based on SMAs are mostly inspired by biology or biomechanics. Increasing the performance of the hardware platform together with miniaturization and increasing the intelligence of the integrated system can be considered as the main challenges related to the robotics domain. By doing so, several technical difficulties arise such as low efficiency, small strain output, miniature electrical connections in case of micro-robots, low electrical resistance, and

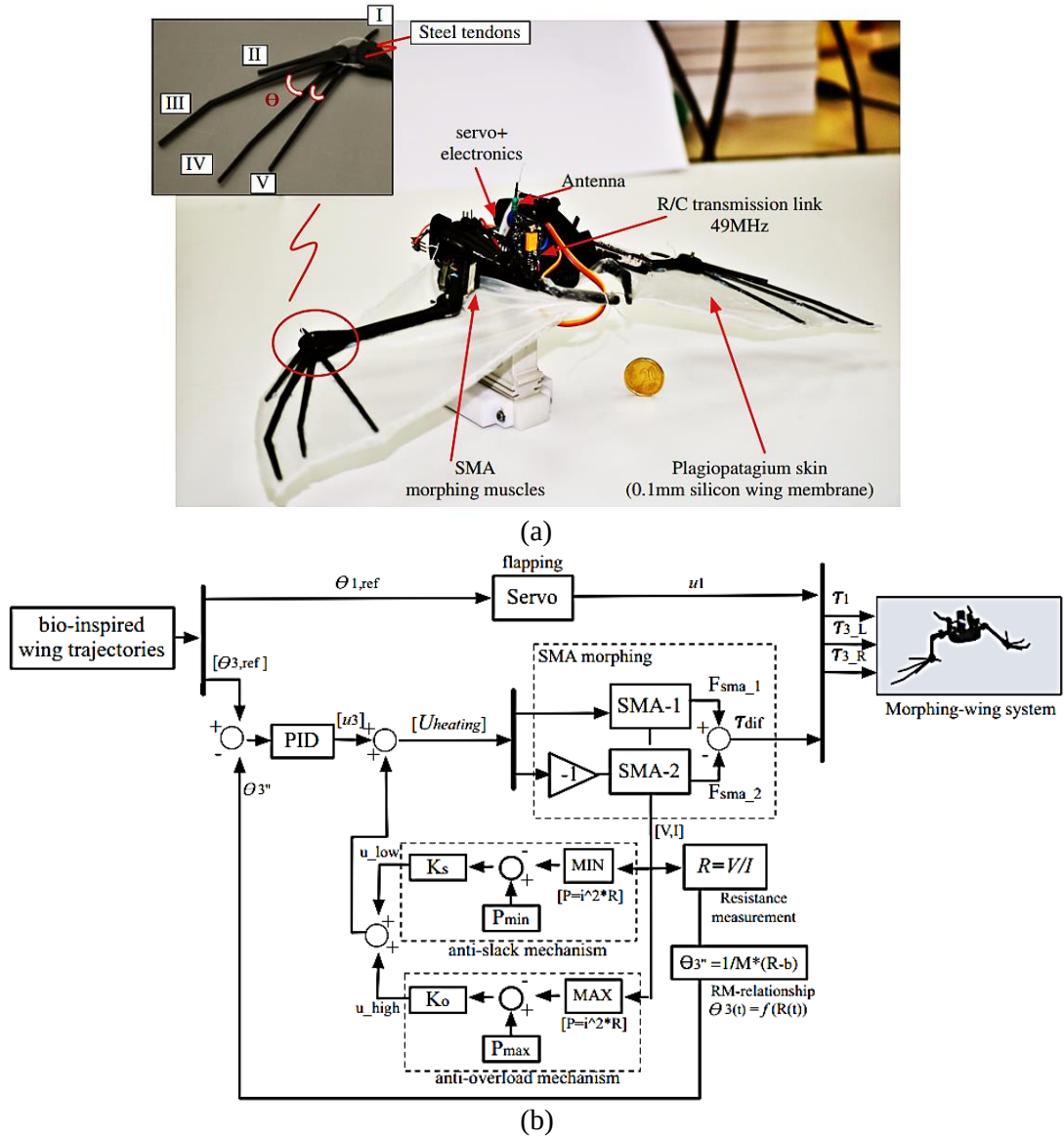


Figure 2.14: Robotic Application **(a)** Bat-like Morphing-wing Robot; **(b)** Morphing-wing Control Architecture

clamping difficulties. These could be solved by choosing suitable modelling techniques and control techniques.

SMA actuator response rate significantly depends on the general size, shape, and Degrees of Freedom (DoF) of the robotic devices. Generally, Joule heating is used for miniature and micro-actuators and indirect heating methods are applied for macro-type actuators [18].

Figure 2.14 [19] shows a Bat-like morphing wing micro aerial robot developed by SMA actuators. NiTi SMAs act as artificial biceps and triceps muscles to achieve morphing capabilities to the wings of the aerial robot. The electrical resistance changes of the SMAs were considered to estimate the morphing motion of the wings. Figure

2.14. (b) presents the control architecture and the SMA morphing block receives the control signal, in order to generate the required torque at the elbow joints. The control module is composed of three blocks: PID controller, anti-slack, and ant-overload mechanisms.

So these controlling techniques compensate for the demerits of SMAs inherently possess which are hindering the performance of the overall system [19]. There are various types of actuators available in the biomedical domain which are developed by using SMA materials. The interest to apply these smart materials for the biomedical domain arises, because of the unique properties of SMA materials such as biocompatibility, corrosion resistance, non-magnetic, and unique physical properties. The interest in the material has grown rapidly in this area due to the possibility of actuating the devices using body temperature itself. Also, the offered isothermal environment in the body solves many design problems. The body temperature is considered to be the proper temperature to activate binary NiTi alloys [20]. Figure 2.15 [20] shows some of the applications where SMA-based actuation is used in the biomedical domain.

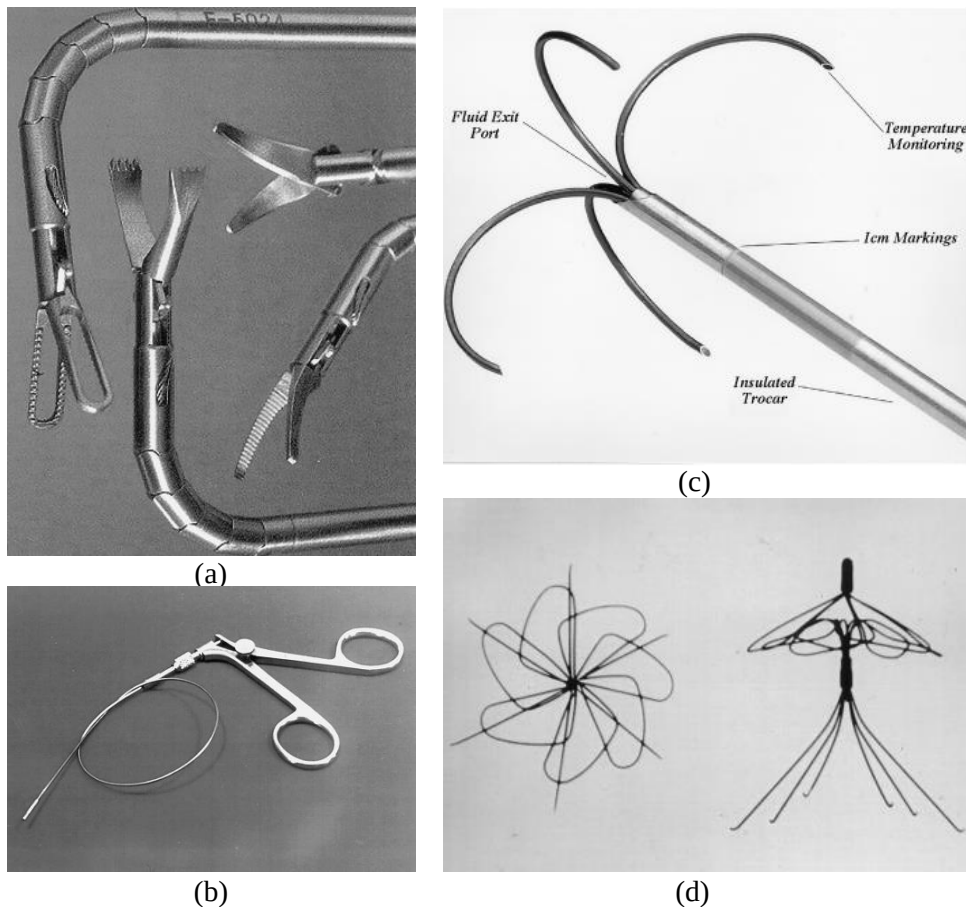


Figure 2.15: Biomedical Applications (a) Endoscopic Instruments; (b) Grasper Tool; (c) Tissue Ablation Device; (d) Simon Vena Cava Filter

2.2.2 Manufacturing of SMA Actuators

Manufacturing of SMA-based actuators is primarily based on heat treating the raw SMA material form (i.e.: wires, tubes, plates, sheets, etc.) by constraining at a specific shape which is, in turn, would be the parent shape when the shape recovering process undergoes in operation. The development of actuators from the raw materials depends upon the properties important in the final application. (i.e.: shape memory or superelastic)

For a super elastic actuator,

- The upper plateau stresses
- The ultimate tensile stress
- An Austenitic final temperature far enough below the operating temperature to ensure superelastic behavior

For shape memory actuators,

- Ultimate tensile stress
- An Austenitic final temperature above the operating temperature

The shape is set to the material by heat-treating the constrained material to the particular shape at different heat treatment conditions to obtain the required transformation temperature range suitable for the application area. The nature of the raw material is also influencing the properties of the material. SMA materials may be purchased in either the ‘straight annealed condition’ or in ‘as-drawn condition’[21]. If an SMA wire is taken as an example, in the first scenario, the wire has essentially been shaped set into a straight length as it leaves the drawing bench. In the latter scenario, the wire is coiled directly from the last drawing step.

Specially developed tooling which is also known as fixtures is required to hold the raw material in the required shape while the heat treatment process has been carried out.

2.2.3 Investigation of Transformation Temperatures of Manufactured Actuators

Manufacturing of SMA actuators should be followed by the transformation temperature investigations to assess the operating temperature range of the actuators. According to the shape setting temperature and time, certain transformation temperatures are programmed to the material and these temperatures dictate the operating status of the developed actuators [21].

Several methods can be identified suitable for the investigation of transformation temperatures. Applied Loading Method (ALM), Electrical Resistance Method (ERM), and Differential Scanning Calorimetry (DSC) are most commonly used for measuring the transformation temperatures.

Differential Scanning Calorimetry

DSC method [22] is used to monitor the energy changes occurring within a sample under heating or cooling cycles. It measures the heat flow in to and out of the samples against a reference. So a range of chemical and physical variations such as melting, crystallization, glass transition, solid-solid transition, enthalpy of fusion or crystallization, reaction enthalpy, polymerization, and pyrolysis can be measured through this test (Figure 2.16. [23]).

Since the transformation phases of SMA material are Austenite (solid) and Martensite (solid), the important temperatures related to these phase transitions could be tracked through the DSC. The transformation from Martensite to Austenite absorbs heat to progress endothermic reaction. It shows a sudden drop in the heating curve. When initiating the cooling cycle, the material sample expels heat to progress exothermic reaction and it shows a peak in the cooling curve as the material transform from Austenite to Martensite. The starting and ending points of those dips and peaks correspond to the transformation temperatures of the SMA material.

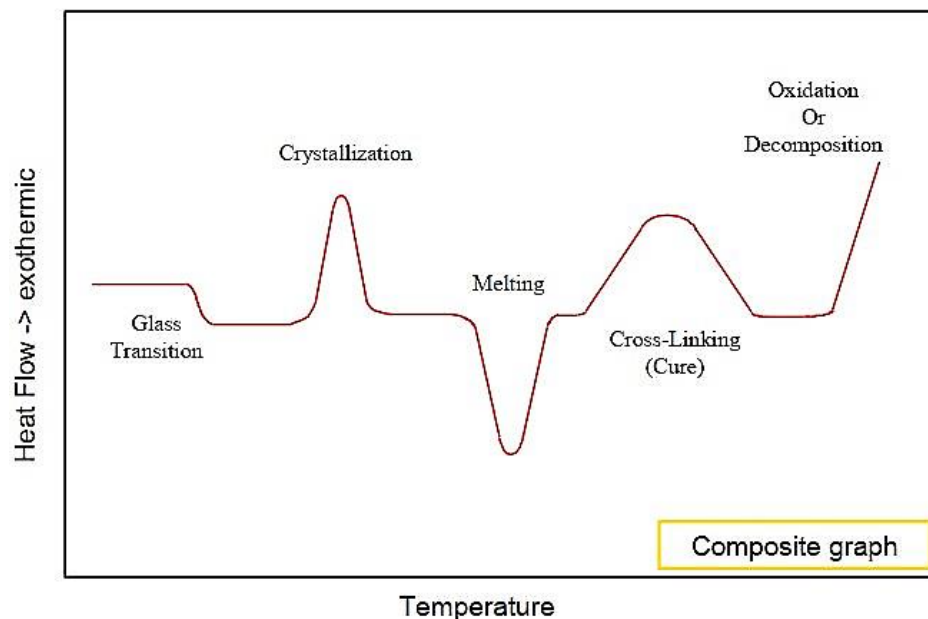


Figure 2.16: Possible Measurable Parameters through the DSC

Steps of Performing the Test

- Sample preparation

Most of the DSC equipment (Figure 2.17 [23]) specifically states a weight margin in milligrams. The samples must be prepared to satisfy the weight and they should be able to insert into the Pan. To improve the thermal contact between the pan surface and the sample, it is important to make a smooth contact surface of the sample. The best way is to cut the samples and smooth the contact surface with the pan and heat treat in an oven. Otherwise, properties could be changed due to cold working when cutting or grinding of samples after heat treatment.

- Setting up the DSC equipment

After preparing the samples, weighing is required, and it should be entered into the program setting. The sample should be carefully placed in the pan and sealed with a crimping press. The sample pan should be placed on the sample platform and a reference pan should be placed on the reference platform. The cell should be closed after placing the pans (Figure 2.18 [23]).

- Thermal program

The required Methods and Procedures have to be set to the thermal program. Methods are the actual steps that the DSC executes during a run. The software provides custom templates. Procedures are the other options along with the Methods such as data sampling intervals, method end conditions, etc.

Use a proper starting and end temperature margin which is assumed to include the transformation temperatures.

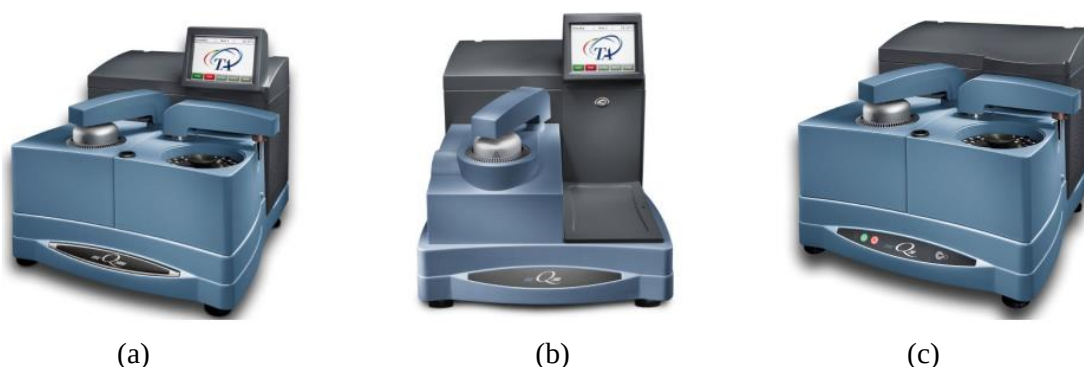


Figure 2.17: Second Generation DSC Equipment **(a)** Q2000; **(b)** Q200; **(c)** Auto Q20

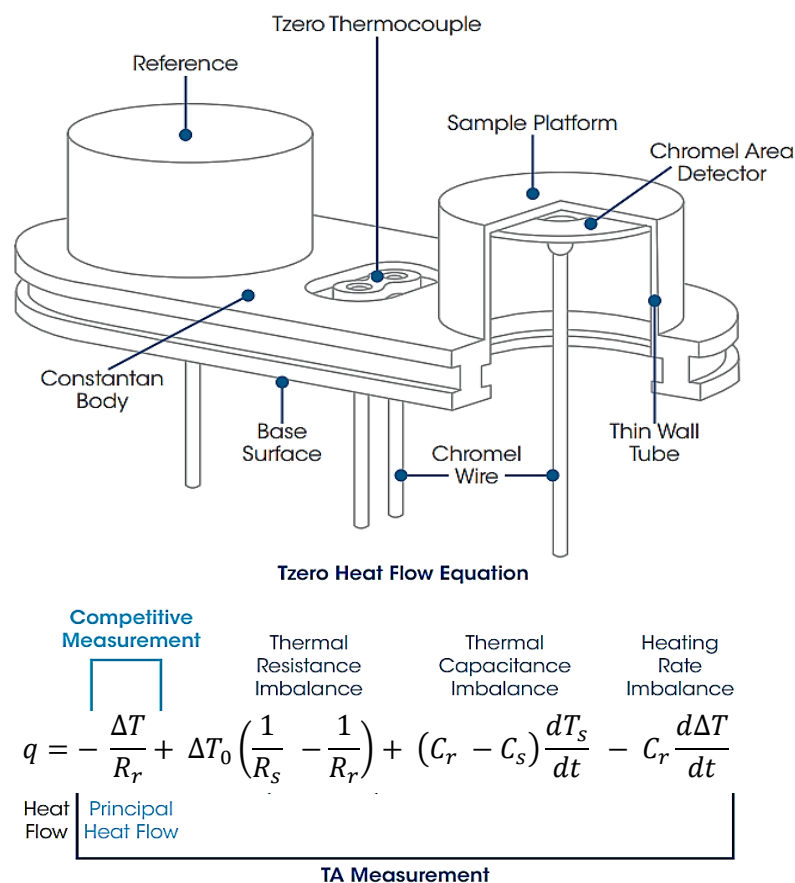


Figure 2.18: Schematic of a DSC Fusion Cell and the Tzero Heat Flow Equation

- Thermogram interpretation

Within the temperature range that the sample is being cycled, an endothermic dip and an exothermic peak can be seen (Figure 2.19.). The transformation temperatures could be found by the intersection points of the tangent lines which are drawn to the points where the curve deviates [24].

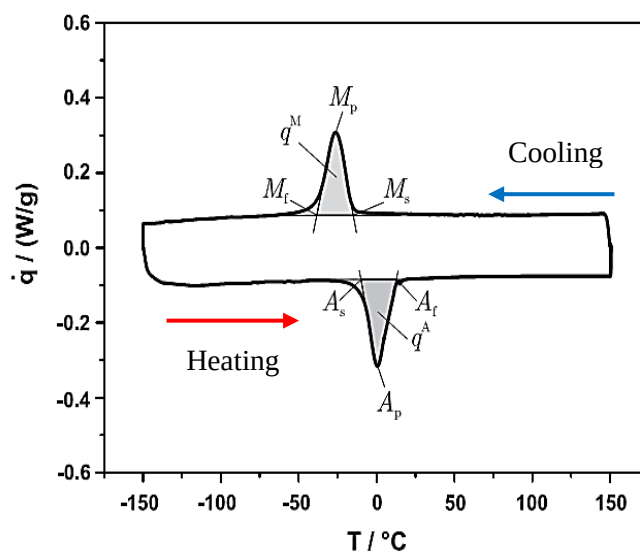


Figure 2.19: Typical Thermogram Obtained Through a DSC

Electrical Resistance Method

Heating and cooling of SMA material exhibit a change in its electrical resistance over the transformation temperature range (Figure 2.20. (a) [24]). As the material is heated to transform from Martensite to Austenite, the resistance gets increased and as the material is cooled to transform from Austenite to Martensite, the resistance gets decreased. The SMA sample stands as a part of the electrical circuit. Transformation temperatures could be obtained by considering the electrical resistant change with the temperature.

Applied Loading Method

The idea behind the applied loading method is that the transformation from Austenite to Martensite and the reverse transformation from Martensite to Austenite happens with a considerable deformation as an external force is applied on the testing sample during shape recovery while heating and also cooling. The temperature at which there is a large change in geometry (Figure 2.20. (b)) is used as a direct identification of the transformation temperature [25].

2.2.4 Actuation Methods of SMA Actuators

According to the previous subsections, the SMA material is needed to be heat treated at a particular temperature that is correlated with the required application-specific activation temperature. These transformation temperatures are then evaluated by a suitable measuring technique. The most suitable technique to measure accurate transformation temperatures can be considered as DSC.

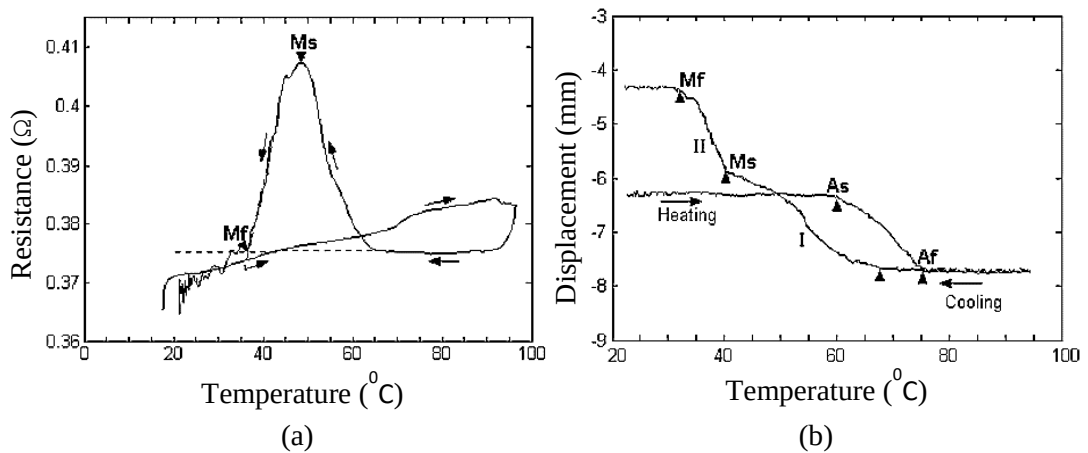


Figure 2.20: Transformation Temperature Evaluation Methods **(a)** Resistance Variation of a SMA Sample; **(b)** The displacement Vs temperature graph for a pre-deformed wire (heat treated at 450 $^{\circ}\text{C}$, 20 min, water-cooled) in a thermal cycle under a load of 10 g.

Finally, the actuators are introduced to the applications and there should be a suitable method to increase the temperature of the material beyond the activation temperatures to produce useful strokes and forces.

These activation methods can be categorized into two possible methods, namely internal heating (Joule heating) and external heating. In the internal heating method, an electrical voltage source is being used to transfer a current through the material and the inherent resistance of the material causes to produce dissipative heat in which the power is equal to the square of the current multiplied by the resistance. When considering the design of the actuators which are driven by the Joule heating method, provisions need to be there for electrical connections as well as a method to reduce the temperature of the actuator between cycles. In that case, ambient cooling, forced air cooling, and liquid-based cooling are the possible cooling methods to drop down the temperature of the SMA material. But, according to the mentioned order, the complexity of the actuator getting increased due to the special requirements of each cooling method.

The energy required to heat the SMA material to the specified temperature is taken by an external means such as a heated coil wounded around the SMA material or a heated fluid flow passing through the SMA material, then the method of heating is known as external heating of the SMA actuator. In the first scenario, the external wire is heated up by the Joule heating method, and the resulting dissipative energy is transferred to the SMA material by conduction. As both are metallic materials, careful electrical isolation is required when combining to form the heating method. The second external heating method involves the flow of heated fluid medium around the SMA element to transfer heat energy through convection. The cooling can also be achieved by a similar method. Both these external heating methods have advantages and disadvantages according to the application area.

2.2.5 Controlling of SMA Actuators

Considering previous details made regarding the behavior and the properties of SMA, many research groups have proposed several controlling techniques. The following paragraph describes a summary of those methods.

Among the researchers who have been involved in the area, one group achieved position controlling of SMA actuators by monitoring the resistance change. Due to the non-linear behavior of the SMA actuator, a neural network was used to

predict the position of the actuator. Feedback control was achieved by using a Proportional Derivative (PD) controller [26].

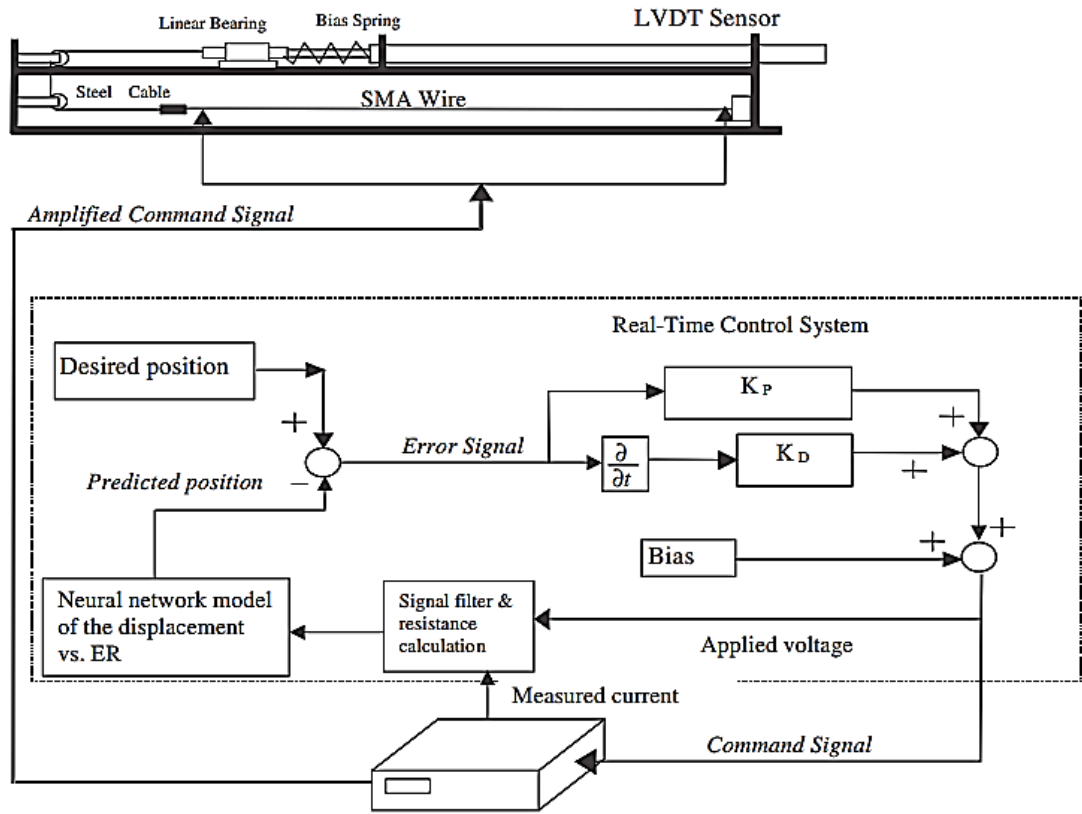


Figure 2.21: Block diagram of the Electrical Resistance Feedback Control System in Ma et al.'s Work

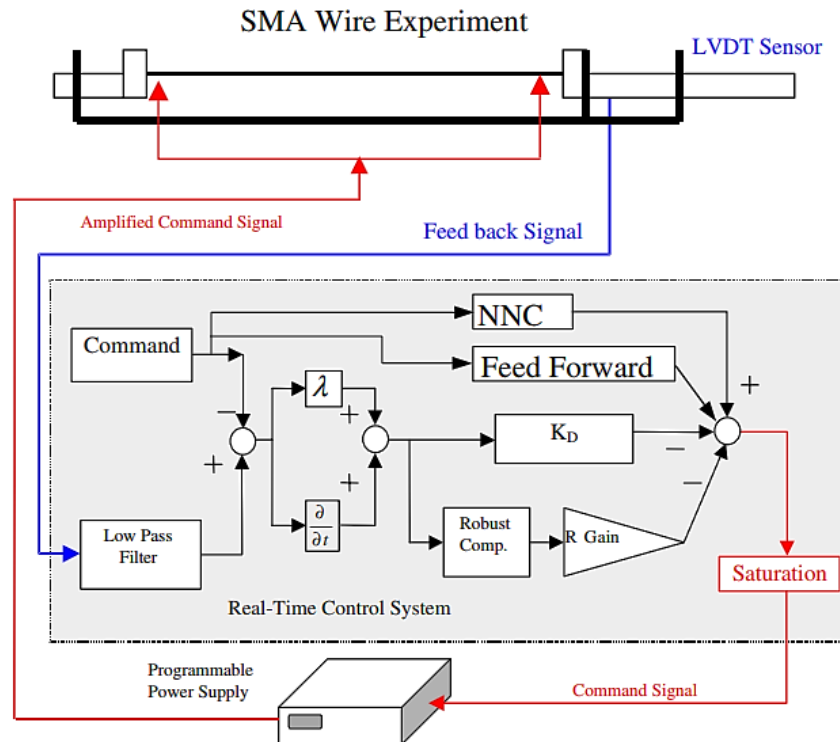


Figure 2.22: Block diagram of the Control System in Song et al.'s Work

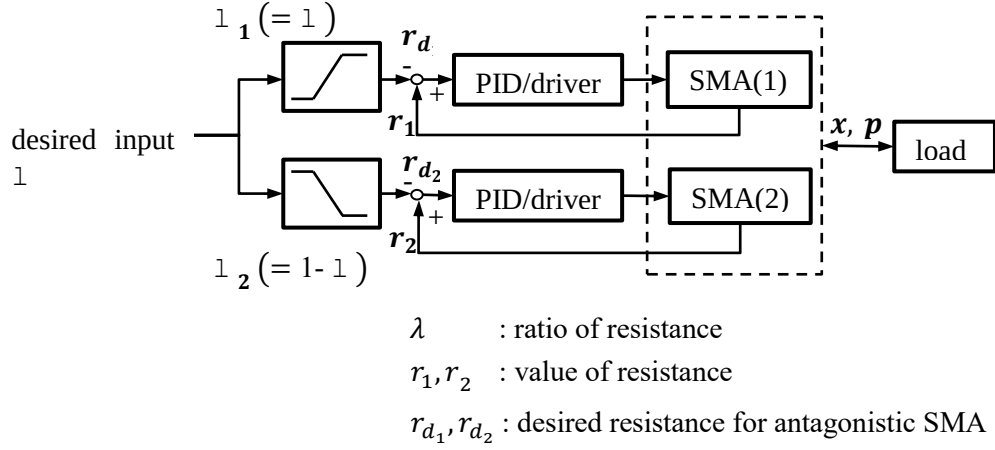


Figure 2.23: Antagonistic Type Resistance Feedback Control System of Servo Actuator System

Song et al. have worked on controlling SMA actuators by compensating the hysteresis of the material by using a neural network and a sliding mode feedback controller. The neural network cancels the hysteresis which can be considered to have position inaccuracies and instabilities. The sliding mode feedback controller was used to work on errors in hysteresis cancellation and to ensure the stability of the controller [27].

Ikuta et al. have proposed a control system for the SMA servo actuator through electrical resistance monitoring. An antagonistic type transformation control scheme was produced using electrical resistance feedback. The proposed control scheme has reduced the open-loop hysteresis and improved the robustness against heat disturbances due to changes in cooling conditions drastically. The resistance feedback system includes a PID controller in the feedback loop. Here, the SMA driving circuitry

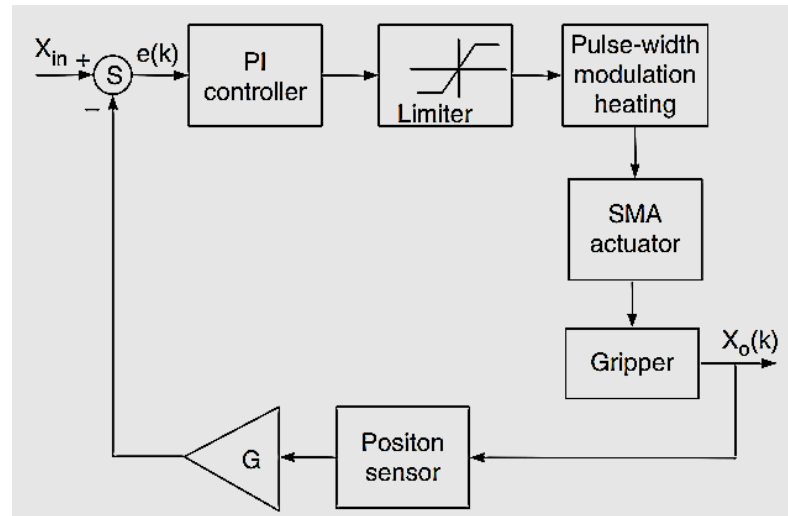


Figure 2.24: Closed-loop Position Control System in Yan et al.'s Work

possesses the ability to supply current through a Pulse Width Modulation (PWM) driver and simultaneously measure the resistance [28].

Yan et al. produced a control system using a proportional Integral (PI) controller to control the position of a gripper actuated by a pair of differential SMA springs. Here, the PI controller was combined with a PWM power amplifier to compensate for estimation errors and to improve the output position accuracy [29].

2.3 Minimally Invasive Surgeries

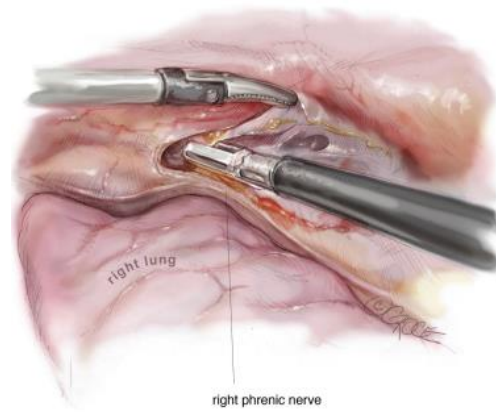
Minimally Invasive surgery is any procedure that is less invasive than an open surgery used for the same purpose [30], [31]. Minimally invasive surgery (MIS) procedures usually involve specially developed tools, devices, and remote-controlled manipulation of surgical instruments with the observation of the surgical field through a scope, either micro or endo. The benefits of the MIS can be categorized as follow,

- Less pain - smaller dose of pain relievers
- Shortened hospital stay - Faster recovery
- Small incisions - Less noticeable scars
- Muscle sparing - Less tissue damage
- Accuracy - Better visualization and magnification of internal organs [32]

Generally, traditional surgeries are performed by making larger incisions sufficient enough to access the organs. And the work is carried around the required area by accessing directly using tools under the direct vision of the surgeon and the supporting staff. Most of the time, the damage done to the skin, muscles, connective tissues, and bones to reach the region of interest causes more injuries than the curative procedure itself [33]. This is a major drawback in terms of pain and trauma to the patient, recovery time, and the cost. To overcome the mentioned issues, the surgery procedures moving towards a trend of what is called Minimally Invasive Surgeries or Minimally Access Surgeries. Here, specially developed tools have been used to perform the surgeries via incisions made through natural orifices such as uterus, anus, mouth, or small artificial incisions made at locations special to the interventions. The vision capabilities are incorporated into the MIS procedures with the aid of miniature



(a)



(b)

Figure 2.25: MIS Procedure **(a)** A Surgeon Performs a MIS; **(b)** A Schematic of Camera View of a MIS

cameras inserted through the ports which are inserted into the incisions made to facilitate the surgery [34].

Figure 2.25. (a) [35] shows a picture of a surgeon performing an MIS with the use of long slender instruments which are inserted through the ports into the surgery area with the aid of screens showing the surgery area which is captured by the scope (camera) inserted. Figure 2.25. (b) [33] shows a schematic of a surgery area inside the body. The tools are being used to perform manipulations with minimum damage to the surrounding organs.



(a)



(b)



(c)

Figure 2.26: Types of MIS **(a)** Endoscopic Sinus Surgery; **(b)** Laparoscopic Surgery **(c)** Robotic Surgery

2.3.1 Types of Minimally Invasive Surgeries

Types of MIS fall under three main areas. Those can be categorized as Endoscopy, Laparoscopy, and Robot-assisted surgery (robotic surgery) Figure 2.26. [36] Endoscopic surgeries are usually performed through the body's natural openings such as the mouth, uterus, and anus. And Laparoscopic surgeries are performed through small incisions made by the surgeons artificially at special locations on the body. Robotic surgery is performed by the tools that are inserted through the incisions and controlled by a surgeon sitting at a nearby computer [37].

2.3.2 Tools used in MIS and Actuation Methods

Due to the unique techniques used in MIS, a set of specially developed tools need to be accompanied and utilized to successfully meet the requirements of minimal invasiveness. There are many types of tools used in MIS and they can be categorized as Conventional and Advanced tools. Conventional tools can be considered as normal handheld instruments named as Forceps, Dilators, Trocars, Graspers, Retractors, Spatulas, Rasps, etc. These types of instruments are made to standard dimensions which are defined by the respective surgical procedures and for Laparoscopic surgeries, the types of tools are categorized by their slender shaft diameters. They are ranging from 2 mm to 15 mm. Advanced tools used in MIS can be considered as Robotic tools which are made to the above-mentioned standards but are mainly controlled by a separate interface. In those tools, the visual aid is normally get through a camera which is also inserted through the ports of the surgery area.

Vision System

The main component can be considered as the vision system which contains an endoscope, an illumination system, and a high-definition screen which uses to display the video feed obtained through the endoscope. The Endoscope is an instrument made out of a long rigid or flexible rod that contains lenses and optical surfaces for effective transmission of light. The illumination system consists of a lamp that connects at the tip of the endoscope. There are a few types of lamps available in recent endoscopes: halide-metal vapor arc lamps, xenon discharge lamps, and quartz halogen incandescent bulbs. The best solution needs to be spectrally biased towards the blue end of the spectrum to compensate for poor fiber transmission and low video sensitivity. Endoscopic cameras are available as Charged-Couple-Discharge (CCD) type. The

most significant limitation of a video monitor is the resolution. They incorporate within reach state of art qualities in the matter of resolution, luminance, and chroma [38].

Mechanical Instruments

Tissue is manipulated in many ways by employing mechanical instruments (Figure 2.27 [38]) during a typical MIS procedure. Some of the basic examples can be considered as manipulation and holding of organs to facilitate access (retractors), sharp dissection, (scissors), holding a tissue to assist dissection, suturing, etc. (tissue graspers), suturing with needles and thread (needle holders). Also, some other mechanical devices include tissue extraction accessories and cannulas, knot pushers, and staplers. Although these instruments are really simple in design, they are developing with time and satisfy irreplaceable demands. Specifically, the tools have to be satisfied with safety and reliability, and also be able to withstand repeated sterilization without degradation to the properties of the materials and function (reusable tool types). The tools must be able to subject thorough cleaning after usage. Additionally, instruments such as scissors and graspers have a diameter of 5 mm, to

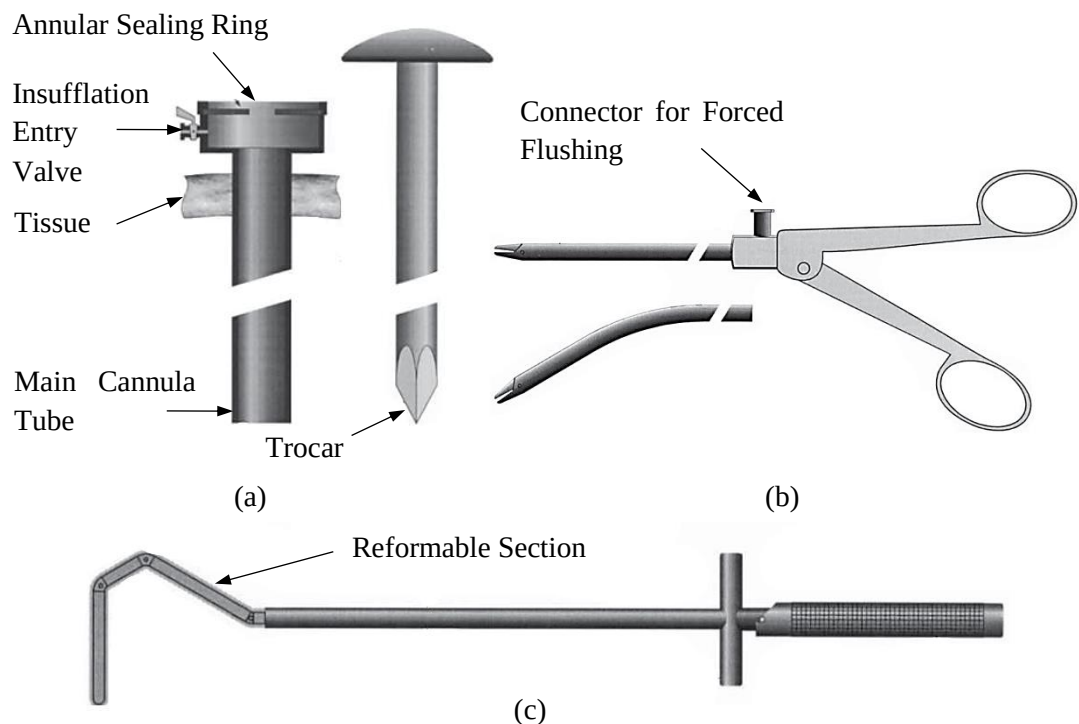


Figure 2.27: Tools Used in MIS **(a)** Cannula and Trocar; **(b)** Needle Grasper; **(c)** Retractor



Figure 2.28: Sophisticated Tools Used in MIS

allow excellent control with unrestricted vision and also to keep up the MIS advantages for small access wounds [38].

Figure 2.28 shows some of the tools developed for MIS with improved degrees of freedom at the tip of the instrument which gives more dexterity to manipulations performed. Almost every tool used in MIS offers multiple DoFs to increase the dexterity of the manipulations. Instead of simple control, there can be seen tools having Intracorporal articulations operated by external actuation methods using mechanical transmission utilizing mechanical rods, mechanical cables, or a flexible structure.

Cable-driven distributed actuation methods are frequently utilized in tools and devices clinically used requiring several local DoFs. These methods are comprised of bendable structures having numerous joints with limited DOFs (1 or 2), limited bending capabilities, or compliant structures actuated by cables that are acting as tendons. A large number of such tools [39] are manually operated through a handle very close to conventional MIS instruments but additional controls are there for additional DoFs.

Cable-driven actuation methods utilizing pulleys and classical pivot can be seen in the application areas such as Endowrist[®] developed for the daVinci[®] robotic system.

The mentioned actuation technologies are used in present clinical practices and many groups researching tools that can improve the MIS procedures further. Figure 2.29 and Figure 2.30 show some of the articulation technologies developed by the researchers [37]–[40].

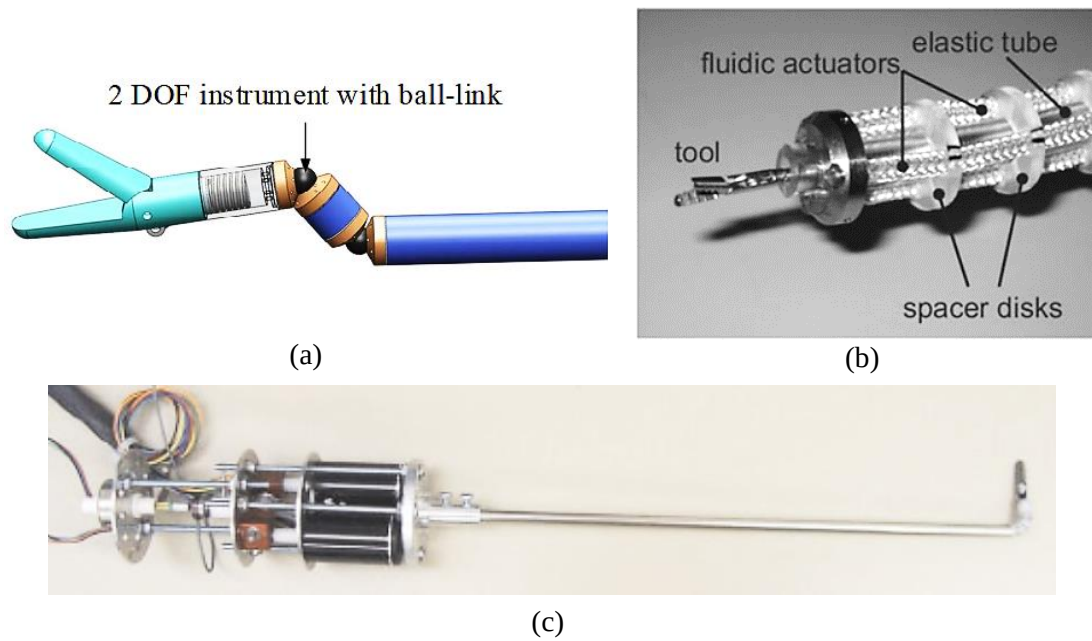


Figure 2.29: Articulation Technologies **(a)** Design of Shi et al. [40]; **(b)** Moers et al.'s Work [41]; **(c)** Berkelman et al.'s Work [42]

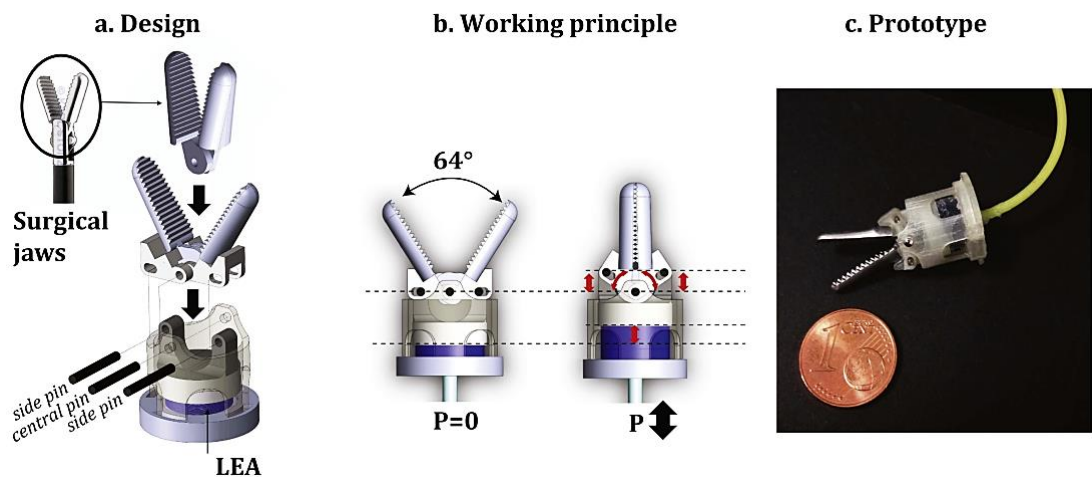


Figure 2.30: Actuation Mechanism Used in the Work Carried out by Gerboni et al.

2.3.3 Limitations of MIS Tool Development

The main limitation in the MIS tool development is the incision size. The ports are available in diameters of 5, 8, 10, 12, 15 mm and it is a critical parameter for the development of tools. Figure 2.31 shows different ports used in MIS.

2.3.4 Required Material Properties in MIS Tool Development

The materials used in developing MIS tools should possess biocompatibility as the tools directly contact the sensitive areas of the body [40]. Also, materials should have the corrosion-resistant capability to withstand moist environments. There are standards on material selection for medical devices utilizing SMAs [41].

2.3.5 Force Requirements of the MIS Tools and Force Sensing

As the surgical procedures are performed by using long slender instruments with different drive mechanisms for operating the end effector, the correct force value has to be exerted on the tissue or organ which is subjected to the operation as the surgeon operates the driving mechanism. To estimate the dimensions of the driver mechanism a thorough understanding of the forces involved with each unique surgical procedure is required. The following paragraph describes several works carried out by different research groups about forces incorporated with different procedures.

In the journal presented by Maksavage et al. specific grip forces exerted by the tips of various EndoWrist instruments are investigated. Also, differences in grip forces for several wrist positions have been studied there. Grip forces ranged from lowest (2.26 ± 0.15 N) to highest (39.92 ± 0.89 N) [42].

In Morimoto et al. they measured the injury potential of various levels of force by grading the trauma produced in a survival animal study. They observed trauma as low 2.7 N of tension applied to the tissue while grasping [43].

Brouwer et al. measured the forces and torques applied to the tool during driving a needle through various porcine tissues. Most of the forces are between 1.5 to 3 N



Figure 2.31: Different Port Sizes used in MIS

with a maximum observed at 12.5 N. They also measured cutting and spreading forces from a specific scissor and a clam and the forces are in between 3 to 6 N [44].

Greenish et al. collected data on different types of scissors during the cutting of the skin, abdominal wall muscle, and liver from animals, they observed cutting forces in the range of 1.6 to 44.8 N [45].

The mechanisms can be developed by considering the force values related to the procedures, and it is also important to produce methods to sense forces associated as the excessive forces may cause damages to the tissues and hinder the advantages of MIS. The force sensing is required to satisfy the following,

- Enables the operating personal to feel organic tissue hardness
- A measure of tissue properties
- Evaluates anatomical structures
- Allows surgeon to carry out necessary force control steps for safe tissue handling
- Reduction of tissue trauma and vital organic tissue damage
- Restore the surgeon's perceptual capability

Figure 2.32. shows the variation of the tractive forces at the hint of tissue damage and the first sign of rupture. Before tissue damage happened, the highest tractive force could be exerted on the fascia and the lowest tractive force on the fallopian tube. The variation of allowable force that can be exerted on these two structures is nearly ten times the other [46].

Another issue related to force sensing is generation trocar friction because of the tool movements inside the trocar. These effects were depicted in Figure 2.33. Peek to peek friction and kinetic friction between trocars varies broadly and the magnitude of the kinetic friction depends on the movement direction and velocity and shows a variation between 0.25 and 3 N for different trocars. Kinetic friction is greater for higher velocities and outward movements which is indicated by negative velocity values [47].

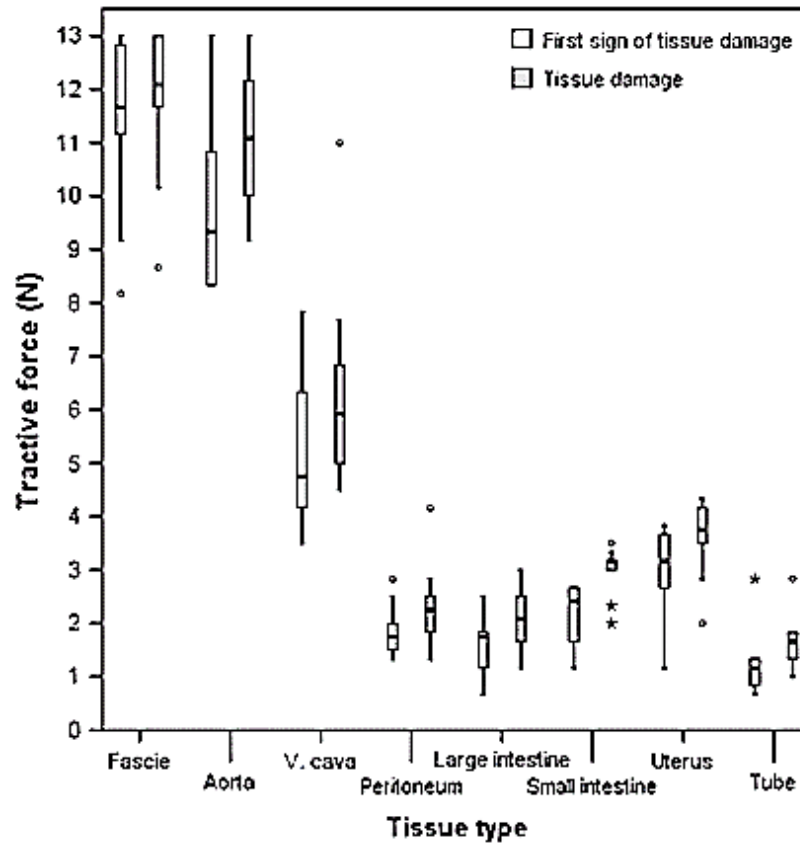


Figure 2.32: Forces on Different Types of Tissues

Different locations on an MIS tool could be identified to place the sensing elements and introduce force sensing capabilities to the tool. Following Figure 2.34. shows the possibilities and issues regarding such sensing element placement on an MIS tool.

At the actuation mechanism, force estimation could be performed by monitoring the stress of the mechanical linkages. But the problem is linkages, friction, backlash, etc. could distort the force values. The shaft outside the body can be identifiably subjected to reaction forces and friction created at the port that is being used to insert tools into the body. Therefore, the sensitivity of the measurement of tissue contact force is reduced. When considering forces on the shaft inside the body, the reactions and friction of the insertion port are minimized but, the issue is, limited space to include a sensing element would disturb the measurement. Also on the instrument tip, the measurements of the applied forces can directly be taken. The friction and other disturbance forces generated from any moving mechanisms do not affect the measurement [48].

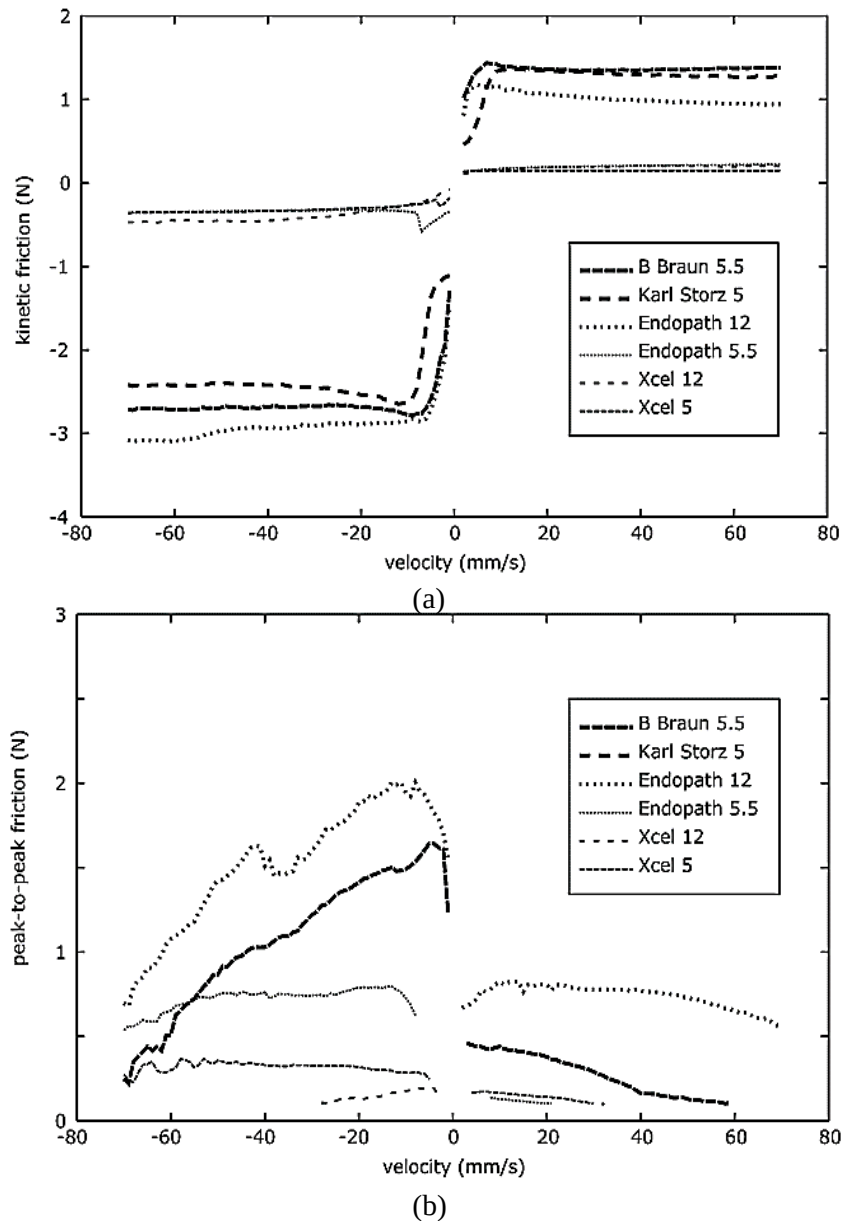


Figure 2.33: Friction Forces between the Trocar and a Dry Shaft **(a)** Kinetic Friction Found for Each Trocar for the Different Velocities; **(b)** Peak-to-peak Friction Relative to the Movement Velocity

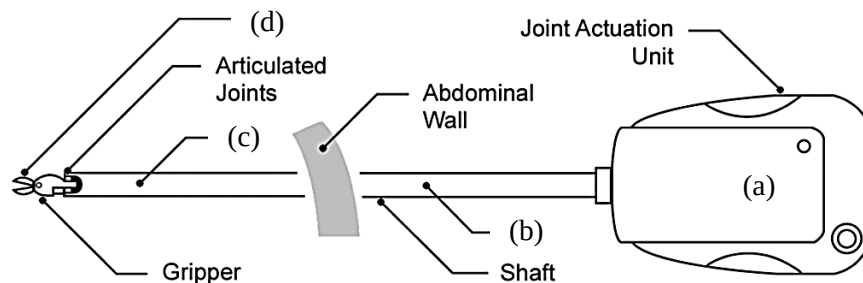


Figure 2.34: Possible Locations for Placing Sensing Elements on a Typical Laparoscopic Instrument **(a)** Near or at the Actuation Mechanism Driving a Joint; **(b)** On the Instrument Shaft Outside the Patient's Body; **(c)** On the Instrument Shaft Inside the Patient's Body; **(d)** At the Instrument Tip

2.4 SMA Based Actuators in MIS

There are many types of considerable actuation methods available for MIS such as Mechanical, Electro-Mechanical, Thermal, Electro-Thermo-Mechanical, Fluidic, etc. and the advantages and disadvantages of those actuators can be categorized as indicated in Table 2.3. From the summarized actuation methods shape memory alloy-based actuators can be considered as the suitable actuation method. Although other methods are having different advantages, the practicability of those is a question in minimally invasive actuator development. When considering electrostatic actuators, though they possess the above-mentioned advantages, the need for high voltage in actuation imposes a threat as high electric fields operate at surrounding soft tissues which are vulnerable. Other means and measures have to be taken to prevent leakage currents and electrical breakdowns.

Considering Magnetic fields as an actuation method, though they possess the required capabilities towards MIS tool development, the scaling down of them will eliminate advantages. Using pressure differential as the actuation method will make the requirement of the need of a pressure source, which will make the design complicated.

So the SMA-based actuators possess remote actuation capabilities which is a major advantage as the MIS tools work inside an isolated environment from the actuation environment. As the SMA can train to different possible shapes, the flexibility towards adaptation to the different environmental conditions is possible since the operating area mainly depends on the type of the surgical procedure. Also, reconfigurable transition temperatures allow the actuation of safe temperature margins. Mainly high possible work densities allow the actuators to design in miniaturized scale, which is an important prospect in MIS tool development.

Also eliminating several disadvantages such as low response time, heating, etc. are the challenges of this research. Since the key effects of SMA are the Shape memory effect (SME) and Pseudoelasticity, a wide range of applications is possible in many areas. NiTi-based SMAs (NiTiNOL) are advantageous for Minimal Invasive Surgery because of their excellent biocompatibility [49] with low toxicity and corrosion resistance [5].

Both super elastic and thermal recovery of SMA can provide large deformations and force for robust surgical devices for MIS. Nitinol is non-ferromagnetic and can be

used as a material for medical devices in MRI-guided surgeries. Devices made of Nitinol can be sterilized by autoclave. SMA-based tools can be purposely designed to overcome the limited degrees of freedom caused by the approach of minimal invasiveness and enable surgeons to achieve complex tasks.

Many applications can be further addressed in the field of biomedical engineering and surgery tool development [50] using NiTiNOL. Existing conventional Laparoscopic surgical instruments have some complexity with their mechanism, and they may need precise calibration. Also developing such complex parts would be a problem for the end-product cost. In [51], a detailed review was conducted about the mechanical characteristics of a Laparoscopic Stapler and its different mechanisms. It can be seen that the complexity of each section of the tool and more parts make the tool more vulnerable during the operation. It is an important aspect that the tools are simple and lightweight in nature.

So the development of Laparoscopic tools using SMA can be considered as a step forward to reduce complexity and to overcome the limited degrees of freedom caused by the minimal invasiveness [52]. Several electro-mechanical systems have developed over the years to facilitate Laparoscopic surgical procedures. Some research groups have developed robotic Laparoscopic systems with the development of Computer Aided Design (CAD), microactuators, and rapid prototyping. Those devices certainly improve the dexterity as well as the spatial awareness of the surgeons [53].

Table 2.3: Different types of Possible Actuation Methods

Actuation Method	Mechanism	Material	Advantages	Disadvantages	References
Electric field	Electrostatic force	Dielectric elastomer actuators (DEAs)	Large strains (10 to 1000%) High energy density ($>3 \text{ MJ m}^{-3}$) Self-sensing Possibly fast (10 ms to 1 s)	High voltage ($\approx 1\text{--}10 \text{ kV}$) Leakage currents risk of electrical breakdown	[54], [55]
Magnetic field	Magnetic force	Various polymers or gels (with embedded magnetic particles)	Remote actuation Complex 2D shape-programming Fast ($<10 \text{ ms}$) High force/torques (can reach torque densities $> 100 \text{ Nm m}^{-3}$)	Scales down poorly	[56]
Pressure Differential	Deformation of chamber or membrane	Elastomers (PDMS, silicones, polylactide, etc.)	High force densities ($>1 \text{ mN mm}^{-3}$) Inexpensive	Pressure source required	[57]
Heat	Thermal expansion Phase change	Bi metals Shape memory alloy	Remote actuation Simple Easy to manufacture Multiple shapes possible High strain ($\approx 50 - 800\% \epsilon$) Tailorable trans. Temp Tunable stiffness High possible work density ($<50 \text{ kJ m}^{-3}$ to 2 MJ m^{-3})	Slow ($\approx 1 \text{ s}$ to 1 min) Slow ($>10 \text{ s}$) Typically, one-way motion Low force (Typical recovery stresses $\approx 0.1\text{--}10 \text{ MPa}$)	[58]

Most of those robotic systems are cable-driven and all the movements are externally controlled by an electromechanical system [59]. It is possible to develop modular-type teleoperation systems that are controlled by joysticks [60].

There are several attempts to develop SMA actuated robotic tools and before the development of the actual model, a mathematical formulation followed by a Finite Element Analysis (FEA) is needed [61]. FEA can be incorporated into SMA actuator design because the material possesses certain strain limits where permanent deformation occurs and can be identified through such a technique [62]. Over the decades there are several biomedical applications [63] been done using SMA and there are still possibilities to perform descriptive work towards the betterment of the field.

2.5 Chapter Summary

The chapter presents an overview of the existing literature related to the research topic. The work carried out was entirely based on a programmable material known as Shape Memory Alloy. Therefore, at the beginning of the chapter, important details about SMA material such as history and evolution of the material, microstructure and phase transformation phenomenon, properties of SMA (i.e.: SME, PE, and Hysteresis), commercially available SMA materials, the fatigue life of SMA and general applications of SMA were discussed. Here, the behavior of the SMA material is primarily based on microstructural changes between two crystallographic structures known as Martensite and Austenite. SMA materials are available in many forms such as wires, tubes, sheets, etc. As the SMA-based actuators are in operation, there can be seen two types of fatigue behaviors known as mechanical fatigue and functional fatigue. This is the main limitation in the development of SMA-based actuators. The SMA-based applications are ranging from automotive, aerospace, robotics, biomedical, and many more where the research is mainly focused on the SMA-based actuators in the biomedical field.

Later in the chapter, a detailed literature review was carried out about types of actuators and operation modes of those actuators, manufacturing of SMA actuators, investigating transformation temperatures manufactured actuators, activating methods of SMA-based actuators, and controlling of SMA actuators. There are many types of applications such as reconfigurable structures, actuators, sensors, etc. that could be

realized by SMA materials. The manufacturing of SMA-based actuators is mainly based on heat treatment of SMA raw material by constraining in a fixture at the required shape to make the constrained shape during heat treatment as the parent shape. The fabricated actuators need to be analyzed in terms of investigation of transformation temperatures and several methods were discussed such as DSC, ALM, and ERM. There can be identified two types of actuation methods of SMA-based actuators according to the application and those are external heating of the SMA material and Internal or Joule heating of the material. Because of the non-linear behavior of the SMA material controlling such has to be done using special controlling techniques and those were presented in this chapter.

Finally, a literature survey was extended regarding MIS as the research focuses on SMA-based actuators for MIS. There, different types of MIS methods are presented and discussed. Also, tools used in MIS and actuation methods and required material properties in MIS tool development were presented. Furthermore, forces related to MIS tools in different procedures and force sensing were presented. Also, the existing research and development work has been presented in the area of MIS that uses SMA as the actuation material.

CHAPTER 3

STUDY ON SMA MATERIAL

3.1 Introduction

A more comprehensive study was conducted in the literature review about SMA and its practical applications. Before going into the actuator design and development stage, it is important to conduct further experimental studies on the material. The materials were obtained as wire type from the commercially available sources and very little information was available at the initial phase. So, it is necessary to perform a preliminary study about the SMA material.

These studies were mainly focused on identifying transformation temperatures of the SMA samples, and microstructural observations with elemental analyses. The obtained samples have a certain transformation temperature margin corresponding to the raw material preparation techniques. But, depending on the application, it is required to alter the transformation temperatures to match with the operating temperatures. So, heat treatment experiments were conducted to get the experiences of the material transformation temperature settings. It is evident that by changing heat treatment conditions, transformation temperatures could be altered and there should be a method of measuring them as well. So, Differential Scanning Calorimetry (DSC) analysis was conducted to obtain the transformation temperatures of the heat-treated samples [64]. Further, a transformation temperature setting criteria was suggested by evaluating the results obtained from the DSC tests. Since the behaviour of SMA material is mainly based on microstructural changes of the lattice structure, it is important to perform microstructural analysis to obtain useful observations and data which are important to deduce the material behaviour.

3.2 Analysis of Transformation Temperature of SMA Material Samples

As described throughout the literature review, transformation temperatures are significant in applications where the temperature could be a limitation such as in the MIS field. These transformation temperatures are controlled by the processing

conditions of the raw SMA material while preparing as actuating elements. Processing conditions can be identified as heat treatment temperature and the aging time of the SMA material. The following subsection explains the heat treatment procedure that has been used to prepare the material and alter the transformation temperatures accordingly.

3.2.1 Heat Treatment of SMA Material

Heat treatment and aging of the SMA material samples that were being subjected to the study were conducted by using an electric furnace. Figure 3.1 shows the furnace that has been used for heat treatment of the materials.

This furnace operates by an on-off controller which the temperature shows a significant oscillation about the setpoint temperature. As an example, if the furnace temperature was set to 400 °C, then the controller activates the heating elements and heats the furnace chamber around 433 °C, and sleeps the power off to the heating elements. Then after the temperature dropped around 387 °C, heating elements were powered up to heat the chamber.

The obtained SMA wires were cut into pieces by using a bench shear. And placed on a metallic pan which was then placed inside the furnace chamber. The samples were then heat-treated at different heat treatment temperatures to identify the changes in the

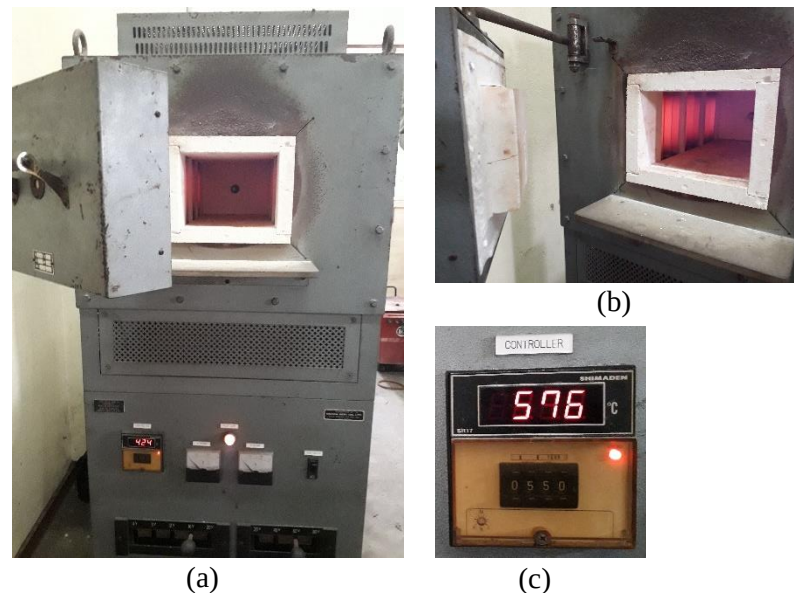


Figure 3.1: Muffle Furnace used in Sample Heat Treatment (a) Furnace; (b) Chamber; (c) Temperature Adjuster

transformation temperatures. After the heat treatment process, samples were water quenched to cool down to atmospheric temperature.

The Next task was to measure the transformation temperatures of the heat-treated material samples. The following subsection presents details about the evaluation of the transformation temperatures through the DSC technique which was described under the literature review section.

3.2.2 Evaluation of Transformation Temperatures of Heat-Treated Material Samples

There are several methods to identify the transformation temperatures of the SMA samples such as the electrical resistance method, applied loading method, and Differential Scanning Calorimetry (DSC) [65] as described in chapter 2. Considering the advantages and disadvantages discussed in the literature review, the DSC procedure was selected as the investigation method to evaluate the transformation temperatures of the heat-treated SMA samples.

DSC monitors the energy changes occurring within a sample under heating or cooling cycles. It measures the heat flow in to and out of the sample against a reference. Since the transformation phases of SMA material are Austenite (solid) and Martensite (solid), the important temperatures related to these phase transitions could be tracked through the DSC. The transformation from Martensite to Austenite absorbs heat to progress endothermic reaction. It shows a dip in the heating curve. When cooling, the transition from Austenite to Martensite expels heat to progress exothermic reaction and it shows a peak in the cooling curve. The starting and ending points of those dips and peaks correspond to the transformation temperatures of the SMA material.

The tests were conducted by the DSC Q200 instrument developed by TA instruments (Figure 3.2). Equipment specifications are presented in Appendix A. Tzero aluminum pans were used as the reference and the sample pans. The samples were subjected to a thermal program (Appendix B) where they were ramped from 0 to 120 °C at 2 °C/min temperature increments and then cooled from 120 to 0 °C at 2 °C/min temperature decrements. Nitrogen was used as the purge gas at a 50 ml/min rate. Figure 3.3. (a) shows a sample pan crimper which is used to seal the sample pans.

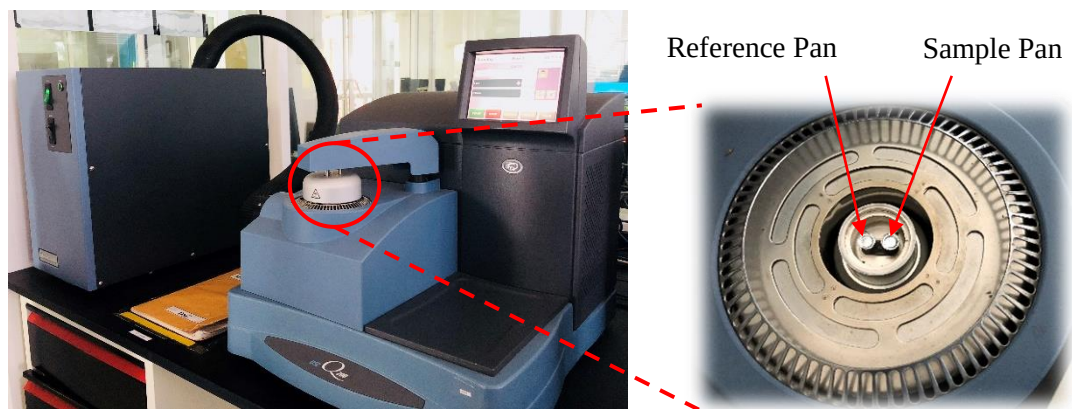


Figure 3.2: DSC Q200 Instrument Developed by TA Instruments

Figure 3.3. (b) shows the prepared sample for the testing and utilized a Tzero pan and lid. Figure 3.3. (c) shows a sealed pan using the crimper tool. Four samples were tested that had been heat-treated to different heat treatment conditions to assess the behavior of the transformation temperatures. Figure 3.4. and Figure 3.5. show the heat flow into and out of the samples during heating and cooling cycles. As depicted in Figure 3.4., the samples were heated up from 0 °C to 120 °C while monitoring the energy change of the sample pan compared to the reference pan.

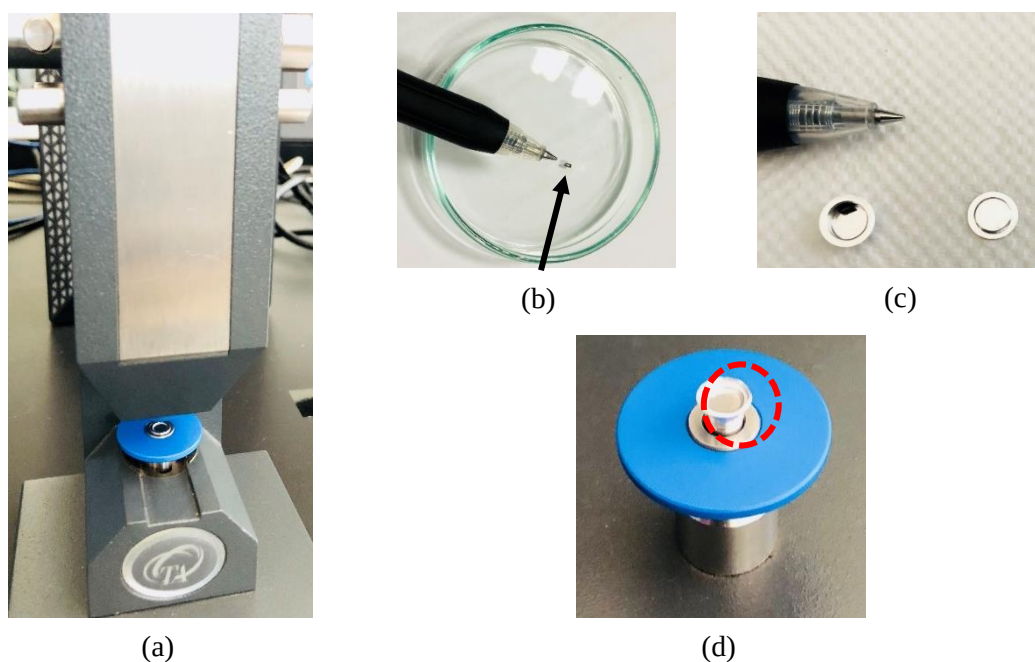


Figure 3.3: Sample and Preparation of Sample Containers for DSC tests **(a)** Crimper Tool; **(b)** NiTiNOL Sample (~10 mg); **(c)** TZero Pan and Lid; **(d)** Sealed Sample Pan

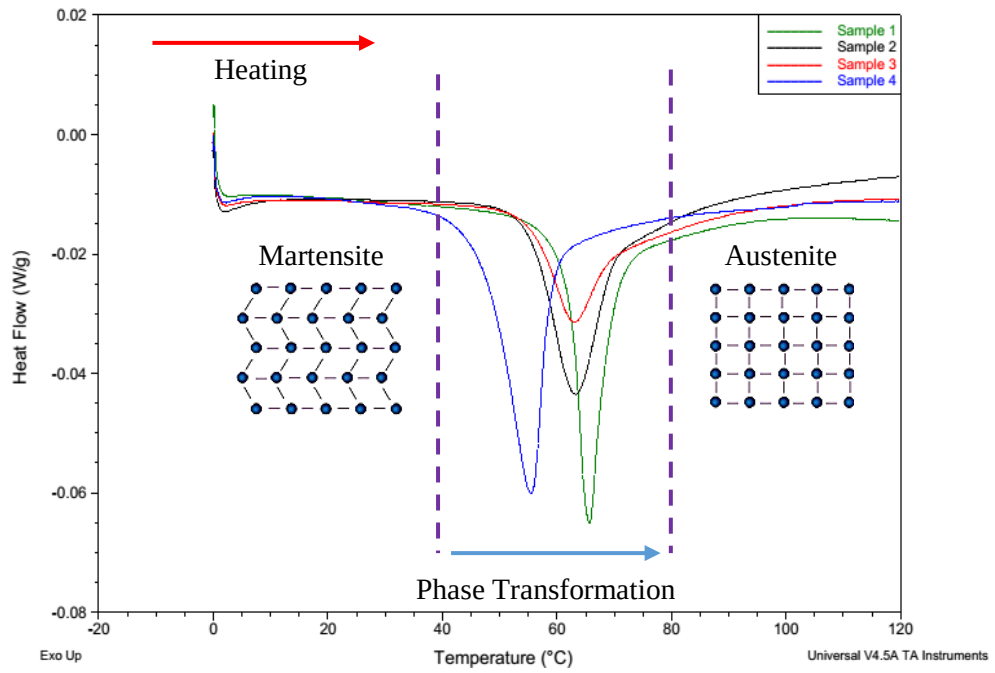


Figure 3.4: Heat Flow vs Temperature Curve for Heating Cycle

According to the heat treatment conditions applied to the samples, the transformation temperatures are supposed to lie in the scanning range of the DSC. So, at lower temperatures, SMA material is in the Martensitic phase, and with the

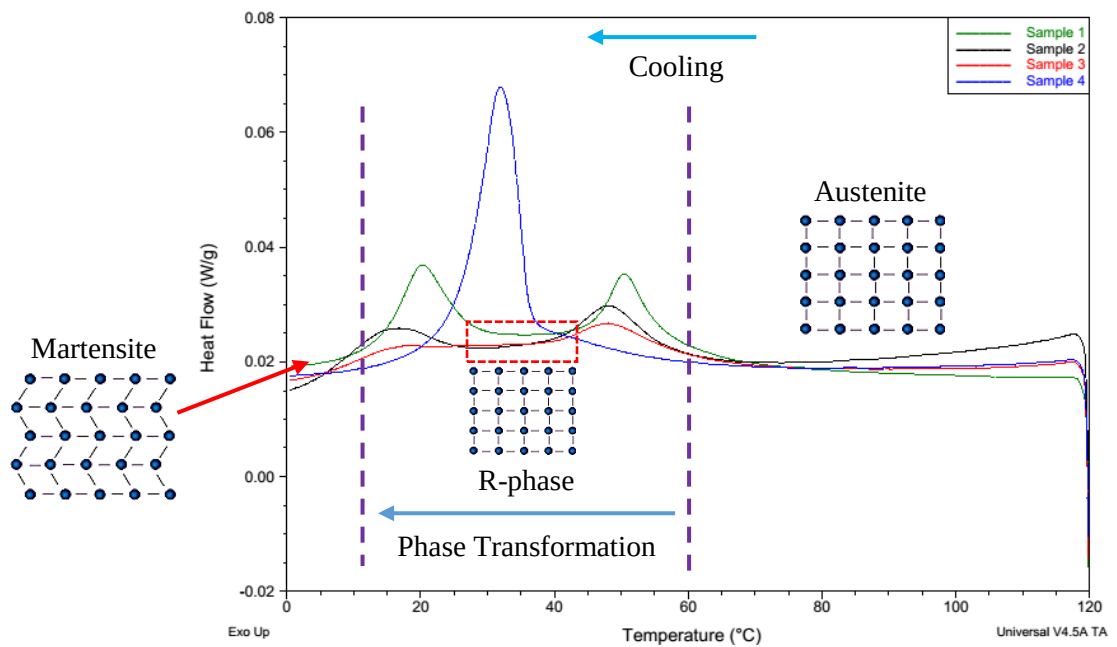


Figure 3.5: Heat Flow vs Temperature Curve for Cooling Cycle

increasing temperature, the sample absorbs heat to crystallize into the Austenitic phase and it shows a dip in the heat flow curve.

As shown in Figure 3.5, samples were cooled from 120 °C to 0 °C while monitoring the energy change of the sample pan compared to the reference pan. So, the material phase changes from Austenite to Martensite, and it shows a peak in the heat flow curve. The mentioned straight transformation from A to M was only exhibited by Sample 4 and the rest of the samples were showing an intermediate phase known as orthorhombic or commonly known as R-phase [66] while transforming from A to M.

The transformation temperatures could be found by analyzing the heat flow curve obtained through the experiments. TA Instruments Universal 2000 software (Appendix C) could be used to analyze the curves and find the onset temperatures of the dips and peaks of the heat flow curve. Following Figure 3.6 shows the heat flow graph or the thermogram which was analyzed through the software and the obtained transformation temperature values.

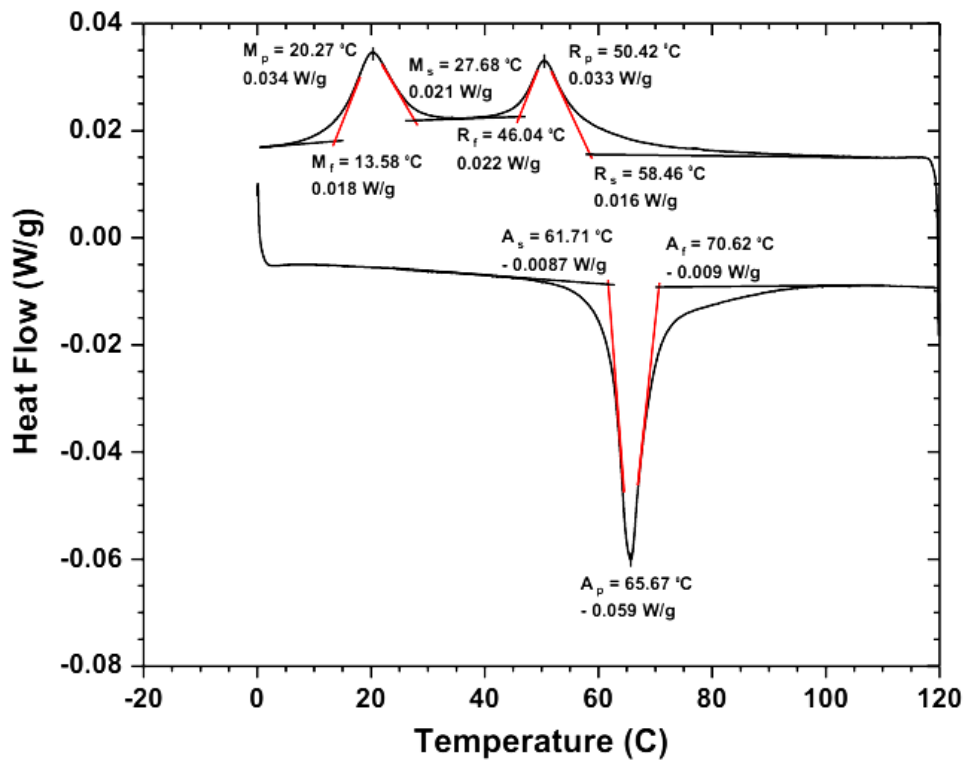


Figure 3.6: Software Analyzed Thermogram Indicating Transformation Temperatures

Thermograms of all the samples were included in Appendix D1 to Appendix D4. Extracted transformation temperature values are shown in the following Table 3.1.

Table 3.1: Acquired Transformation Temperatures

Sample #	A_s (°C)	A_f (°C)	R_s (°C)	R_f (°C)	M_s (°C)	M_f (°C)
1	61.71	70.62	58.46	46.04	27.68	13.58
2	55.46	71.35	61.33	41.19	26.25	03.46
3	55.49	72.44	63.92	40.00	23.22	04.80
4	46.20	59.52	-	-	37.00	24.66

By analyzing the acquired data through these experiments, it is evident that the transformation temperatures of the SMA material could be altered by subjecting the materials to different heat treatment conditions and that would, in turn, affect the operating temperature range of the material.

To conduct the transformation temperature setting procedure systematically, it is required to formulate a proper criterion that suits the obtained material sample. And also, that can be expanded to any Ni-Ti based SMA material. The following subsection describes an experiment conducted to formulate the shape setting criteria.

3.2.3 Transformation Temperature Setting Criteria for SMA Materials

To proceed with the experiments, 5 samples were prepared according to the pan size, sample weight range of the DSC equipment, proper contact between the pan and the material. Samples were subjected to five different temperature conditions as indicated in Table 3.2 during the heat treatment process. Here, the main idea was to monitor the variation of transformation temperatures with the changing heat treatment temperature by maintaining equal aging time for each sample.

Table 3.2: Heat Treatment Conditions of the Samples

Spring Identification	Average Heat Treatment Temperature (°C)	Heat Treatment Time (mins)
Sample 1	400	30
Sample 2	450	30
Sample 3	500	30
Sample 4	550	30
Sample 5	600	30

The heat-treated samples were water quenched and the DSC test was performed to investigate the transformation temperatures. DSC 25 equipment developed by TA Instruments was used to investigate the transformation temperatures of the material samples. Equipment specifications are given in Appendix H. Here the scanning range was 0 to 100 °C at a scanning rate of 3 °C /min during the heating cycle and the same



(a)



(b)

Figure 3.7: DSC 25 Instrument **(a)** Pan Preparation Tools; **(b)** Sample and Reference Pans Placed on the Respective Platforms Prior to Testing

scanning rate was used when cooling the samples from 100 to 0 °C temperature. Tzero Aluminum pans were used as the sample and reference pans and Nitrogen was used as the purge gas at 50 cm³/min. The corresponding thermograms for the respective samples were overlaid for quick observations and the conclusions could be drawn in a fast manner. The overlaid figure is shown in Figure 3.8.

More detailed plots are included in the annexures from Appendix F1 to Appendix F5. After the software-based analysis which is similar to the mentioned procedure in the previous sub-section, obtained transformation temperatures are highlighted in Table 3.3.

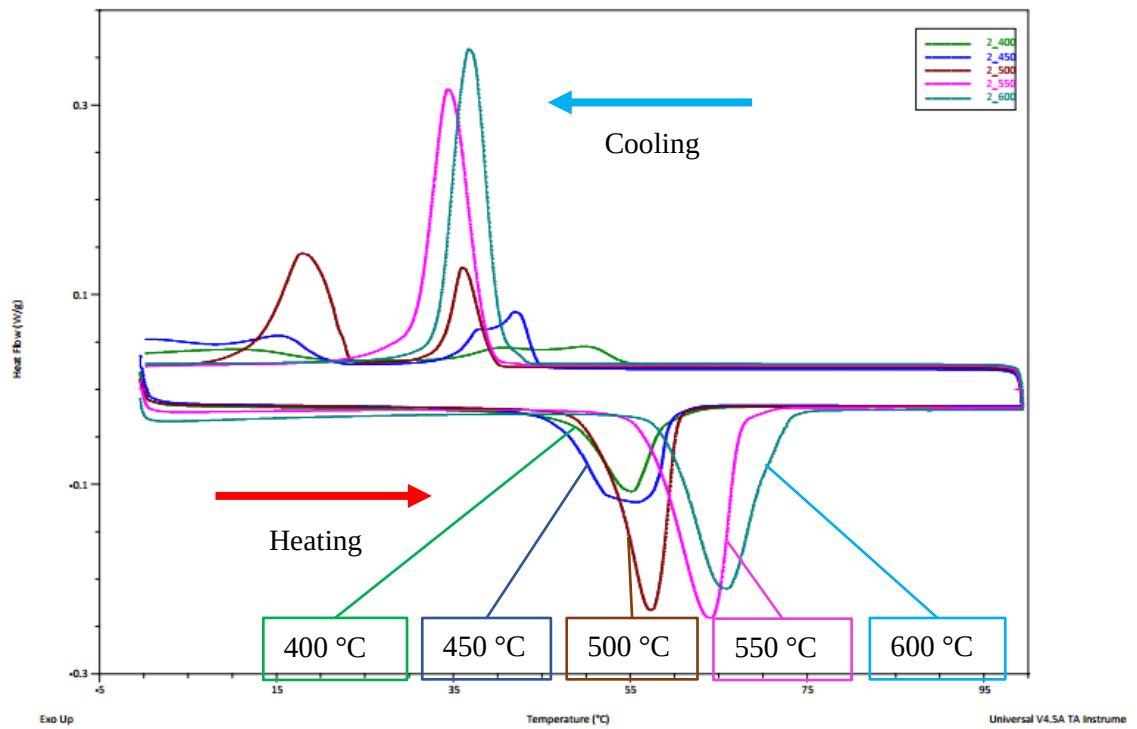


Figure 3.8: Thermogram Overlay of the Heat-Treated Material Samples

Table 3.3: Transformation Temperatures Acquired from the Thermograms

Spring Identification	A _s (°C)	A _f (°C)	R _s (°C)	R _f (°C)	M _s (°C)	M _f (°C)
Sample 1	48.71	58.98	54.68	34.81	13.37	0.2
Sample 2	47.00	59.44	44.43	35.10	20.56	14.48
Sample 3	51.87	60.22	39.23	33.71	22.84	12.66
Sample 4	56.99	67.25	-	-	38.52	30.70
Sample 5	59.07	71.34	-	-	40.20	33.15

Figure 3.9 shows the variation of transformation temperature with the heat treatment condition of the sample and the following conclusions could be drawn by looking at the above figure.

- Heat treatment temperatures below 500 °C exhibit Rhombohedral (R-phase) phase
- Above 500 °C heat treating temperatures, the samples only exhibit the main phases
- Characteristic temperatures are increasing with the increase of heat treatment temperature

By observing the results that came out from the explained experiments, it can be concluded that by changing heat treatment conditions accordingly, the required application-specific transformation temperatures are possible to achieve.

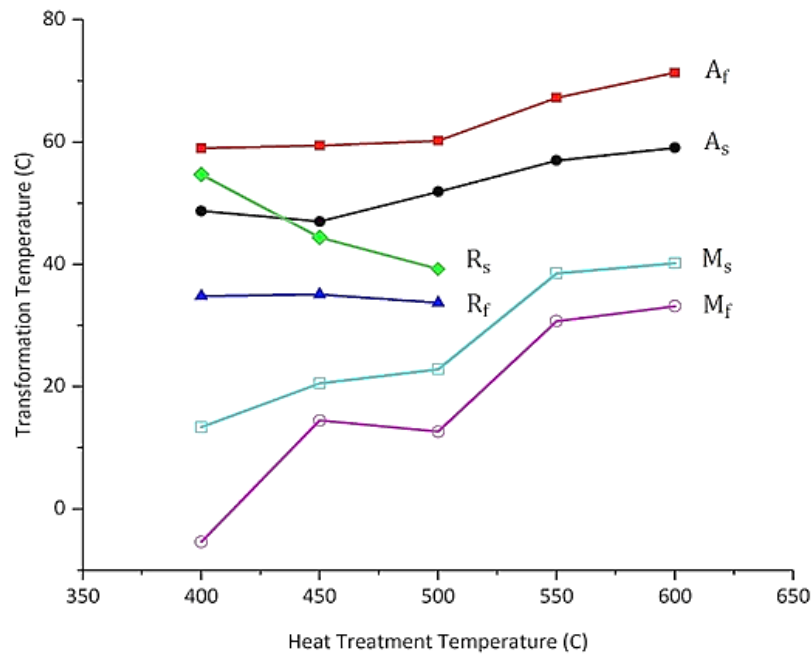


Figure 3.9: Transformation Temperature Variation with Heat Treatment Temperature

3.3 Microstructural Analysis of SMA Material Samples

The observable macroscopic effects such as stroke, and force are mainly because of the microstructural changes in the material. Also, one of the parameters which affect the transformation temperatures can be identified as the alloying composition of the SMA material. Figure 3.10. (a) [67] shows the Ni-Ti phase diagram exhibiting which phases are to be expected at metastable equilibrium for different combinations of Ni

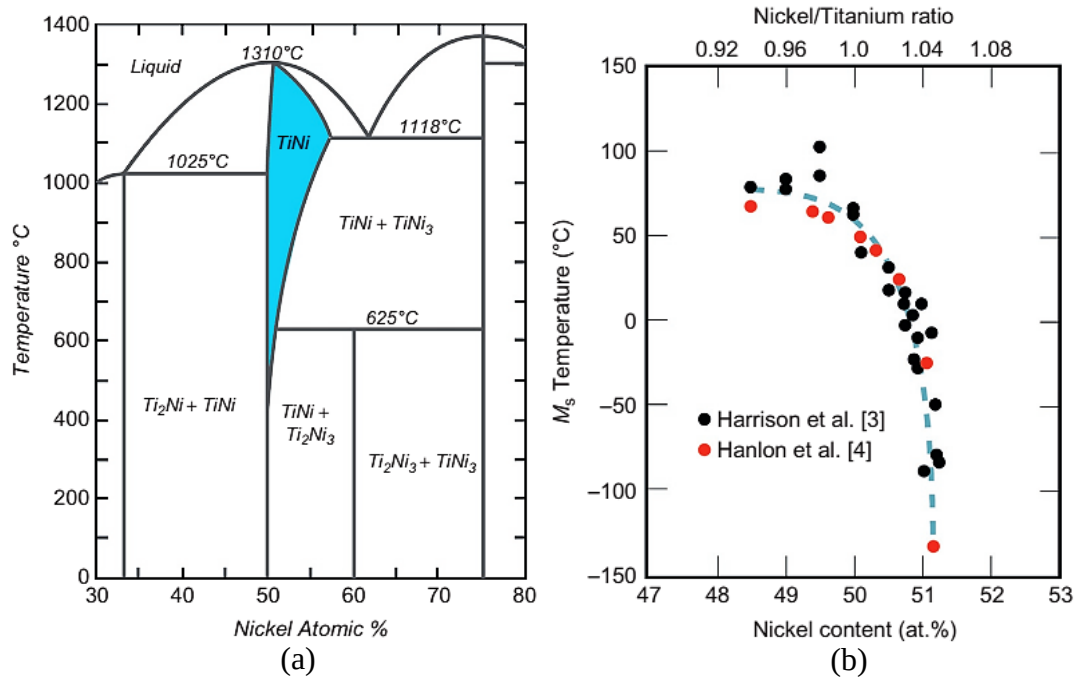


Figure 3.10: Effect of Material Compositions **(a)** Ni – Ti Phase Diagram; **(b)** Transformation Temperature Variation with Ni Percentage

content and the temperature. By varying the alloying ratio and the temperature some variants (i.e.: Ti₂Ni, Ti₂Ni₃, TiNi₃) could be identified related to the alloy which can be formed upon heat treatment. These variants highly dictate the properties of the SMA materials. Also, Figure 3.10. (b) [68] shows the variation of Martensite start temperature (M_s) with the Ni content, and it can be seen that the slightest variation of alloying ratio would cause a change in the transformation temperatures on a higher scale. Due to these reasons, identifying raw NiTiNOL composition is highly important in justifying the test results obtained through the DSC as well as the performance of the alloy.

3.3.1 Elemental Analysis by Energy Dispersive X-Ray Spectroscopy

To get the alloying element content, elemental analysis was performed using a Scanning Electron Microscope (SEM) (Figure 3.11. (a)). It can perform Energy Dispersive X-Ray Spectroscopy or known as EDX to find out the alloying compositions. Figure 3.11. (b) shows the tested sample placed on the sample holder of the SEM equipment.

EDX is an analytical technique used for the elemental analysis or chemical characterization of a sample. It focuses on an interaction of a source of X-ray excitation and a sample. Its characterization capabilities are based on the fundamental principle that each element has a unique atomic structure allowing a unique set of peaks on its electromagnetic emission spectrum.

When an X-ray beam is focused on a material sample, the electrons at the lower energy levels are kicked out from the atoms of the contained elements. This in turn creates holes at those lower energy levels and the atoms at higher energy levels tend to jump into the vacant holes by emitting radiation energy (Figure 3.12. (b)). If a jumping happens from the neighboring energy level, then it is identified as alpha (α) energy peak and if the transferring happens from the energy level which is next to the neighboring one, it is identified as beta (β) energy peak.

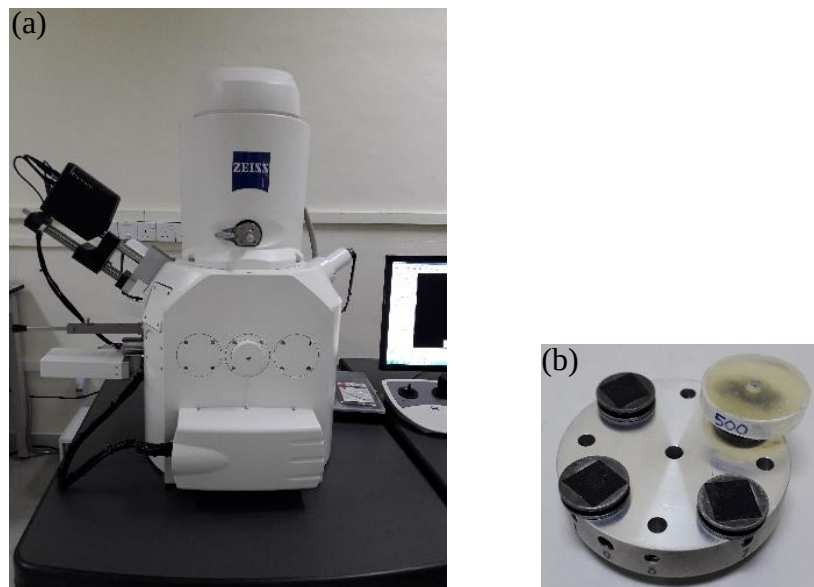


Figure 3.11: SEM **(a)** ZEISS EVO|18 Research SEM; **(b)** Sample Mounted on the Sample Holder

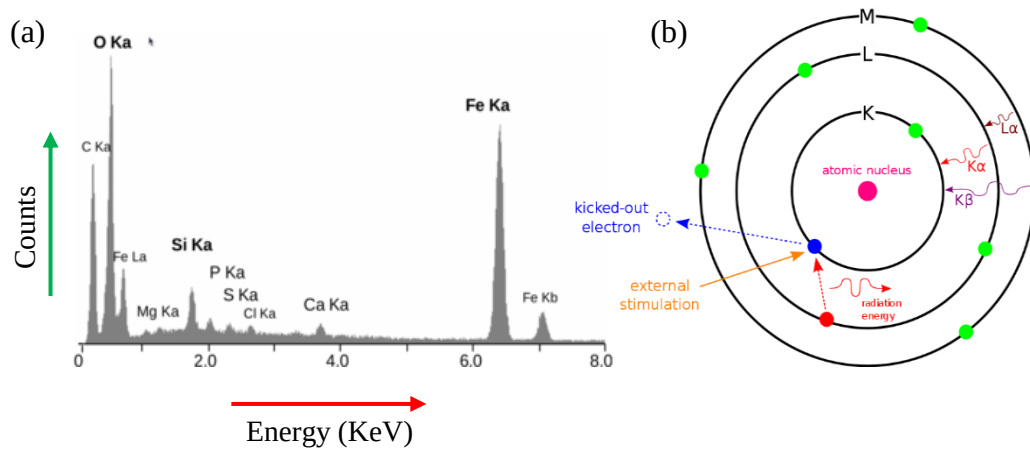


Figure 3.12: SEM EDAX **(a)** An EDX Spectrum; **(b)** Schematic of an Atom Elaborating the Phenomenon

The energy released due to these jumps was recorded by the instrument and it gives an energy spectrum indicating the number of counts or jumps that occurred at a certain energy level (Figure 3.12. (a)). Figure 3.13 depicts the EDX spectrum and the magnified view of the analyzed area of the NiTiNOL sample. So, it can be concluded that the commercially purchased material sample for testing only contains Ni and Ti.

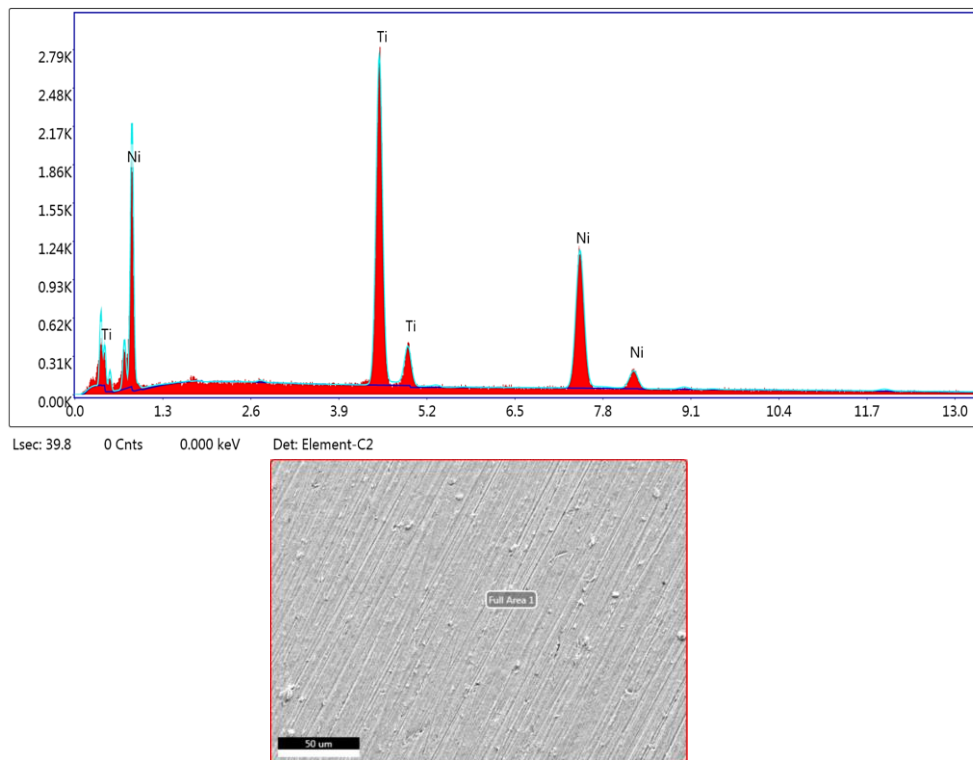


Figure 3.13: EDX Spectrum of NiTiNOL Sample and the Analyzed Area at 1000X

Appendix G presents the results obtained from analyzing the indicated EDX spectrum and the material contains Ni - 53.08 % and Ti - 46.92%

3.3.2 Morphological Analysis of SMA Samples

After obtaining the composition of the material, a morphological analysis was conducted to observe the variants which can be formed as precipitates during the heat treatment process. The presence of these precipitates is possible according to the details provided by the Ni-Ti phase diagram and the observation of the R-phase below 500 °C heat treatment temperature which was observed through DSC results. To perform such morphological observations, samples have to be prepared in a certain manner and it is described in the following Figure 3.14.

Since the DSC tested samples were somewhat small in size to handle, a special type of method was required to fix the sample on an epoxy resin which can then be prepared easily. First, a cylindrical-shaped plastic mould was taken, and the material samples were placed in the center of the mould on top of a paper. Then an epoxy resin was filled into the mould and left to solidify. After solidification, the material sample was stuck on the epoxy surface and held firmly while the grinding and polishing

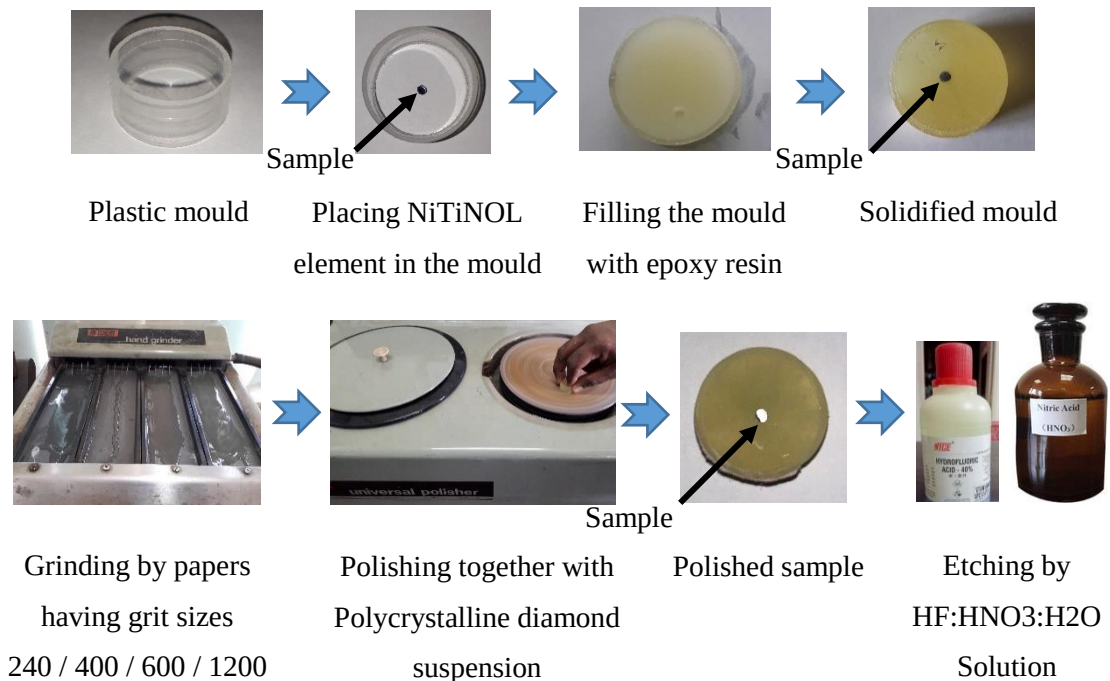


Figure 3.14: Sample Preparation Process Prior to the Morphological Analysis

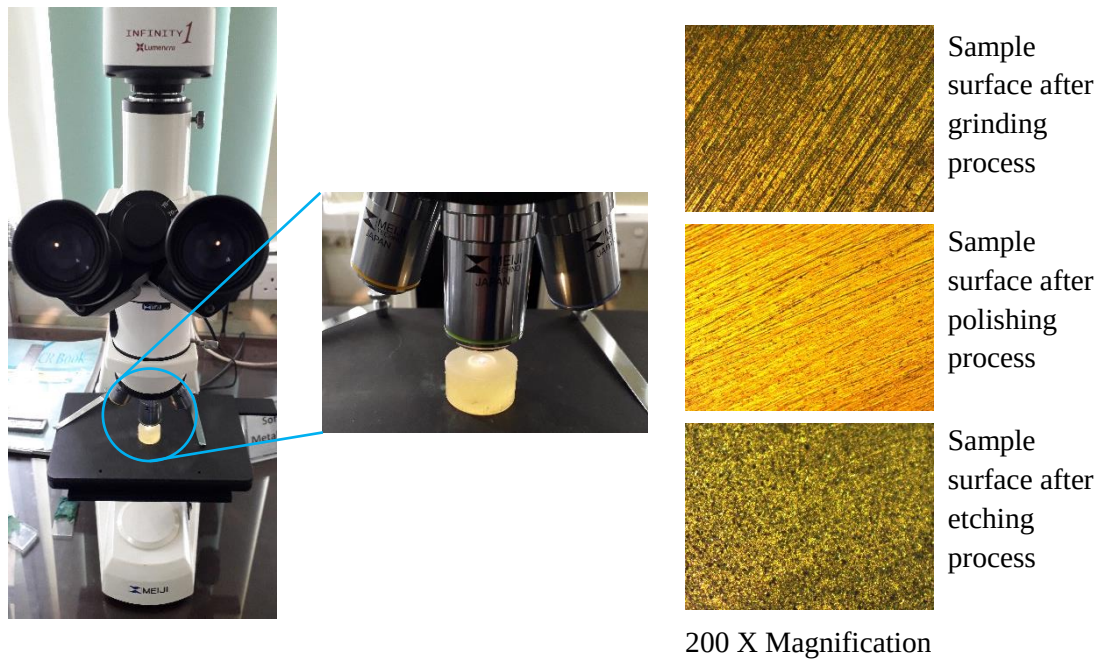


Figure 3.15: Optical Microscopic Images of Sample Surfaces at 200X Magnification

processes are being performed to prepare the material surface. Finally, the sample surface was etched by using an HF: HNO₃:H₂O solution.

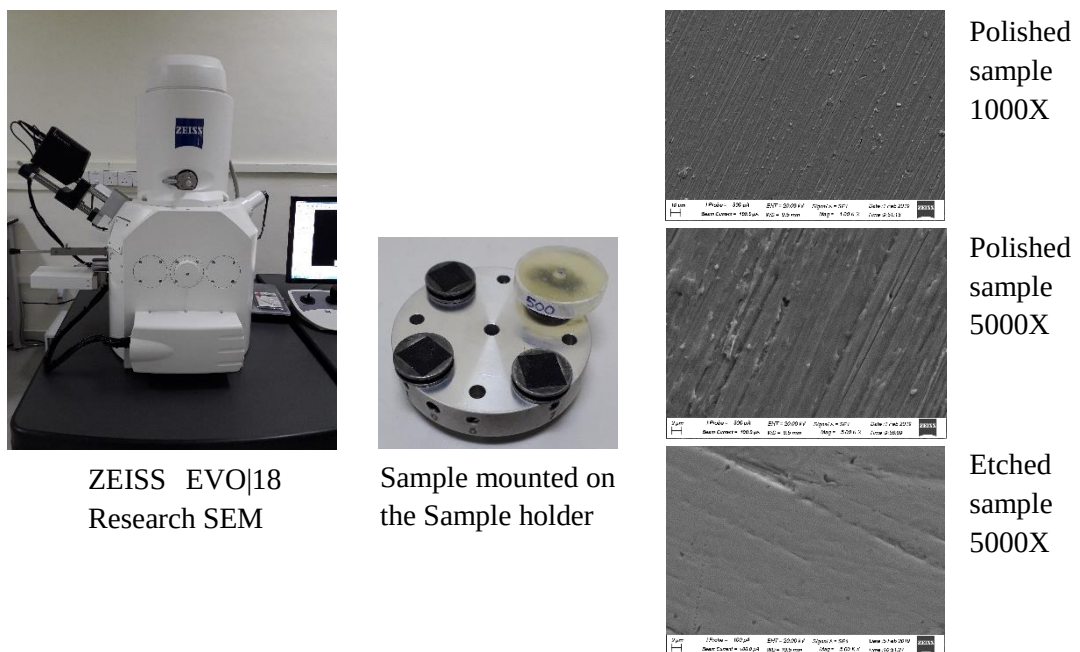


Figure 3.16: Scanning Electron Microscopic Images of Sample Surfaces

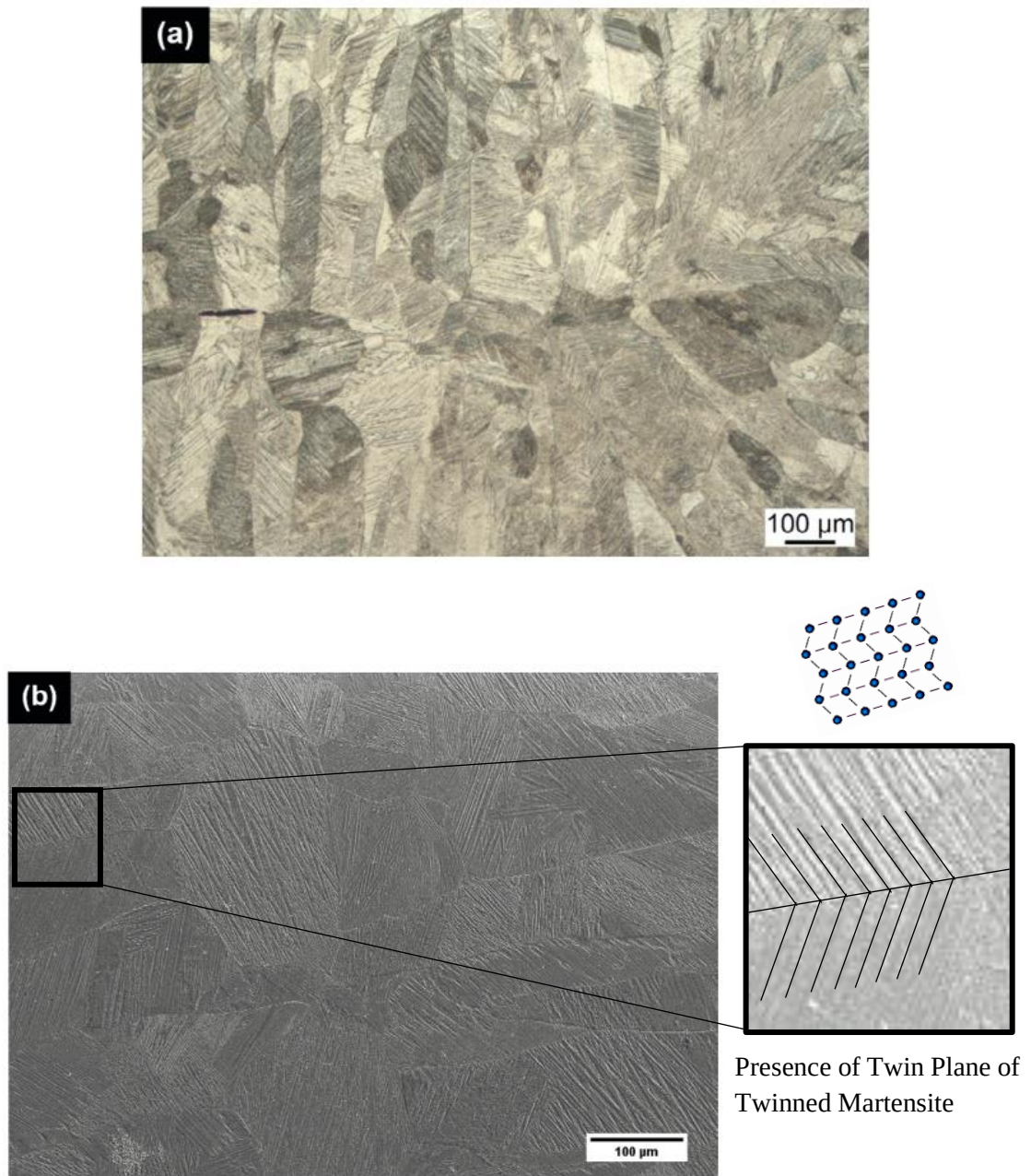


Figure 3.17: Micro Structural Observations **(a)** OM; **(b)** SEM Secondary Electron Images of Untreated Sample having Zigzag Shaped Martensite Morphology

Figure 3.15 and Figure 3.16 [69] show the Optical microscopic and SEM images of the prepared samples. After a proper sample preparation process, the twinned structure of the Martensite phase can be seen, and also the precipitations. Figure 3.17 shows such an observation achieved through Optical Microscope and an SEM. There can be seen the presence of twin planes of the martensitic microstructure as well as the grain boundaries.

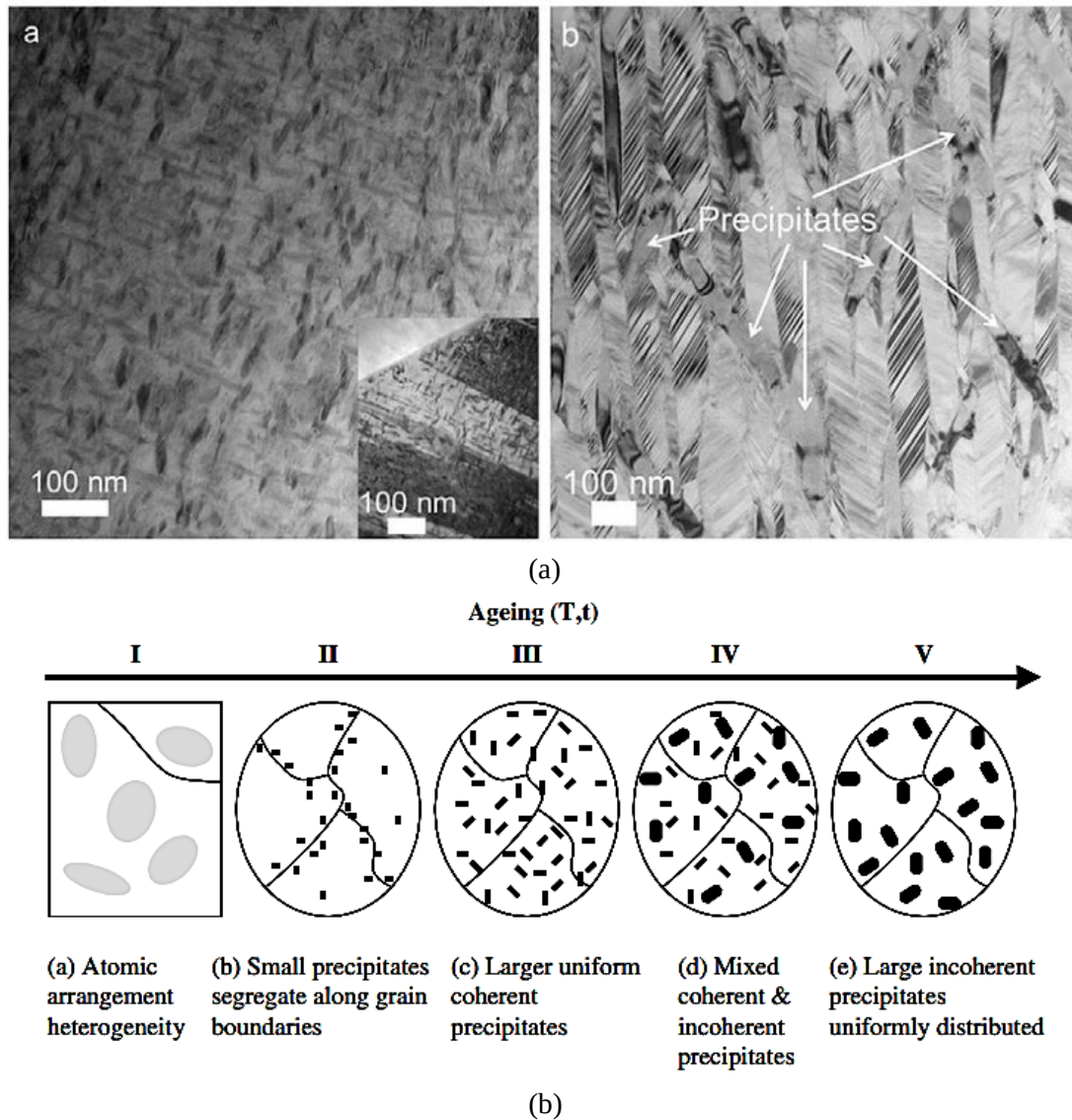


Figure 3.18: Precipitation Phenomenon **(a)** Microstructural Observation of NiTiNOL; **(b)** Precipitation Stages During Aging

Figure 3.18. (a) shows the precipitation of SMA alloy exhibiting variants that can be formed during the aging of the alloy. Some precipitates may affect in transformation behavior of the alloy as well as the mechanical properties [66]. Aging may result in internal stress variation as well as changes in chemical composition such as the formation of precipitates. With aging time the transformation behavior is shown in Figure 3.18. (b) [70].

3.4 Chapter Summary

The chapter mainly presents the outcomes of the study conducted on SMA before developments have been done using the material. Firstly, the materials were subjected to different heat treatment conditions to assess the change in transformation temperatures. There, several material samples were subjected to different heat treatment temperatures and aging times. Then the heat-treated samples were tested using the DSC technique. DSC Q200 instrument was utilized to conduct the DSC tests by setting up the instrument according to the standard guidelines and experimenting techniques [22].

Furthermore, another set of SMA samples was used to set up a transformation temperature setting criteria for commercially purchased NiTiNOL material before fabrication of actuator elements. There, DSC 25 instrument was used for test samples having different heat treatment temperatures with equal aging time. There, the samples were tested, and the results have shown that with the increasing heat treatment temperature, four temperature parameters related to the Martensite and Austenite were increased and the temperatures related to the R-phase were decreased and vanished at a certain heat treatment temperature.

Finally, the samples were subjected to microstructural observations for identification of grain structure and presence of precipitates. Also, the morphology of the samples was observed using OM and SEM. The transformation temperatures are mainly depending on the material composition, elemental analysis was conducted using the SEM EDX method. There, the commercially purchased materials were found out to be Ni-rich binary alloy having Ni - 53% and Ti - 47%.

CHAPTER 4

DESIGN AND DEVELOPMENT OF A SHAPE MEMORY ALLOY BASED ACTUATOR ELEMENT

4.1 Introduction

Throughout the previous chapter, the operational theory and material properties of SMA are thoroughly discussed and it is important to understand the SMA properties, behaviors, and practical limitations which are focused on the development of SMA-based actuators for the MIS applications. According to the work carried out, the next task was to design and develop an SMA-based actuator element as it was one of the most important aspects of this research. An actuator is a device that produces useful work on the environment according to the actuation mode. SMA-based actuators are thermo-mechanical or electro-thermo-mechanical actuators that produce work based on a pre-defined shape. As discussed in the literature review, compared with the available actuation methods, SMA-based actuators are advantageous in miniaturization, customization, cost reduction, etc.

Selection of suitable commercially available material type is required before forming or defining a shape to the actuators. As the commercially available raw materials are in raw forms (wires, plates, tubes, etc.), a fixture was needed to form the required actuator shape. According to the application, the parameters of the actuators were selected. Special fixtures were manufactured by considering the required parameters and raw material was fixed into the required shape using the fixtures, before the shape setting process. Shape setting was performed at high temperatures to form the required actuator shape. Depending on the requirements, the activation temperatures were being selected, and accordingly shape setting temperature and time were chosen.

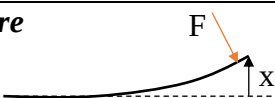
4.2 Selection of the Actuator Type and Actuator Material

There are various types of SMA actuator material available for use in different application areas. Among those, NiTiNOL [71] was selected as the SMA material to

develop the actuator. The main reason behind the selection is due to the biocompatibility of the NiTiNOL material over the other SMA material types.

NiTiNOL is available as wires having different diameters. Among many types of actuator configurations, a linear-type actuator was selected to use in the mentioned application area. When considering linear actuators for MIS tools, force and stroke capabilities are important. The following comparison gives an overview and justification for the selection of actuator type in this work.

Table 4.1: Possible Actuator Types

Actuator Type	Stroke	Force
Wire 	Moderate	Low
Wave 	High	Moderate
Spring 	High	High

Wire-type actuators can produce moderate strokes, but forces are somewhat low. Wires can be formed into Wave shapes to maximize the stroke and acquire more force than wire-type actuators. The most promising shape which can be formed by the wire type material is the spring shape. It produces high strokes and high forces according to the spring parameters chosen as per the necessity of the applications. The following subsection describes the process of the spring-type actuator forming technique.

4.3 Design and Fabrication of SMA Based Actuator Element

Comparing the advantages and disadvantages of discussed actuator element shapes, spring shape was selected, and several parameters were identified at the designing stage. As the requirement was to obtain a usable stroke with a proper force output from the spring element, the following parameters were selected as the governing parameters. Figure 4.1. shows the parameters.

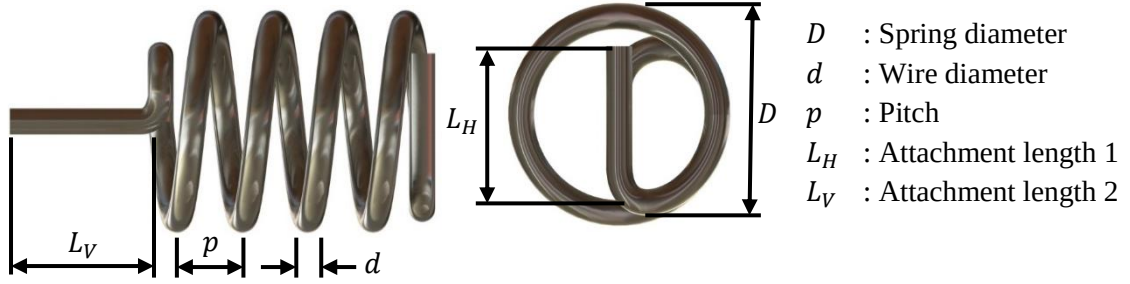


Figure 4.1: SMA Spring Parameters

4.3.1 Parameter Selection for the Actuator Element

Wire diameter (d) was a limiting parameter to the spring diameter (D) as the minimum spring diameter that can be manufactured mainly depends on it. Also, usable force output was mainly depending on the wire and spring diameter, which is going to be discussed in a later chapter. Pitch value was a factor to be considered in stroke selection. The combined effect of initial extension and the pitch dictates the usable stroke at zero load condition and when loading comes into play, the stroke depends on the load as well. Attachment lengths assist to mount the actuator element within the linear actuator. Wire diameter is one of the main parameters which dictates heating and cooling rates of the actuator element and in turn control the response time of the actuator.

4.3.2 Development of a Fixture for SMA Material

As explained in the Literature review and the Introduction sections, the selected SMA material is wire type and available in the form of straight wires at temperatures above Austenite final temperature. Since forming or shape setting has to be performed at elevated temperatures, without a fixture SMA tends to regain its raw shape. Considering that effect, special fixtures need to be designed to develop actuators with various shapes.

Firstly, to get an understanding of the manufacturability of such a spring shape, SMA wires having two different diameters were used with simple fixture types as depicted in the following figures.

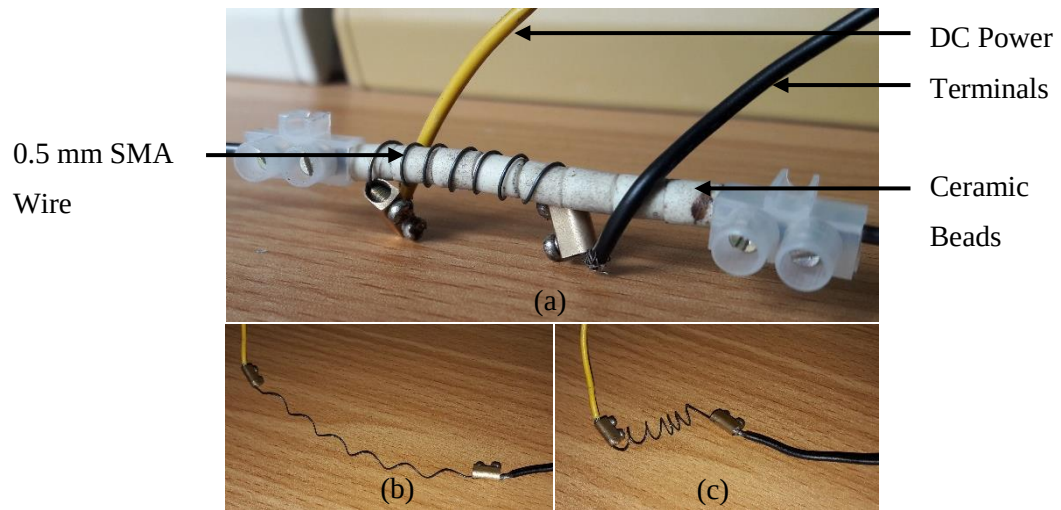


Figure 4.2: Shape Setting by Direct Heating **(a)** Simple Spring Forming Fixture; **(b)** Deformed Spring; **(c)** Shape Recovered Spring

Figure 4.2. shows a simple fixture created by using ceramic beads and the SMA wire was wound around the beads to form an approximate spring shape. The two ends were tightly held together and connected to a DC power supply, which was used to heat the material by Joule heating to set the spring shape. But the maximum temperature that could be attained through this method was approximately around 120°C . Though the spring formation was taken place and exhibited operation when subjected to heating and cooling cycles, it has shown very few operation cycles before losing the shape memory effect.

Figure 4.3. shows simple fixtures developed from standard nuts and bolts to hold SMA wire in the spring shape while the shape setting operation was taking place. The SMA wires were wound around the threaded part to obtain a spring shape and fixed at the two ends. These fixtures were then placed at the furnace as described in Chapter 3 to form the spring shape. These two were given good results in terms of the uniform shape of the spring and the number of cycles of operation since they are heat-treated at higher temperatures compared with the Joule heating method. But, through this method, there was a problem of increasing the coil diameter as the heat treatment process proceeded, due to expansion of the SMA wire radially. Because the spring shape was not constrained in the radial direction. Also, there are issues with customizing the shape of the free ends of the actuator element through this method.

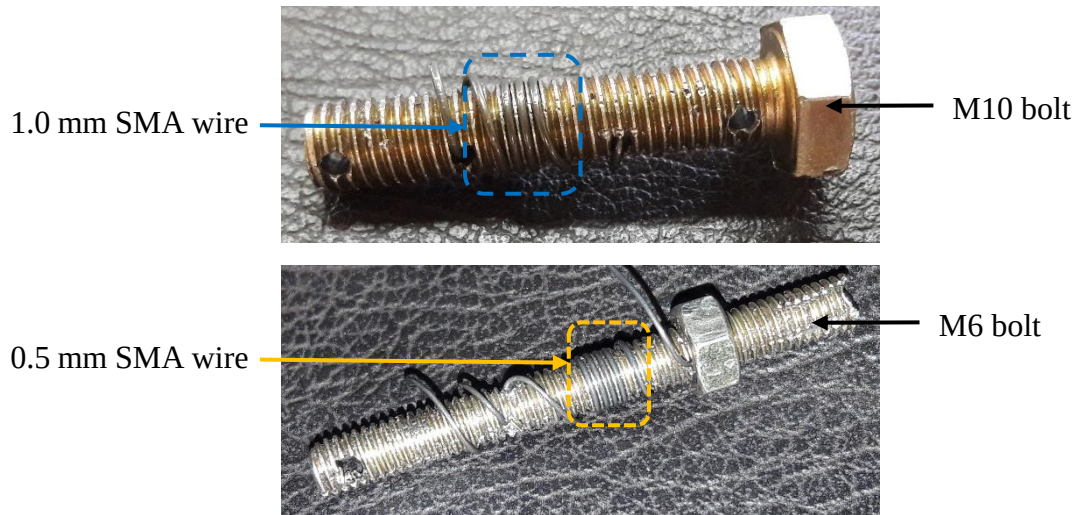


Figure 4.3: Spring Forming Fixtures for Furnace Heat Treatment

To avoid the above-mentioned difficulties and facilitate flawless spring formation, a novel fixing method was introduced. So, a novel fixture was designed and developed using conventional machining techniques. Figure 4.4 shows the conceptual design of the Fixture. Detailed drawings are presented in Appendix P1 through Appendix P3. It comprises a wire attaching section with a spiral-shaped groove, attachment length forming grooves (AL1 and AL2), and a sleeve to hold the spring shape during the heat treatment process. The fabricated fixture is shown in Figure 4.5.

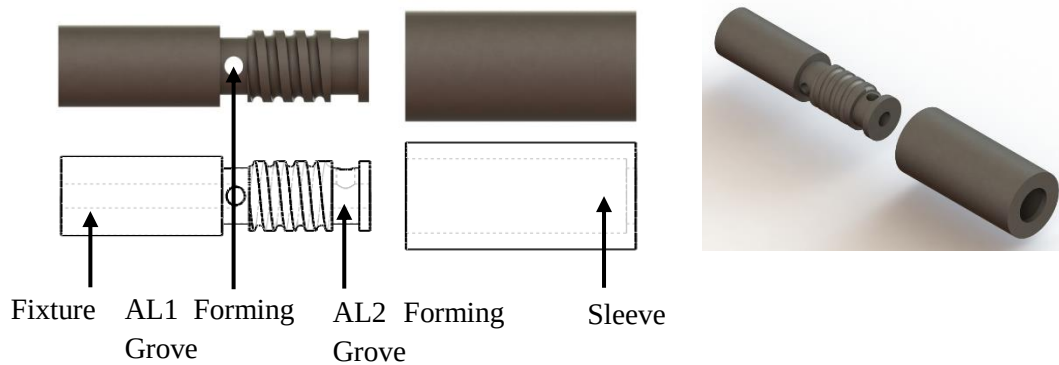


Figure 4.4: Customized Fixture Design for SMA Spring Formation



Figure 4.5: Spring Forming Fixture **(a)** Fabricated Fixture and Sleeve; **(b)** Assembled Fixture

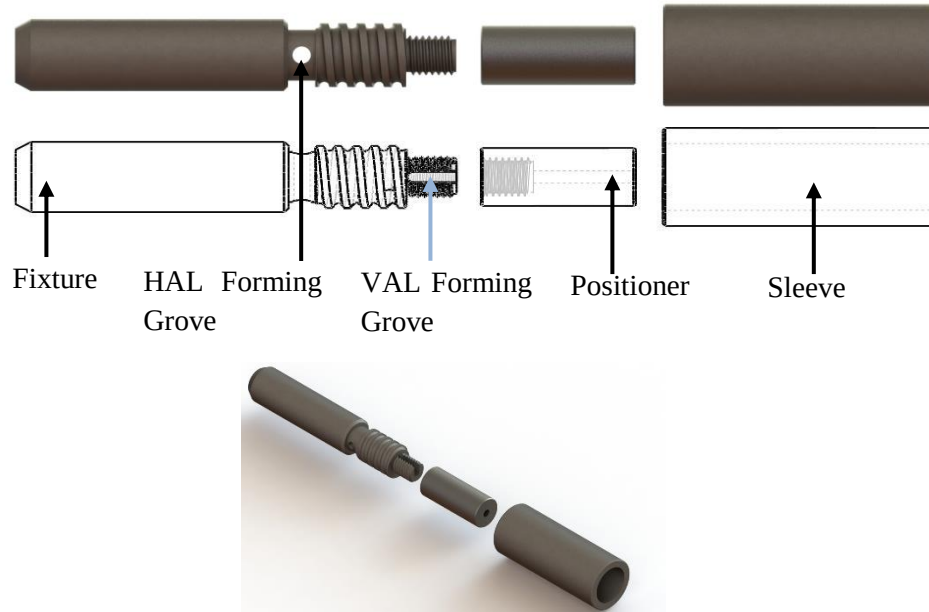


Figure 4.6: Modified Fixture Design for Attachment Length Correction

Figure 4.5. (a) shows the fixture and sleeve parts separately and Figure 4.5. (b) shows the assembled configuration of the fixture. There were slight deviations of the attachment lengths in the final spring shape formed through the fixture shown in Figure 4.5. A new design was implemented to solve this problem which is shown in Figure 4.6. and the fabricated fixture is shown in Figure 4.7. Production drawings are presented in Appendix P4 through Appendix P7.

Figure 4.7. (a) shows the fixture, positioner, and sleeve parts separately and Figure 4.7. (b) shows the assembled configuration of the fixture and the positioner and Figure 4.7. (c) shows the final configuration of the fixture after inserting the sleeve. Material selection for the spring forming fixture has to be conducted properly. Cooling of the SMA actuator after the heat treatment process is mainly dictated by the fixture material. At the same time, the material should have a low thermal expansion coefficient and should withstand a higher number of thermal cycles.

The material for the Fixture is AISI 1010 Carbon Steel and machining was done as the manufacturing process. The helical grooved shape in the fixture is designed to satisfy these parameters for the spring actuator.



Figure 4.7: Modified Fixture **(a)** Fabricated Sleeve, Positioner and the Fixture; **(b)** Positioner Assembled with the Fixture; **(c)** Assembled with the Sleeve

Raw SMA wires need to be wound around the spiral groove located at the fixing part and attachment length sections need to be formed by guiding the ends of the wires through the attachment length forming grooves before shape setting operation takes place. The Vertical Attachment Length ($VAL - L_V$) is aligned with the axis of the spring by the positioner. The spring is then constrained by a sleeve to hold its shape

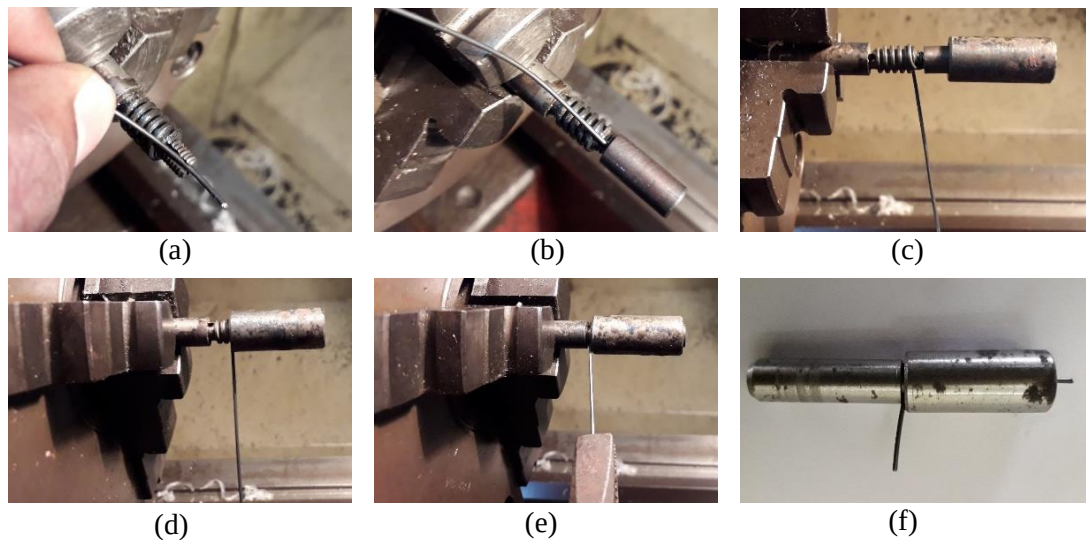


Figure 4.8: Fixing the Material **(a)** Positioning the VAL; **(b)** Tightening VAL by the Positioner; **(c)** Winding the Wire; **(d)** Constraining by the Sleeve; **(e)** Tightening the Sleeve; **(f)** Wire and the Fixture before Shape Setting

during the heat treatment process. The Horizontal Attachment Length (HAL - L_H) is formed by guiding through a hole located perpendicular to the axis of the fixture.

The gauge of NiTiNOL wire used in the actuator development is 1 mm and initially, it possesses a considerable amount of bending resistance when it is bent beyond a certain radius of curvature. Winding straight wire into a spring shape would require a special technique (see Figure 4.8).

The process of forming the initial spring shape would require a rigid holding method for the fixture and at the same time to acquire a rotational motion. A rotatable chuck was used to hold the fixture while the winding process is performed. The fixture part was tightly held within the chuck jaws and the VAL was placed at the centering groove. Then the Positioner was screwed to the fixture. The free end of the NiTiNOL wire was pulled and guided through the helical groove by rotating the chuck. As the wire is winding along the helical groove, the sleeve was used to constrain the spring shape to avoid the unwinding of the wire due to bending resistance. At the final turn of winding, the free end was guided through the hole located perpendicular to the axis of the fixture to form the HAL. Finally, the sleeve was tightened to the fixture.

4.3.3 Shape Setting of the Actuator

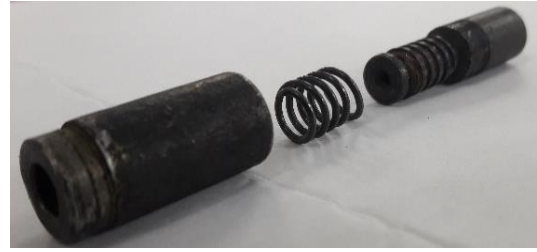
As discussed in subsection 3.2.1. Shape setting operation is carried out in a Muffle furnace at elevated temperatures and heat treatment times. Based on the literature review transformation temperature mainly depends on the composition of the NiTiNOL material, Heat treating temperature and time. Since the composition is assumed to be uniform throughout the material, by changing the heat treatment temperature and the time, the required transformation could be achieved. Spring actuators produced from the two fixtures are shown in Figure 4.9. and Figure 4.10.



(a)



(b)



(c)

Figure 4.9: Spring Fabricated by Fixture 1.0 **(a)** Fixture after Heat Treatment; **(b)** Shape Set Spring Attached to the Fixture; **(c)** Fabricated SMA Spring



(a)



(b)



(c)

Figure 4.10: Spring Fabricated by Fixture 2.0 **(a)** Fixture after Heat Treatment; **(b)** Shape Set Spring Attached to the Fixture; **(c)** Fabricated SMA Spring

4.4 Chapter Summary

This chapter presents about design and development of SMA-based actuator elements. After getting an overview of the material characteristics and limitations of SMA material, the next step was to develop an actuator for a specific application. The actuator was selected as a spring-type actuating element by considering the advantages and disadvantages of other actuator geometries. The material used for the actuator development was a commercially available SMA material known as NiTiNOL.

As the next step, several parameters related to the spring geometry such as coil diameter, number of turns, pitch, and configuration of the end connections were carefully selected by considering the manufacturability of such geometry. According to these parameters, a fixture was developed using conventional machining techniques. The NiTiNOL wire material was fixed on the fixture by a special assembling technique and subjected to heat treatment under known conditions. The heat-treated materials were then disassembled from the fixture and the result in spring shape was finalized to apply in developments of linear actuators for MIS applications which are described in a later chapter.

CHAPTER 5

CHARACTERIZATION OF THE SMA BASED ACTUATOR ELEMENT

5.1 Introduction

Chapter 4 mainly discusses the design and development of the actuator from selected SMA material. The actuator element is the key to obtaining forces and strokes on the mechanism to do useful work. The next task is to characterize the developed actuator in terms of force. Because the magnitude of the actuator force is important to get an understanding of the forces in its applications. Here, the actuator element was activated through two possible activation methods as mentioned in the literature review by Joule heating and external heating. A force characterization apparatus was developed using a custom-made full bridge load cell. A simulation was carried out before monitoring the force, to get an understanding of temperature distribution near the actuator element, when the external heating process was carried out.

5.2 Activation Methods for SMA Materials

As discussed earlier there are two possible activation methods named Joule heating and external heating available for applications. The following sections describe these activation methods.

5.2.1 Joule Heating Method

SMA material possesses an internal resistance as it is an alloy. When the material is connected to a voltage source, a current passes through and causes the material to heat because of its inherent resistance. The amount of heat generated is proportional to the square of the current passing through the material and it is known as Joule heating of the material. Figure 5.1. (a) shows a schematic of Joule heating circuitry. The material heats up internally, hence named as internal heating of SMA material and

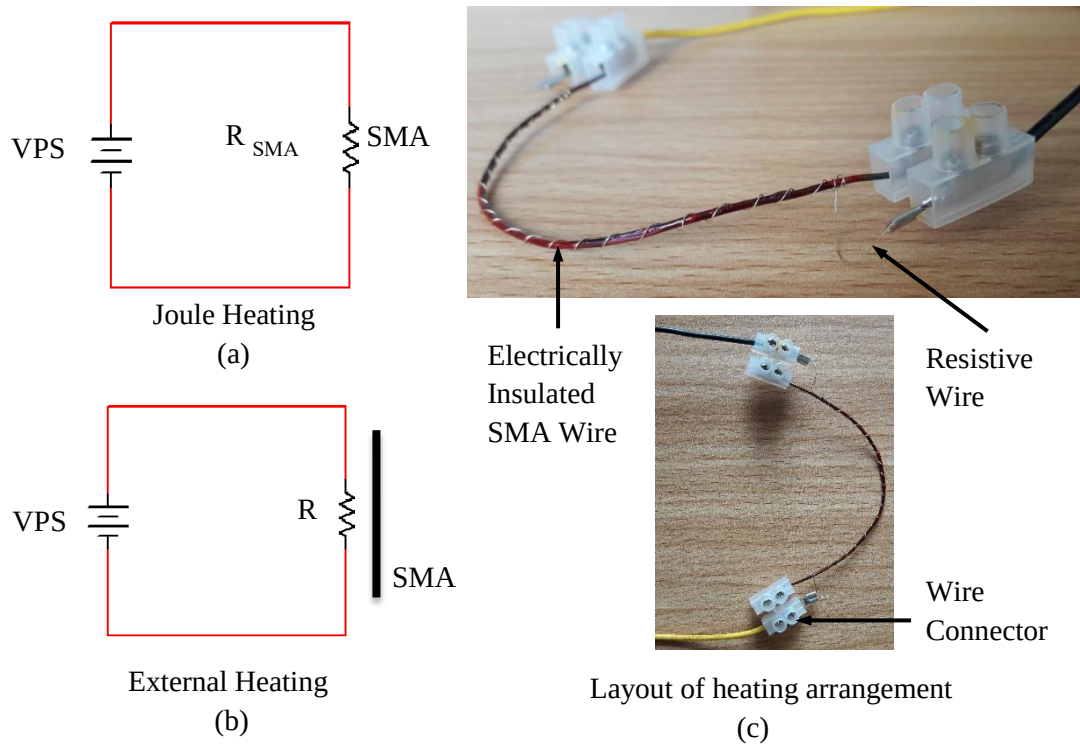


Figure 5.1: Activation Methods of SMA **(a)** Joule Heating; **(b)** External Heating; **(c)** Layout of Heating Arrangement

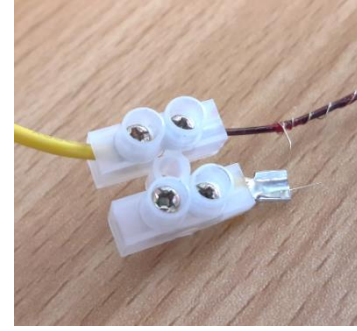
it takes a lesser time than the external heating method. A proper cooling method should be introduced to enhance the response time of the SMA actuators operating by Joule heating.

5.2.2 External Heating Method

Heating the SMA material by an external mean is known as external heating of SMA material. With this method, SMA heats up externally and the heating time would be slightly higher than the Joule heating if equal energy is being provided at both instances. Figure 5.1. (b) shows an instance where a resistive wire is wound around the SMA wire material, and a voltage source is connected at the two ends of the resistive wire. The voltage source and the wire connector are shown in Figure 5.2. The wire heats up by Joule heating and it acts as an external heat source to the SMA material. This external heating method requires electrical insulation between SMA alloy material and resistive wire material. Figure 5.1. (c) shows an arrangement of this sort of heating method. An electrical insulation coating was applied to the SMA material before winding up the resistive wire.



(a)



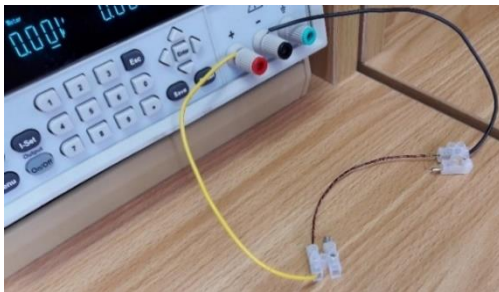
(b)

Figure 5.2: Joule Heating **(a)** Variable Power Supply (VPS); **(b)** 5A Electrical Connector and Wires

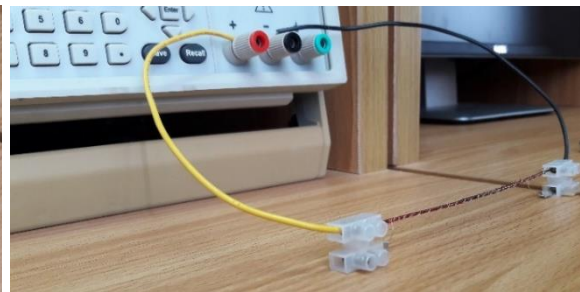
SMA wire-type material elements were tested by direct (Joule) and indirect (external) heating methods to get an understanding of the actuation time variation. The wire element has a straight shape (Figure 5.3. (b)) when it is in its parent phase (Austenite) or the high-temperature phase.

SMA wire was curved by applying an external force (Figure 5.3. (a)) at room temperature which is lower than the transformation temperature and upon applying heat by the respective method it was transformed into the parent form.

But as actuation cycles go on, the insulation layer tends to crack because of the shape change of SMA material. Therefore, fluid-based external heating methods are more successful than the above-mentioned method. Considering the compactness, the described method is more compact than the fluid-based method, because of additional fluid channels needed around the SMA actuator element. Therefore, more focused design is required with a fluid-based external heating method.



(a)



(b)

Figure 5.3: Shape Recovery of SMA **(a)** Deformed Shape; **(b)** Parent Shape

The next section describes the force characterization of the actuator element which is discussed in Chapter 4.

5.3 Force Characterization of SMA Actuator Element

The main idea of the force characterization is to measure the amount of force that will exert by the actuator element on the outside environment when it is in operation. The developed actuator element is a spring shape actuator, and it is capable of exerting forces and producing useful strokes in the axial direction. So, the characterizations were carried out by constraining the spring at one end and fixing the free end to a force sensor. At this stage, the spring was extended beyond its initial shape. As the temperature increases beyond the transformation temperature margins, the spring tries to recover to its initial shape. In here force sensor senses the amount of force exerted by the spring element. This scenario is defined as constrained recovery of the spring actuator. Depending on the initial extension/ deformation, the force sensor gives the maximum force output from the spring element. The most important part is how the temperature of the actuator element is raised and it was achieved by the external heating method. A fluid-based external heating method was used to heat the spring element and a specially developed force characterization apparatus was used to measure the forces. The following subsections will describe the individual components of the system.

5.3.1 Development of the Force Characterization Apparatus

Force characterization apparatus consists of a force sensor, fluid container, fixtures, electronics, and computer-based software interfaces. The following subsection explains the selection procedure of the force sensor.

Selection of the Force Sensor

A force sensor is a device that converts force into measurable electrical output. A load cell is a type of force sensor when connected to appropriate electronics, returns a signal proportional to the mechanical force applied to the system. Although there are many varieties of load cells such as hydraulic, pneumatic, etc., strain gauge based load cells are the most commonly used type in load measuring applications. Moreover,

bending beam type load cells are widely used in various industries for measurements varying from process control to tank weighing systems. Strain gauges bonded to the surface are used to measure the strain and convert it to an electrical output. With stress raisers, the sensitivity of the load cell can be increased.

The sensing element which was used in developing the force sensor is a Strain Gauge and it is an Electromechanical device that converts material strains at the place where strain gauges are tightly bonded, into a voltage output. There are many types of strain gauges. Among them, a universal strain gauge has a structure such that a grid-shaped sensing element of thin metallic resistive foil (3 to 6 μm thick) is put on a base of thin plastic film (15 to 16 μm thick) and is laminated with a thin film (Figure 5.4 [72]).

The strain gauge is tightly bonded to a measuring object so that the sensing element (metallic resistive foil) may elongate or contract according to the strain borne by the measuring object. When bearing mechanical elongation or contraction, most metals change electric resistance. The strain gauge applies this principle to strain measurement through the resistance change. Generally, the sensing element of the strain gauge is made of a copper-nickel alloy foil. The alloy foil has a rate of resistance change proportional to strain with a certain constant. The principle [73] can be depicted by the following equation,

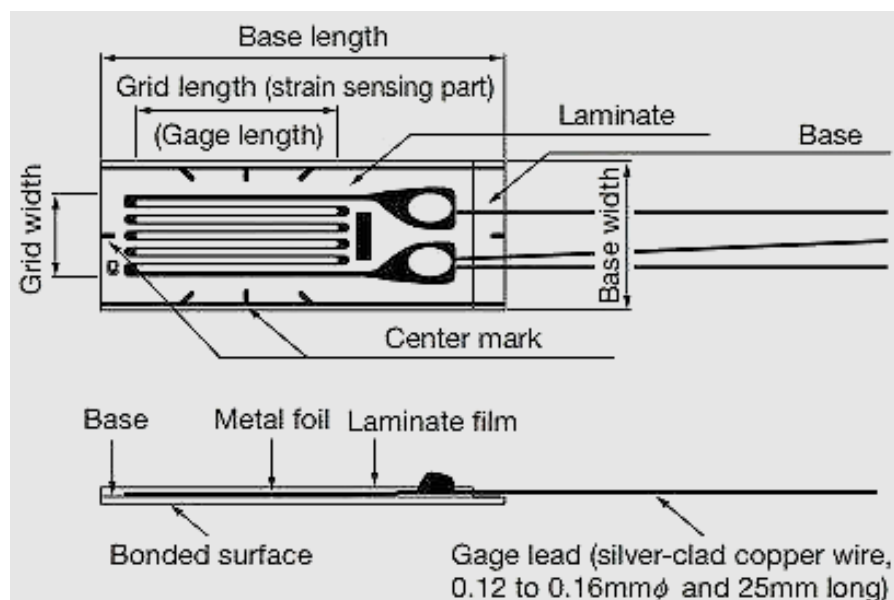


Figure 5.4: Structure of a Strain Gauge [80]

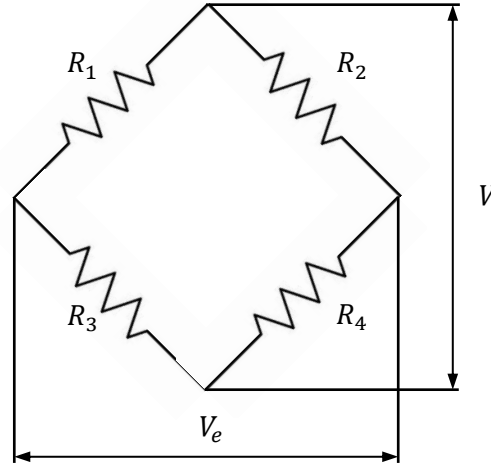


Figure 5.5: Wheatstone Bridge

$$\frac{\Delta R}{R} = K \cdot \varepsilon$$

Where,

- R : Original resistance of strain gauge, Ω (ohm)
- ΔR : Elongation- or contraction-initiated resistance change, Ω (ohm)
- K : Proportional constant (called gauge factor)
- ε : Strain

Since the material strains are low, the resistance change of a strain gauge is around the micro range and the output voltage cannot be measured using conventional measuring instruments directly. So, these minute changes are directly measured by a special circuitry called the Wheatstone bridge circuit.

The Wheatstone bridge is an electric circuit suitable for the detection of minute resistance changes. Therefore, it is used to measure the resistance change of a strain gauge. In general, a Wheatstone bridge is configured by combining four resistors as shown in Figure 5.5.

Suppose,

$$\frac{R_1}{R_4} = \frac{R_2}{R_3}$$

Then, regardless of the applied input voltage (V), the output (V_e) is zero. Such a bridge status is called “balanced”. When the bridge loses its balance, it outputs a

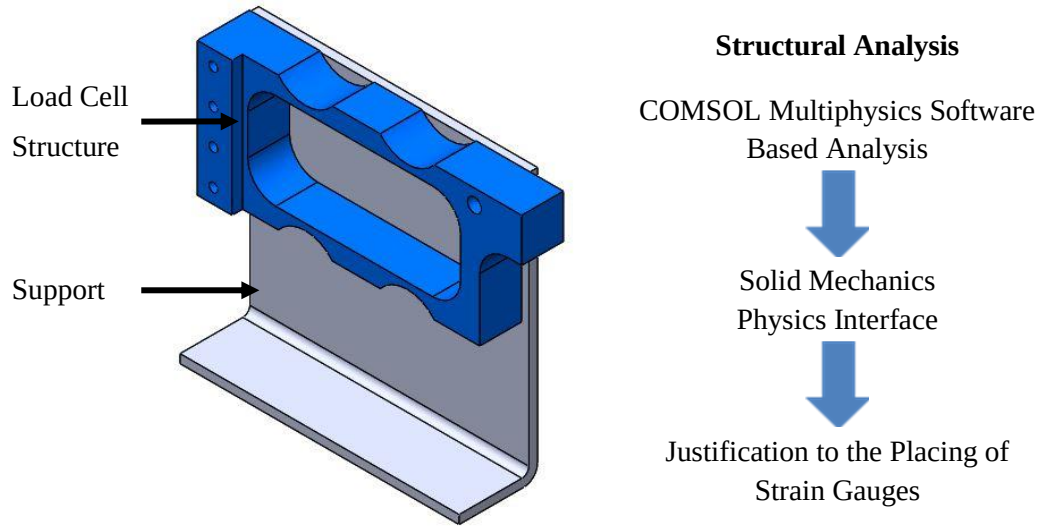


Figure 5.6: Conceptual Design of the Load Cell Structure and Simulation Details

voltage corresponding to the resistance change. In a structure depending on the number of strain gauges, output voltage differs. To get a higher resolution at the output a full-bridge configuration was selected in developing the load cell.

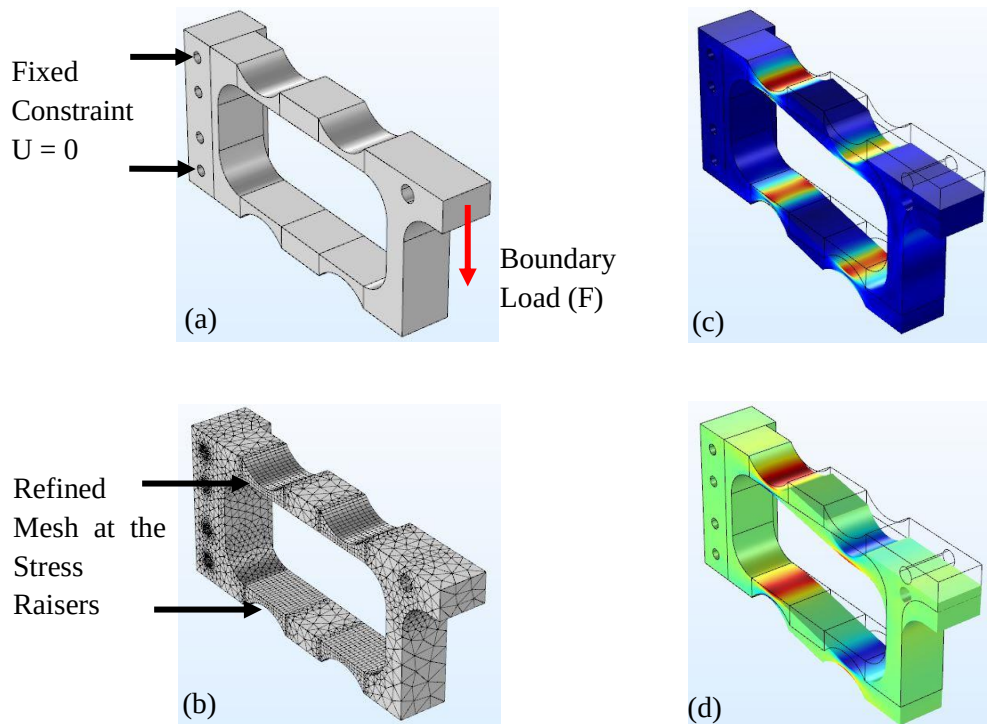


Figure 5.7: Simulation of Strain Gauge Structure **(a)** Boundary Conditions; **(b)** Meshing; **(c)** Stress Variation; **(d)** Strain Variation

The structure of the load cell is made out of Aluminum and the placement of sensing elements (strain gauges) was justified through a computer-based simulation. Figure 5.6. shows the conceptual design of the load cell structure (Appendix Q1). A software-based simulation was performed to find out optimum locations to place the strain gauge elements. COMSOL Multiphysics is one of the commercially available software interfaces to perform Finite Element Analysis (FEA). The structural mechanics module which is included in the COMSOL was used to perform the analysis.

The simulation was initiated using the Solid Mechanics physics interface and computed as a stationary study. The structure was fixed at the screw holes as depicted in Figure 5.7. (a) and applied a boundary load at the free end which imitates the actuator force. The material was assigned accordingly at the respective settings in the simulation and meshing (Figure 5.7. (b)) was conducted by identifying critical sections which are more important in placing strain gauges. Figure 5.7. (c) and Figure 5.7. (d) show the stress and strain variation obtained at the post-processing stage of the simulation. A significant amount of strain variation can be identified at four locations (Figure 5.8. (a)) and those are the most suitable locations to place strain gauges.

According to the results obtained from simulation, the corresponding strain variation is in micro-scale. Since the sensing element is a strain gauge, it gives a resistance change with the change of strain at the strain gauge mounted location. So, the resistance change is in the micro ohm range and it is difficult to measure using standard measuring instruments. To cater to the problem, strain gauges were attached as branches of a Wheatstone bridge circuit and the resistance changes were converted to a voltage change. These micro voltages were then amplified through an amplifying

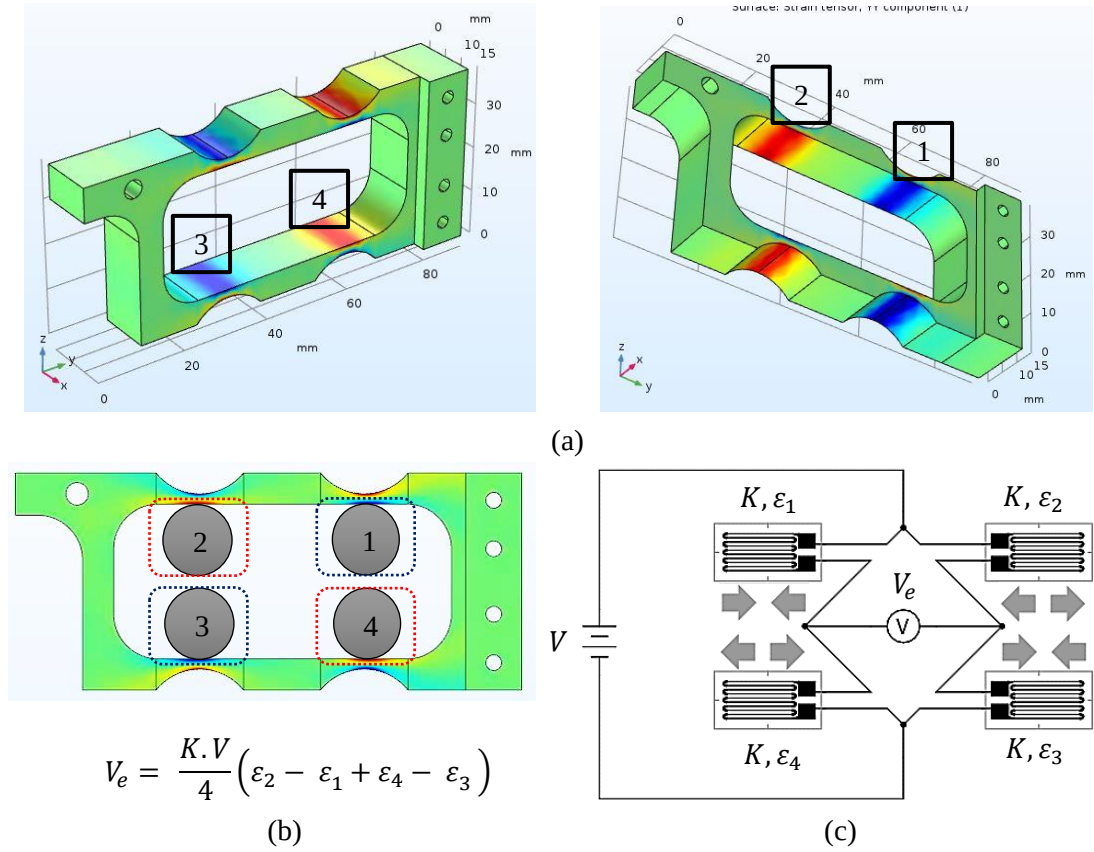


Figure 5.8: Results Interpretation **(a)** Strain Gauge Placing Locations; **(b)** Theoretical Bridge Output Voltage; **(c)** Wheatstone Bridge Arrangement of Strain Gauges

circuitry to make it a measurable output. Figure 5.8. (c) shows the Wheatstone bridge arrangement of the strain gauges in full-bridge configuration and theoretical equation Figure 5.8. (b) for calculating bridge voltage output with the change in strain. The theoretical bridge output voltage depends on the bridge excitation voltage, the gauge factor of the strain gauges, and the strain variation at the strain gauge mounted locations. Descriptive details are presented in a later subsection about supporting electronics utilized to acquire the sensory data.

Thermal Analysis of the Activation Medium

The SMA actuator element was heated by submerging in a fluid container (Figure 5.9) and heating the fluid to the required temperature. An electric heater was used to heat the fluidic medium. Before performing the experiments, a thermal simulation was carried out using COMSOL Multiphysics software to get to know about temperature variation near the SMA actuator with respect to the heater power.

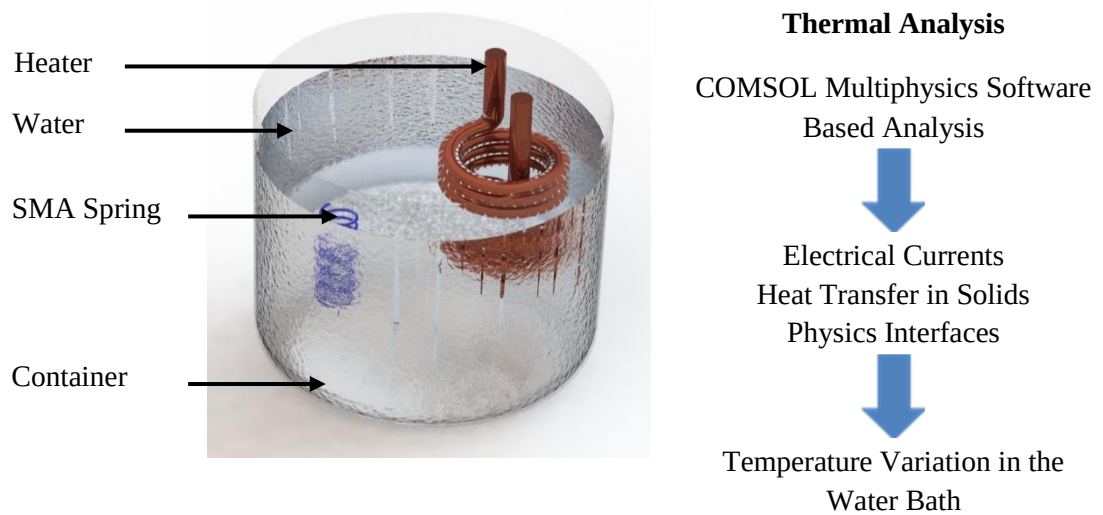
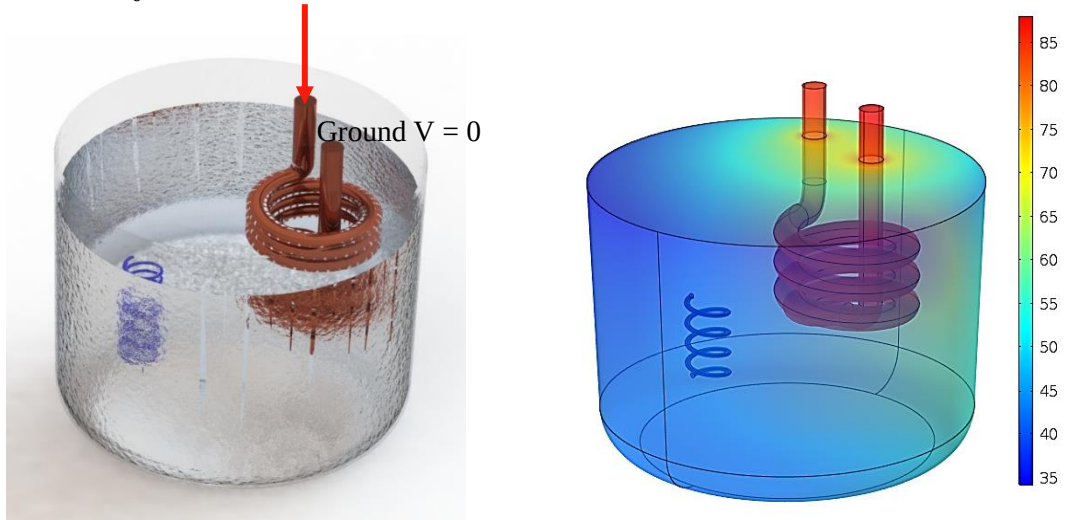


Figure 5.9: Conceptual Design of the Heating Medium and Simulation Details

The analysis was conducted with the aid of Electrical Currents and Heat Transfer in Solids physics interfaces. Figure 5.10. (a) shows the applied boundary conditions at the pre-processing stage. Appropriate material properties were added to the SMA element, Heater, Container, and Fluid as per the requirement. There should be a heat loss during the experiments, and it was added as a convective heat loss at the pre-processing stage. Figure 5.10. (b) shows the results obtained from the post-processing and it can be observed that with the variation of heater power, the temperature is varying near the SMA element as depicted in Figure 5.10. (c)

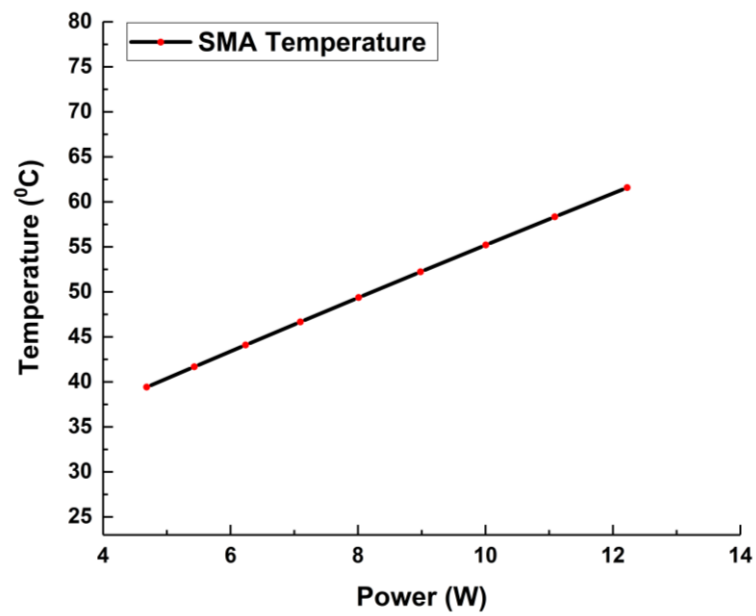
The heater power was controlled through a controller which is described in a coming chapter. To develop the controller by selecting proper tuning parameters, and to get an understanding of temperature distribution with different heater powers around the SMA spring, it is important to conduct simulations to a simplified apparatus. The simulation model consists of a container filled with a heating medium (water), an electrical heater model, and a NiTiNOL Spring model. During the force characterization task, the energy is supplied to the SMA Spring through Joule heating of a heater coil followed by convection through the water. In that case, the same parameters have been set to the model to get a close enough depiction of temperature distribution in the spring according to the power controlling of the heater. So the outcomes of the simulation were used to develop the closed-loop controller.

$$\text{Current } I_0 = \int J \cdot n \, dS$$



(a)

(b)



(c)

Figure 5.10: Simulation Results **(a)** Boundary Conditions; **(b)** Temperature Distribution Around Water Bath; **(c)** Average Temperature Variation near SMA element with heater power

Implementation of the Force Characterization Apparatus

Previous subsections described the selection of force sensor and justification of its operation through simulation environment and also the temperature variation in the heating medium. The next step is to develop the force characterization apparatus by combining these elements. So, the apparatus was designed as depicted in Figure 5.11 and the full-bridge load cell is attached to a support. A bracket was mounted on the base of the container which fixes the SMA spring element at one end. The free end of the spring is mounted on a rod that connects to the load cell structure.

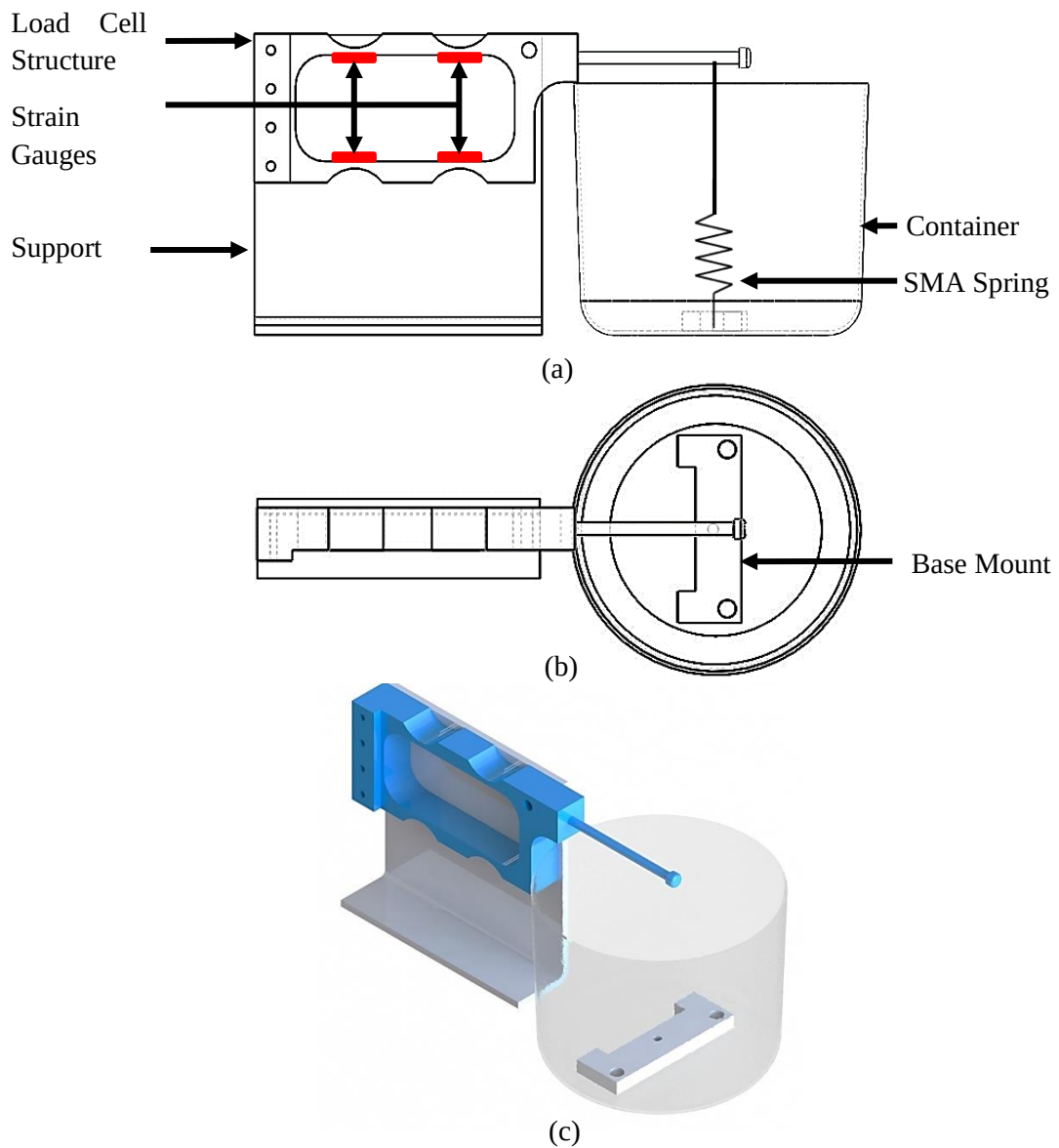


Figure 5.11: Conceptual Design of the Force Measuring Apparatus (a) Front View; (b) Plan View; (c) Isometric View

The initial extension of the SMA spring could be set accordingly and as the temperature increases near the spring, it tries to recover to its initial shape by pulling the beam of the load cell making the load cell generate an output voltage. But, before measuring the actual force, the load cell needs to be calibrated and the calibration was done by applying known weights at the spring fixing location.

Figure 5.12. (a) shows the developed force characterization apparatus which consists of load cell combined with the Wheatstone bridge circuitry, Fluid container, and attachments. Figure 5.12. (b) shows the known weights weighing 10 g each together with a 5 g weight hanger. Figure 5.12. (c) shows how the loads are applied at the spring fixing location while the calibrating process is being carried out.

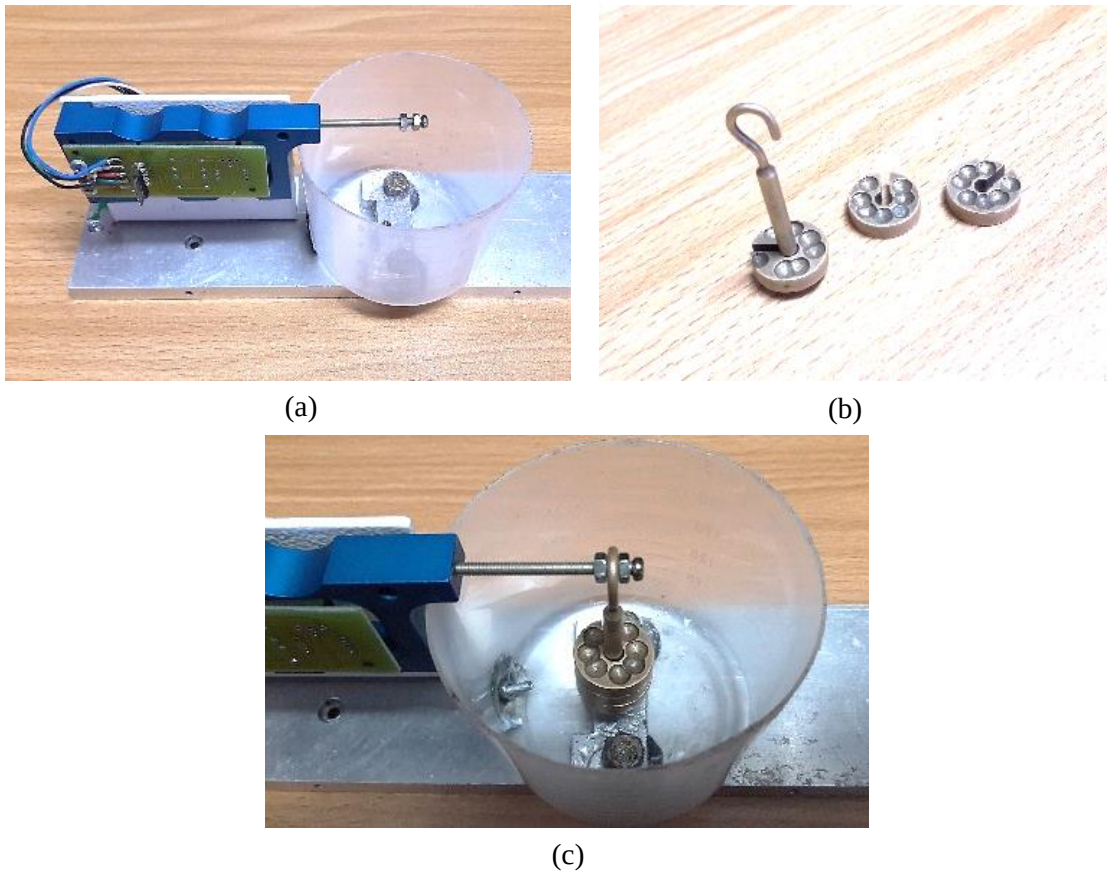


Figure 5.12: Fabricated Apparatus **(a)** Apparatus with Full Bridge Load Cell; **(b)** Known Weights for Load Cell Calibration; **(c)** Placing Loads at the Spring Attaching Location

5.3.2 Planning of Supporting Electronics for the Experiments

The force characterization task has to be carried out by incorporating necessary electronics with the implemented apparatus. As discussed in previous sub-sections, the minute output voltage from the Wheatstone bridge which is connected to the full-bridge load cell should be amplified to a measurable quantity. The amplification of the Wheatstone bridge output voltage was carried out by a 24 – bit Analog to Digital Converter (ADC) which is a well-known load cell amplifier branded as HX711 (Appendix K). And the HX711 was connected to a microcontroller (ATmega328P) (Appendix J) based development board to acquire data (Figure 5.13). After obtaining raw data values from the amplifier, the development board sends those raw data to a computer via serial communication, and all the data processing tasks were conducted from a LabVIEW-based software interface and more details about the interface will be discussed in a proceeding chapter.

Acquiring the real-time temperature of the fluid container is important because force output from the SMA spring element would highly be depending on it. In order to do so, a K-type thermocouple probe was used, and it was connected to a four and half-true RMS Digital Multimeter (Appendix O1) which is compatible with the thermocouple probe. The Multimeter has a computer-based software interface to display and acquire temperature data (Appendix O2). Figure 5.14 shows the connections of the load cell with the HX711 ADC and connections of the ADC with the microcontroller board.

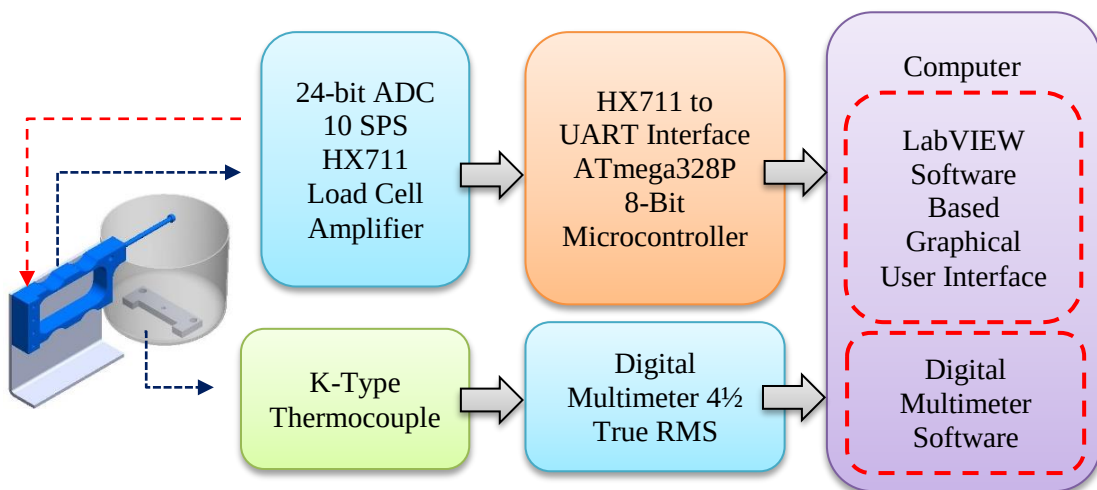


Figure 5.13: Layout of the Proposed Force Measuring System

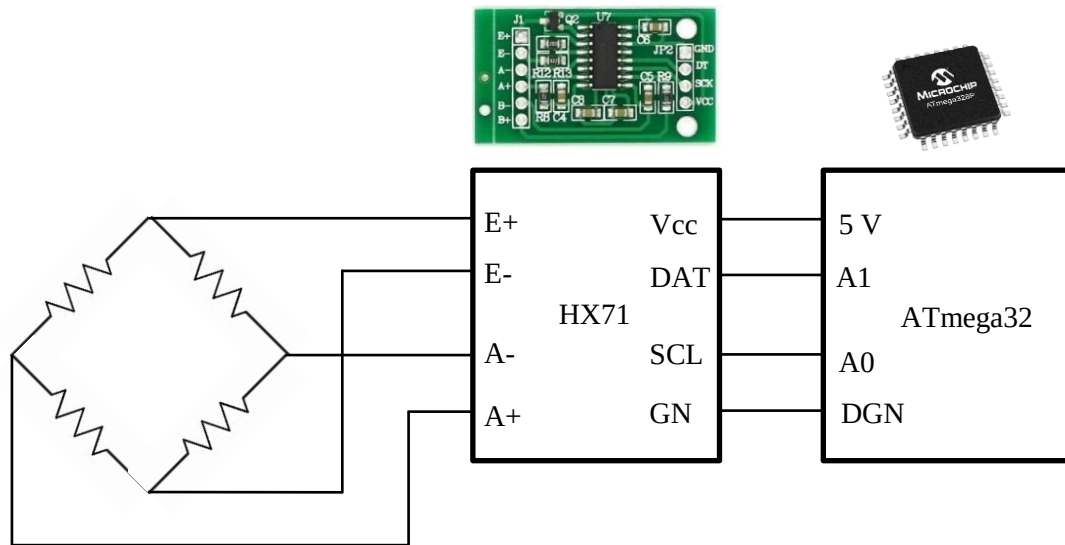


Figure 5.14: Load Cell Amplifier and Connections with the Microcontroller

HX711 is a precision 24-bit analog-to-digital converter (ADC) designed for weighing scales and industrial control applications to interface directly with a bridge sensor. No programming is required for the internal registers. All controls to the HX711 are through the pins.

5.3.3 LabVIEW Based Interface for Force Monitoring

The HX711 is a 24 - bit ADC and it assigns the Wheatstone bridge reading into these bits. The MSB reserves for the sign and the other 23 bits are used for representing the numerical value. So, the load cell reading could occupy values in the range of - 4,194,304 to 4,194,303 including zero. The program which is running on the ATmega328P microcontroller-based development board is reading these data from the HX711 registry and send through serial communication protocol to the computer. The computer receives these numerical data as a continuous string since the load cell continuously produces output according to the force applied to it. To identify every data value separately, a data protocol is required, and it is being done by the code segment in the program which arranges individual data strings starting with a character and ending with a separate character. As an example, one data string was arranged as “B248542C B250384C B2603402C”

The LabVIEW software package provides program blocks for data communication, data processing, data display, etc. So, it was utilized to generate a

graphical program to gather serially received data, extract load cell readings from the receiving string, calibrate the load cell, display data values and plot them to further analysis. A pseudo program of force monitoring is as follows,

Initialization:

VISA Write

Send character “C” for start communication with 10 Hz sample rate

VISA Configure Serial Port

VISA source name: COM port number

Baud rate: 9600 Bps

Loop:

While stop button is pressed

VISA Read

read buffer “B248542C B250384C B2603402C” continuous string

Match Pattern

extract after substring matching with regular expression “B”
“248542C B250384C B2603402C”

Match Pattern

extract before substring matching with string “C”
“248542”

Scan Value

convert the string into numerical value 248542

Store 20 samples of data in **Tare Buffer**

Store 10 samples of data in **Read Buffer**

If (Tare Button is pressed)

Take the **Mean** value of the Tare buffer and assign the answer to
Variable **Offset**

else

forward the value in **Offset** to calculations

If (Set Scale Button is pressed)

Subtract Offset from the **Mean** value of the Read buffer and divide
the answer by **Calibration Weight**. The result is assigned to Variable
Scale

else

forward the value in **Scale** to calculations

Calculation:

take the **Mean** value of the **Read Buffer**.

Subtract Offset from the above value

Divide the answer by **Scale**

The answer is the Load cell reading in grams

Divide the gram value by 100

The answer is the Load cell reading in Newtons

Data Visualization:

Indicate the final results using **Numeric Indicators, Gauges and Chats**

Figure 5.15 shows the Front Panel of the LabVIEW program which was created to manipulate the data received from the microcontroller development board. And the corresponding block diagrams are shown in Figure 5.16. (a) and Figure 5.16. (b).

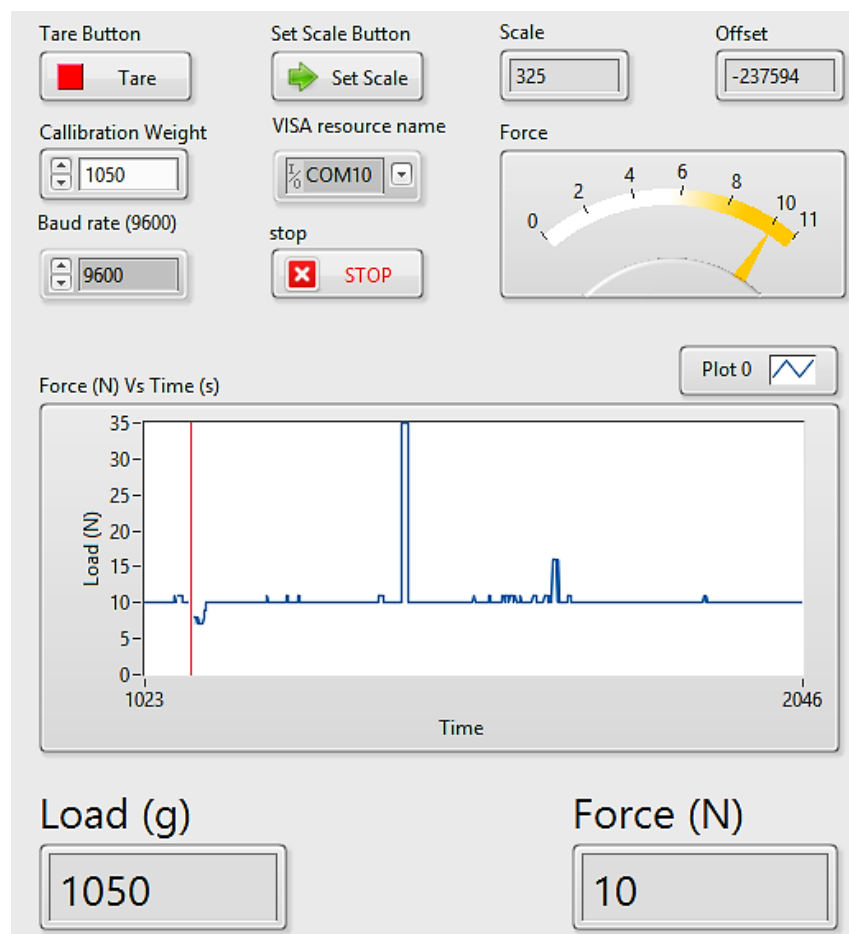


Figure 5.15: Front Panel

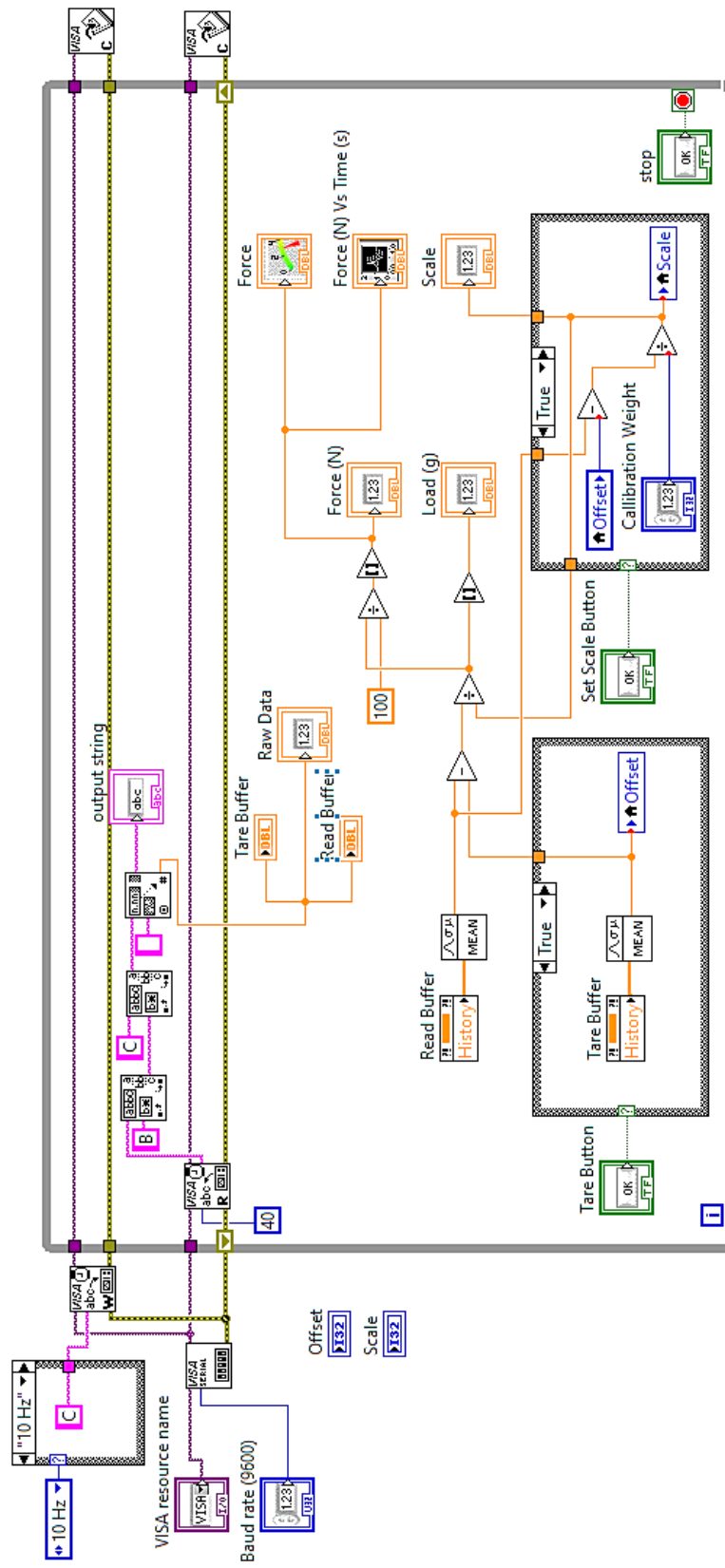


Figure 5.16. : (a) Block Diagram 1



As the NI-VISA instrument driver is installed in the computer, LabVIEW possesses program blocks that are useful for dealing with external instruments. NI-VISA abbreviated from National Instrument Virtual Software Instrument Architecture and VISA is a standard for configuring, programming, and troubleshooting instrumentation systems comprising GPIB, VXI, PXI, serial (RS232, RS475), Ethernet/LXI, and USB interfaces. A more detailed description of the LabVIEW program is as follows.

LabVIEW contains functional blocks in data communication → protocols → serial, which can be used to configure communication between the microcontroller development board and the computer. First, the serial port was configured using VISA configure serial port block and a control port was assigned for the VISA source and selected the data rate as 9600 bits per second. VISA write block which writes data to the specified VISA source, is used to send the required data rate to the program which is in the microcontroller development board which in turn sets the data rate setting in the HX711. There are two selectable data transfer rates available with the HX711 as 10 SPS and 80 SPS. The data rate of 10 SPS was set for the HX711. Then the serially received data was read by VISA read block which reads a specified number of bytes and assigns those bytes to the read buffer as a string. The read buffer output string is then directed to a match pattern block which is available at string functional blocks in LabVIEW. Match pattern block splits the string into three substrings known as, before substring, match substring, and after substring according to the regular expression given for matching. Here, the regular expression was given as the starting letter of a data cluster receiving in (i.e.: “B”). And the, after substring (i.e.: “248542C B250384C B2603402C”) is directed as the input string for the second match pattern block, and the regular expression, was selected as the ending letter of a data cluster (i.e.: “C”). Here, the before substring (i.e.: “248542”) was acquired and transferred to the scan value block which is another string manipulating block to convert the string into a number specified as the default data type. These converted numerical values were assigned to two separate waveform charts which are named Read Buffer and Tare Buffer.

These charts store data for calculations that are needed to conduct further within the program. Read buffer chart has a history length of 10 samples and it reads the

instantaneous data received through the communication between the computer and the microcontroller board. To minimize the fluctuations of the data, a mean value was calculated by feeding the acquired 10 samples into a programming block which can be found at Mathematics→ Probability & Statistics section in the LabVIEW environment.

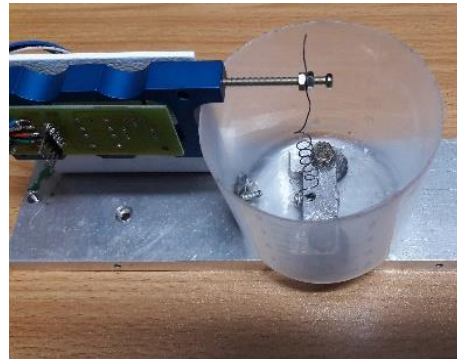
From this point onwards, the mean value is used for the required calculations. Due to the manufacturing variations of strain gauges and slight variations in placing strain gauges at correct locations on the load cell structure, there might be balancing problems of the Wheatstone bridge, even though the same type of strain gauges are being used. So, without applying any force, the load cell gives a reading, and this is known as the offset value. This is a common problem in this kind of load cell-based application and the offset value was avoided by including a Tare option in the program. It was done with the use of Tare buffer. The waveform chart which represents the Tare buffer has a history length of 20 samples and the mean value of those values are being stored in a variable called offset. So, the offset value is subtracted from readings received through the Read buffer and avoided the initial reading due to the imbalance of the Wheatstone bridge. Further, to convert the raw data received to the computer into meaningful value, a parameter was defined as Scale in the program. The Scale is calculated by applying a known weight to the load cell and received raw data value then divided by the applied load. Unit of the Scale would then be per kg or g. So, whenever an unknown force is applied at the load cell, dividing the raw data value by the Scale variable would give the applied force. Finding the Offset and Scale values is known as calibrating the load cell. All the mathematical operations and logic that are required to perform the calibration process were included by utilizing respective functional blocks which are available in the LabVIEW environment. Also, real-time force values were indicated in the Front panel by using graphs and gauges to easily grasp the variation of force with the temperature and at the same time to store data.

5.3.4 Experimental Results of Force Monitoring

Force monitoring experiments were conducted on three sets of SMA spring actuators fabricated by the techniques described in Chapter 4 and the transformation temperatures were measured using the methods that are described in Chapter 3. Details of the experimented spring actuators are given in Table 5.1.

Table 5.1: NiTiNOL Wire Shape Setting Details

Wire Diameter (mm)	Shape Setting Temperature ($^{\circ}\text{C}$)	Aging Time (mins)	Transformation Temperature ($^{\circ}\text{C}$)
0.5	440	20	70 ± 5
1.0	500	25	60 ± 5
1.0	500	30	80 ± 5



(a)



(b)

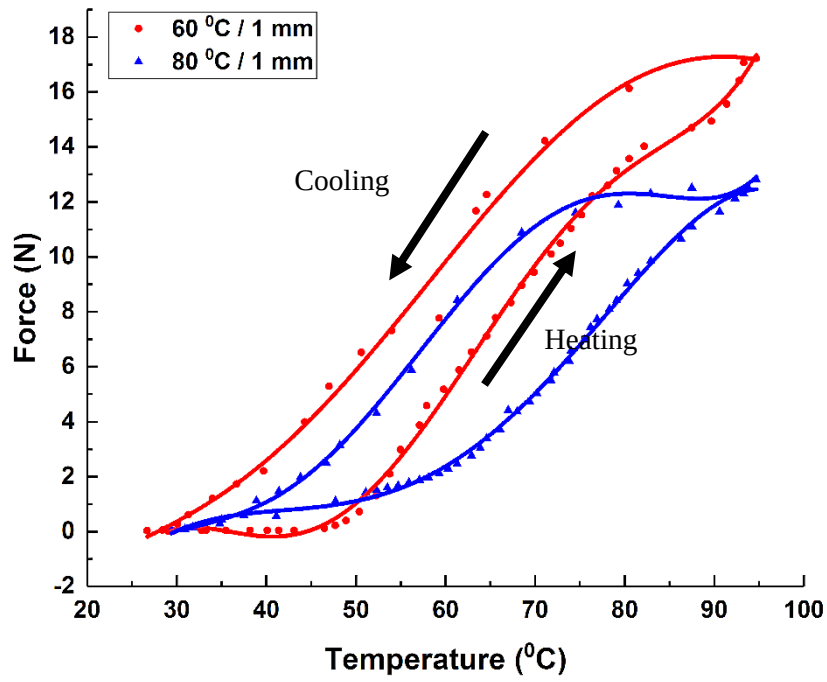
Figure 5.17: Experimental Setup **(a)** SMA Spring Attachment with Force Measuring Apparatus; **(b)** Measuring Temperature through the Thermocouple Probe

The springs were attached to the force characterization apparatus as seen in Figure 5.17. (a) and the temperature of the water bath was measured through the Multimeter as depicted in Figure 5.17. (b). an electrical heater having a power of 500W was used to increase the temperature of the water bath.

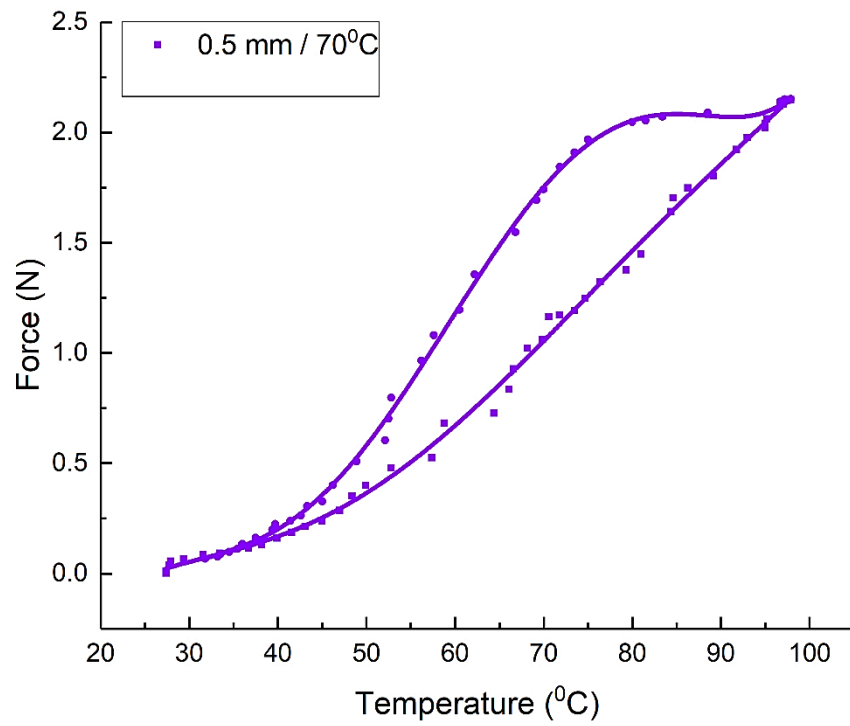
With these arrangements, obtained force measurement results with uncontrolled heating and cooling can be depicted as in the following figures, Figure 5.18. (a) and Figure 5.18. (b). Here the temperature of the SMA spring element is continuously increased using the heater with its total available power without any controlling and simultaneously measured generated force. Also, an uncontrolled manual cooling method was used to reduce the temperature at the highest testing temperature. By this method, hysteresis behavior of SMA material was observed which is important when properly controlling the actuators in the respective applications which are going to discuss in later chapters.

Also, the results show that in Figure 5.18. (a), as the transformation temperature reduces with the same wire diameter, the required force could be achieved quickly as both the springs were tested under the same conditions. By comparing Figure 5.18. (a) and Figure 5.18. (b), it can be concluded that with the reduction in wire diameter, attainable force is significantly reduced through the transformation temperature is higher in the smaller diameter spring.

Through these experiments, it is evident that by changing the temperature of an SMA actuator element, the output force could be changed. As the actuator elements are used in applications, controlling the output force is very much important. So, the following chapter discusses controlling techniques of the actuator force.



(a)



(b)

Figure 5.18: Force Results **(a)** For 1.0 mm SMA Wire; **(b)** For 0.5 mm SMA Wire

5.4 Force Controlling of SMA Actuator Element

Evaluating actuator force and controlling is important for force-sensitive applications. Since the SMA spring-based actuators were designed and developed for tools used in MIS, force controlling is a requirement. As described in the previous chapter, force monitoring experiments were conducted by changing actuator temperature continuously by a heater which was operated at its total wattage. But the results obtained through the thermal simulation clearly show that to maintain the water bath at a certain temperature which in turn heat the SMA element to that particular temperature with time only needs a certain amount of heater power. So, by controlling the heater power, the temperature of the water bath could be controlled. And this is one of the controlling methods described in this chapter, which is known as temperature feedback control. Maintaining the temperature of the SMA element would certainly give a constant force output according to the results obtained in the previous sub-section. So, temperature-controlled force monitoring experiments were also conducted.

Also, it is important to know about the controlling of force at certain force set points when it comes to the applications. Since the force characterization apparatus comprises a force sensor that is used to monitor the force output behaviour of the SMA spring element, it has also been used to control the force at certain force set points. The force feedback was used to control the temperature accordingly to control the temperature as to control force at certain force set points. This method is known as force feedback controlling and will be discussed in this sub-section.

To accomplish both these controlling methods, there is a need for a controller. Since both temperature and force need to be controlled by considering set points, a Proportional Integral Derivative (PID) [74] based closed-loop controller was designed and developed in this work. The following subsection describes the PID closed-loop controller in detail.

5.4.1 Development of PID Based Closed Loop Controller

The behaviour of the actuators depends on the mode of applying heat energy. Therefore, heat control is an important and required area when developing SMA-based actuators. This section describes a multifunctional closed-loop controller for SMA actuators that is driven by the external heating method. The developed controller has two operational modes which are essential for force characterization. They are named Temperature feedback control mode and Force feedback control mode (Figure 5.19).

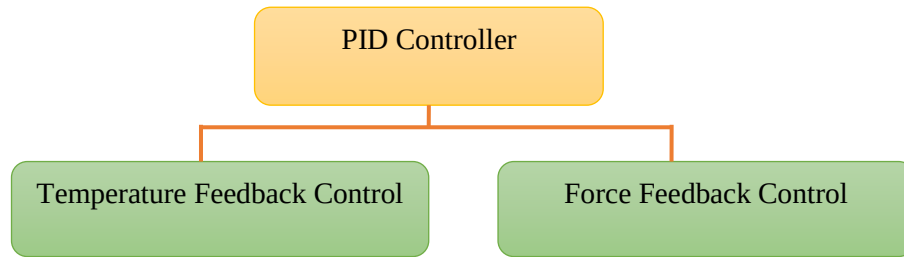


Figure 5.19: Controlling Modes

Temperature feedback control mode

Temperature feedback controlling mode caters to monitoring the force with respect to a constant temperature condition of the water bath. In section 5.3, the temperature was gradually increased without controlling to monitor the force. It was important to get an idea of the force range that can be obtained through a particular actuator. But, as the actuators are designed to work in a specific application area, it is important to get knowledge about the consistency of the actuator force output with constant temperature conditions. Figure 5.20 shows the block diagram related to the explained control mode. The system has the force characterization apparatus explained in an earlier section which was used to monitor the force. There is a separate

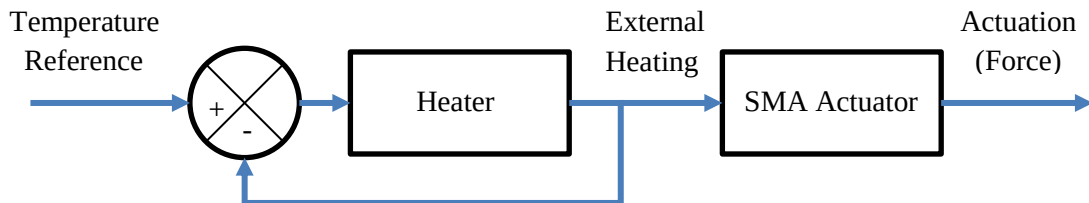


Figure. 5.20: Block Diagram of Temperature Feedback Controlling

customized controller which is developed to cater to the tasks and it has the capability of controlling the heater temperature and acquiring the temperature data during the experiments. Users can set a temperature setpoint to the controller and according to the temperature reading taken from the water bath, the controller adjusts the heater power accordingly to set the correct temperature value at the water bath.

Force feedback control mode

Force feedback controlling mode caters for maintain the force output at a constant value by varying the temperature of the water bath. This experiment assesses the capability of an SMA actuator to achieve constant forces and validates the force controlling capabilities of the developed controller. Figure 5.21 shows the block diagram related to the explained control mode. The system uses the described force characterization apparatus in previous sections which were used to monitor the force. The controller is capable of setting a particular force value and with the force feedback data received through the force sensor, it controls the heater power accordingly to control the temperature of the water bath. And in turn the force output.

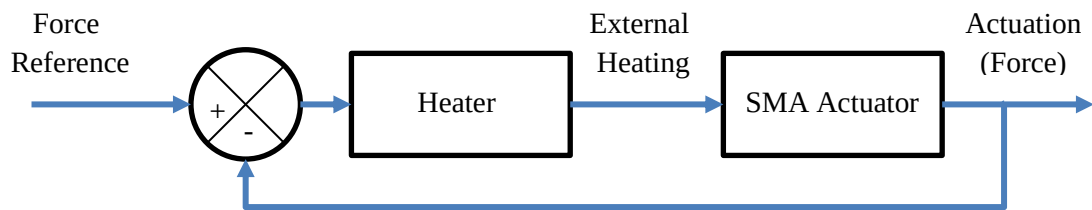


Figure. 5.21: Block Diagram of Force Feedback Controlling

Development of the hardware prototype for the PID controller

The developed controller consists of two sensory input modules for temperature measurement and force measurement, an output module for drive electric heater and an auxiliary relay module to drive a pump or a fan which could be used as the cooling method of the heated medium, and a communication interface module (Figure 5.22.)

The controller is based on an 8-bit microcontroller (Appendix H) which operates at 20 MHz clock frequency. Sensory systems can be categorized into two sections as thermocouple interface and load cell interface.

Thermocouple interface is based on MAX6675 12-Bit cold-junction-compensated K-type Thermocouple to digital converter (Appendix L) which is having 0°C to +1024°C measuring range with 0.25 °C resolution. The converter is capable of taking 5 measurements per second and it has SPI compatible digital serial interface to connect to the microcontroller.

The load cell can measure the tensile and compressive forces which are generated by the SMA element. A 24-bit Analog to Digital Converter (ADC) (HX711) which is specially designed for weighing scales was used to interface load cells with the microcontroller. Selected ADC has 80 samples per second data acquisition rate, and was is connected to the microcontroller through the digital serial interface. The microcontroller was reading the ADC and converts it into grams. Other necessary features such as calibration, tare, and weight to force conversions were developed on computer-based application software.

Figure 5.23. Shows the main components of the developed controller. The electric heater is the main component of the system which is used for heating the SMA element to required temperatures. An optically isolated thyristor (Appendix M2) is used for heater power control to control heater output linearly and smoothly.

Maintaining a desired temperature throughout the SMA element is the main purpose of the closed-loop controller. According to the system behaviours under different environmental conditions, it is difficult to control the temperature of the SMA element manually. So that, a closed-loop controller was implemented to run on the microcontroller as a Proportional-Integral-Derivative (PID) controller. PID controlling is one of the most common control algorithms used in most control applications. The basic function of a PID controller is to read an input, then compute the error between the desired output and the input, minimize the error accordingly by using the feedback

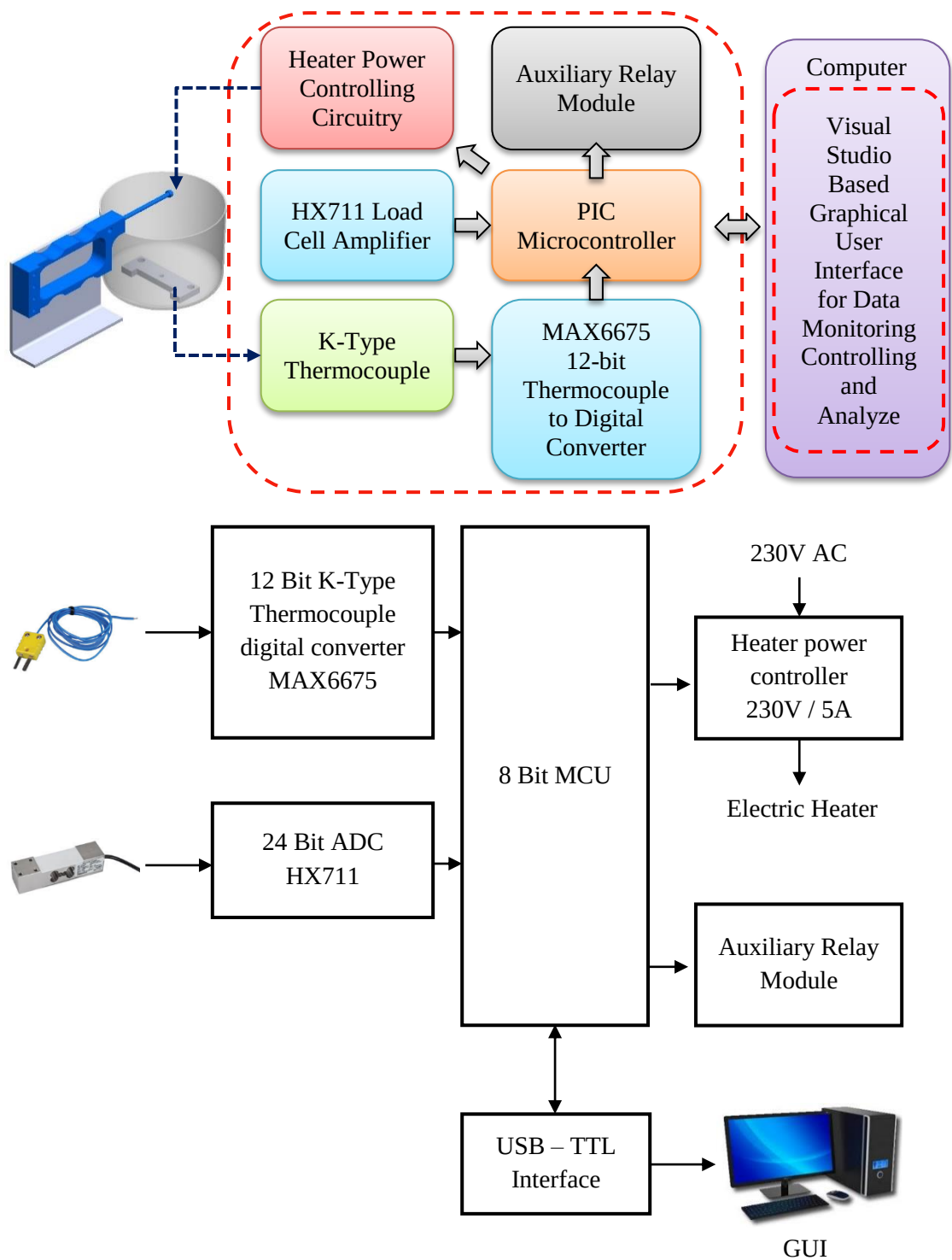


Figure 5.22: Layout of Developed Controller

from Proportional, Integral, and Derivative components of that error and finally make the output stabilized at the desired value as per the requirement of the system. The electric heater which is used to heat the SMA material is controlled by a thyristor-



Figure 5.23: Developed Controller Specifications

based cycle control method. There, thyristors are used to switch on the circuits for a few cycles and off for certain cycles so the power output from the heater in turn changes.

5.4.2 Visual Studio Based Graphical User Interface for Force Controlling

A computer-based software application was implemented to make the interface between the hardware controller and the user. Figure 5.24. shows some features of the GUI. System monitoring, controlling, data login, and data visualization are the main features of the developed application. Using this application software, the user can control the system under temperature control mode and force control mode for single set-point or multiple set points. For all the modes, the software will plot the major parameters in a graph while visualizing the numerical values. Also, the user can tune the PIDs of both controlling modes by applying suitable values to the GUI. This is very helpful to understand the system behaviors, characteristics, and transient response of the system under different conditions. At the initial stage, both the sensors need to be calibrated and that can also be done through the GUI itself. The developed software has features to generate comma-separated value data files (.CSV) for data storing. The software application is implemented with the use of Visual Basic (VB) software package

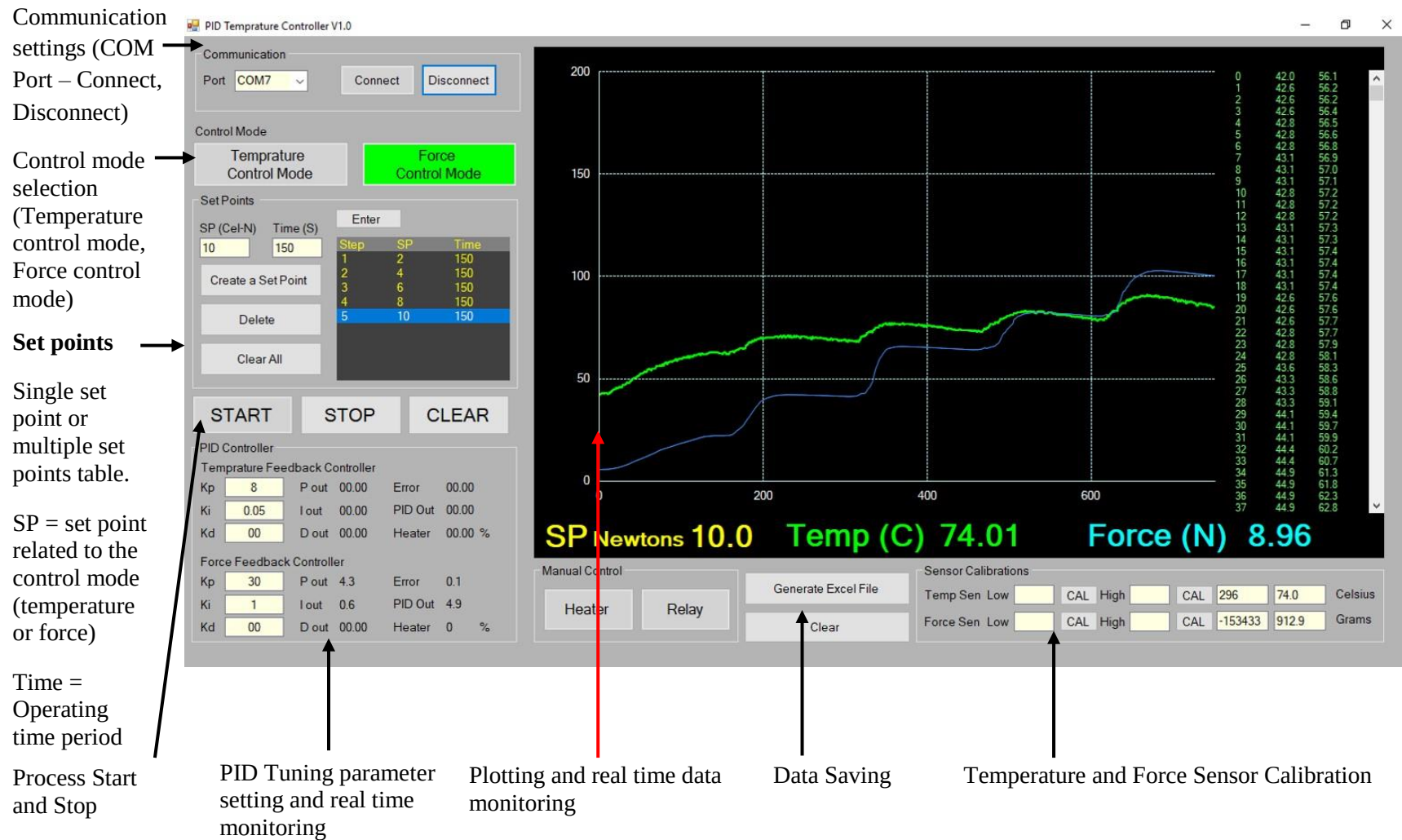


Figure 5.24: Graphical User Interface

5.4.3 Experimental Results of Force Controlling

Force measurement results with uncontrolled heating and cooling were depicted in Figure 5.18 which was described under force monitoring results. Here the temperature of the SMA spring element is continuously increased using the heater with its total available power without any controlling and simultaneously measured generated force. Also, an uncontrolled manual cooling method was used to reduce the temperature. By this method, hysteresis behaviour of SMA material was observed which is important when properly controlling the actuators. But the reliability of the data was very much low, because of the possibility of a lag between data readings. Corresponding forces for relevant temperatures have to be obtained correctly which is very much important when it comes to characterizing and precise controlling of forces from the actuators. Therefore, the developed PID-based closed-loop controller was used to obtain more reliable data.

Experimental Results of Temperature Feedback Control Mode (TFCM)

In this control mode, the SMA element was subjected to different controlled temperature conditions through the controller. The controller provides pre-determined temperature or the set point of the PID, to heat the SMA element accurately by controlling the Electrical Heater. The setpoint temperature may be a fixed temperature value (Figure 5.25.) or a series of temperature values maintained between user-preferred time intervals (Figure 5.26.). According to the applied temperature set points, the controller maintains the desired temperature levels in the thermic fluid (water) bath accurately. This is done by the tuned PID controller with a temperature feedback system as shown in Figure 5.20. This helps to observe the static response, dynamic response, and force generation in different temperature conditions of the spring actuator. Temperature feedback-controlled force characterization is important when accounting for the design parameters of an application.

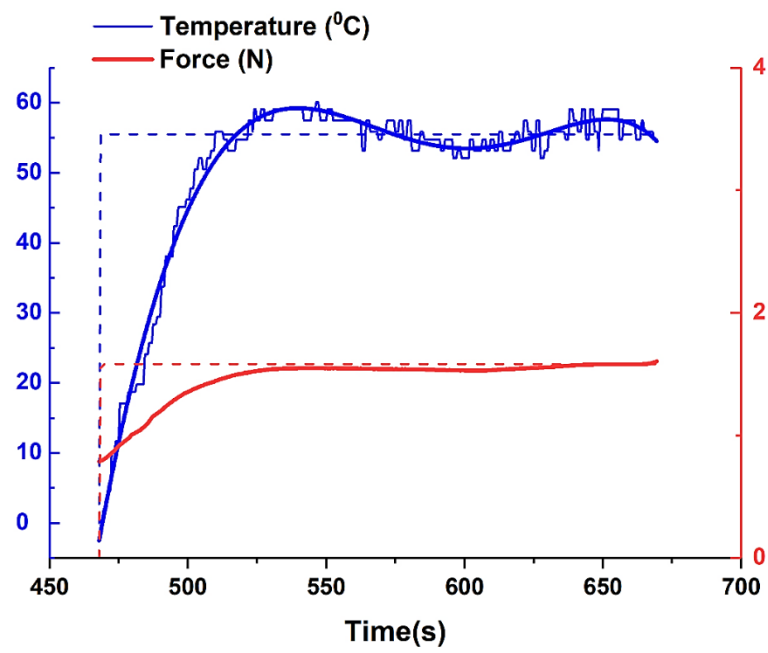


Figure 5.25: TFCM Results for Single Set Point

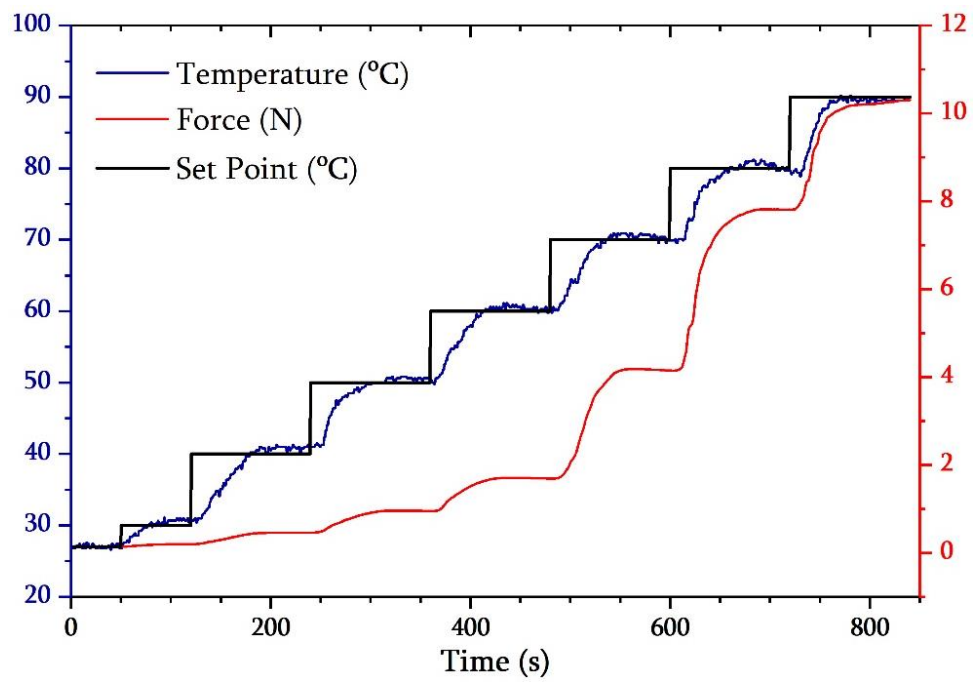


Figure 5.26: TFCM Results for Multiple Set Points

Experimental Results of Force Feedback Control Mode (FFCM)

In this control mode, the force generated through the SMA element can be controlled within predetermined or desired values. The controller provides a predetermined force or the set point of the PID, to control the output force from the actuator element. This is done by controlling the temperature of the SMA element according to the required force set points (Figure 5.27). As the temperature varies, output force from the SMA actuators also gets varied depending on the biasing method in the respective applications. By considering this relationship, the desired force can be achieved through the developed PID controller with the force feedback system shown in Figure 5.21. In the force control mode, the controller changes the temperature of the SMA element according to the required force set points.

This is very much important for the SMA actuators, where the actuators function inside the instruments such as grippers in force-sensitive applications.

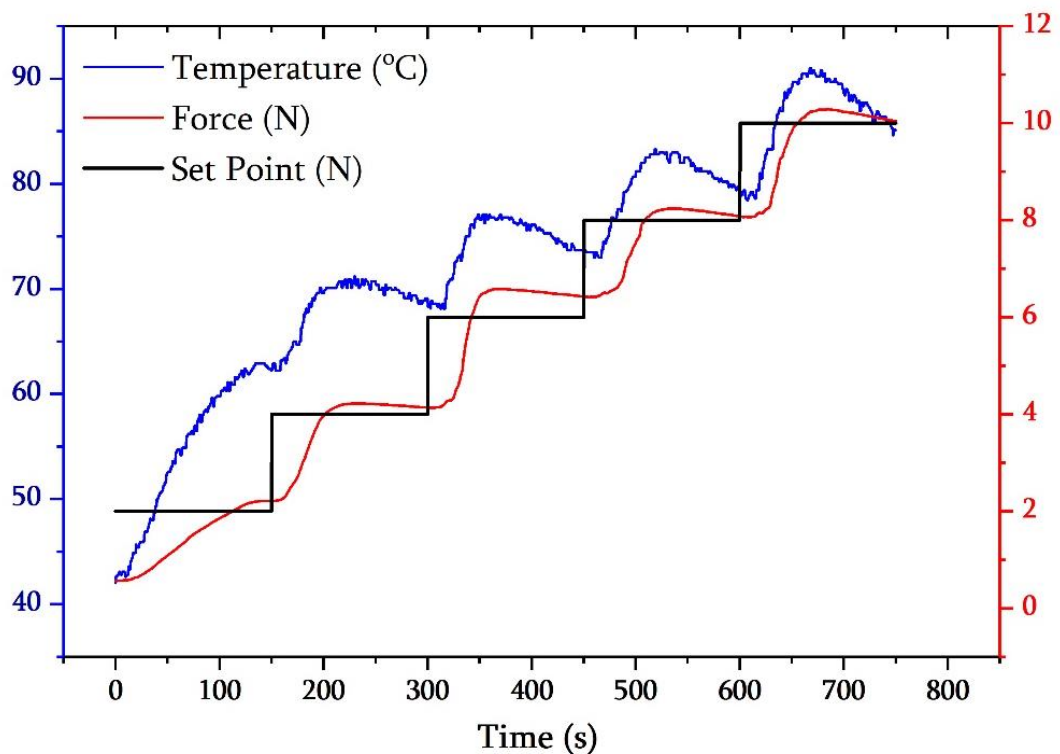


Figure 5.27: FFCM Results for Multiple Set Points

5.5 Chapter Summary

This chapter presents the characterization of the fabricated NiTiNOL spring actuator. The activation methods of SMA actuators are discussed at the beginning of the chapter which is an external heating method and the Joule heating method. The external heating method uses an external medium to heat the SMA element and the Joule heating method uses the resistance of the SMA material to generate heat which is needed to increase the temperature. Before going into the application area, the fabricated SMA spring actuator was characterized in terms of force by the development of a customized force characterization apparatus. The force characterization apparatus was supported with a specially developed controller and computer interfaces in order to adjust parameters and data acquisition tasks.

Later, the developed force characterization apparatus was used to assess the controller performance which was developed based on PID controlling technique, in order to control the temperature and the force output from the SMA actuator at desired set points. The results show that the developed controller is capable of achieving the required objective.

CHAPTER 6

DESIGN AND DEVELOPMENT OF SMA SPRING ELEMENT BASED LINEAR ACTUATORS

6.1 Introduction

So far, all the chapters have presented preliminary work carried out with the SMA material, including studying the behavior of SMA material, development of SMA-based actuator elements, and characterization of SMA materials. According to the details and results presented in each chapter, it is clear that the material could be manipulated according to the requirement and the application area. It is time to discuss applications of the developed SMA actuating elements. This chapter presents the details of the design and development of linear actuators which are based on the developed spring-type SMA actuator elements and the actuation was facilitated by two types of actuation methods. One is the external fluid-based heating and cooling method and the second is the Joule heating and air-cooling method. Finally, the developed linear actuators were extended to application areas related to minimally invasive surgeries.

The linear actuator designs, development, and testing procedures are described under the following sub-sections.

6.2 Development of the Linear Actuator Activated by External Heating and Cooling

6.2.1 Design of the Linear Actuator

The design of the linear actuator which is discussed under this subsection is based on the developed SMA-based spring actuator element and the axial extension – compression motion assists for the stroke of the linear actuator. Figure 6.1. shows the conceptual design of the developed linear actuator. It was designed as a piston-cylinder configuration and the SMA spring element is inside the Cylinder. At one end, there is an End Cap that is threaded to the Cylinder. Vertical Attachment Length (VAL) of the

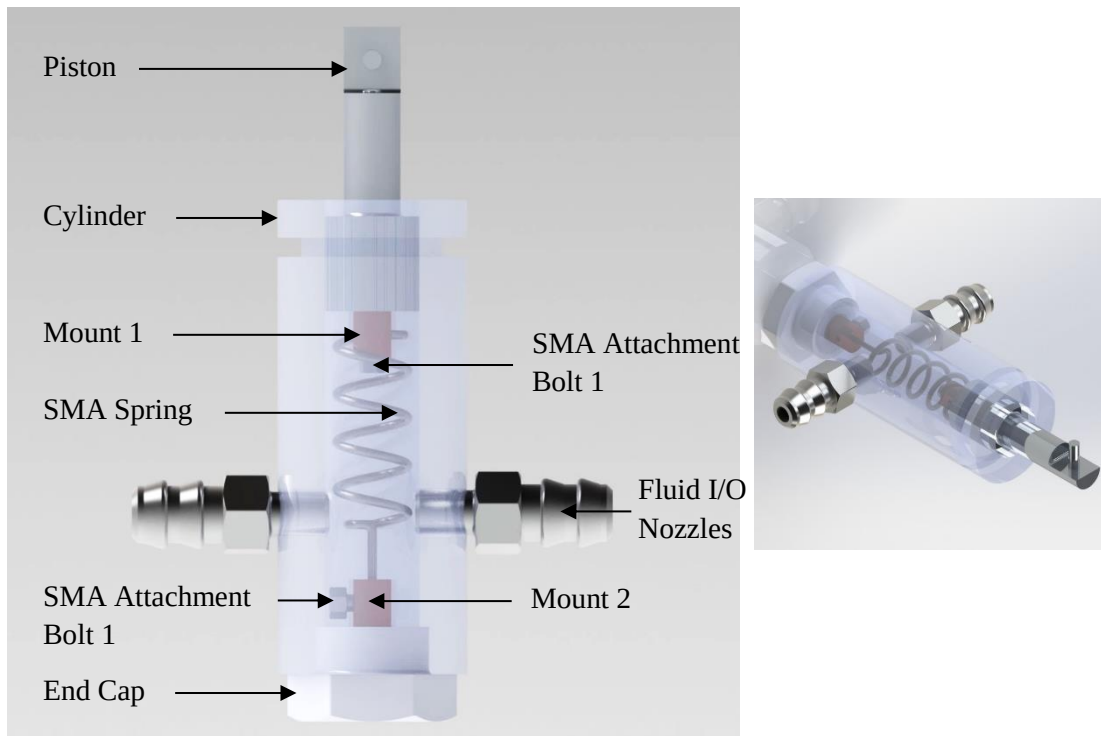


Figure 6.1: Conceptual Design of the Linear Actuator

SMA spring passes through a hole whose axis is collinear with the Cylinder axis located at Mount 2 which is threaded to the End Cap. VAL is fixed at Mount 2 by the SMA attachment bolt 1. The Horizontal Attachment Length (HAL) of the SMA spring passes through a hole perpendicular to the Cylinder axis which is located at Mount 1. It is fixed to Mount 1 by the SMA attachment bolt 2. Mount 1 is threaded to the Piston as shown in Figure 6.1. Also, there are two Fluid I/O nozzles threaded to the cylinder body to transfer the SMA activation fluid medium in to and out of the cylinder.

As the heated fluid medium is supplied by using a nozzle into the Cylinder, the temperature of the SMA element increases and it begins to change its shape into parent configuration by contraction (Assumption: at the lower temperature SMA element is in the extended form) creating Piston to displace along the Cylinder axis. This motion in turn provides a usable stroke and a force on the environment making the assembly an actuator.

6.2.2 Fabrication of the Linear Actuator

The fabrication process of the linear actuator was carried out by utilizing conventional machining techniques. Primarily, lathe machines were used to perform

the turning facing and thread cutting operations related to manufacturing of almost every component depicted in Figure 6.1. As the activating medium of the SMA element is fluidic, a leak-proof assembly of the components is highly important to make an efficient fluid flow and a heat energy transfer. All the threaded components are less susceptible to leak after assembly compared to the Cylinder – Piston sliding contact. So, precise machining must be performed to obtain a leak-proof but sliding joint. A close running fit was used to define the tolerances for Piston and Cylinder dimensions which are of interest. Production drawings of all the components are included in Appendix R1 through Appendix R6. Figure 6.2. (a) and Figure 6.2. (b) shows the fabricated components in exploded configuration and the partially assembled configurations respectively.

According to the design of the linear actuator, Piston is subjected to repetitive back and forth movement while producing the stroke. Hence, should be manufactured with a material having a lower density in turn providing parts with less weight. This reduces the inertia of the piston and supports efficient force transfer to the environment. So, the piston was manufactured using Aluminum material. Brass was used to manufacturing the Cylinder, Mounts, and Nozzles of the actuator. With the

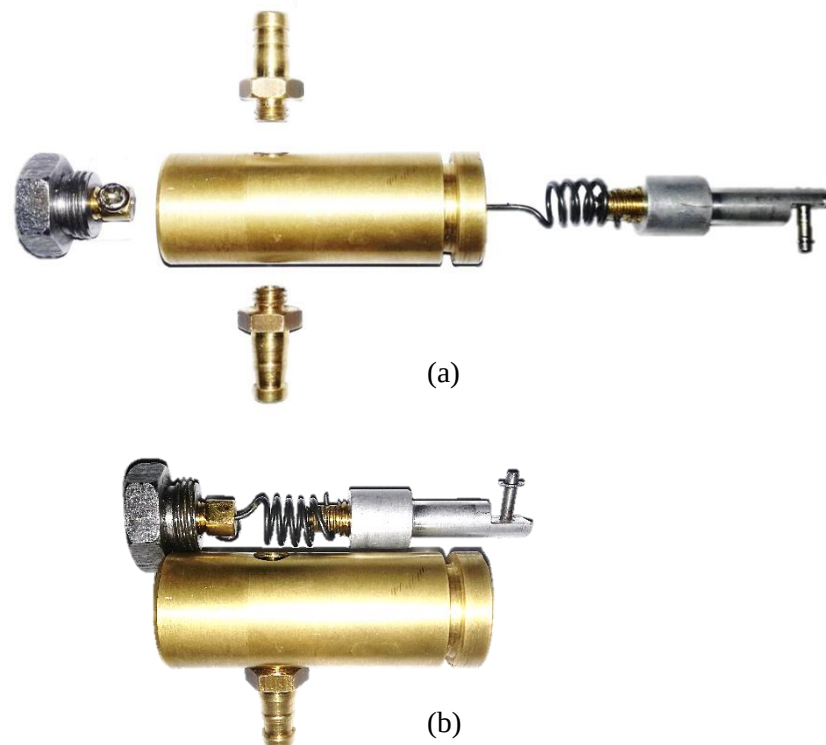


Figure 6.2: Fabricated Linear Actuator **(a)** Exploded Configuration; **(b)** Half-assembled configuration

increase of temperature, Aluminum expands more than brass volumetrically and in turn, results in a more fluid-tight connection between Piston – Cylinder prismatic joint while facilitating axial displacements. Steel was used to fabricate the End Cap part. The galvanic corrosion effect might be problematic in the long-term operation of the actuator due to the dissimilar material selection, but the sequence was selected to corrode components that can be easily manufactured and susceptible for wear quickly. But considering the functional fatigue of the SMA springs, these effects can be neglected.

6.2.3 Integration of the Linear Actuator with a Gripper Application

According to the literature review conducted on the application areas related to the MIS field, there are many tools associated with the surgeries. From those tools, gripping tools were considered as the first application area for SMA-based actuator which was discussed in the previous subsection. First, several designs were done to assess the feasibility of applying the developed actuator, and Figure 6.3. shows those designs.

A – F in Figure 6.3 shows studied mechanisms for the gripper. A and B shows two gripper designs that could be operated by the developed linear actuator and the specialty of these mechanisms is to grip objects using parallel type gripper jaws. The presence of the increased number of joints in the mechanism has been a reason to not proceed further with this design. In the first two designs, both jaws are operated by the linear actuator. Designs C – F are based on angular type jaw configurations and the

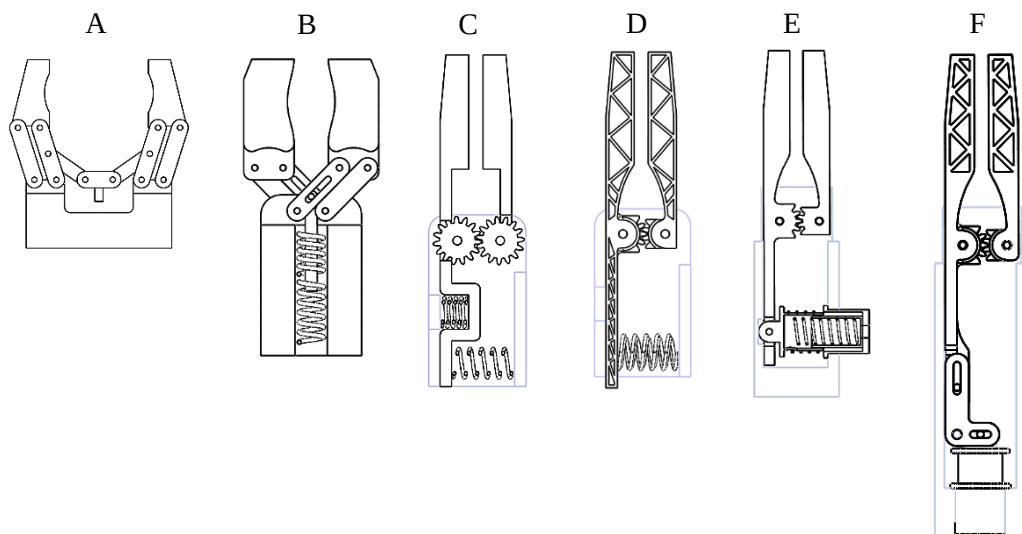


Figure 6.3: Studied Gripper Mechanisms

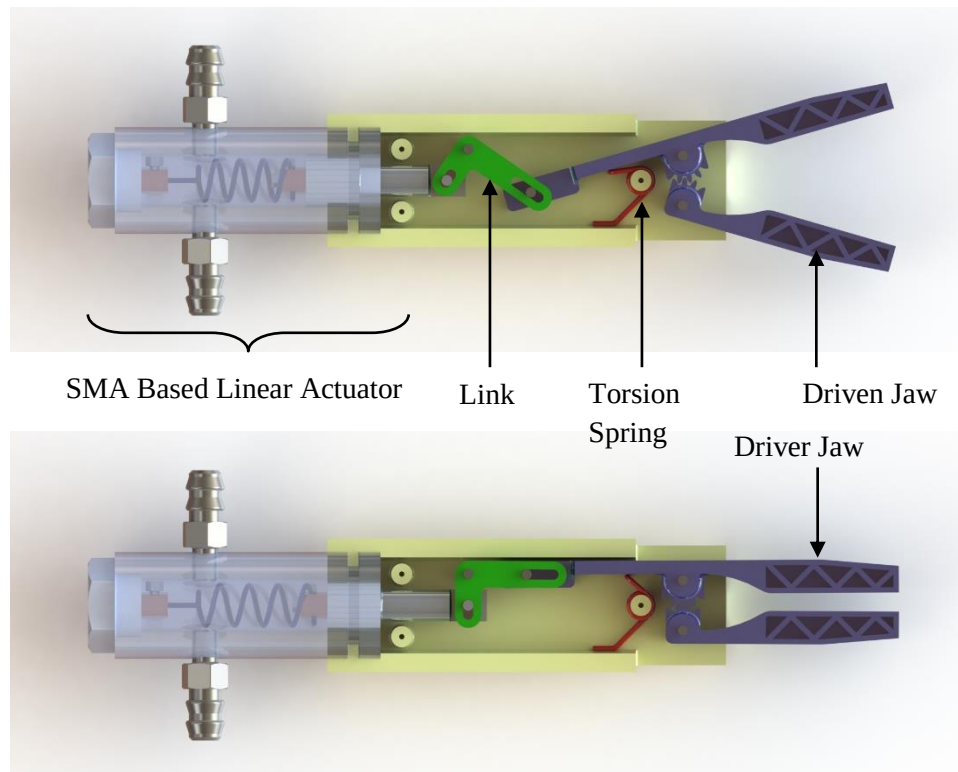


Figure 6.4: Conceptual Design of the Finalized Gripper Mechanism Combined with the Linear Actuator

compactness was achieved by incorporating a gear mesh. Here, the linear actuator operates a jaw which is named the driver jaw, and at the hinged location of the gripper, the jaw consists of a gear profile. It meshes with the gear profile which is connected to the other gripper jaw-hinged location. The later jaw is driven by the first jaw, hence named as the driven jaw of the gripper. By comparing those later designs, F was selected as the gripper mechanism which satisfies compactness, simplicity, and manufacturability of components that comprise it. Figure 6.4. shows the components of the designed gripper mechanism. The linear motion of the piston was converted to an angular motion by the link which is hinged to the base structure. The link consists of two slots that limit the motion and two pins that connect the piston and the driver jaw. The slots were designed in a manner in which no sudden lockups will occur. The rotational motion of the link is transferred to the driver jaw by the reaction force between the pin and slot joint which makes the jaw rotate around a hinge that is located at the Base. In order to compact the mechanism, the gripper pair was connected through a sector gear pair. The main two actuation elements are the SMA spring and the steel torsion spring which support the opening and closing of the gripper jaws respectively.

Parameter Selection and Mathematical Modelling of the Gripper

Several parameters were identified which govern the overall operation of the gripper. Figure 6.5. shows the geometrical and force parameters which incorporate with the gripper operation. Table 6.1. provides the descriptions of the parameters indicated in Figure 6.5.

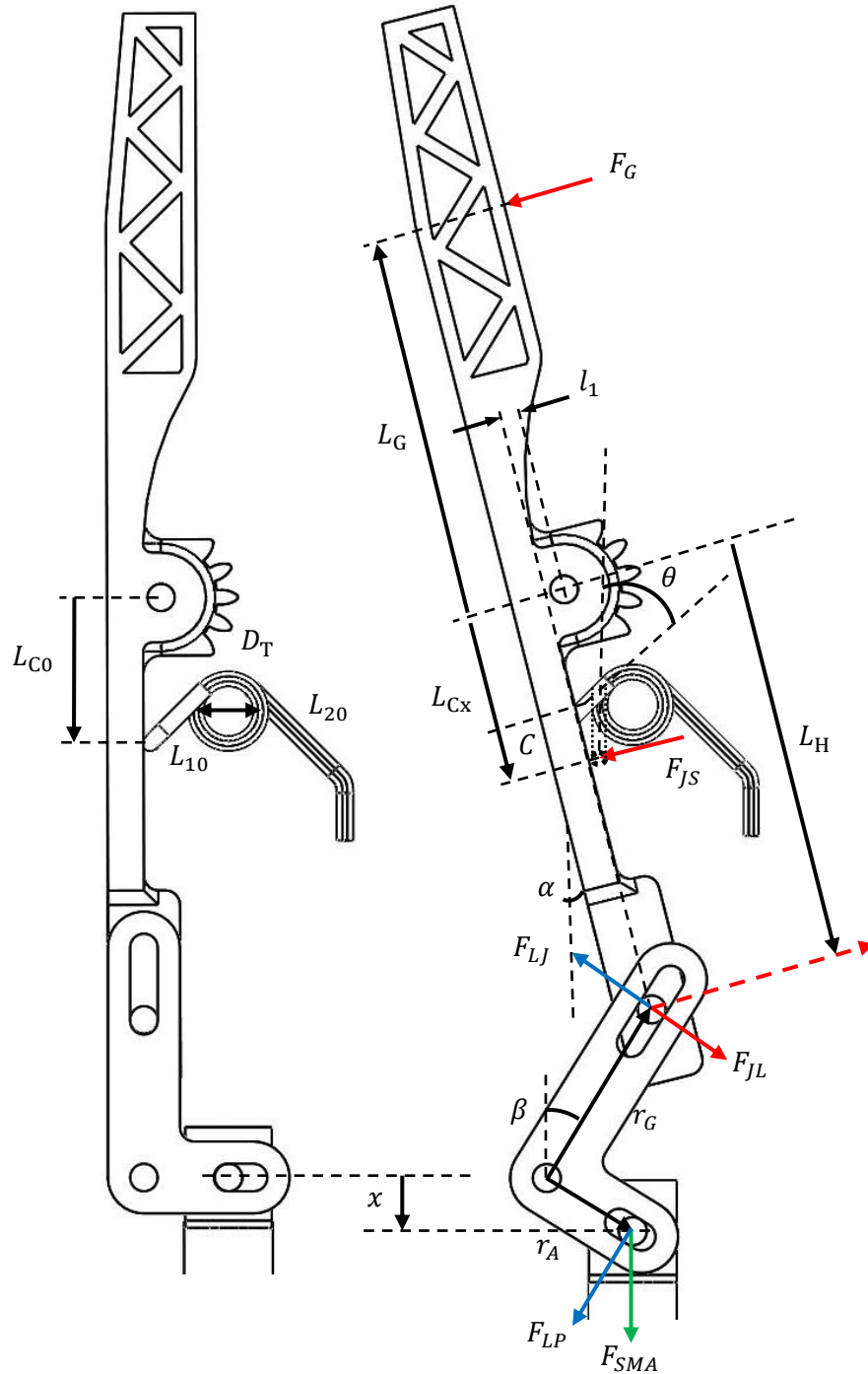


Figure 6.5: Free Body Diagram of the Gripper Mechanism

Table 6.1: Parameter Description

Symbol	Description
Force parameters	
F_{SMA}	Linear actuator force
F_{LP}	Reaction force applied on the Link by the Piston pin
F_{LJ}	Reaction force applied on the Link by the Driver jaw pin
F_{JL}	Reaction force applied on the Driver jaw pin by the Link
F_{JS}	Force applied on the Driver jaw by the Torsion spring
F_G	Gripping force
Distance parameters	
Variables	
x	Piston displacement
r_A	Actuator pin displacement along the slot from the link pivotal axis
r_G	Driver jaw pin displacement along the slot from the link pivotal axis
L_{Cx}	Distance from the Driver jaw pivot to the line of action of F_{JS}
L_{1x}	Length of the Torsion spring shorter leg at θ angular displacement
Constants	
r_{A0}	Initial actuator pin displacement along the slot from the link pivotal axis
r_{G0}	Initial driver jaw pin displacement along the slot from the link pivotal axis
L_H	Distance from the Driver jaw pivot to the slot pin
L_{C0}	Initial distance from the Driver jaw pivot to the line of action of F_{JS}
L_G	Distance from the Driver jaw pivot to the line of action of F_G
l_1	Diver jaw slot pin offset form the pivot
L_{10}	Initial Length of the Torsion spring shorter leg
L_{20}	Initial Length of the Torsion spring longer leg
D_T	Coil diameter of the Torsion spring
Angular parameters	
α	Angular displacement of the Driver jaw
β	Angular displacement of the Link
θ	Angular displacement of the Torsion spring shorter leg

Few mathematical relationships can be defined using above mentioned parameters to define the motion of the gripper as well as the forces involved with the gripper operation. Some of the useful equations are as defined below.

$$F_{LP} = F_{SMA} \cos(\beta)$$

$$F_{LJ} = \frac{r_{A0} F_{SMA} \cos(\beta)}{r_{G0} - l_1 \sin(\alpha) + L_H [1 - \cos(\alpha)]}$$

$$F_{JL} = F_{LJ}$$

$$F_{JS} = \frac{F_{JL} L_H \cos(\alpha + \beta) + F_G L_G}{L_{Cx}}$$

$$L_{Cx} = L_{C0} + C$$

$$C^2 = L_{10}^2 + L_{1x}^2 - 2 L_{10} L_{1x} \cos(\theta)$$

$$L_{1x} = L_{10} - \left(\frac{D}{2} \right) \theta$$

$$\tan(\beta) = \frac{L_H \sin(\alpha) + l_1 [1 - \cos(\alpha)]}{r_{G0} - l_1 \sin(\alpha) + L_H [1 - \cos(\alpha)]}$$

$$x = r_{A0} [\sec^2(\beta) - 1]^{\frac{1}{2}}$$

$$r_A = r_{A0} [\sec(\beta) - 1]$$

Several graphs were generated w.r.t. the Driver jaw angular displacement (α) for displacement and force parameters defined by the above-mentioned equations. Figure 6.6. shows the Link angular displacement with the change in gripper jaw opening angle. Figure 6.7. shows the displacement of the piston pin along the slot, within the opening range of the gripper jaw, it can be seen that the rate of change has an increasing gradient and later gets linear. By observing Figure 6.8., it can be concluded that the piston displacement should happen approximate linear manner throughout the gripper jaw opening angle. According to Figure 6.9., the effective force on the Driver jaw which creates a useful torque about the jaw pivot is approximately half of the force applied to the link by the SMA actuator.

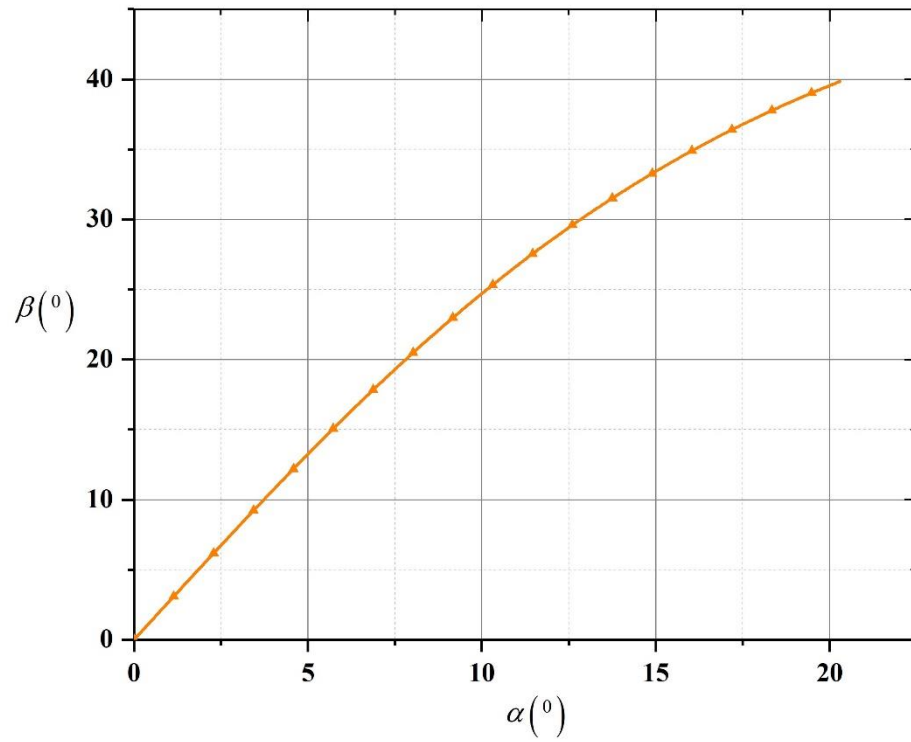


Figure 6.6: Link Angular Displacement Vs Gripper Jaw Opening

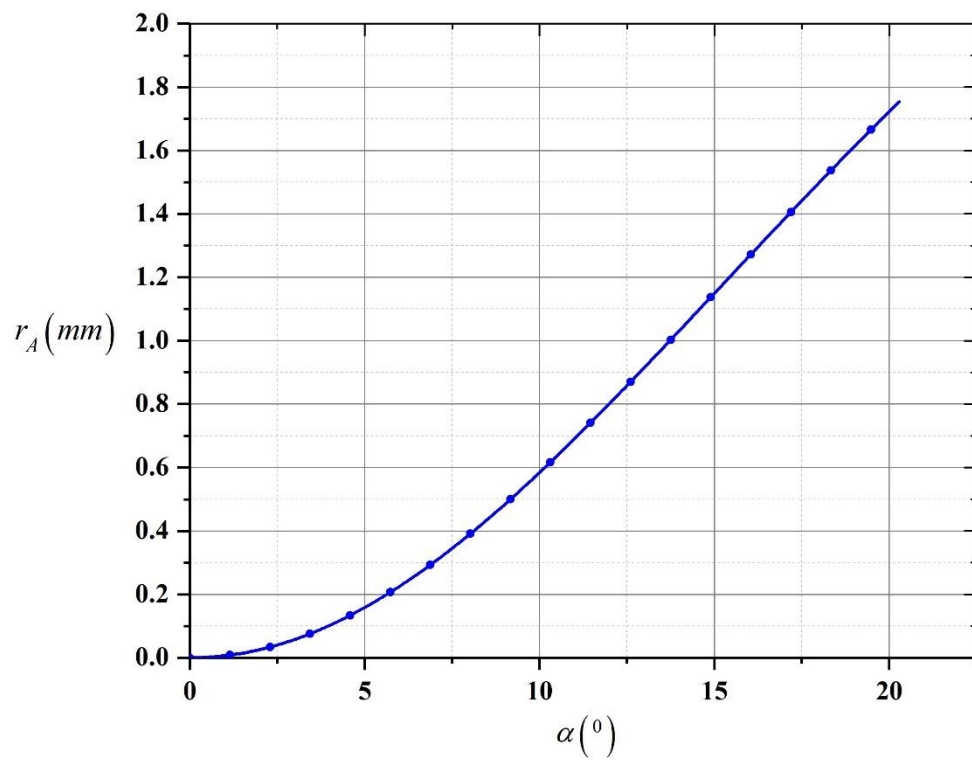


Figure 6.7: Actuator Pin Displacement along the Slot Vs Gripper Jaw Opening

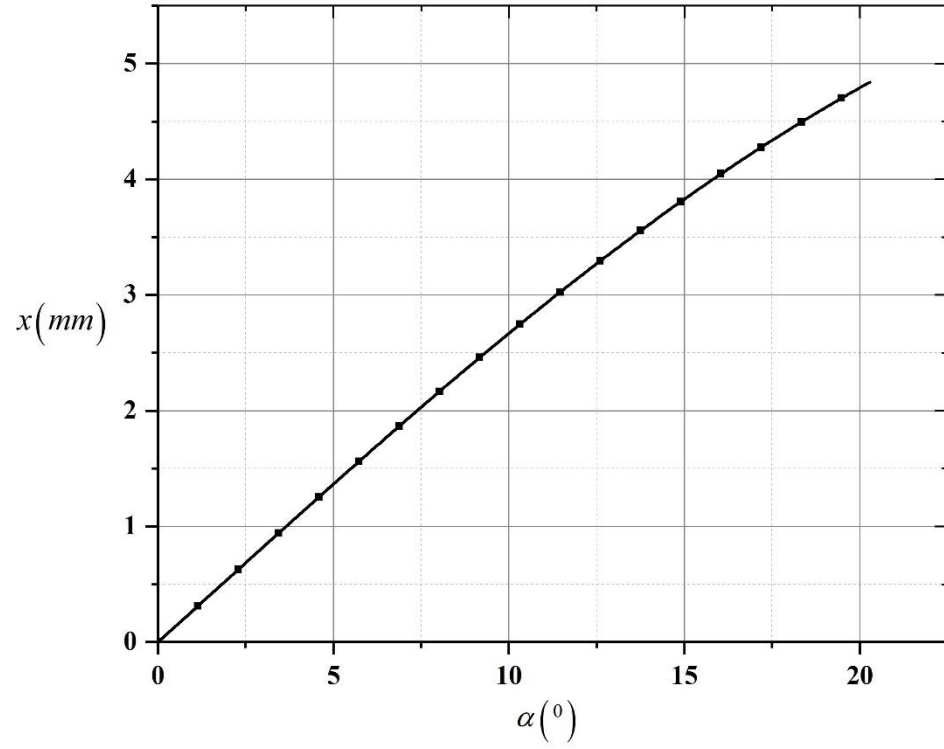


Figure 6.8: Piston Displacement Vs Gripper Jaw Opening

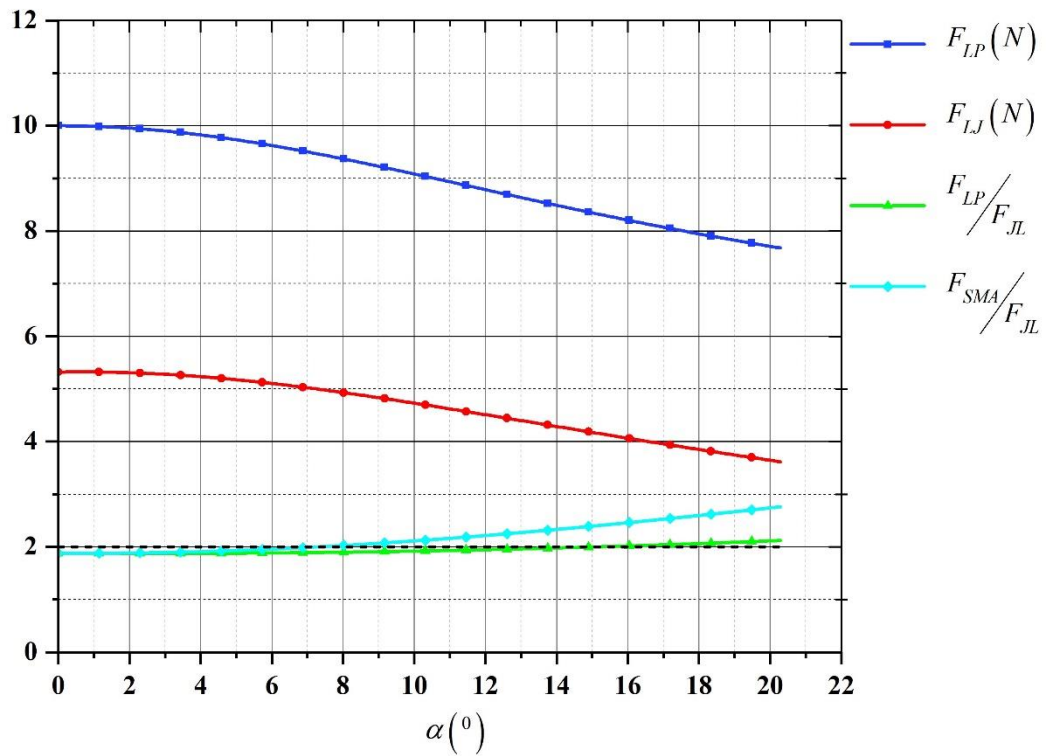


Figure 6.9: Reaction Force Variation w.r.t the Gripper Jaw Opening

Software Based Motion and Dynamic Analysis of the Gripper

The previous subsection described the mathematical modelling of the proposed gripper mechanism and the forces at special locations. Motion validation by software-based simulation is discussed and the results are presented under this subsection. Since the gripper is comprised with individual components which exhibit motion relative to the other. So, the motion of the gripper mechanism can be identified as a Multibody Dynamic Problem (MBD) and solved using COMSOL Multiphysics software package. Figure 6.10. shows the simulation results of the motion analysis.

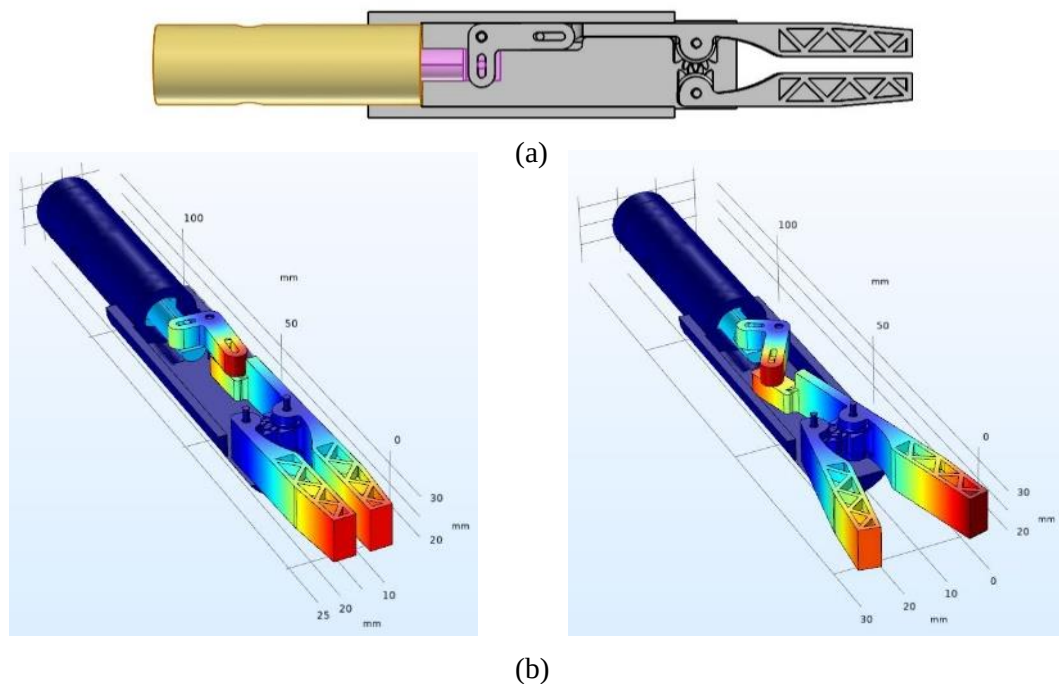


Figure 6.10: Simulation Results (a) Simplified Gripper Model; (b) Displacement 3D plots

Component Design of the Gripper for Manufacturability and Assembly

The design of the linear actuator was described in a previous subsection and the design of the other components such as gripper enclosure, Jaws, and link are explained under this subsection. Though the gripper was designed as a prototype, the intention was to incorporate compactness and easy assembly of the components.

All the components are in motion have to be connected to a common structure, and it was designed comprising two halves (Figure 6.11. (a) and Figure 6.11. (b)) to avoid assembling difficulties. The bottom cover (Figure 6.11. (a)) facilitates holding the linear actuator by aligning with the groove located at the Cylinder. There is a boss

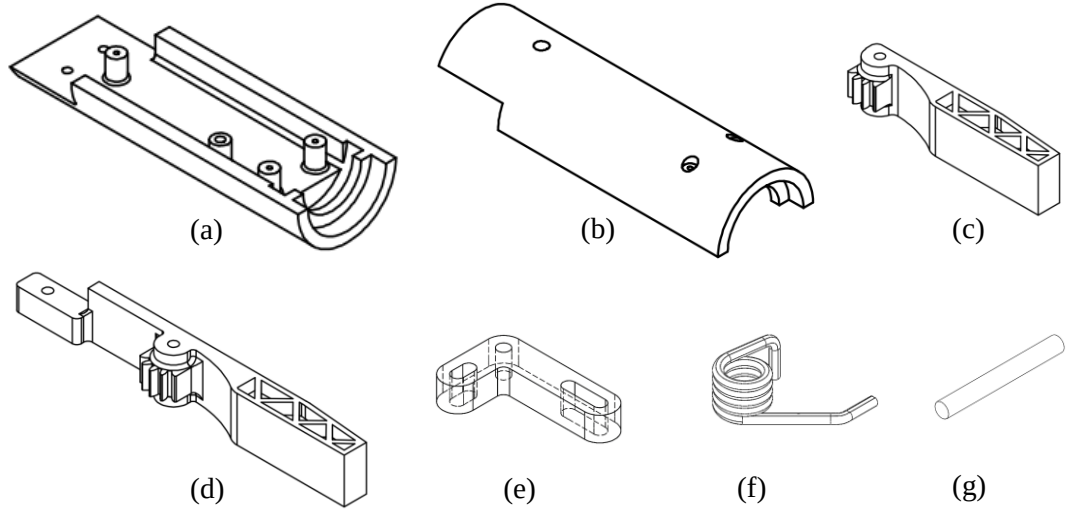


Figure 6.11: Gripper Components **(a)** Bottom Cover; **(b)** Top Cover; **(c)** Driven Jaw; **(d)** Driver Jaw; **(e)** Link; **(f)** Torsion Spring; **(g)** Pin

located at the bottom cover where the Link hinge is fixed. Also, it has provisions to mount gripper jaw pins. After assembling the components at the respective locations of the bottom cover, the mechanism is enclosed by the top cover. Torsional spring (Figure 6.11. (f)) was designed based on the following equations.

$$F_{SJ} = k_{per\ turn} \left(\frac{\theta}{2\pi} \right)$$

$$k_{per\ turn} = \frac{d^4}{10.8 D N_T A}$$

$$N_A = N_B + N_E$$

$$N_E = \frac{L_{10} + L_{20}}{3\pi D_T}$$

Here N_A , N_B and N_E are the Actual, Body, and Effective turns of the torsional spring.

6.2.4 Fabrication of the Gripper Components

The top cover, bottom cover, and the gripper jaws (Figure 6.11. (c) and Figure 6.11. (d)) were made out of one of the rapid prototyping techniques. (i.e.: 3D printing) The material that was used to manufacture these components is ABS Plus and it provides promising specific strength (strength to weight ratio = 39-43 kN.m/kg) compared to the other 3D printing materials. The Link (Figure 6.11. (e)) was made out of Polymethyl methacrylate (PMMA) or commercially named as Perspex by Laser cutting technique. The production drawings of all the components are included in Appendix S1 through Appendix S6. Torsional spring was made out of 1 mm steel wire by using a spring forming machine. Figure 6.12 shows the manufactured components assembled and two states of the gripper.

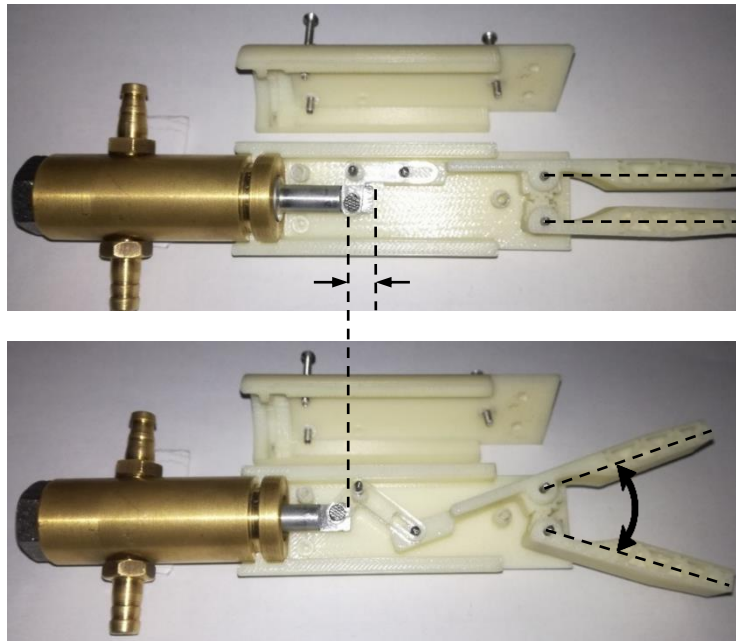


Figure 6.12: Fabricated Gripper Components in Assembly

6.2.5 Development of a Testing Apparatus for Gripper Actuation

According to the design of the SMA based spring-actuated gripper, which was discussed throughout the previous subsections, it is supposed to be operated under a flow of heated fluidic medium around the SMA element which is located in the linear actuator. So, it is a necessity to plan a fluid guiding system for the gripper and a method of controlling fluid flow and the temperature accordingly to make the linear actuator operate in a controlled manner. This subsection introduces a gripper testing apparatus that can be used to operate SMA actuated gripper.

Development of the Pump Control System

The apparatus has two pumps to transfer hot and cold fluid from the respective reservoir to the actuator and a multifunctional controller. The controller previously described under force characterization of the SMA actuator section was modified to control the pumps and hot reservoir temperature. Figure 6.13. shows a layout of the gripper testing apparatus. The computer software interface developed to control the parameters for force characterization was upgraded to control the pumps and temperature set point of the hot reservoir. According to the user inputs, the controller sets the required temperature in the hot reservoir, and as the pumps are being operated using a Pulse Width Modulated voltage which gives the intended flow rate through the pumps. Figure 6.14. shows the conceptual design and the fabricated gripper testing apparatus. Detail drawings are shown in Appendix T1 through Appendix T4.

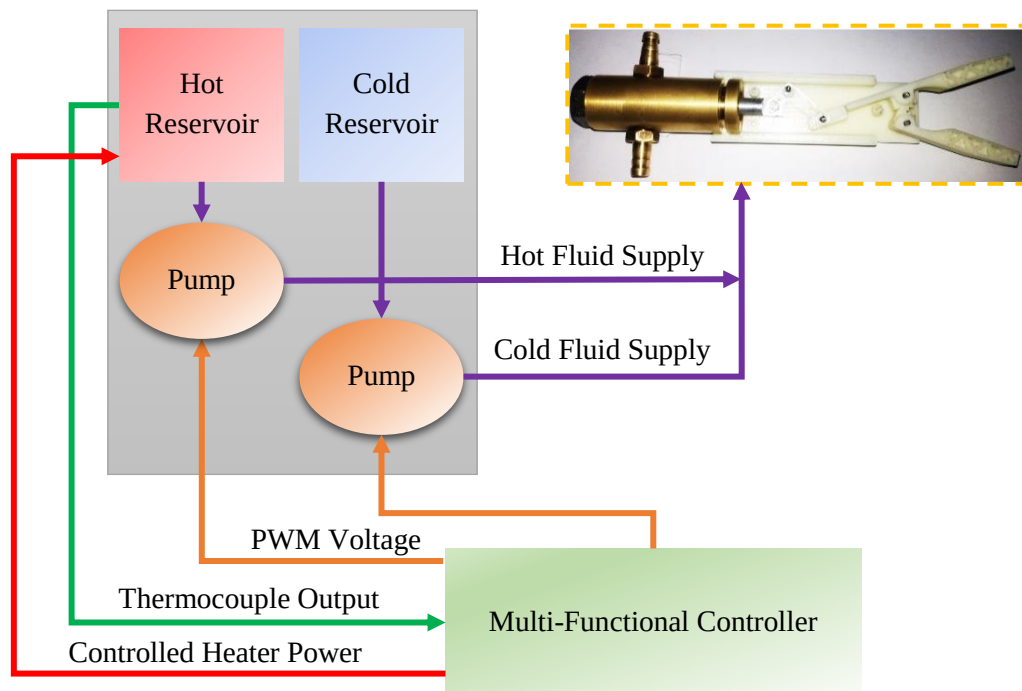


Figure 6.13: Layout of the Proposed Testing Apparatus

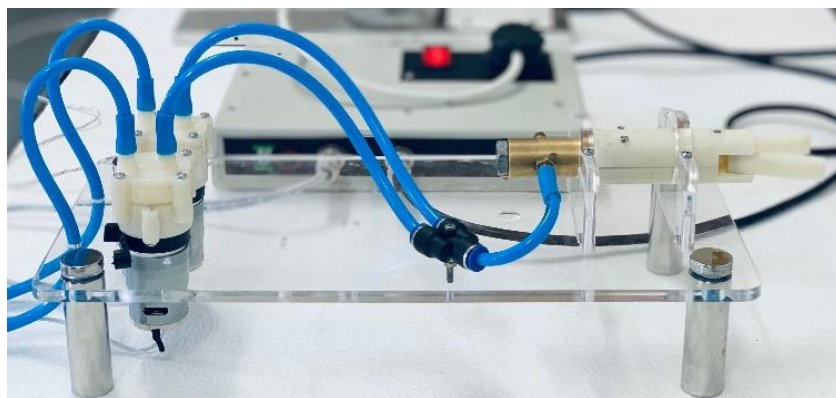
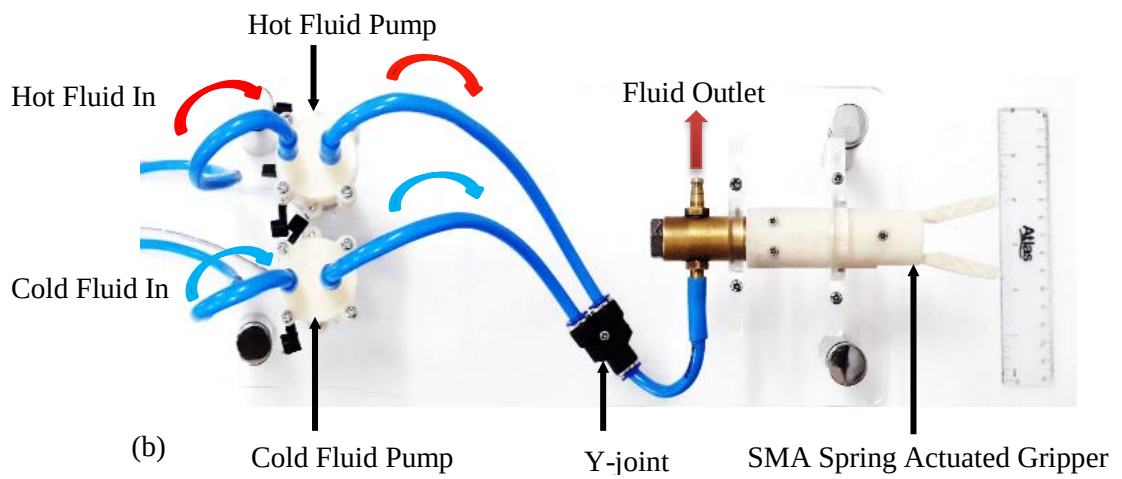
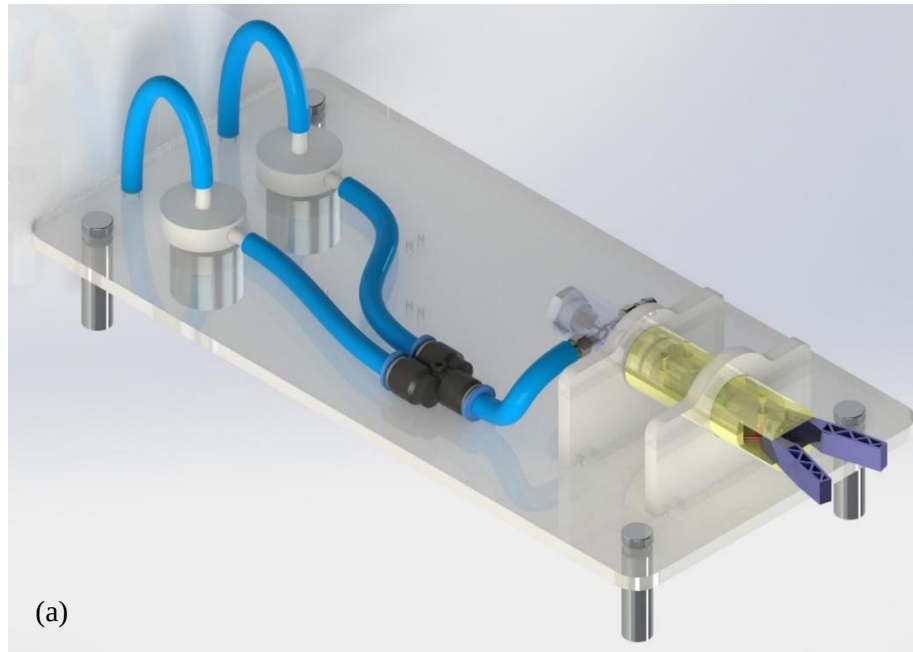


Figure 6.14: Gripper Testing Apparatus **(a)** Conceptual Design of the Proposed Testing Apparatus; **(b)** Component Description and Fabricated Testing Apparatus

Development of a Controller for the System

As described earlier in this subsection, there is a need for a controller which is capable of initializing and controlling parameters, assists data monitoring and data acquisition tasks. Figure 6.15. describes, how the controller and the hardware setup combine to make the testing a success. At the initial stage of the controller design, it can set flow rates of the pumps and operate those in a feed-forward manner. The hot reservoir temperature is maintained at the desired temperature setpoint by a PID closed-loop controller by monitoring the temperature through a K-type thermocouple probe and controlling heater power which heats the hot reservoir accordingly. The temperature setpoint (SP) is depending on the activation temperature (Transformation temperature (TT)) of the SMA actuator. To conserve the fluid circulating in the system, two solenoid-operated valves were introduced at the actuator exit fluid flow which guides the exit fluid to the respective reservoir.

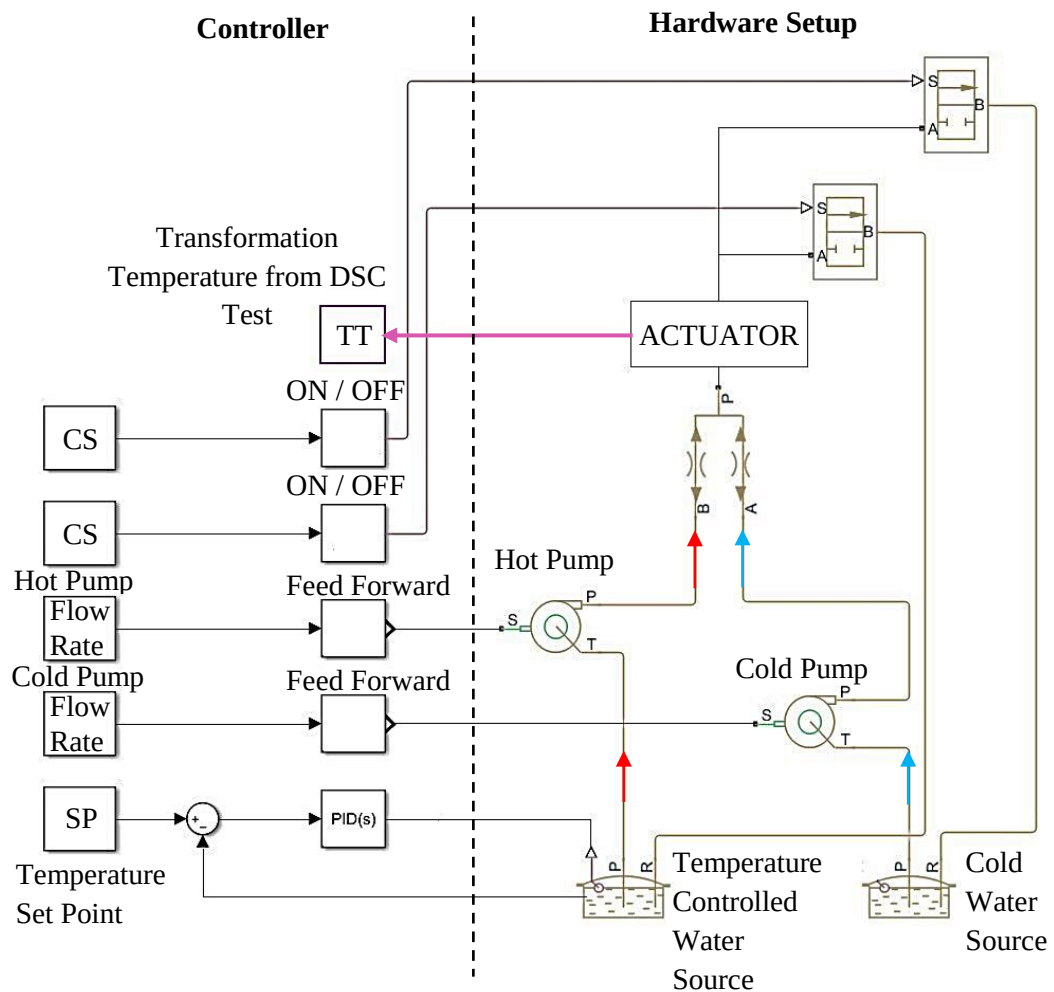


Figure 6.15: System Layout of the Testing Apparatus

The operation of the pump controller is to control the fluid flow through the gripper mechanism to maintain the required temperature for activation of the SMA spring actuator. The pump controller is mainly based on an 8-bit Microcontroller (Appendix H) and it has several supporting circuitries. (Figure 6.16.) The controller is powered by 230V AC power (Appendix M4) and it is converted to 12 V DC by a Switching Mode Power Supply (SMPS) unit. Since there is a need for a hot water source for activation purposes, a Thyristor-based electric heater power controller circuitry (Appendix M2) is introduced to the system, and to maintain the hot water source at a required temperature, the heater power is controlled by the microcontroller. There is a separate pump controller circuitry (Appendix M7) to control the flow rate according to the temperature requirement of the actuator. The hot water source is maintained at the desired temperature by the controller using its temperature control mode. Figure 6.17. (a) shows the I/O s of the modified hardware and Figure 6.17. (b) shows the electronic circuitry arrangement inside the developed controller hardware.

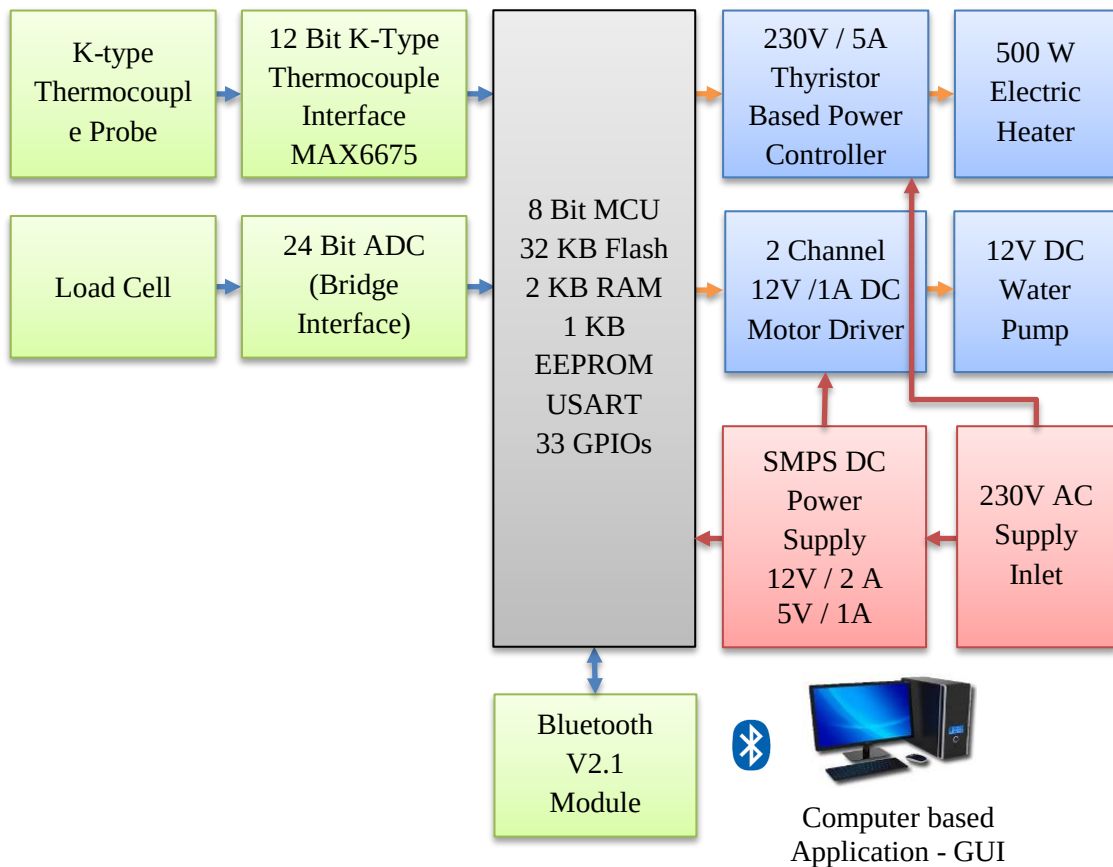


Figure 6.16: Controller Hardware Architecture

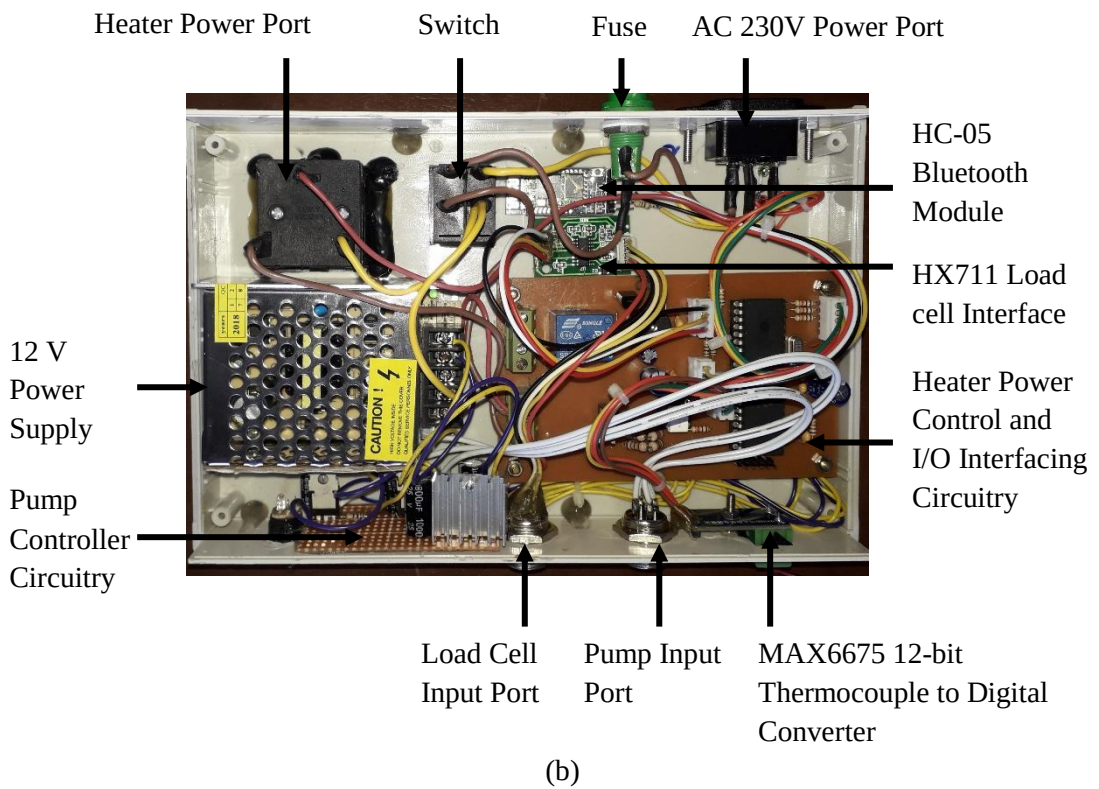
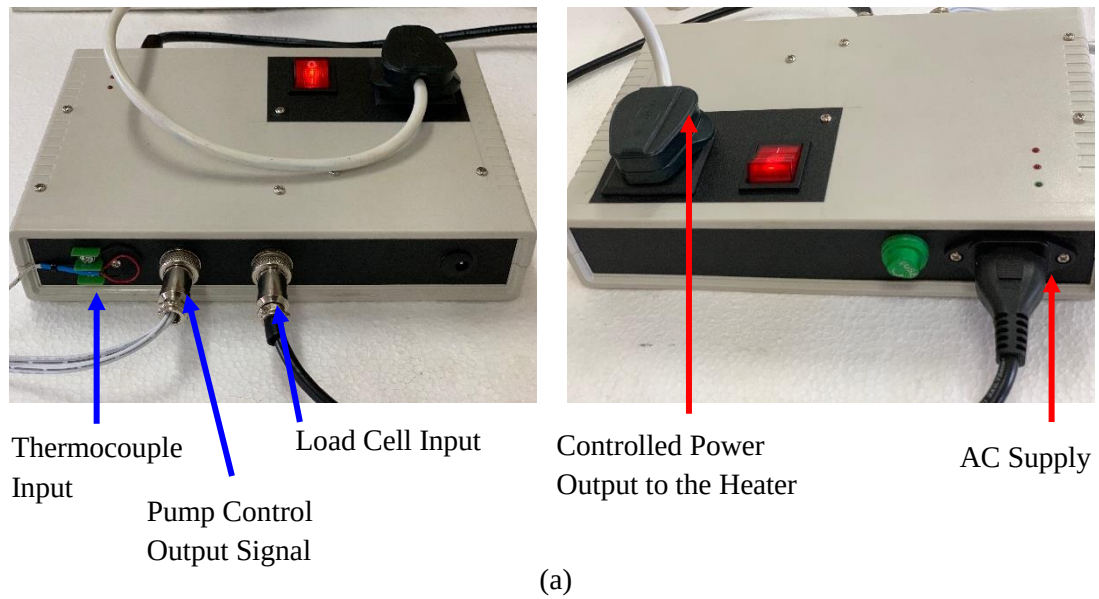


Figure 6.17: Multifunctional Controller **(a)** Modified Controller I/O s; **(b)** Controller Circuitry Arrangement

Figure 6.18. shows the arrangement of the controller and the hardware setup for study capabilities of the SMA spring-actuated gripper.

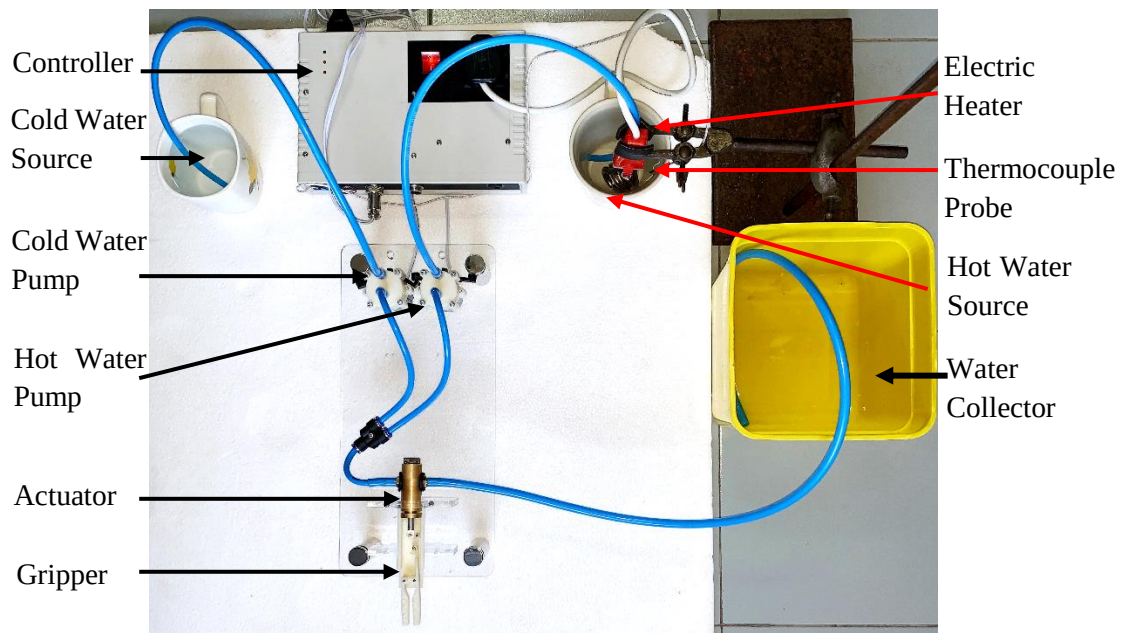


Figure 6.18: Gripper Testing Apparatus

Visual Studio Based Controlling Interface

The controller is connected to a computer-based Graphical User Interface (GUI) via Bluetooth. Temperature calibration, parameter tuning, Heater power controlling, Pump controlling, Data plotting, and acquisition options are available with the developed GUI (Figure 6.19.).

The GUI is an extension of the one developed in the work carried out for force characterization and controlling of the SMA spring actuator.

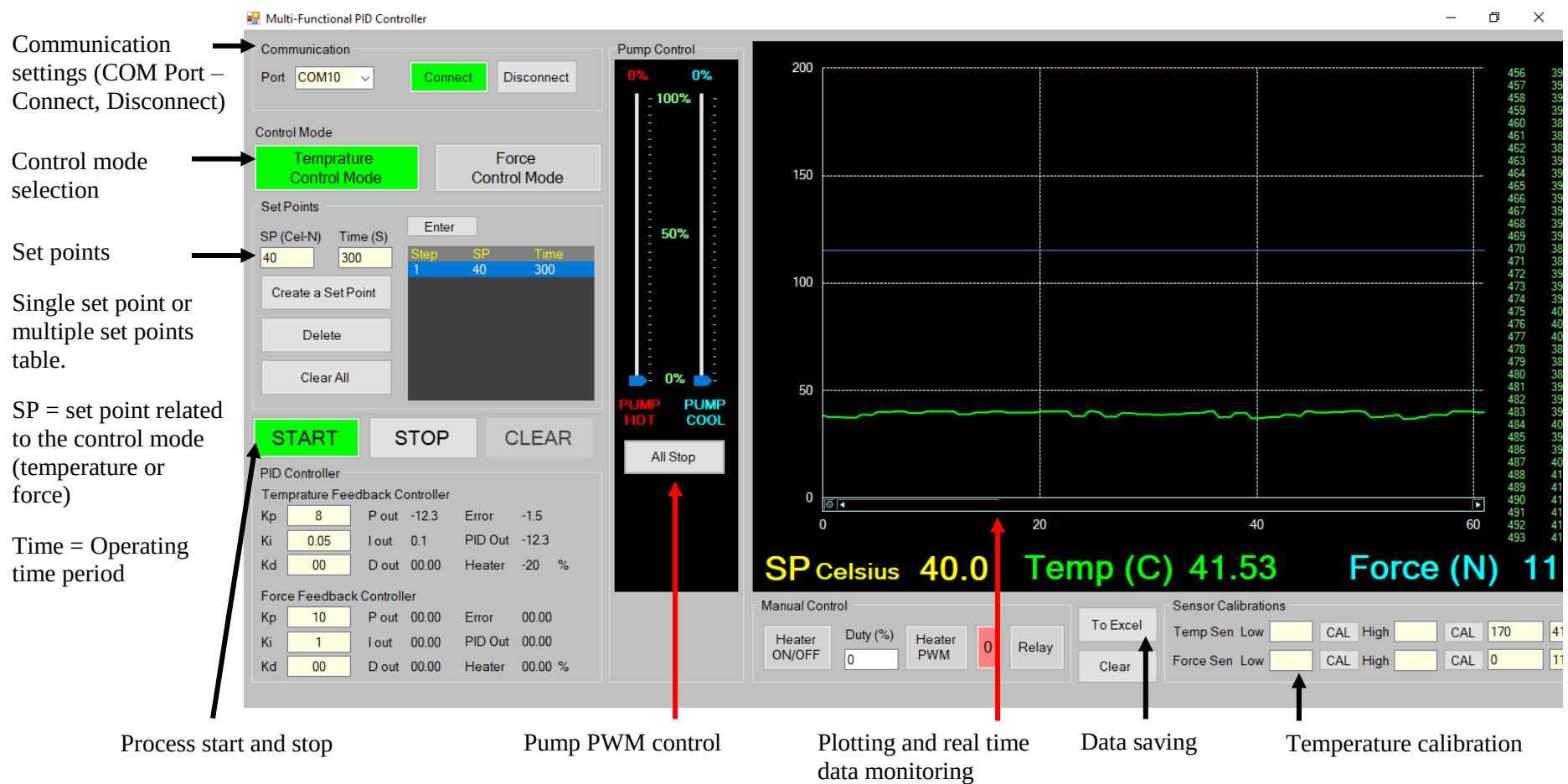


Figure 6.19: Modified Graphical User Interface (GUI)

6.2.6 Gripper Force Sensing, Monitoring and Controlling

The design and development of the SMA spring-actuated gripper were introduced throughout the previous sections, starting from the development of the spring element to the gripper testing apparatus. So, the outcome of the gripper was to apply in MIS surgery applications. Most of the time, these types of surgeries are force sensitive in nature, and applying excessive forces would cause tissue damage and many complications. In this subsection, gripper force sensing, monitoring, and controlling techniques were introduced to the developed gripper.

Development of a Force Sensing System for the Gripper

There are various sensing principles available in force sensing and Table 6.2.[48] summarizes their performance based on several indicators. According to the details presented in the literature review section, there are several possible locations to attach sensing elements on an MIS tool. By considering the gripper design and the possible sensing method presented, a Resistance based (Figure 6.20. (a) [73]) force sensing method was introduced to the gripper. In the proposed method, a precisely located strain gauge has been used as the force-sensing element which was bonded to the gripper arm. Due to the limitation of miniaturization, a single element has to be used as the sensing element. So, the placing location of the strain gauge is important, because of measuring the tensile and compressive strains (i.e.: bi-directional force measurement) at a single location. In order to find out the optimum location a Finite Element Analysis (FEA) was conducted using COMSOL Multiphysics software. (Figure 6.21.)

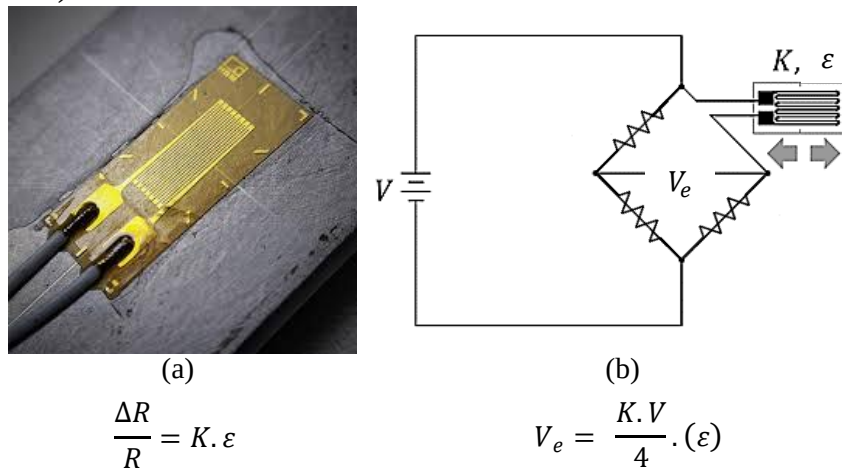


Figure 6.20: Resistive Type Sensor Element **(a)** A Strain Gauge Bonded to a Surface; **(b)** Wheatstone Bridge Arrangement (Quarter Bridge)

Table 6.2: Possible Force Sensing Methods in MIS

Sensing Method	Simplicity	Additional Systems	Dependency to System Accuracy	Measurement Accuracy	Use of Predictive Models to Improve Accuracy
Displacement-based	High	Low	High	Moderate	Low
Current-based	High	Moderate	High	Very Low	High
Pressure-based	Moderate	High	High	Low	Very High
Resistance -based	High	Low	Moderate	High	Low
Capacitance-based	Moderate	Moderate	Moderate	Very High	Low
Piezo-electric-based	High	Moderate	Moderate	Very Low (static) High (time varying)	Low
Vibration-based	Low	Very High	High	High	Low
Optical-based	Low	Very High	Very High	High	Low

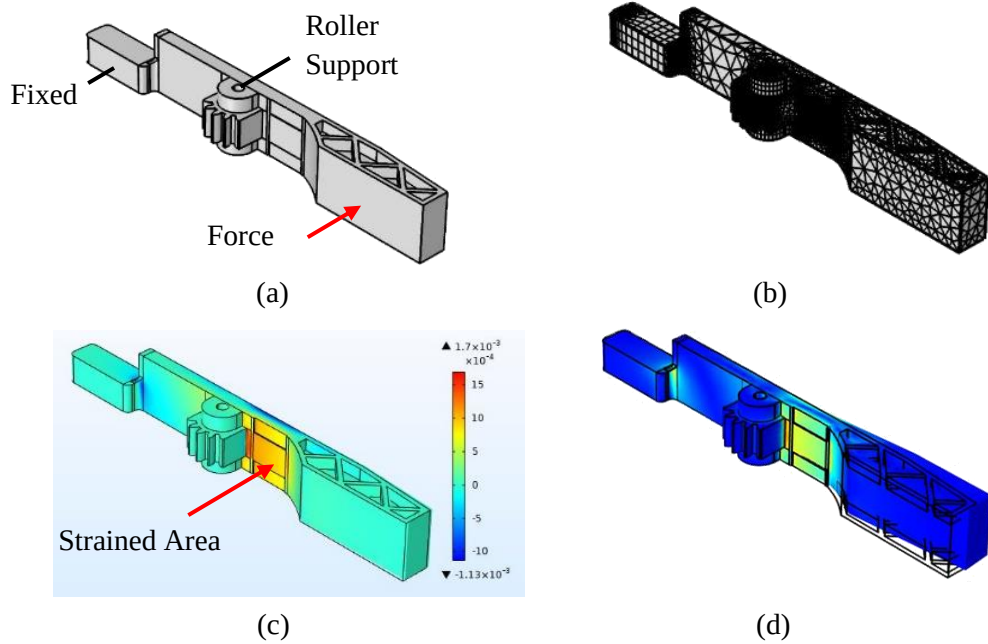


Figure 6.21: **(a)** Boundary Conditions **(b)** Mesh **(c)** Strain Variation **(d)** Stress Variation

The strain gauge is connected to the Winston Bridge as a quarter bridge (Figure 6.20. (b)) assembly to convert resistance changes of the strain gauge to the differential voltage level to interface with a bridge amplifier and ADC. After conducting several loading, unloading, and initializing tests the coefficients for the ADC were obtained to measure gripping forces accurately up to the resolution of 0.01N. The strain gauge placing area was modified to maximize the strain variation and Figure 6.22. shows the highlighted strain gauge placing area and the variation of strain along the X – direction marked in the figure.

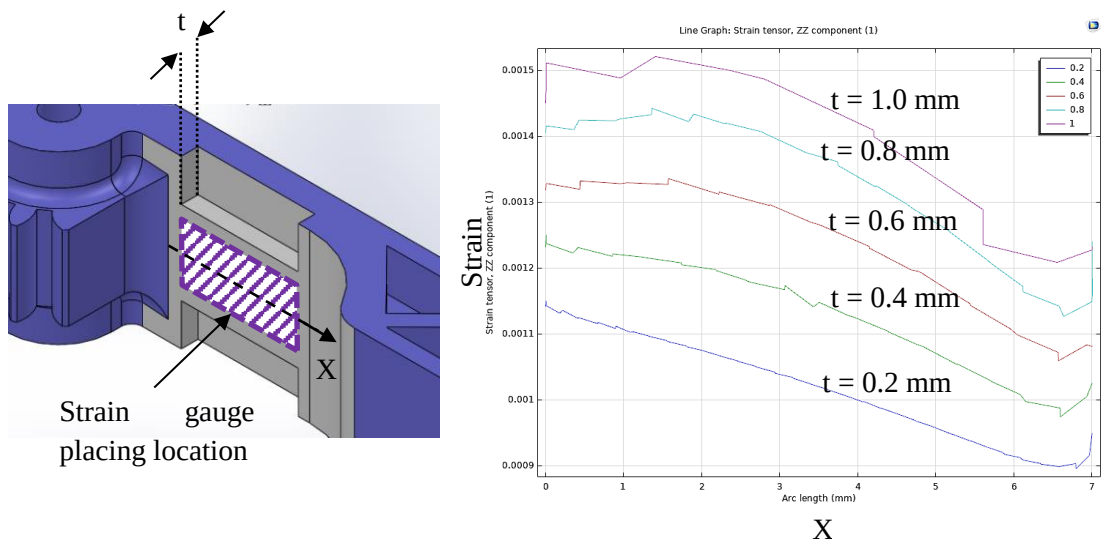


Figure 6.22: Enhancing Strain Variation through Thickness Variation

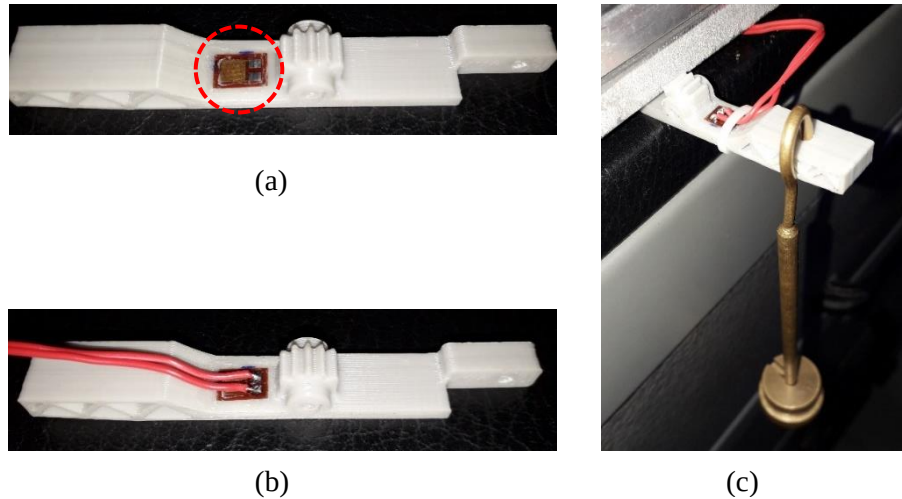


Figure 6.23: **(a)** Strain Gauge Placement **(b)** Wired Strain Gauge **(c)** Calibration Weights

The gripper jaws were modified (Appendix T5) to carefully place the strain gauge on the highlighted location of the driver's jaw. Figure 6.23. (a) shows the bonded strain gauge on the gripper jaw and Figure 6.23. (b) shows the wire connections of the strain gauge which connects to the Wheatstone bridge circuitry. It is important to calibrate the strain gauge by applying known weights before being introduced in force sensing experiments and Figure 6.23. (c) shows how the calibration process was conducted by applying weights on the gripper jaw at a point that is assumed to be touching with the objects.

After the calibration process, the scale value was stored in the program which supports force sensing and controlling. The gripper jaws were then assembled to the gripper and the gripper was then fixed at the apparatus which was discussed in the previous subsection to conduct the experiments.

Figure 6.24. shows the gripper mechanism containing a Linear actuator, Bias torsion spring, and the sensing element as well as the Wheatstone bridge circuitry developed to assist in converting resistance variation of the sensing element due to the strain variation upon loading into a voltage value. The Wheatstone bridge output was then connected to the controller. The controller which was used for the experiments of the gripper testing apparatus has an HX711 load cell amplifier which was used to characterize the force of the developed SMA spring actuator. Since the same technique is being used here with quarter bridge configuration, the same hardware controller (Figure 6.26.) was used for these experiments, and modifications were introduced to the controller algorithm.

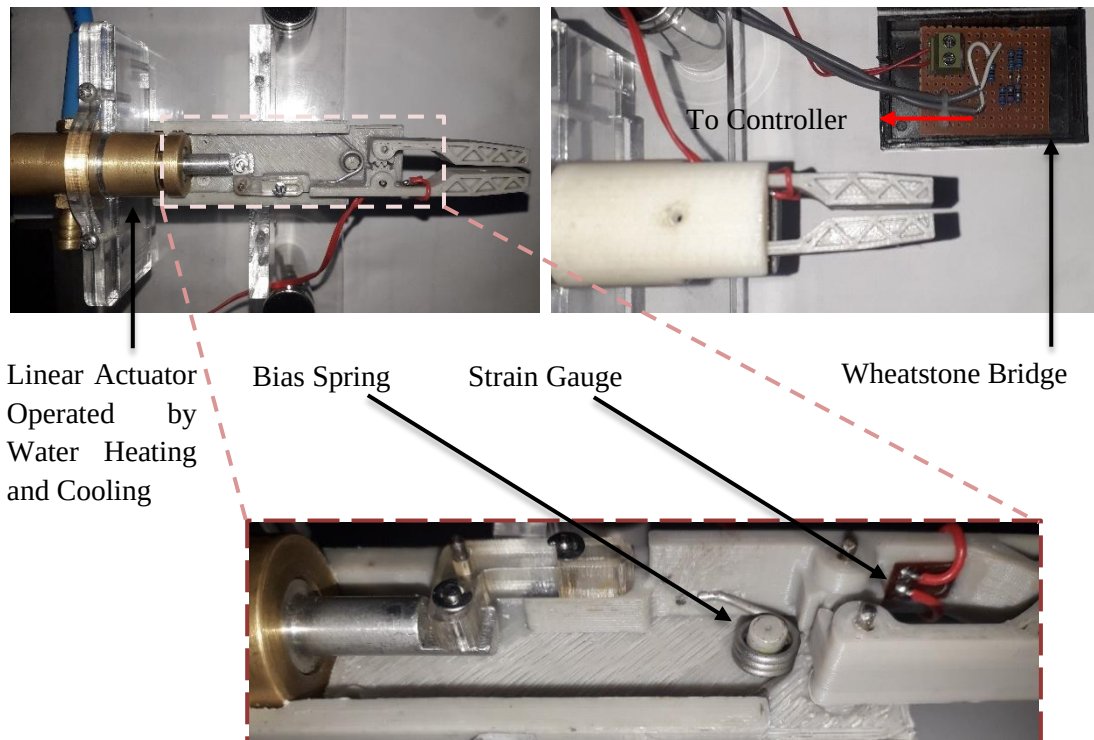


Figure 6.24: SMA Spring Actuated Gripper Integrated with the Force Sensing Method

Figure 6.25. shows the layout of the force sensing and controlling system. As the gripper grabs an object due to the forces acting on the jaws would cause strain at the strain gauge placed location and the sensing element exhibit a resistance change. This minute change in resistance is converted to a voltage by the Wheatstone bridge circuitry. The voltage is then amplified to a measurable value by the amplifier. At the beginning parameters such as force set point and the opening and closing, directions were introduced to the controller. Then the controller accordingly adjusts the hot and cold pumps flow rates to control the SMA actuator temperature and in turn applied force on the object.

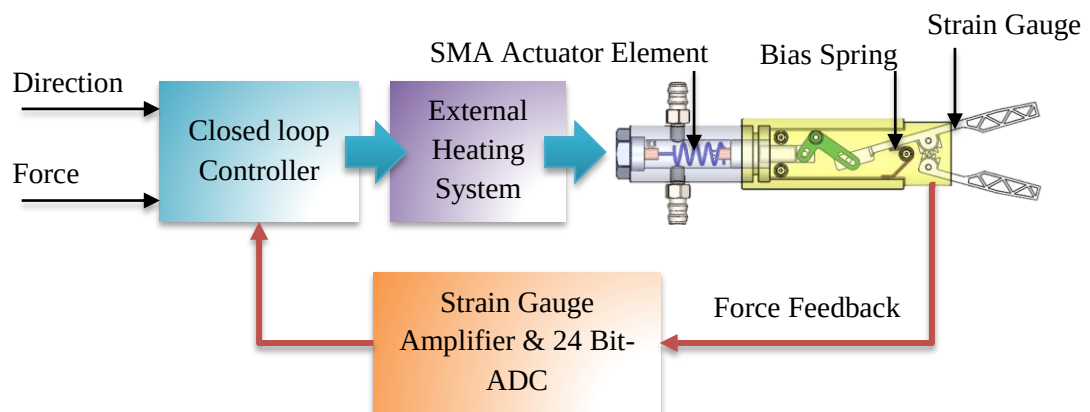


Figure 6.25: Layout of the Proposed Force Sensing and Controlling Method

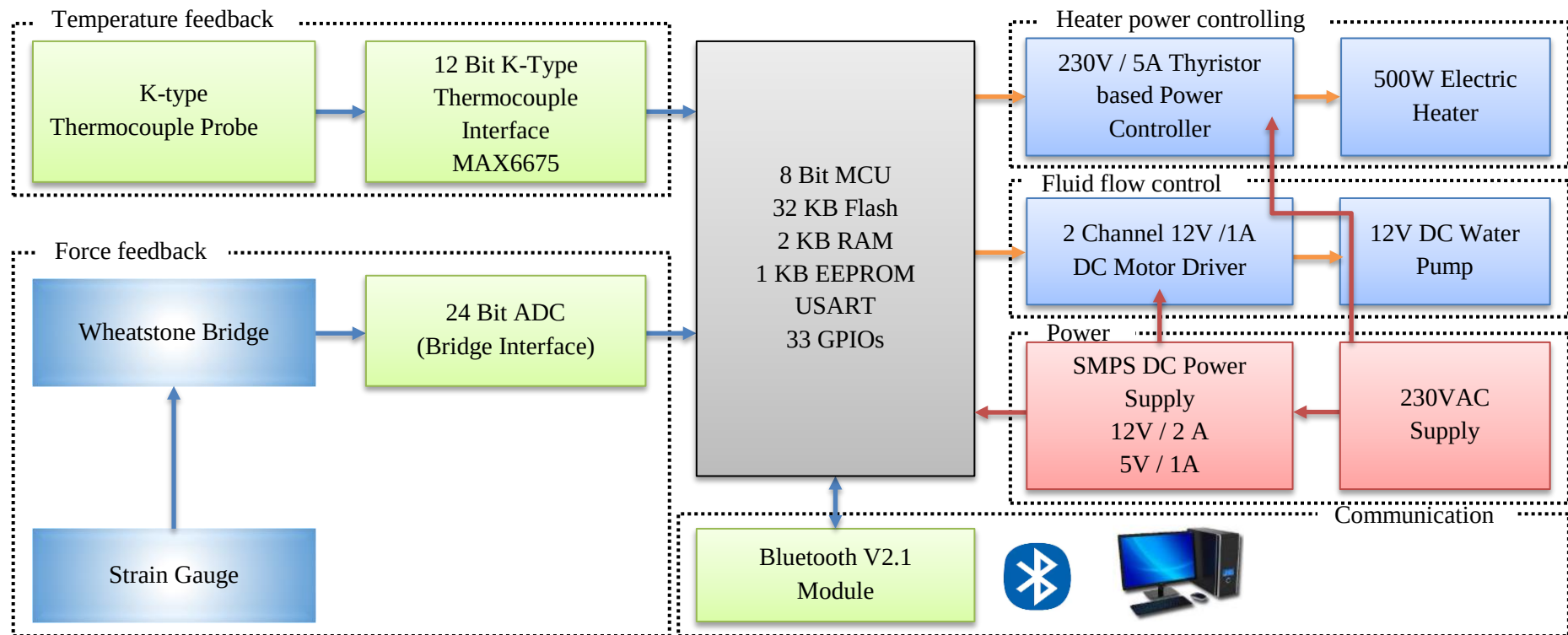


Figure 6.26: Modified Controller Hardware Layout

Experimental Results of Force Controlling

Figure 6.27. shows the experimental results of the transient response of the system under the best tuning conditions. As per the obtained results, it exhibited a fast response (approximately 1 sec) compared to the previous research based on SMA actuators under one-way motion Joule heating techniques. It's due to the fluid-based two-way external heating system used in this approach. But it has significant oscillation in the steady-state due to the low response of the fluid delivery system of the external heating system.

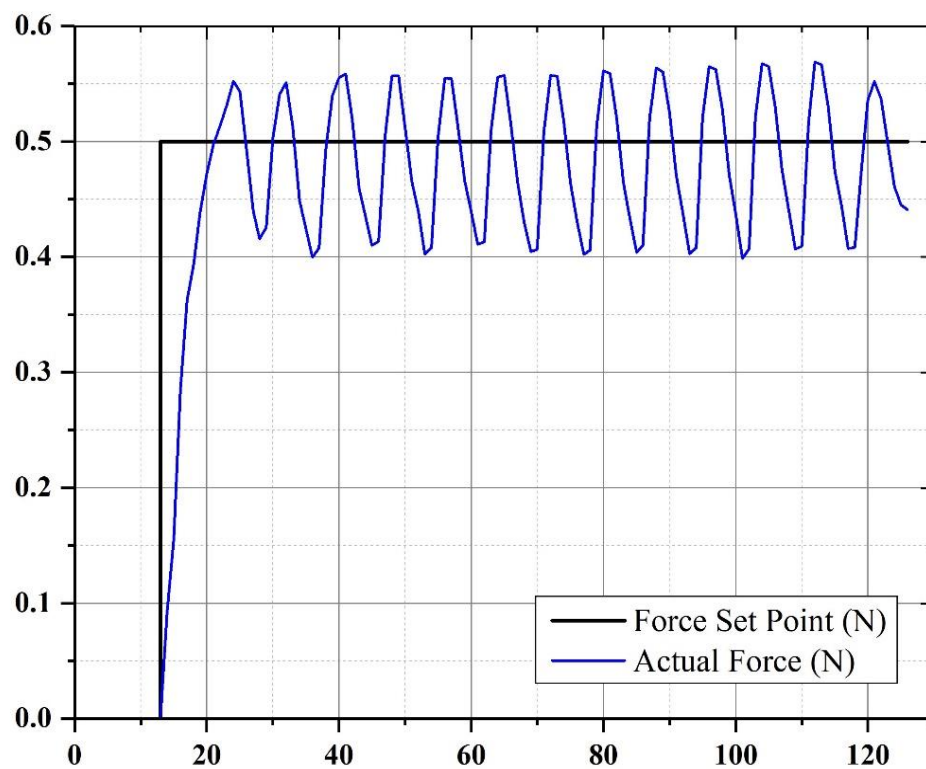


Figure 6.27: Force Controlling Results

6.3 Development of the Linear Actuator Activated by Joule Heating and Air Cooling

The previous subsection presented the design and development of a gripper activated by a linear actuator based on the SMA spring element which is activated by external heating and cooling. Here, the work carried out in developing another type of linear actuator which utilizes SMA springs is presented, and it is activated by Joule heating and air cooling. Figure 6.28. summarizes the discussed linear actuator types throughout the research. The linear actuator discussed earlier is a one-way SMA actuator and the recovery of the SMA spring happens against the torsional biasing spring. So, half of the stroke is controlled by the SMA spring, and the returning stroke is controlled by the biasing spring. The actuator which is going to be discussed here is an Agonist-Antagonist (A-A) type linear actuator which comprises two SMA spring actuators connected in series. Recover of one SMA spring causes the other to deform and vice versa to create a complete actuator stroke. The first subsection of the chapter discusses mathematical modelling of A-A type actuator and secondly, carried out the designing task. Then accounted for the best possible prototyping process of the designed actuator and carried out the fabrication. The fabricated actuator was then characterized in terms of stroke. Finally, a developed A-A linear actuator was applied to an application area related to the MIS procedure.

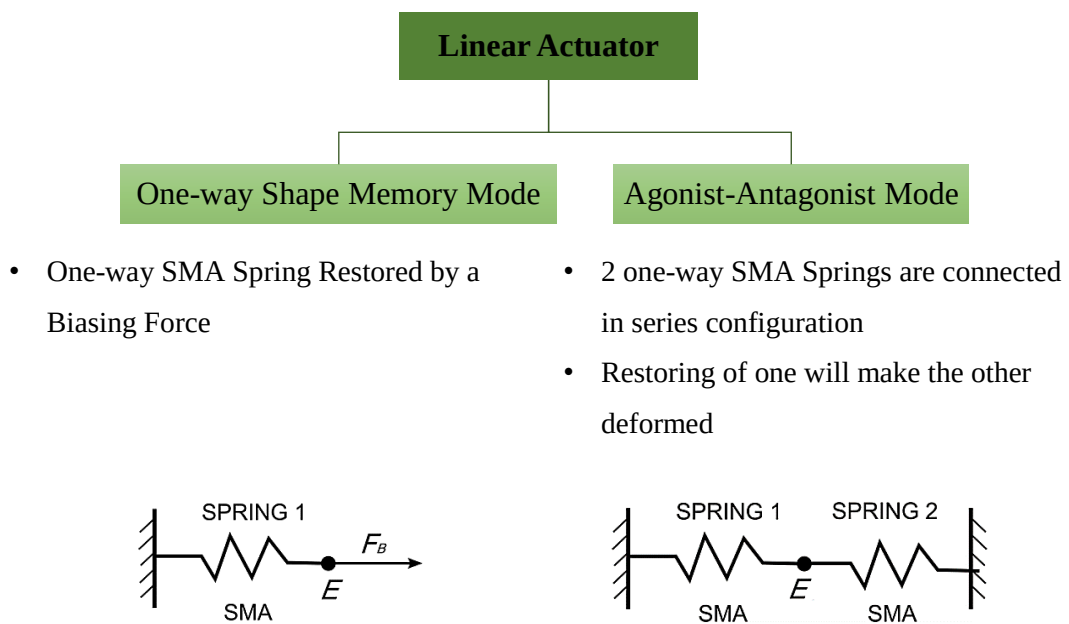


Figure 6.28: Interested Linear Actuator Types

6.3.1 Mathematical Modelling of the Linear Actuator

To proceed with the mathematical modelling, several parameters namely, s_1 , s_2 , s_F , and s_0 were defined. These dimensionless parameters are important in the simplifying process of the design expressions. Though these parameters are dimensionless they carry a physical meaning. The parameter s_1 can be considered as a property of the SMA. It was defined as the ratio between the stiffness values of the SMA springs which are in a heated state (K_{1SH} or K_{2SH}) or in the cold state (K_{1SC} or K_{2SC}). Also, the same dimensionless parameter can be defined as the ratio between elastic moduli of the austenite and martensite phases with the assumption of that the geometric changes related to the deformations of the springs do not influence the elastic moduli [75] Hence,

$$s_1 = \frac{K_{1SH}}{K_{2SH}} = \frac{K_{1SC}}{K_{2SC}} = \frac{E_A}{E_B}$$

By the above definition, it can be concluded that the value of the parameter s_1 is the same for two SMA springs made out of the same SMA material and designed as two antagonistic active springs. The parameter s_2 is important in two spring configurations and is defined as the ratio between the minimum stiffness of the bias spring (K_{min}) and the stiffness of the active spring (K_{1SC}) in the cold state. In the antagonistic configuration of two SMA springs, the minimum stiffness equals the cold stiffness of K_{2SC} [75]. Hence,

$$s_2 = \frac{K_{2SC}}{K_{1SC}}$$

The parameter s_F represents the effect of dissipative forces related to the motion of the SMA actuator. s_F is introduced as the ratio between the design dissipative force (F_F) and the maximum force assisted by the primary spring in the cold state. This primary force is calculated by multiplying the stiffness of the SMA spring at the cold state (K_{1SC}), with the maximum deflection ($L_C - L_{01}$) at the cold state [75]. Hence,

$$s_F = \frac{F_F}{K_{1SC} \cdot (L_C - L_{01})}$$

The parameter s_0 represents the effect of the conservative force related to the motion of the SMA actuator. s_0 is defined as the ratio between the conservative force (F_0) and the maximum force assisted by the primary spring in the cold state. This

maximum force is calculated by multiplying the stiffness of the SMA spring at the cold state (K_{1SC}), with the maximum deflection ($L_C - L_{01}$) at the cold state [75]. Hence,

$$s_0 = \frac{F_0}{K_{1SC} \cdot (L_C - L_{01})} \quad \text{Therefore, } s_0 = \frac{F_0}{F_F} \cdot s_F$$

Figure 6.29. shows an agonist-antagonist SMA spring configuration. Figure 6.30. shows the correlation between the exerted force and the deformation of the springs while they are operated between these positions by thermal actuation. Several assumptions are made about the two SMA springs as they are made of the same material and subjected to equal deformation. Therefore, the parameter s_1 is the same. As the two springs are not joined at the free ends and kept apart by a gap of p by applying heat to recover to their parent shape, the free lengths of the springs are assumed as L_{01} and L_{02} , as shown in the top drawing in Figure 6.29. (a). As there are no external forces applied to the springs, the same lengths can be seen when the springs are cooled down. This instant is represented by the origin O in Figure 6.30. for spring 1 and origin O_B for SMA spring 2. As the two springs are joined together by taking the free end of the SMA spring 2 which is at the heated state and the free end of the SMA spring 1 which is at the cold state, the combination of springs is subjected to a total pre-stretch p . Because of this unbalanced state of the stretch acts on the two springs which are in the different thermal states, the joined point moves to the right as in Figure 6.29. (b). by overcoming the dissipative force (F_F) which acts against the bias force exerted by SMA spring 2 and to the external conservative force (F_0). Because of the resultant action of SMA spring 2 and the forces F_F and F_0 , SMA spring 1 attains its maximum length (L_C) as shown in Figure 6.29. (b). This instant is represented by point A in Figure 6.30. $L_C - L_{01}$ measured from the free length of SMA spring 1. To satisfy static equilibrium conditions of the joined point following has to be fulfilled [75],

$$K_{1SC} \cdot (L_C - L_{01}) = K_{2SH} \cdot [p - (L_C - L_{01})] + F_0 - F_F$$

Solving this equation using the above equations gives,

$$p = (L_C - L_{01}) \cdot \left(\frac{s_1 \cdot s_2 + s_F - s_0 + 1}{s_1 \cdot s_2} \right)$$

Therefore,

$$L_C = L_{01} + p \cdot \left(\frac{s_1 \cdot s_2}{s_1 \cdot s_2 + s_F - s_0 + 1} \right)$$

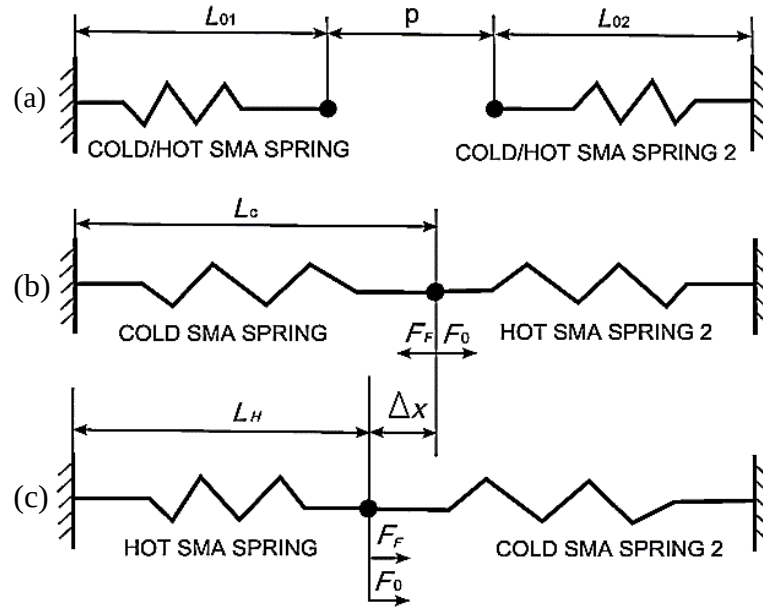


Figure 6.29: Stages of the Binary Actuator [83]

As the temperature of the SMA spring 1 is increased and the temperature of the SMA spring 2 is simultaneously decreased, the length of the SMA spring 1 reduces to length L_H , while the dissipative force (F_F), the bias force of SMA spring 2, and the external conservative force (F_0) acts opposite to the SMA spring 1 force (Figure 6.29. (c)). this instance is depicted by point B in Figure 6.30. To satisfy static equilibrium conditions of the joined point following has to be fulfilled [75],

$$K_{1SH} \cdot (L_H - L_{01}) = K_{2SC} \cdot [p - (L_H - L_{01})] + F_0 + F_F$$

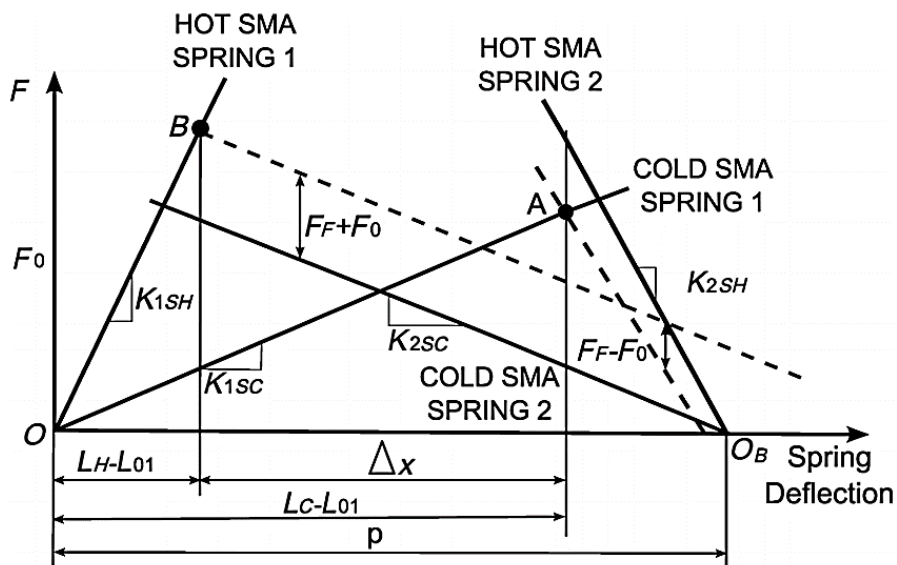


Figure 6.30: Force Vs Deflection [83]

By simplifying this equation we get,

$$L_H = L_{01} + p \cdot \left(\frac{s_2 [s_1 \cdot (s_2 + s_F) + s_0 \cdot (s_1 - 1) + s_F + 1]}{(s_1 + s_2) \cdot (s_1 \cdot s_2 + s_F - s_0 + 1)} \right)$$

The productive stroke of the actuator, $\Delta X = L_C - L_H$ between the limit positions in Figure 6.29, can be obtained by following equation [75],

$$\Delta x = p \cdot \left(\frac{s_2 [(s_1 - s_F - 1) \cdot (s_1 + 1) - s_0 \cdot (s_1 - 1)]}{(s_1 + s_2) \cdot (s_1 \cdot s_2 + s_F - s_0 + 1)} \right)$$

6.3.2 Design of the Linear Actuator

Several designs were created using binary SMA springs by considering the discussed parameters. All the designs contain a structure, SMA spring attaching mounts, and a rod connecting with the SMA springs and moving relative to the structure to generate stroke has to be comprised with separate air flow lines to cool down the SMA elements. Also, it has provisions on the actuator rod to adjust the pre-stretch. Design 1 possesses assembling complexity and Design 2 was created with alterations. As shown in Figure 6.31. (b), the SMA springs are located outside the

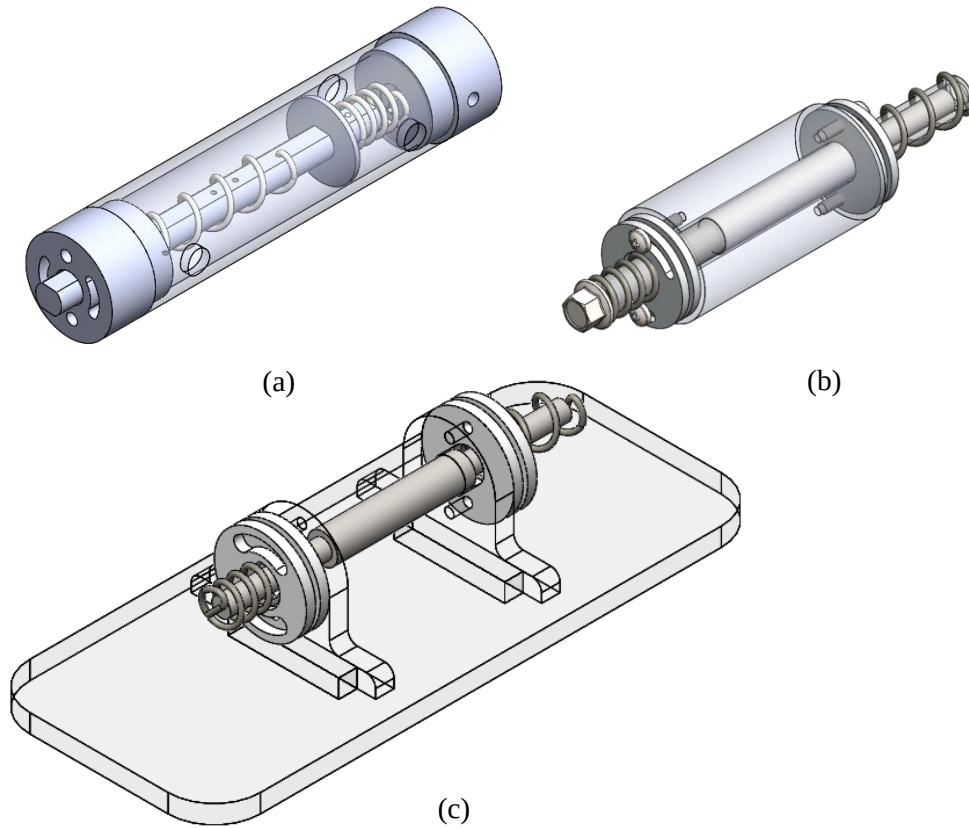


Figure 6.31: Conceptual Designs **(a)** Design 1; **(b)** Design 2; **(c)** Design 3

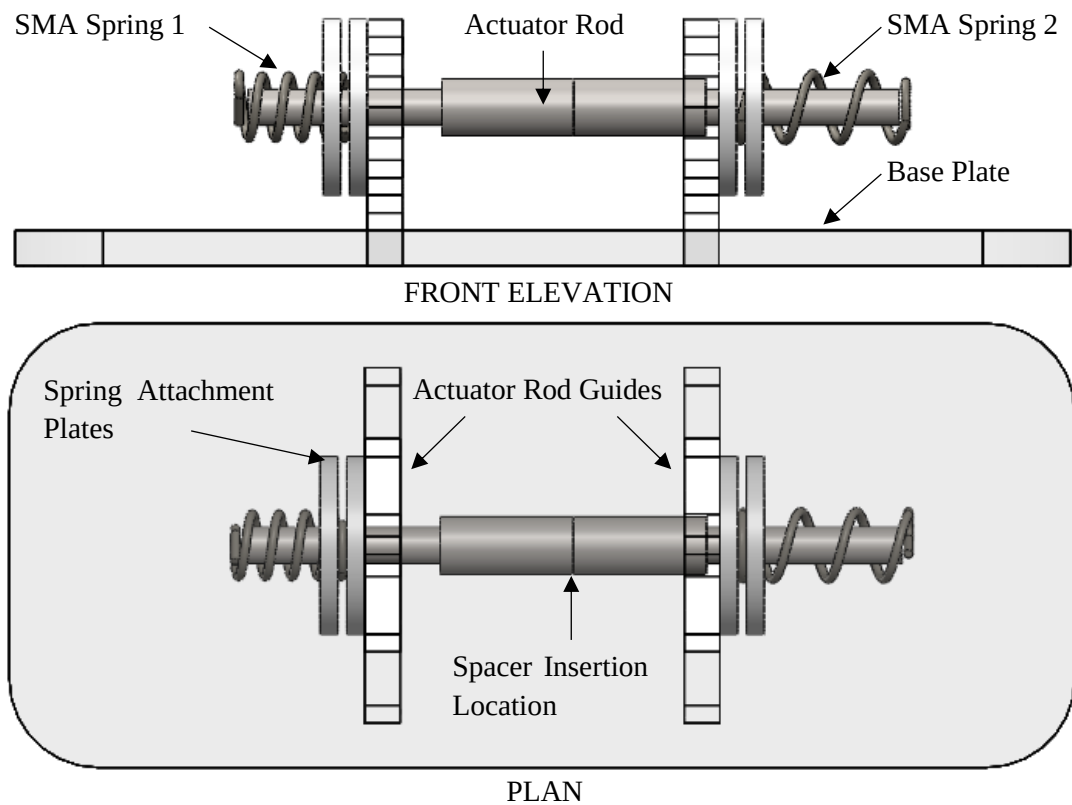


Figure 6.32: Design 3 Component Descriptions

cylindrical structure and mounted on the shaft at one end and the other end to the structure using mount plates that are screwed to the structure. Here the actuator rod consists of two-part which are screwed together to form it and by inserting spacers at the interfacing end, the pre-stretch can be adjusted according to the requirement.

Design 2 is then simplified as Figure 6.31. (c) to fit in with the testing apparatus which is described in the preceding subsection. Figure 6.32. shows the component description of the prototyping design

6.3.3 Fabrication of the Linear Actuator

The finalized design was fabricated by using easily available materials such as Stainless-steel rods, PMMA plates, and standard screws for prototyping convenience. Conventional machining techniques were used to manufacture the actuator rod to the planned shape and metric thread tapping die and tap were used to generate mating threads of the two parts. A laser cutter machine was used to cut the required structural parts and the SMA attachment plates from the PMMA plates. Figure 6.33. shows the fabricated assembly of the binary SMA spring-based linear actuator operated by Joule

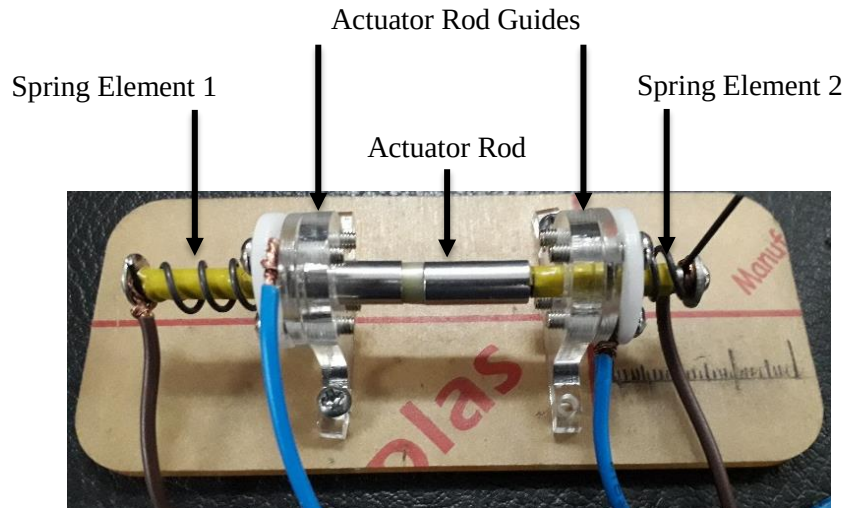


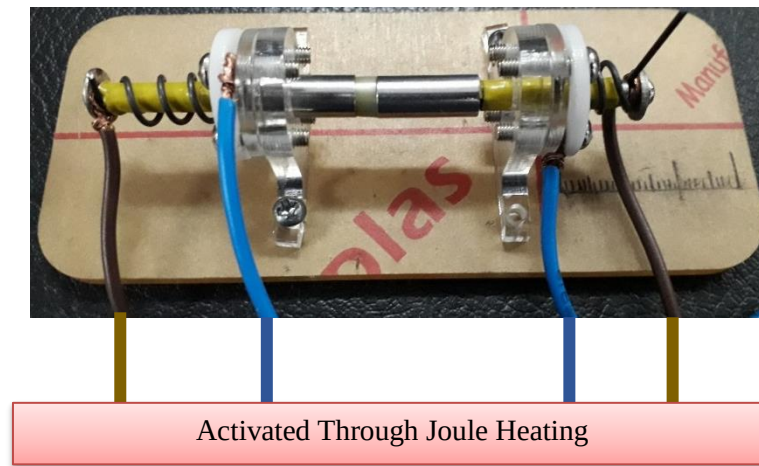
Figure 6.33: Fabricated Design 3

heating and air cooling. Details drawings are shown in Appendix U1 through Appendix U6.

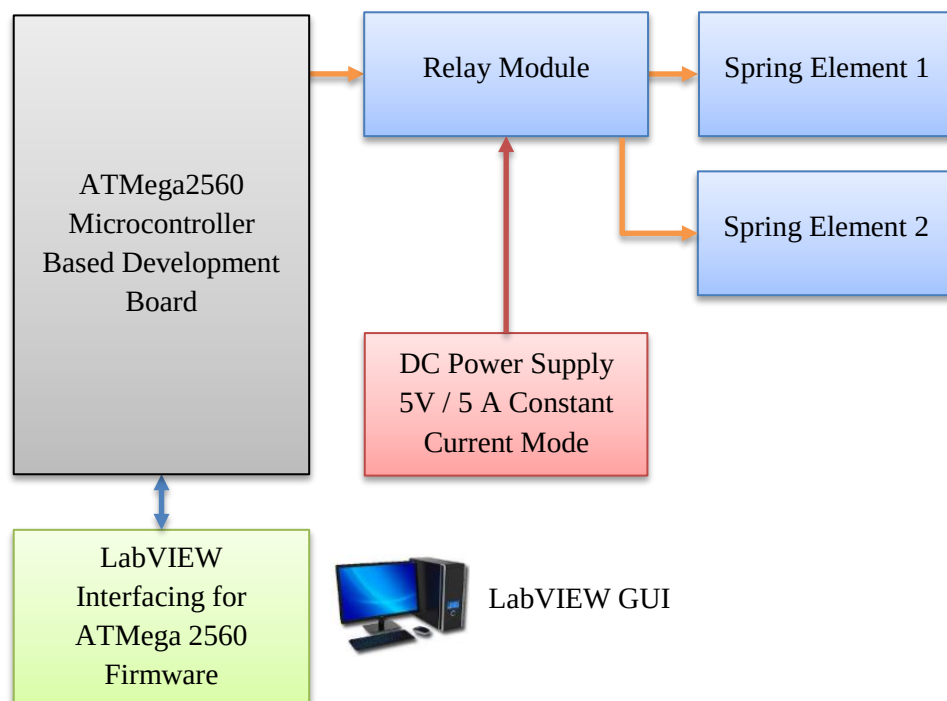
6.3.4 Characterization of the Linear Actuator

After the fabrication process, activation and calibration of the actuator are important before applying in a particular application. So, this subsection describes the activation method of the developed linear actuator and later the characterization process. As described earlier, the developed binary actuator is activated through heating up the SMA element by the Joule heating method and the inherent resistance of the SMA material helps to create heat while an electric current passes starting from one end to the other end of the material. Each SMA spring element is attached with wires (Figure 6.34. (a)) at the two ends and connected with a DC power source. To control the two springs while performing the experiments, the connections are made through a relay module and the relay is controlled through a microcontroller development board (Appendix I) and a LabVIEW generated GUI. Figure 6.34. (b) shows how the SMA spring elements are connected to the DC power supply through the relay module. The LIFA base firmware supports the communication between the GUI and the microcontroller board to operate SMA elements according to the operator inputs through the GUI. Figure 6.35. shows the front panel and the block diagram of the LabVIEW software-generated GUI for the experiments.

After setting up the testing setup for the actuator stroke characterization task, the buttons at the GUI operated to achieve actuator displacements shown in Figure 6.36.



(a)



(b)

Figure 6.34: Linear Actuator Controlling **(a)** Wire Connections to the Spring Elements; **(b)** Interfacing Block Diagram

The exact graph can be seen if the cooling of the spring element 1 has been completed within 1 second which is hard to achieve through ambient cooling. When the forced cooling method replaces the ambient cooling, this might be possible to achieve. Now, it is clear that the cooling method is highly important in obtaining a fast response.

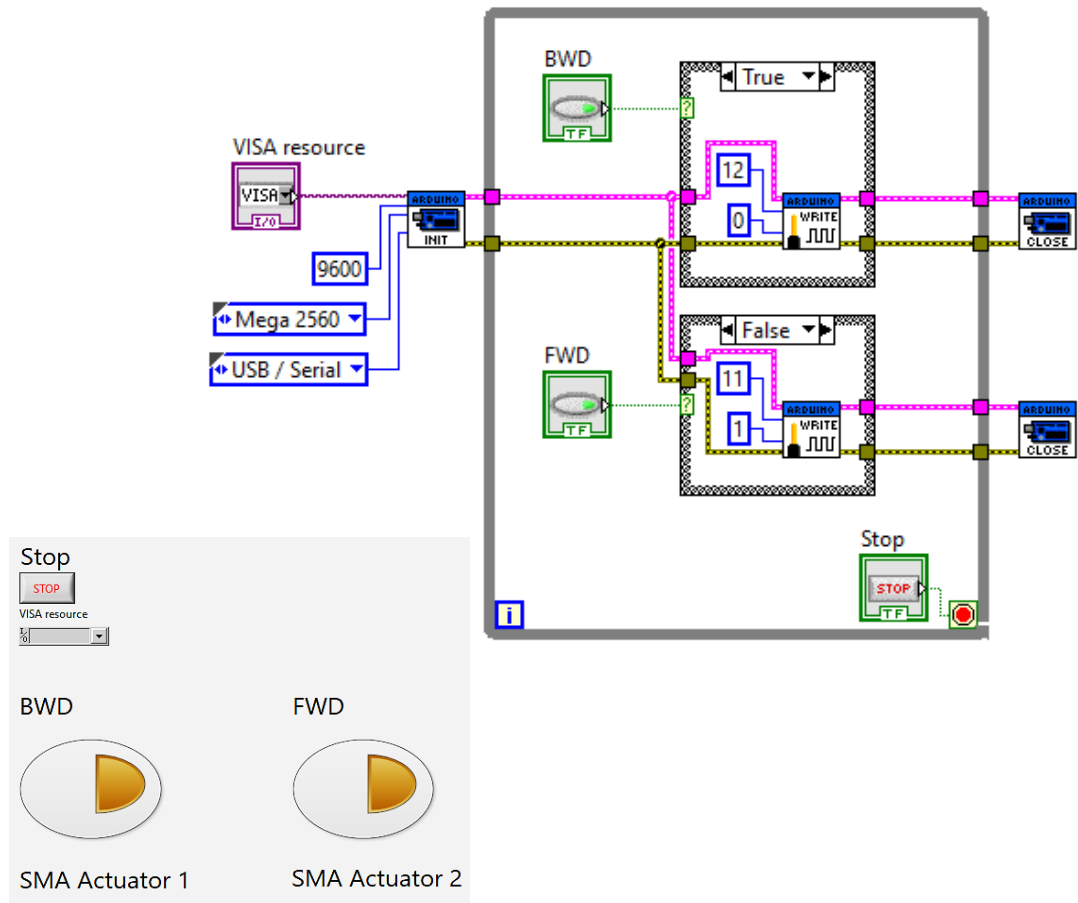


Figure 6.35: Block Diagram and the Front Panel of the LabVIEW Program

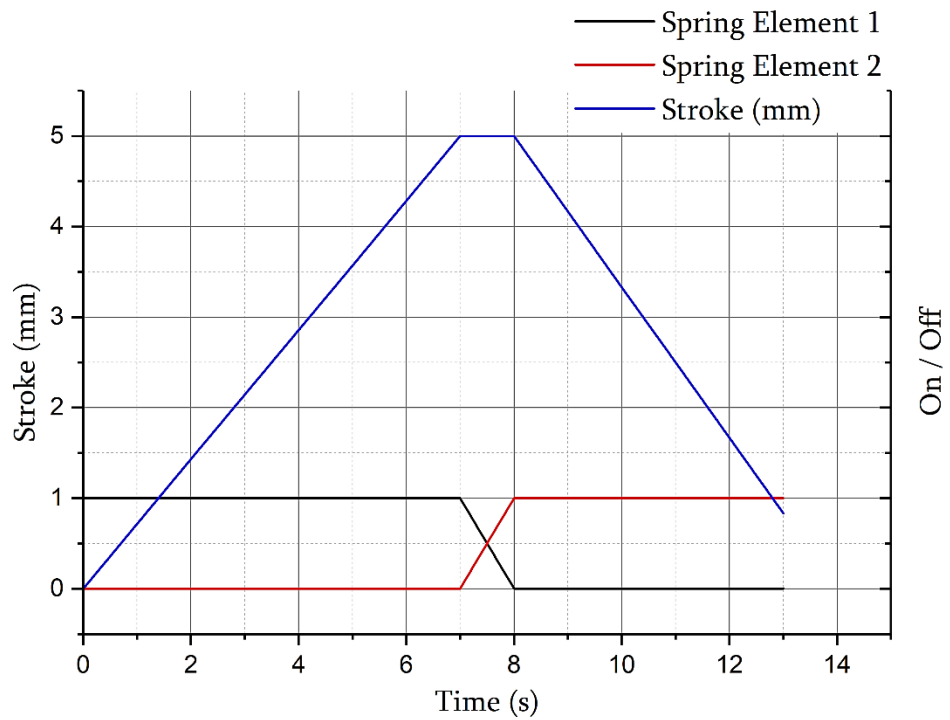


Figure 6.36: Spring Elements Energizing Sequence and the Expected Linear Actuator Stroke

Figure 6.37. (a) shows a single cycle actuation allowing sufficient cooling of SMA elements to proceed with the activation of the second SMA element.

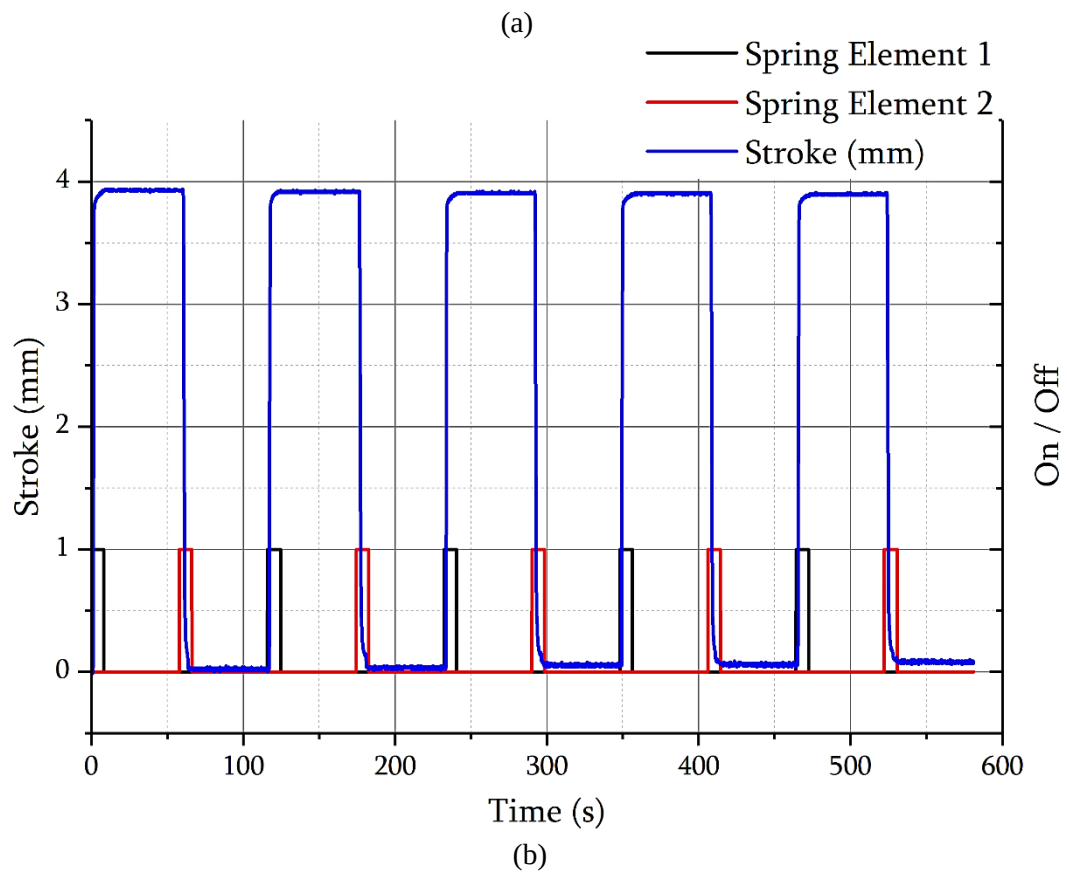
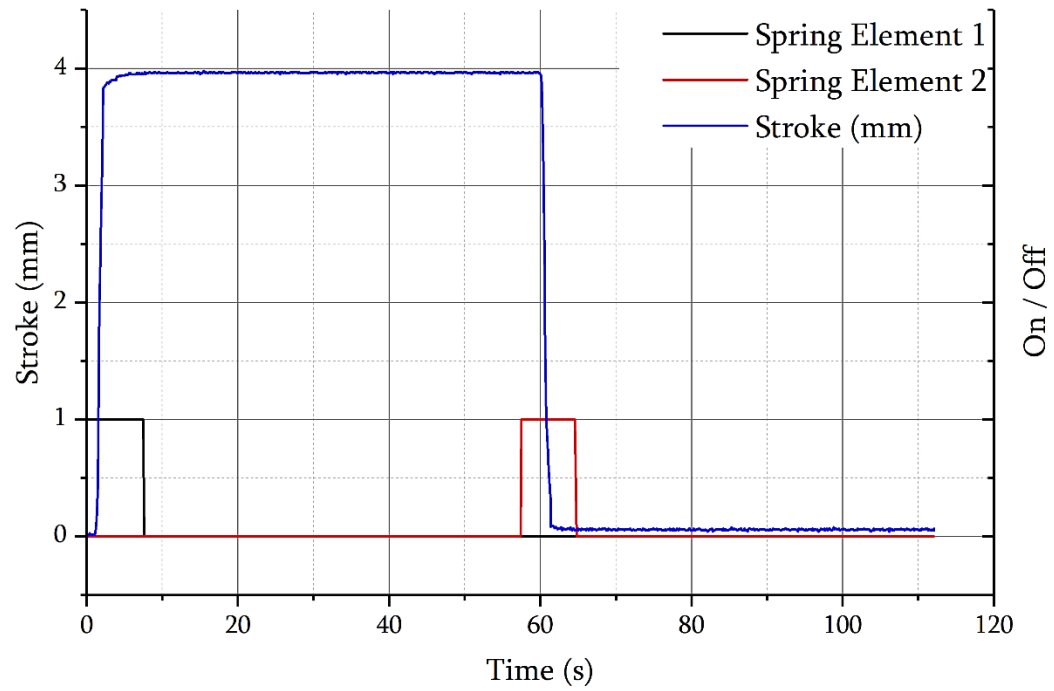


Figure 6.37: Experimental Results **(a)** Single Cycle Actuation; **(b)** Multi-Cycle Actuation

Figure 6.37. (b) shows multi-Cycle actuation results over a longer time to assess the actuator stroke repeatability and it shows Figure 6.38. kind of variation of achievable maximum stroke through the binary SMA linear actuator.

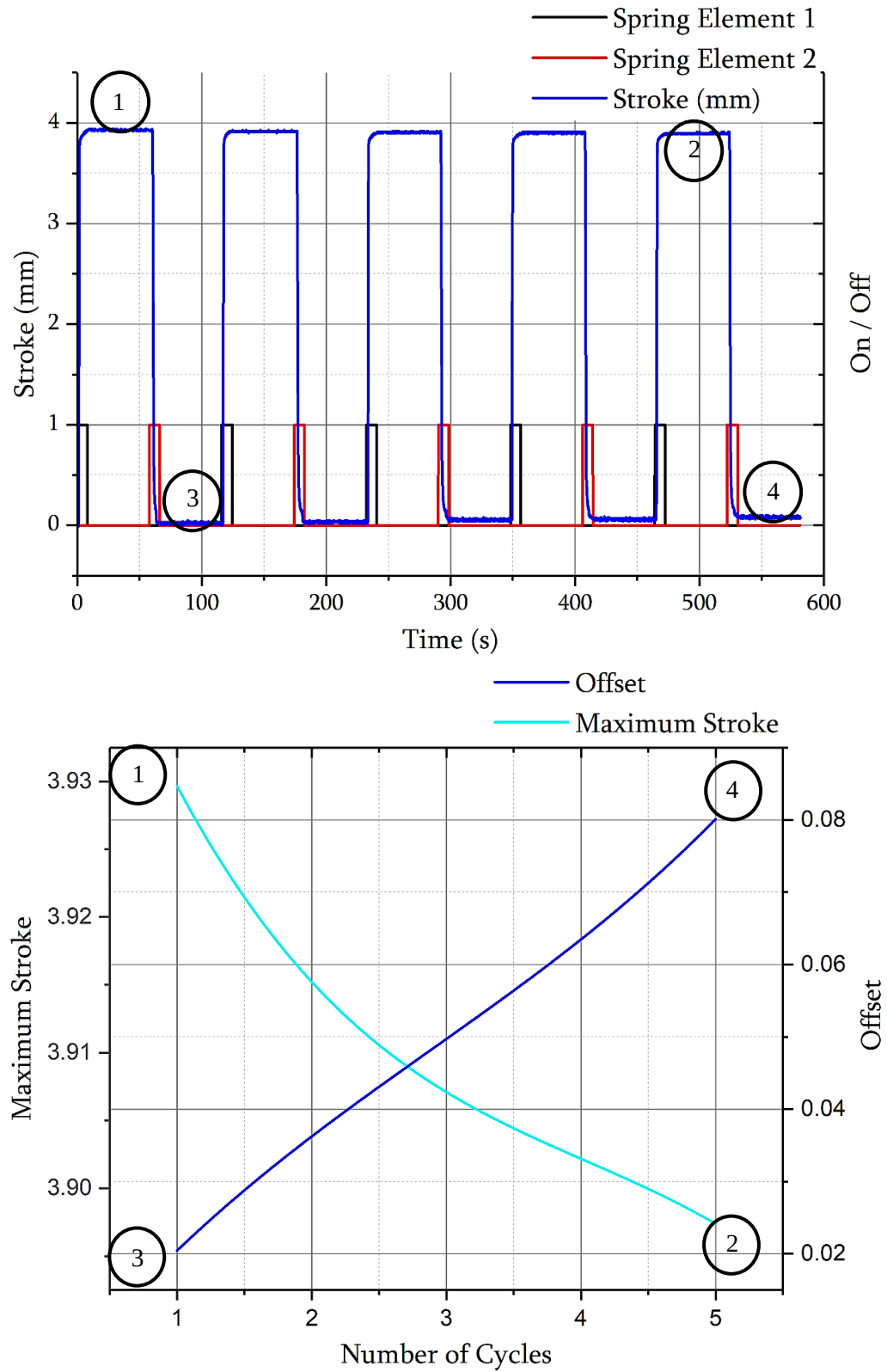


Figure 6.38: Repeatability for Ambient Cooling

6.3.5 Integration of the Linear Actuator with a Retractor Tool for Laparoscopic Surgeries

The developed binary SMA spring linear actuator was then applied to a laparoscopic retractor tool which has a mechanical actuation method. As described in the Literature review section, the Laparoscopic procedure is one of the MIS methods in which the intervention is mainly in the vicinity of the abdomen. The vision is assisted by a laparoscope which gives a video feed to a screen in the theatre area. There are a gripper, cutter, suture, and many more tools available in such an intervention. Also, there is a tool called a retractor which assists to make space by retracting surrounding organs near a surgery area. Figure 6.39. shows a schematic of the mentioned laparoscopic retractor.

A laparoscopic retractor is a long slender instrument that can be passed through a standard MIS port and the instrument is operated by supportive staff. Most of the retractors have mechanical actuation such as rotatable knobs. (Figure 6.40.) after insertion into the body through the ports, the required manipulations are performed by operating these knobs. Here, the tool is an Endo Retract II and the rotary motion of the knobs is converted to a linear motion by a rack and pinion method and the rack is connected to a rod which is guided inside the long slender tube up to the tooltip. So, the idea is to replace the mechanical actuation with the developed binary SMA spring-based linear actuator. The retractor force transmission mechanism and the end effector were used in the developing process of the SMA actuated retractor tool.

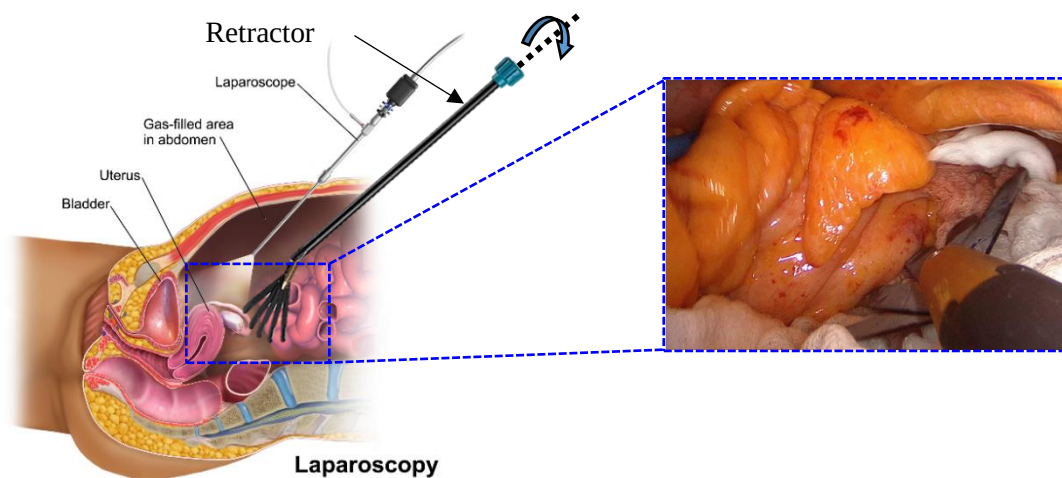
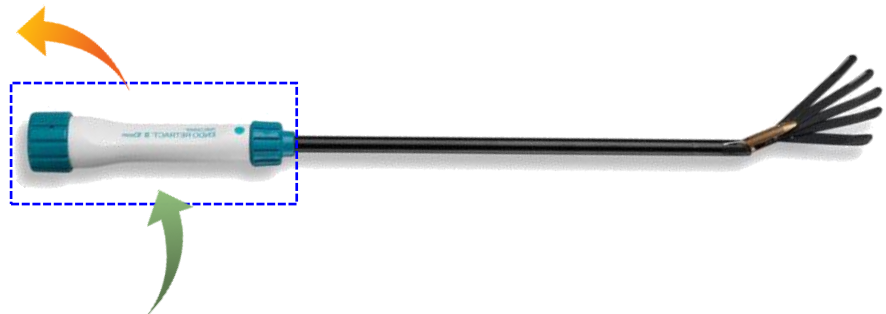


Figure 6.39: Schematic of Laparoscopic Procedure



Mechanical Actuation = Rotatable Nobs



Electro – Thermomechanical Actuation = SMA actuator activated by Joule heating

Figure 6.40: Construction of a Laparoscopic Retractor and Introduced Modifications

Design and Modelling of the Retractor Tool

First, it is important to identify the configurations and components of the utilizing laparoscopic tool. Figure 6.41. show two configurations of the retractor mechanism without the mechanical actuation handle. The end effector of the tool consists of fingers like retractor plates which can operate in abduction-adduction motion. These plates are connected to a tip that can undergo flexion-extension motion.

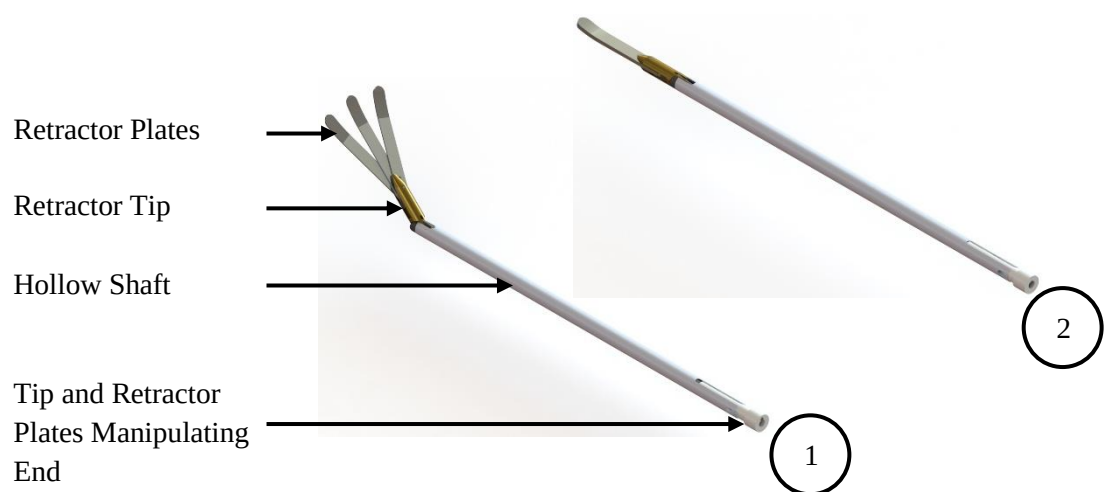


Figure 6.41: Configurations and Components of a Laparoscopic Retractor Tool

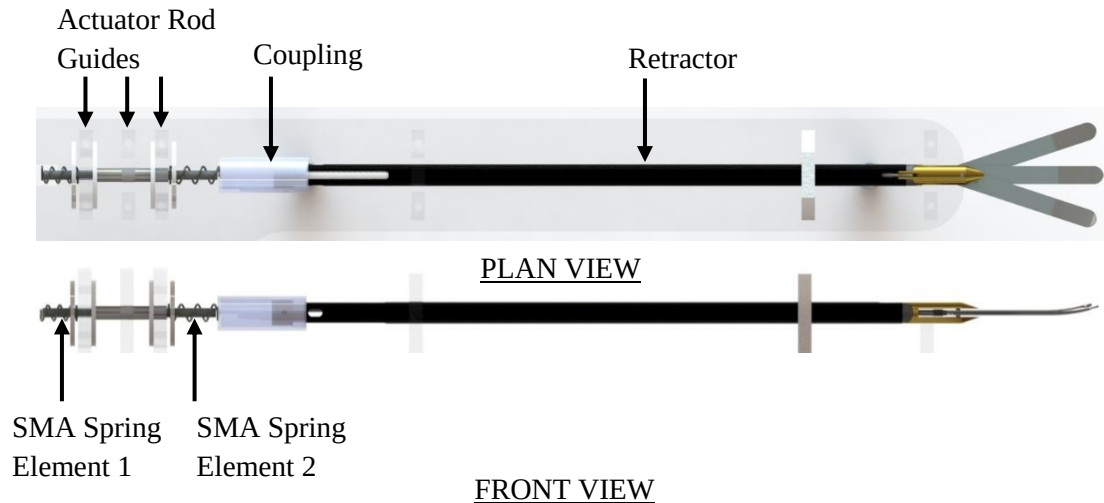


Figure 6.42: Conceptual Design of the Retractor Mechanism and the Linear Actuator

These four movements are achieved through links passing through the hollow shaft indicated in the figure up to the end of the hollow shaft (Appendix V1).

Figure 6.42. shows the conceptual design of the retractor mechanism coupled with the developed binary SMA spring linear actuator. At the instant when the linear actuator was connected with the retractor mechanism the tooltip was at the extended position. And the SMA spring 2 was stretched while SMA spring 1 remain its parent shape. As the SMA spring 2 is energized by the power source it regains its parent shape by contracting while stretching the SMA spring 1 and producing a pull on the mechanism to flex the tooltip. Similar way, the extension of the tooltip could be achieved by energizing SMA spring 1 and making it recover to its parent shape while making a push on the mechanism.

Mathematical Modelling of the Retractor Mechanism

Figure 6.43. shows the important parameters related to modeling the motion of each degree of freedom in terms of motion and forces. An x displacement at the retractor tip would cause a θ angular displacement around the tooltip hinge. Also, a y displacement of the other link would cause retractor plates to abduct (or adduct) at an α angle around the plate hinge. The mathematical modeling was conducted only to the flexion-extension motion by considering above mentioned parameters. Figure 6.44. shows the parameters for modelling the flexion-extension motion. It can be mathematically proved that the angle varies with the stroke of the SMA linear actuator according to the following mathematical relationship.

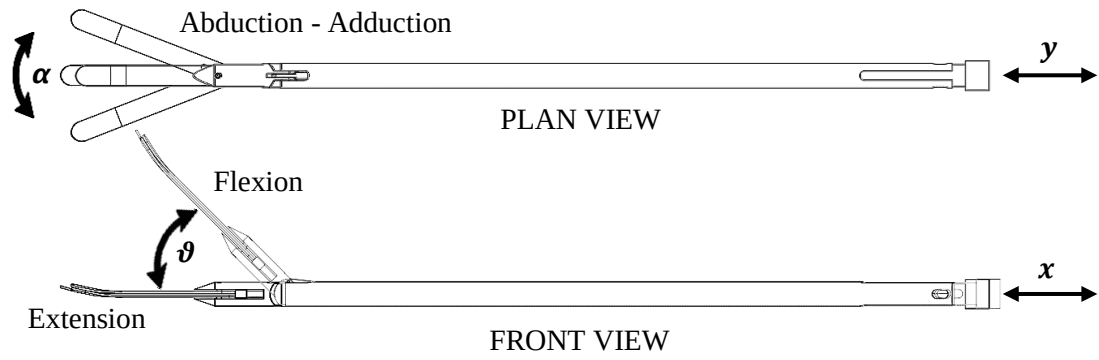


Figure 6.43: Interested Parameters in Defining the Motion of the Retractor

$$\vartheta = \cos^{-1} \left[\cos \left(\frac{\pi}{4} \right) - \frac{x}{r_1} \right] - \frac{\pi}{4}$$

Kinematic Analysis of the Retractor Mechanism by Software Based Environment

MATLAB SIMMechanics [76] based analysis was conducted to justify the motion of the retractor tool and the mathematical model which was developed to prove the flexion-extension motion. Figure 6.45. shows the motion validation results as a motion graphic and the tooltip angle were obtained through a joint sensor and plotted simultaneously in the SIMMechanics environment and it shows perfect correlation with each other. The graph in Figure 6.45. shows the variation of the above-mentioned joint angle. The SIMMechanics block diagram is shown in Figure 6.46.

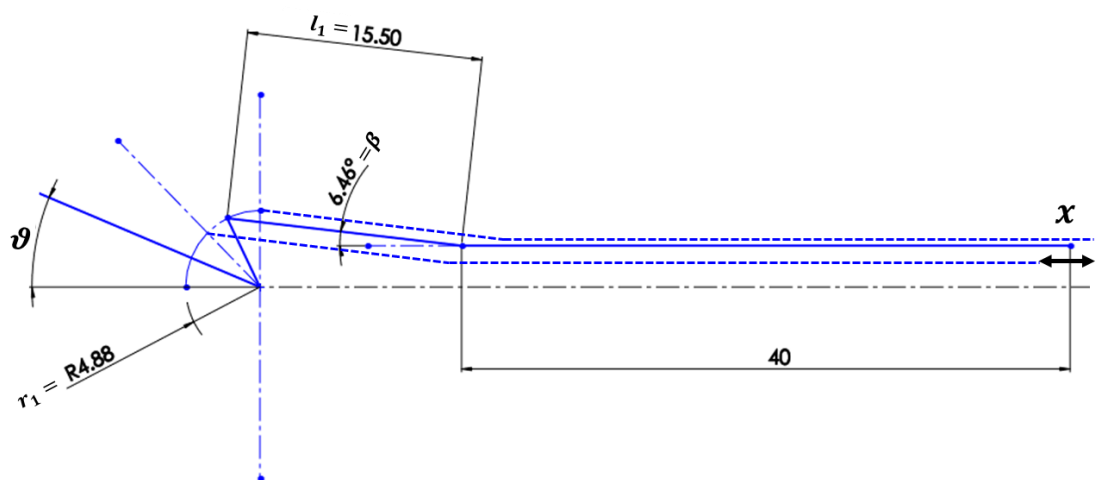
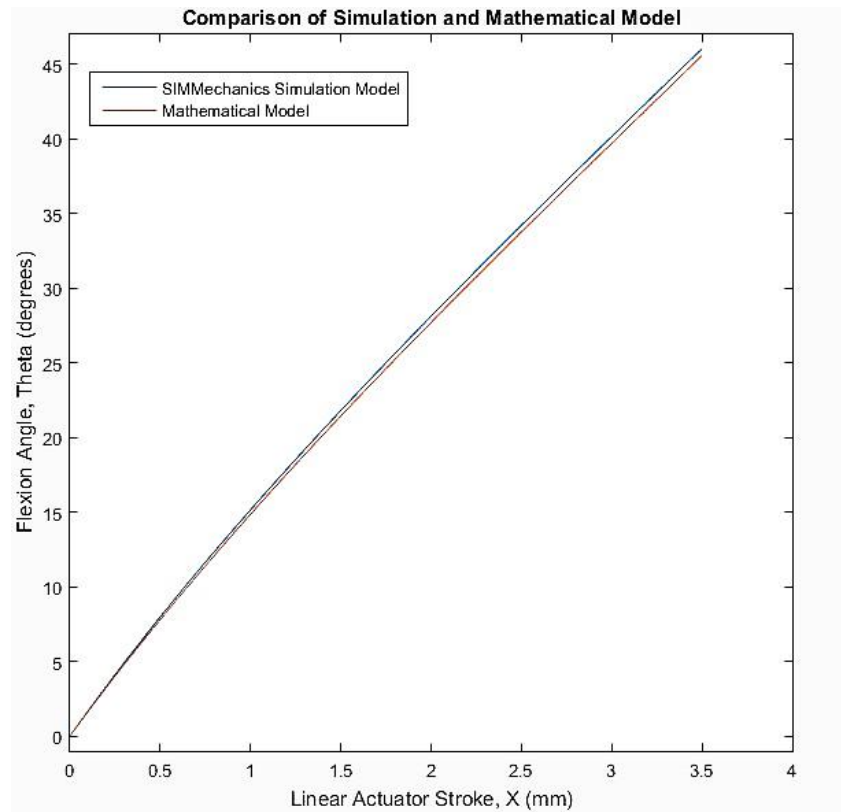
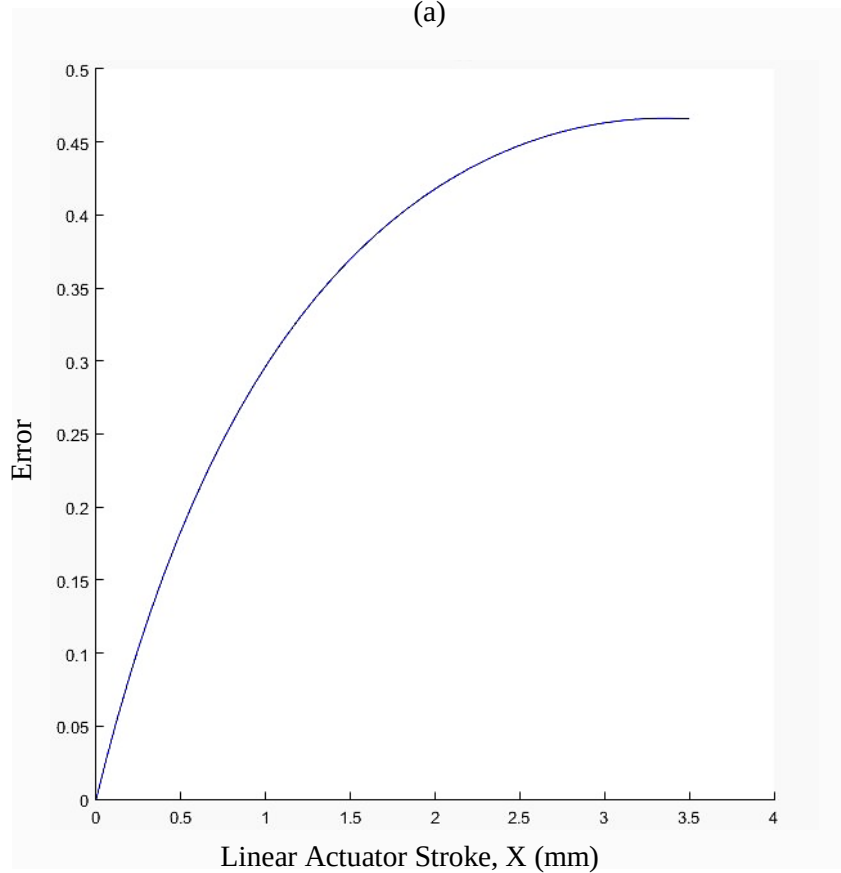


Figure 6.44: Interested Parameters in Modelling the Flexion Extension Motion



(a)



(b)

Figure 6.45: Comparison of Mathematical and Software Model **(a)** Flexion Angle w.r.t. the Stroke; **(b)** Error between Mathematical and Software Model

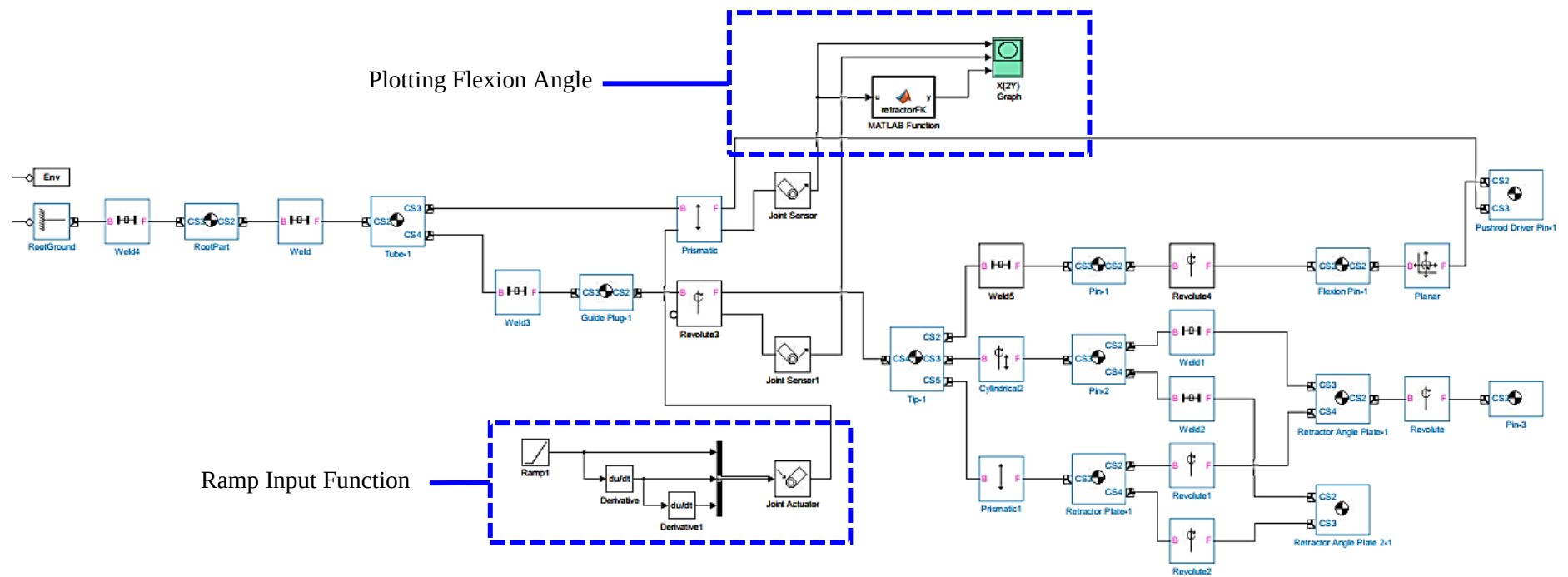


Figure 6.46: MATLAB SIMMechanics Block Diagram

6.3.6 Development of a Testing Apparatus for Retractor Application

After validating the motion through mathematical and software-based methods, an apparatus was developed to test and validate the operation of the retractor tool combined with the developed linear actuator. Figure 6.47. shows the system block diagram of the retractor testing apparatus which was developed to validate the laparoscopic tool.

The apparatus consists of a structure to mount the retractor and the binary SMA spring linear actuator, DC power supply, power controller circuitry, microcontroller development board, linear potentiometer, and a computer software interface for parameter adjustment, data visualization, control, and acquisition. Energizing the SMA springs was done by the power controller circuitry which was controlled by ATmega328p microcontroller-based development board (Appendix J). The displacement and the position of the linear actuator were taken by a linear potentiometer (Appendix N2) attached to the actuator and the data are gathered by the microcontroller and those were serially sent to a visual studio-based software interface to visualize and control. In this manner, the flexion-extension motion and retractor end-effector position were controlled and through the developed apparatus.

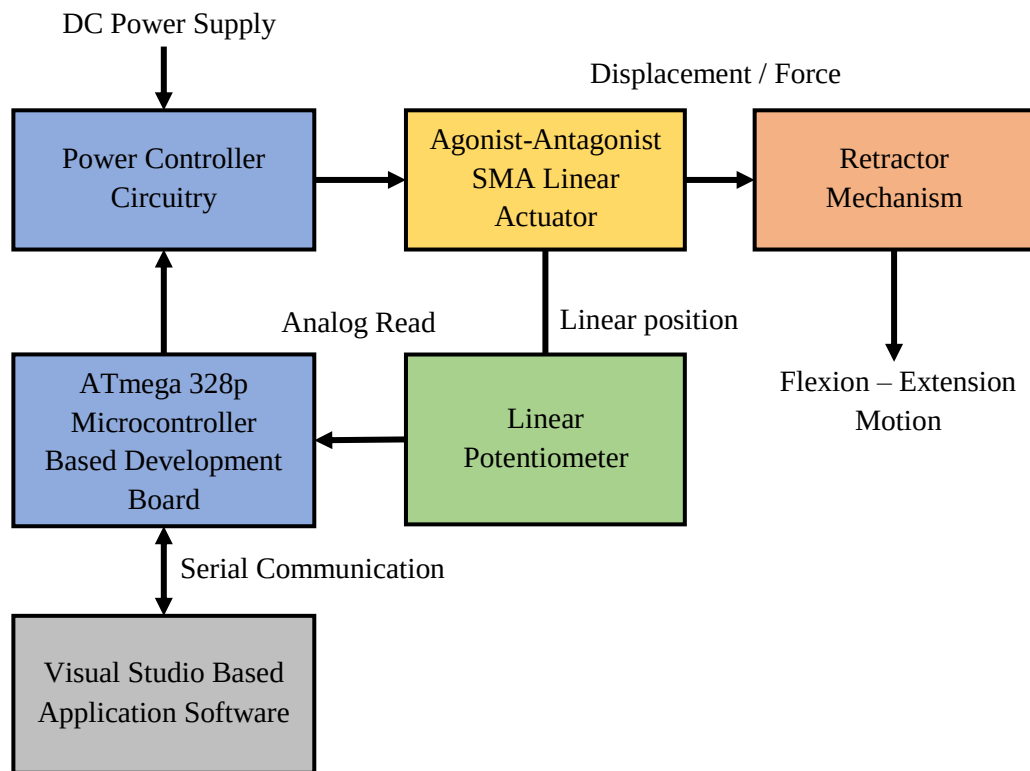


Figure 6.47: Retractor Testing Apparatus System Block Diagram

Development of the Controller Circuitry for the A-A Linear Actuator

According to the descriptions made so far throughout the previous subsections, it is clear that the developed binary SMA springs were activated by Joule heating and the source of power was a DC power supply. To achieve a stroke in a particular direction or in other terms, to achieve flexion or extension motion of the retractor, SMA springs need to be energized according to a specific manner. In order to achieve this repeated task, an electronic circuitry was developed based on Field Effect Transistors (FETs). Figure 6.48. shows the detailed view of the developed circuitry. Schematic and the PCB layout are presented in Appendix N1 and Appendix N3 respectively. The circuitry consists of IRFZ44N FETs facilitated with heat sinks, SMA spring element power output ports, DC power input ports, FET controlling signal ports, and FET activity indicator LEDs to identify the energizing sequence. The circuitry was first simulated using schematics in the Proteus Software which is a professional electronic design software package, and the mask was created. Then the mask was printed on photo paper and transferred to a copper clad board by compressing the printed mask against the copper clad board while applying heat. Then the mask transferred side of the copper-clad board was immersed in a ferric chloride solution until dissolving the negative areas of the mask. Finally, the pinholes were drilled using a hand drill.

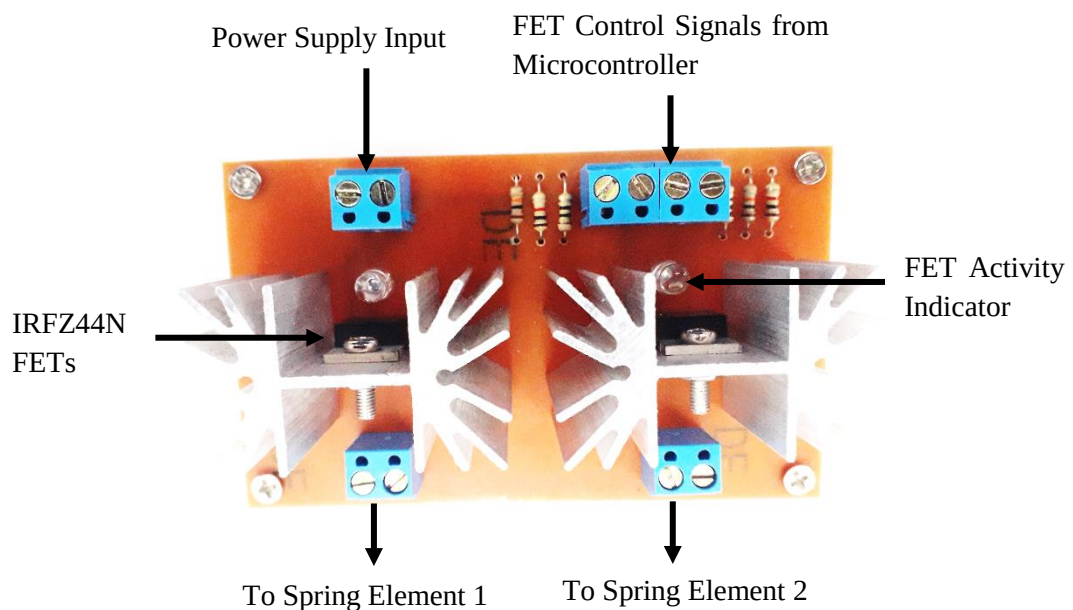


Figure 6.48: Binary Spring Actuator Controller Circuitry

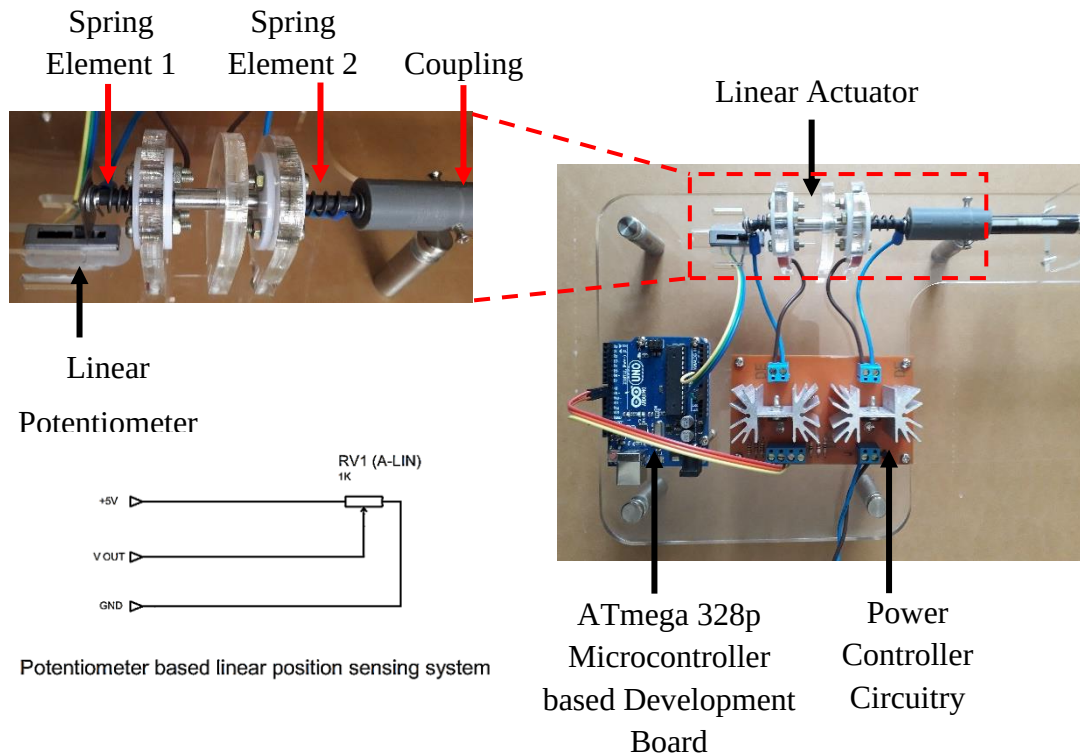


Figure 6.49: Assembled Configuration of the Testing Apparatus

Figure 6.49. shows the detailed components highlighted in Figure 6.47. and Figure 6.50. shows the developed retractor testing apparatus.

Development of the Human Machine Interface for the A-A Linear Actuator

A graphical user interface was developed to assist with the experiments using the Visual Studio software package. Figure 6.51. shows a detailed description of the developed Human Machine Interface (HMI) and its functionality. The computer and the microcontroller development board were connected through serial communication and the interface can select the appropriate COM port to initialize the communication. Also, Interface provides two modes of operation namely, manual mode and automatic mode. Manual mode facilitates manual activation of SMA springs by pressing FDE and RDE buttons. This enables to account for the time requirements of a particular spring to completely recover to parent shape and cool down to room temperature. The later automatic mode enables to activate flexion and extension motion continuously or single cycle operation by setting up energizing interval and cooling interval in the interface. A PID controller was introduced to position controlling of the retractor tip and the interface facilitates tuning of the controller as well.

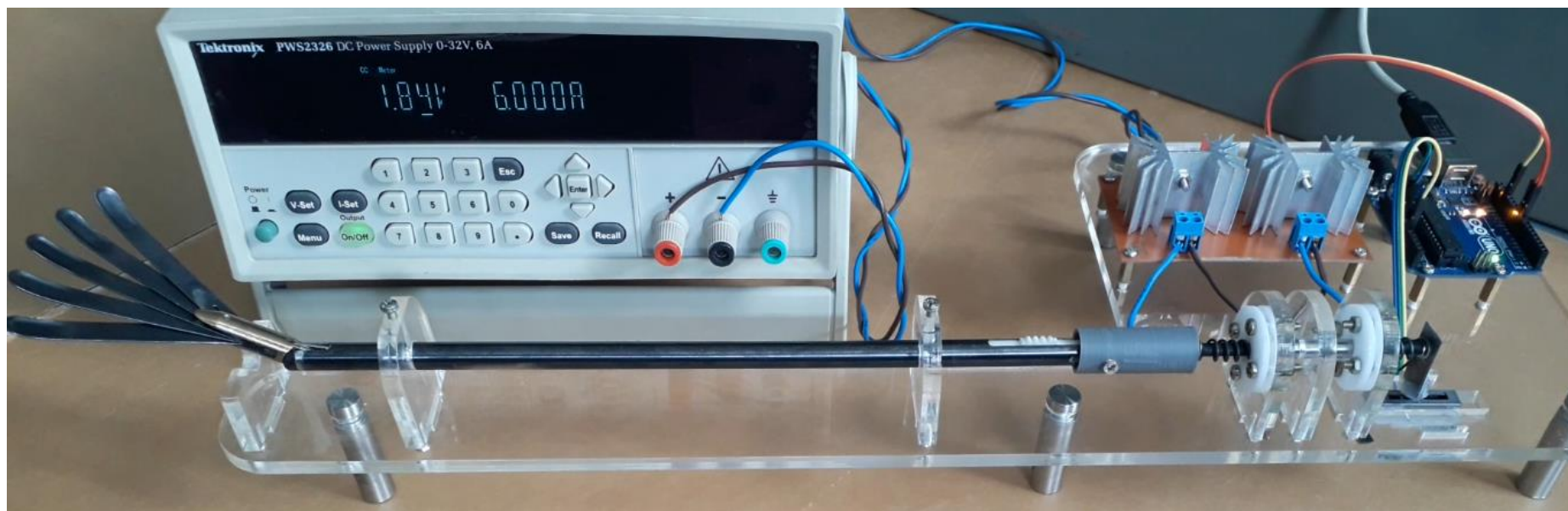


Figure 6.50: Retractor Testing Apparatus

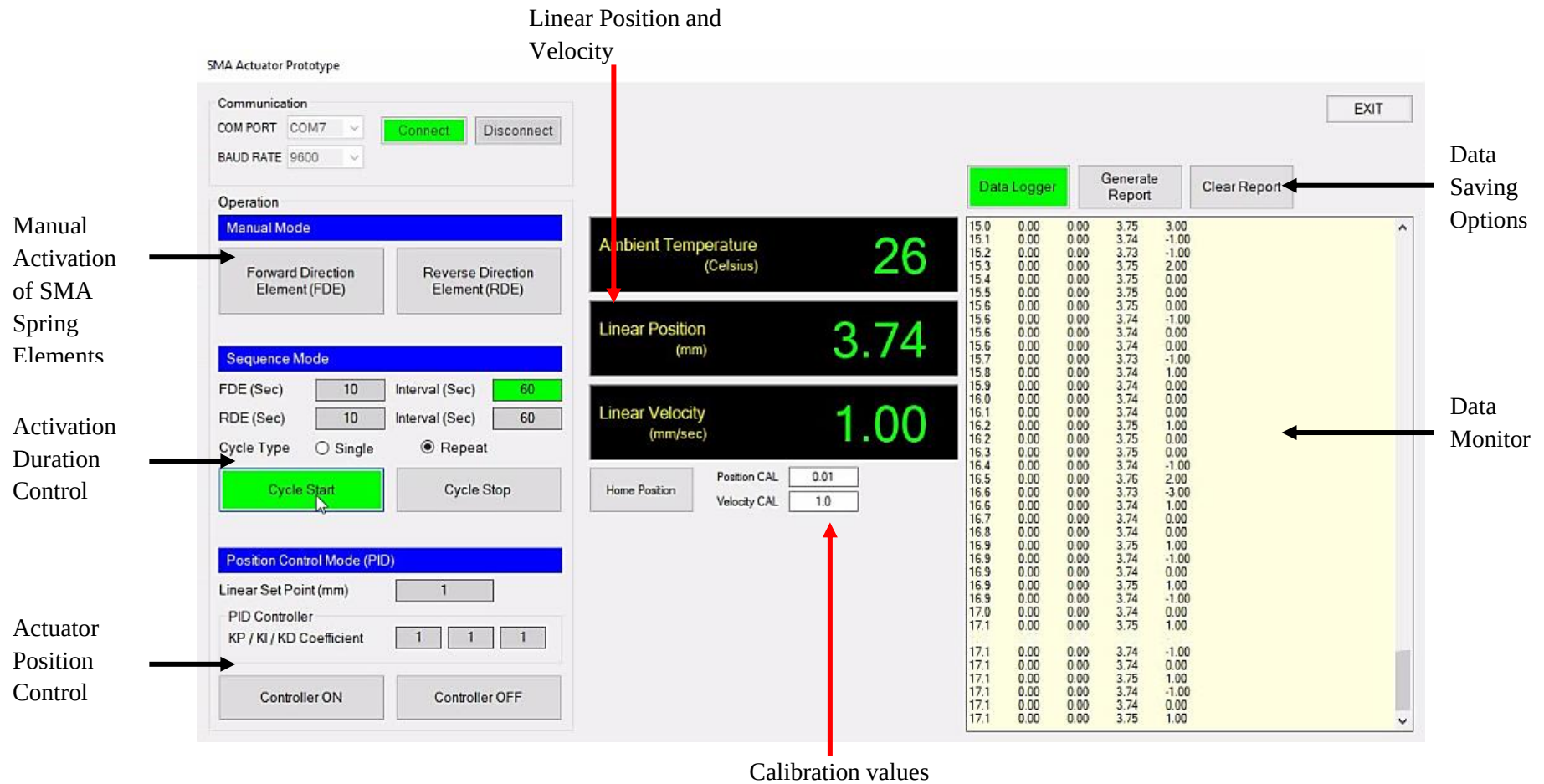


Figure 6.51: Visual Studio Based HMI

Also, the interface provides a calibration for the linear potentiometer. GUI has special sections for displaying the linear position of the actuator and the velocity as well as to visualize real-time position data as a data log. Additionally, it is capable of saving obtained data to an external file.

6.3.7 Characterization of the Laparoscopic Retractor Tool

With the use of developed apparatus and data acquiring facilities, the retractor tool was characterized in terms of stroke and the following subsections are presenting results related to those experiments.

Stroke Evaluation of the Retractor

Under the automatic mode, required initializations were carried out and the laparoscopic Retractor tool was operated for one flexion-extension cycle. Figure 6.52. shows the stroke variation of the linear actuator with time. As the SMA Spring 1 is activated by Joule heating and the retraction stroke happens. Since the ambient cooling was used to cool down actuator elements after 1-minute time interval SMA Spring 2

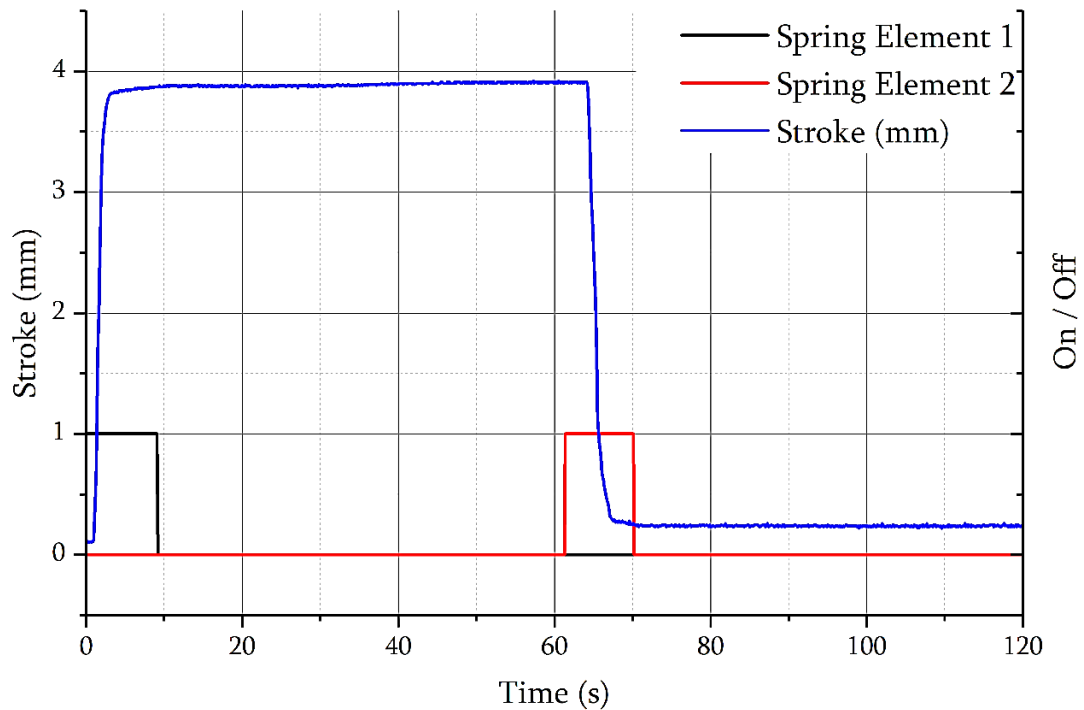


Figure 6.52: Single Cycle Actuation of Retractor Tool

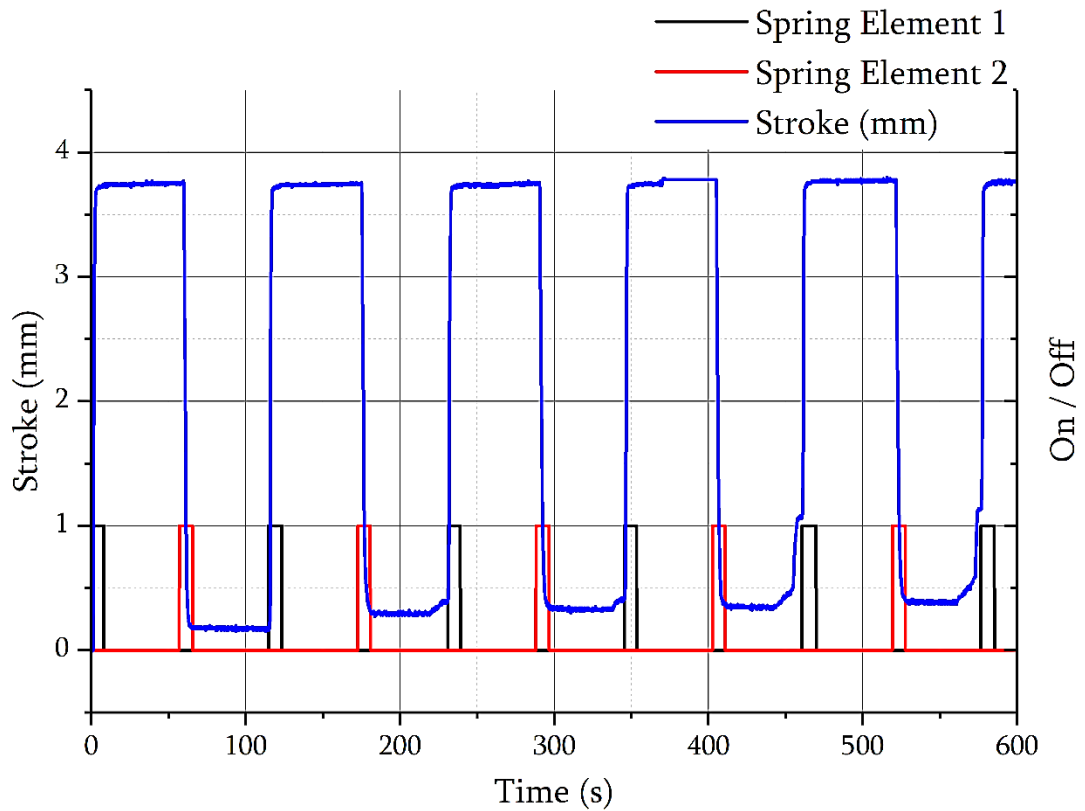


Figure 6.53: Multiple Cycle Actuation of Retractor Tool

was operated and initiated the extension stroke. An offset can be observed due to improper cooling of the SMA springs.

Figure 6.53. shows the stroke variation as the Retractor operated for several cycles to assess the position repeatability. It can be concluded that a proper cooling method is required to obtain improved repeatability.

6.4 Chapter Summary

This chapter introduces the design and development of SMA spring element-based linear actuators actuated by the two activating methods. In the first subsections, the design and development of the linear actuator operated by the external heating and cooling method were described. There, the linear actuator was designed as a piston-cylinder assembly that operates by an external heated fluid medium that passes through the cylinder and transfers heat energy into the SMA element by increasing temperature. This would cause the spring element to convert into the parent shape while producing useful force and stroke on the connected mechanisms. A similar way bypassing cold fluid into the actuator cools down the spring element to produce the return stroke by converting into a flexible material phase while subjected to the biasing force. The linear actuator was fabricated using conventional machining techniques. The developed linear actuator was then included in a gripper application. A novel gripper mechanism was introduced and kinematically proven by a software-based environment. Then the gripper components were produced using rapid prototyping techniques.

A testing apparatus was developed in order to test the gripper. The apparatus was supported by a customized controller together with a computer software interface. There, the interface was used to adjust the parameters of the system and control the hot and cold fluid flow rates. A strain gauge-based force-sensing method was introduced to the gripper after the justification got from software-based simulation which was carried out to find out the optimum place to place the strain gauge element. There the developed controller was further modified in order to facilitate force sensing and controlling capabilities into the apparatus. Also, the chapter describes the development of a linear actuator activated by the Joule heating method. The linear actuator was developed as an antagonistic type using two SMA spring elements. The linear actuator was mathematically modeled. Then the linear actuator was fabricated and a stroke characterization was conducted to justify the selected parameters. The fabricated linear actuator was integrated with a laparoscopic retractor mechanism to control the flexion-extension motion and a testing apparatus was developed to

experiment with the actuator retractor assembly. The retractor mechanism was kinematically and mathematically proven and finally, the retractor was characterized.

CONCLUSION

Shape Memory Alloys (SMA) are particularly used for many applications in the biomedical engineering domain. But there is limited progress of the actuator development in the Minimally Invasive Surgery (MIS) field and most of them are at the research level. Due to the increased interest in MIS over conventional open surgeries, there is a need of developing tools that satisfy the limitation of the MIS while fulfilling the main requirements. SMA has several properties which are surprisingly matched with the requirements of the MIS. Few of those can be summarized as miniaturization capability while having comparatively high energy density per unit volume of the material, biocompatibility, corrosion resistance, programmable transformation temperatures.

In this research, the main motivation was to design and develop SMA-based novel actuators for MIS procedures. The overall work can be divided into several key areas. At the initial stage of the research, a study was conducted to get an understanding of material behavior. As a result of this initial work, SMA transformation temperature setting criteria were implemented for the acquired NiTiNOL material. The heat-treated material samples were tested by the DSC technique to obtain the transformation temperatures. Also, microstructural observations were carried out to observe precipitation stages of Ni-Ti. Elemental analysis was conducted to obtain the elemental composition by SEM EDX analysis.

After understanding the material behavior, the obtained raw NiTiNOL wires were converted to a spring shape actuator element. In order to do so, a specially designed fixture was used to hold the wire into a spring shape while subjected to heat treatment. Spring with the same geometrical parameters but different transformation temperature ranges were fabricated with the knowledge gained from previous work carried out to define transformation temperature setting criteria. Then the fabricated springs were characterized using a specially developed force characterization apparatus. There the spring force was measured while holding at a pre-strained configuration with increasing temperature. A custom-made controller was used to monitor and acquire data from the experiments.

Finally, the characterized actuator element was used to develop two types of linear actuators. One of them was activated by a heated fluidic medium and the other linear actuator was activated through Joule heating which uses the inherent resistance of the spring actuator element. The actuator which was driven by external or fluidic heating was included in a gripper application. A novel gripper mechanism was introduced and was able to kinematically prove in a software-based environment. The gripper was fabricated by rapid prototyping techniques. A strain gauge-based force-sensing method was introduced to the gripper and the controller was modified to achieve force controlling capabilities. With these improvements, the SMA spring-actuated gripper was able to maintain the gripping force at a certain force set point by controlling the flow of hot and cold fluid sources.

The linear actuator which was driven by Joule heating was made using two SMA spring actuators working as an antagonistic pair. The linear actuator stroke was characterized and introduced for a laparoscopic retractor mechanism to control the flexion-extension motion. The retractor mechanism was kinematically and mathematically proven by a software-based interface. The linear actuator was successfully operated the retractor tool. With these experiments, it can be concluded that the SMA-based actuators could be promisingly used to operate MIS-related surgical tools by mitigating drawbacks related to the rapid cooling of SMA material.

- An SMA (NiTiNOL) based actuator element was designed and developed to facilitate MIS tools
- SMA actuator element was characterized to evaluate maximum attainable force output
- SMA material was characterized to evaluate important properties such as composition and transformation temperatures
- Two types of linear actuators were developed by the SMA actuator element
- Developed linear actuators were activated by external heating and Joule heating to achieve force and stroke requirements in the specific application areas

- Two possible applications in the area of MIS were studied, namely Gripper and Retractor by integrating developed linear actuator with the mechanics
- The proposed mechanisms were evaluated mathematically, kinematically, and in software-based environments
- A force sensing and controlling method was introduced to the Gripper application
- Position sensing and controlling method was introduced to the Retractor application to achieve the required degree of freedom to the system
- Conventional Laparoscopic tools have limited DoF near the Surgery area due to restricted movement at the trocar and fulcrum effect. To improve the DoF of the tool, articulated tooltips are being used and are operated by cables or links. This adds complexity and bulkiness to the tool.

List of Publications

Journal Publication(s)

1. **“Design and Fabrication of a Minimally Invasive Surgical Device with Customized Shape Memory Alloy Spring Actuator”**, in Journal of Robotics, Networking and Artificial Life, Volume 5, Issue 3, December 2018, Pages 194 - 198. DOI: 10.2991/jrnal.2018.5.3.11

Book Section(s)

2. **“Fabrication, and Experimental Evaluation of Shape Memory Alloy based Spring Actuators for Laparoscopic Grippers”**, Sustainable Design and Manufacturing. KES-SDM 2021. Smart Innovation, Systems and Technologies, Volume 262. Springer, Singapore, Pages 224-234. DOI:10.1007/978-981-16-6128-0 22

Conference Publication(s)

3. **“Design and Development of a Force Feedback System for an SMA Based Gripper as a Minimally Invasive Surgical Tool”**, in IEEE SENSORS 2019, At: Montreal, QC, Canada. DOI: 10.1109/sensors43011.2019.8956849
4. **“Development of a PID Based Closed Loop Controller for Shape Memory Alloy Actuators”**, in Moratuwa Engineering Research Conference (MERCon 2018), At: University of Moratuwa, Katubedda, Sri Lanka. DOI: 10.1109/MERCon.2018.8421929
5. **“Design and Development of a Shape Memory Alloy Spring Actuated Gripper for Minimally Invasive Surgeries”**, in International Conference on Artificial Life and Robotics (ICAROB 2018), At: B-Con Plaza, Beppu, Oita, Japan, Pages 566 - 569. DOI: 10.5954/ICAROB.2018.OS14-5

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APPENDICES

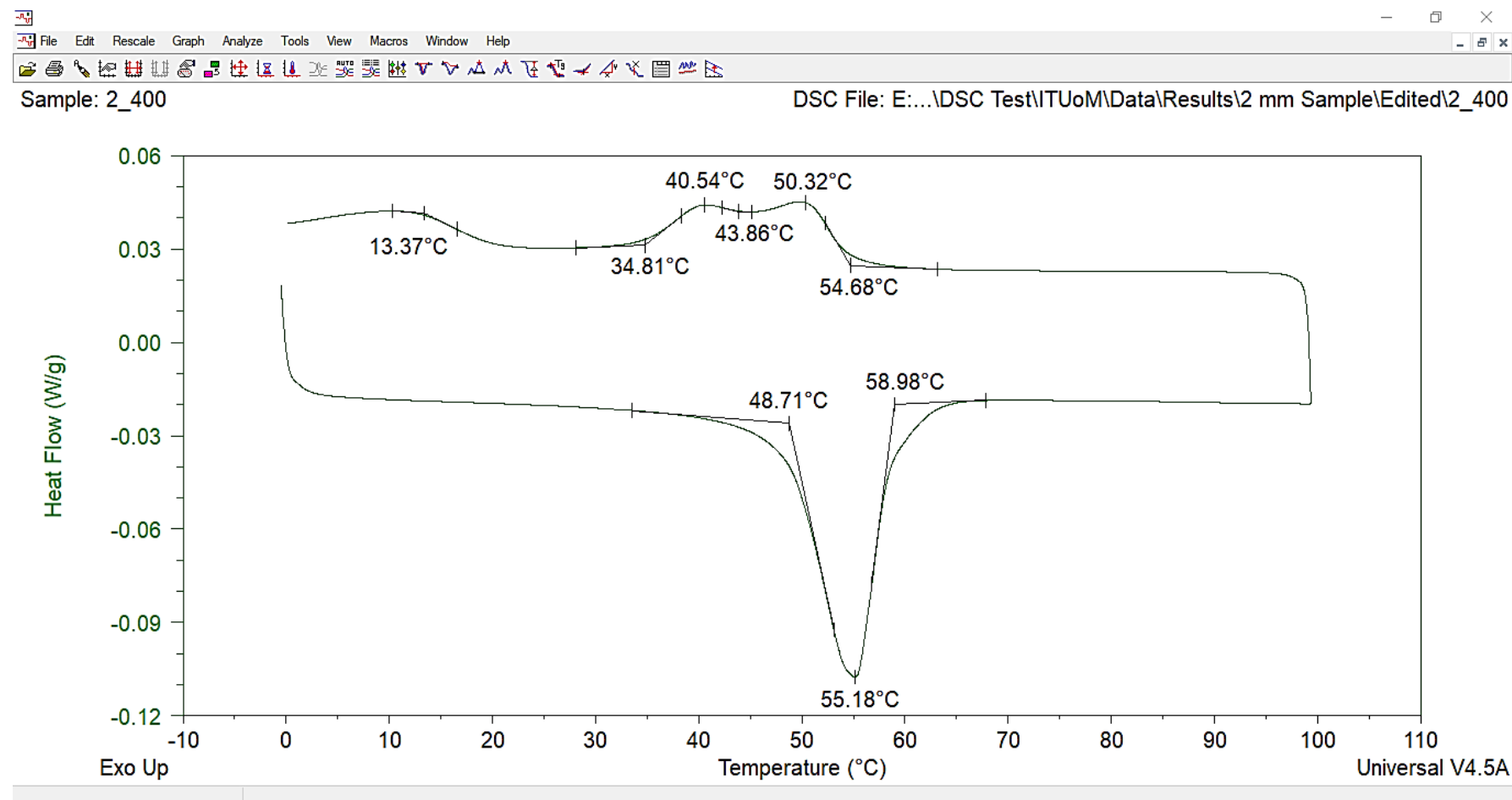
Appendix A: Specifications of DSC Q200 Instrument

Dimensions (Q2000, Q200, Q1000 & Q100)	Depth 56 cm (22 in.) Width 46 cm (18 in.) Height 48 cm (19 in.)
Dimensions (Auto Q20/Q20/Q10)	Depth 56 cm (22 in.) Width 46 cm (18 in.) Height 41 cm (16 in.)
Weight (without Autosampler) Weight (with Autosampler) Weight of cell alone Weight of Autosampler alone Weight of transformer	25 kg (54 lbs) 29 kg (65 lbs) 1.6 kg (3.5 lbs) 4.5 kg (10 lbs) 8.6 kg (19 lbs)
Power	120 Vac, 47–63 Hz, 500 W (4.5 amps) standard 230 Vac, 47–63 Hz, 500 W (2.25 amps) if configured with a voltage configuration unit
Accessory Outlets	Power: 120 V, 47–63 Hz, 400 W each Compatible accessories: LNCS, DPC
Operating Environment Conditions	Temperature: 15–30 °C Relative Humidity: 5–80 % (non-condensing) Installation Category II Pollution Degree 2 Maximum Altitude: 2000 m
Temperature Range: with FACS with Quench Cooler with RCS 90 with RCS 40 with LNCS	Room temperature to 725 °C* -180 °C to 550 °C** -90 to 550 °C -40 to 400 °C -180 to 550 °C
* You must use an inert atmosphere above 600 °C. ** Helium purge gas must be used for temperatures below –100 °C	
Sample size	0.5 to 100 mg (nominal)
Sample volume	10 mm ³ in hermetic pans
Sample pans	Various open or hermetically sealed (standard and Tzero series)
Purge gases	Recommended: air, argon, helium, nitrogen, or oxygen
Typical purge flow rate	50 mL/min
Cell volume	3.4 mL

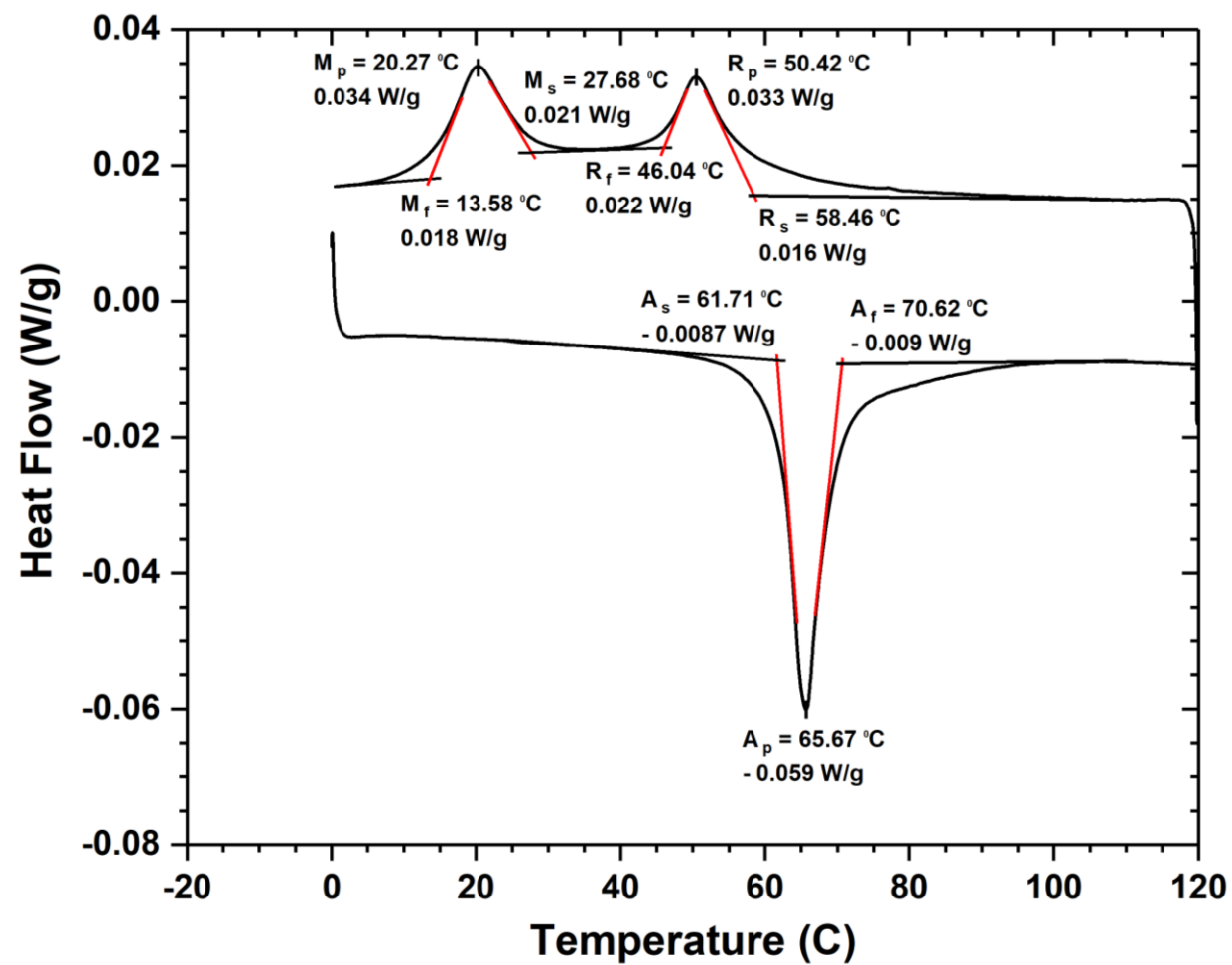
Appendix B: Thermal Program used for Preliminary Testing

- 1: Event state On
- 2: Data storage Off
- 3: Ramp 10.00 °C/min to 0.00 °C
- 4: Equilibrate at 0.00 °C
- 5: Data storage On
- 6: Ramp 2.00 °C/min to 120.00 °C
- 7: Mark end of cycle 1
- 8: Ramp 2.00 °C/min to 0.00 °C
- 9: Mark end of cycle 2
- 10: Data storage Off
- 11: Event state Off

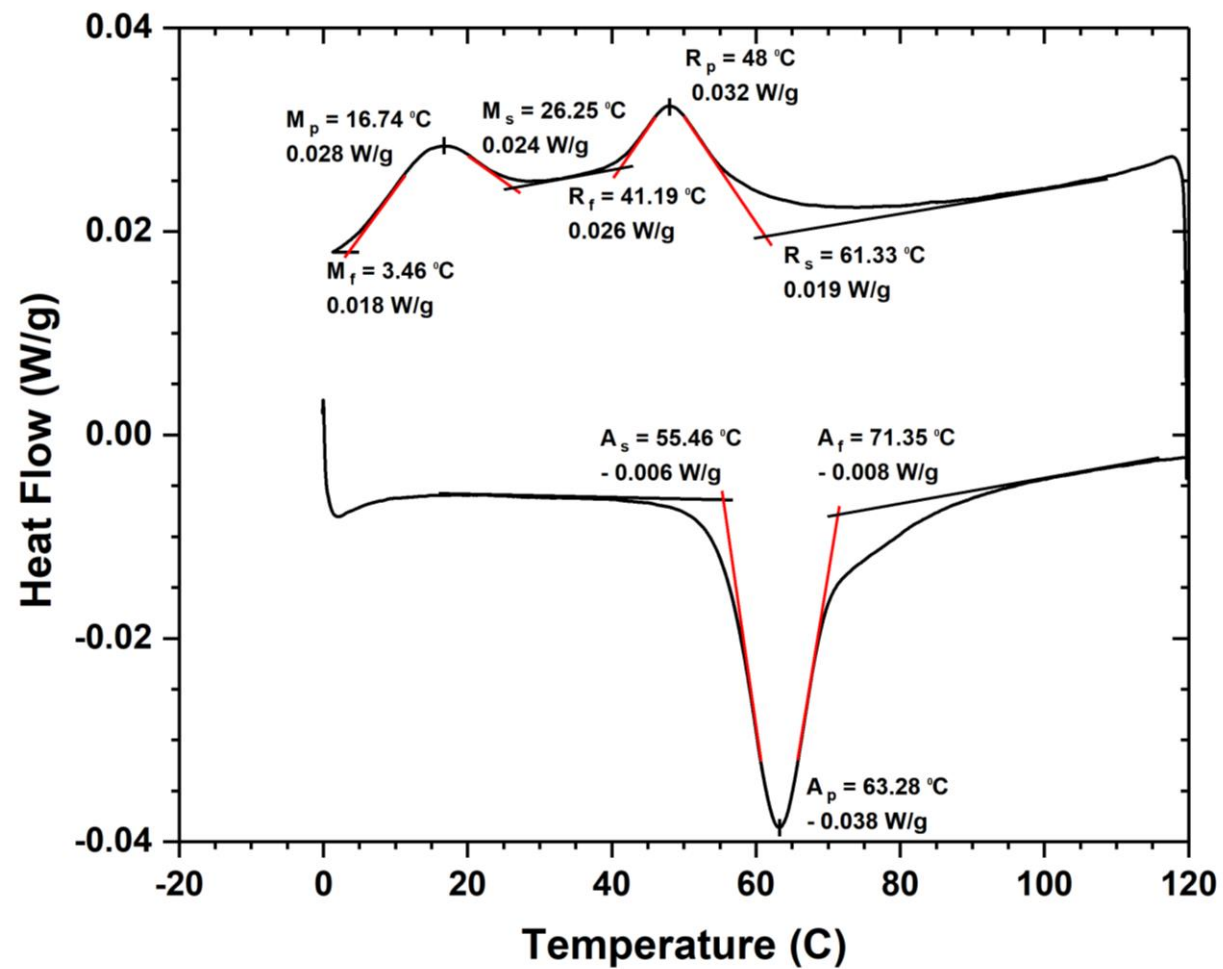
Appendix C: TA Instruments Universal 2000 Software



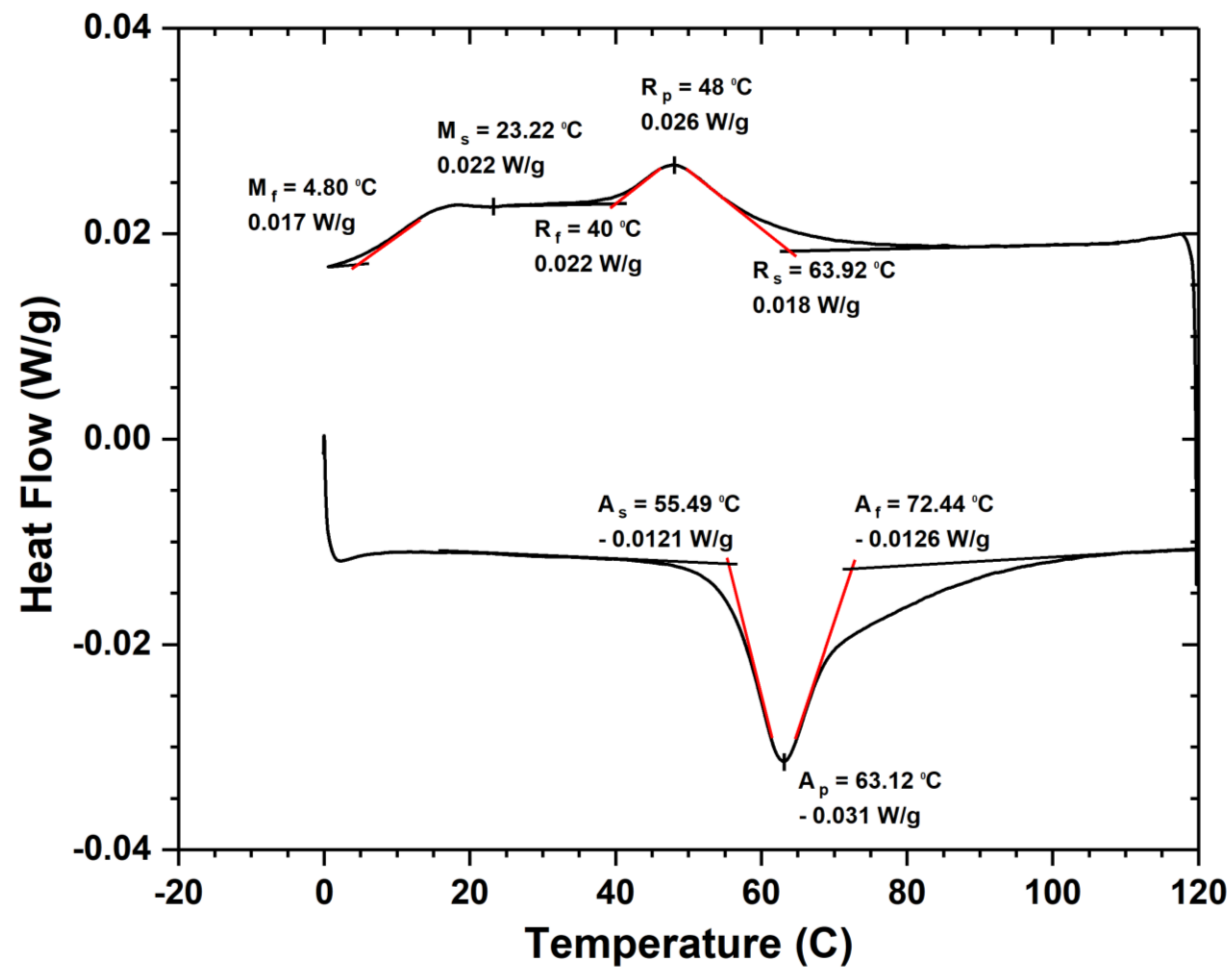
Appendix D1: DSC Q200 Thermogram of Sample 1



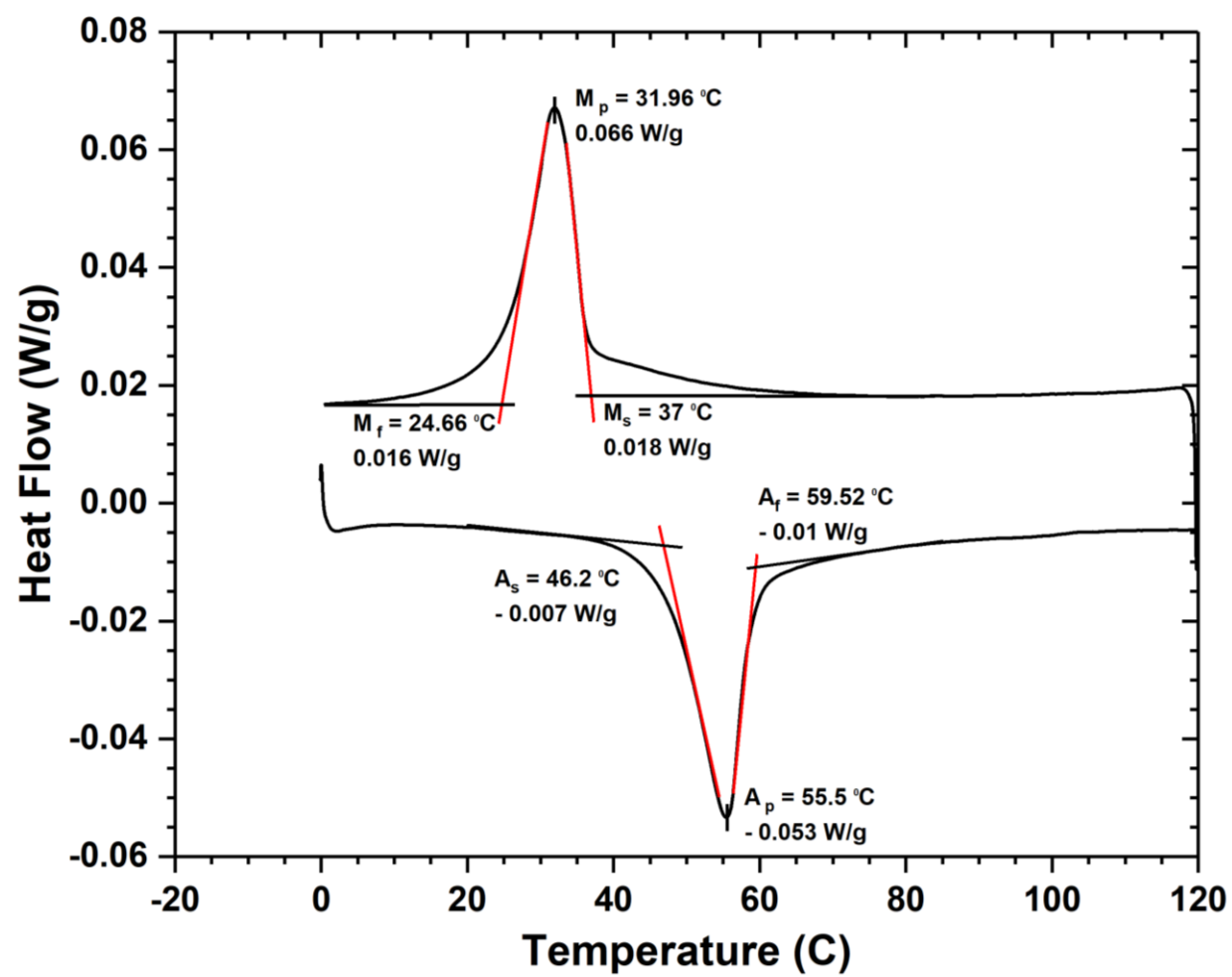
Appendix D2: DSC Q200 Thermogram of Sample 2



Appendix D3: DSC Q200 Thermogram of Sample 3



Appendix D4: DSC Q200 Thermogram of Sample 4



Appendix E: Specifications of the DSC 25 Instrument

Instrument Features	DSC25
Fusion Cell™	●
MDSC®	●
Standard Heat Flow	●
Tzero® Heat Flow	—
Advanced Tzero Heat Flow (T4P)	—
Direct Cp Measurement	—
User Replaceable Cell	●
54-Position Autosampler	○
Dual Input Gas-Delivery Manifold	●
Color App-Style Touch Screen	●
Photocalorimeter	—
Microscope Camera	○
Optical Accessory Kit	○
Specifications	
Baseline Flatness (-50 to 300 °C) ⁽¹⁾	<100 µW
Baseline Repeatability (-50 to 300 °C)	<40 µW
Temperature Range	-180 °C to 725 °C
Temperature Accuracy	±0.1 °C
Temperature Precision	±0.01 °C
Enthalpy Precision	±0.1%

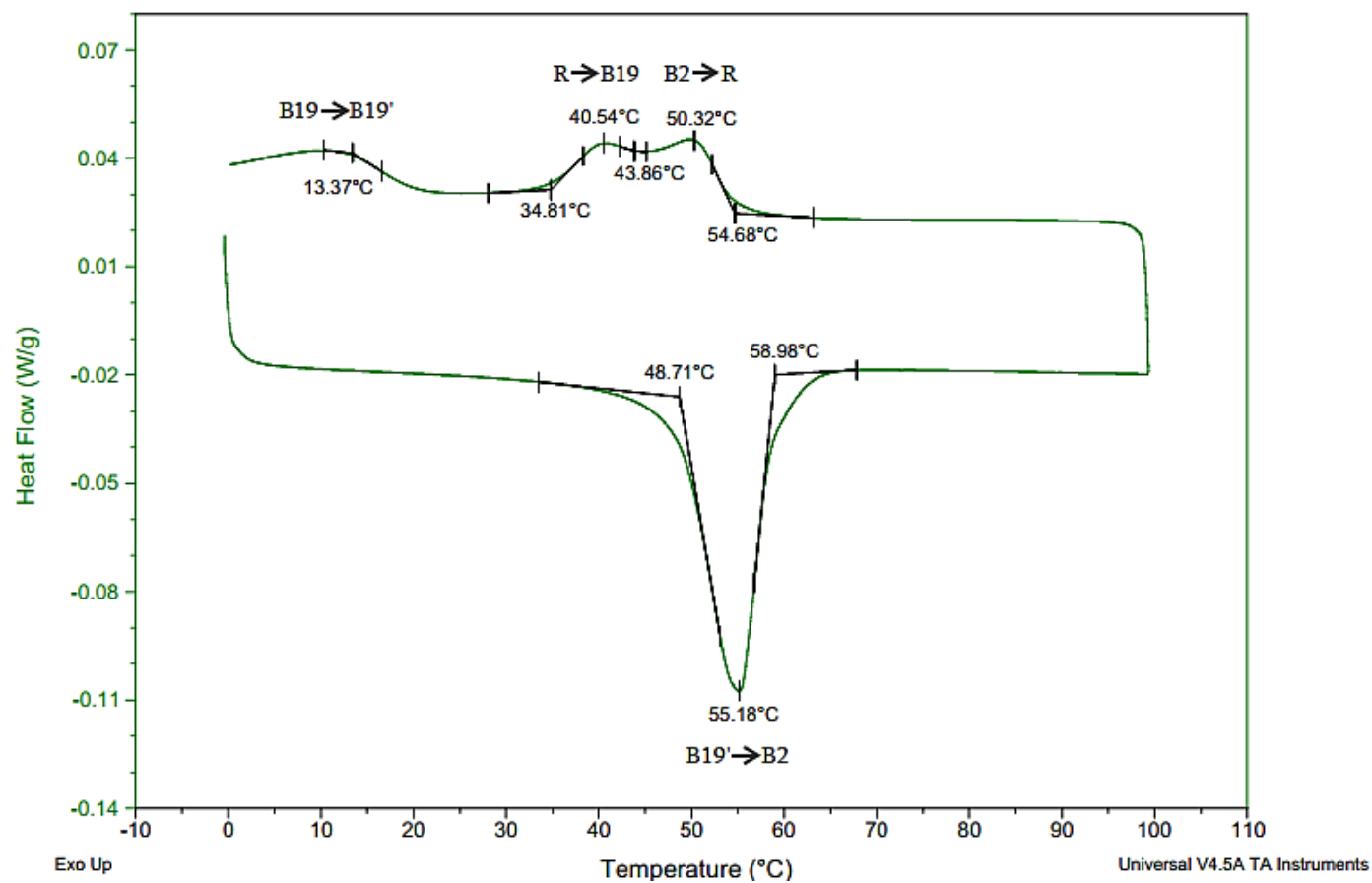
● Included ○ Optional — Not Available ⁽¹⁾ No baseline subtractions

Appendix F1: DSC 25 Thermogram of Sample 1

Sample: 2_400
Size: 11.9000 mg

DSC

File: E:\Results\Source files\Edited\2_400
Operator: Thilini
Run Date: 23-Nov-2018 14:31

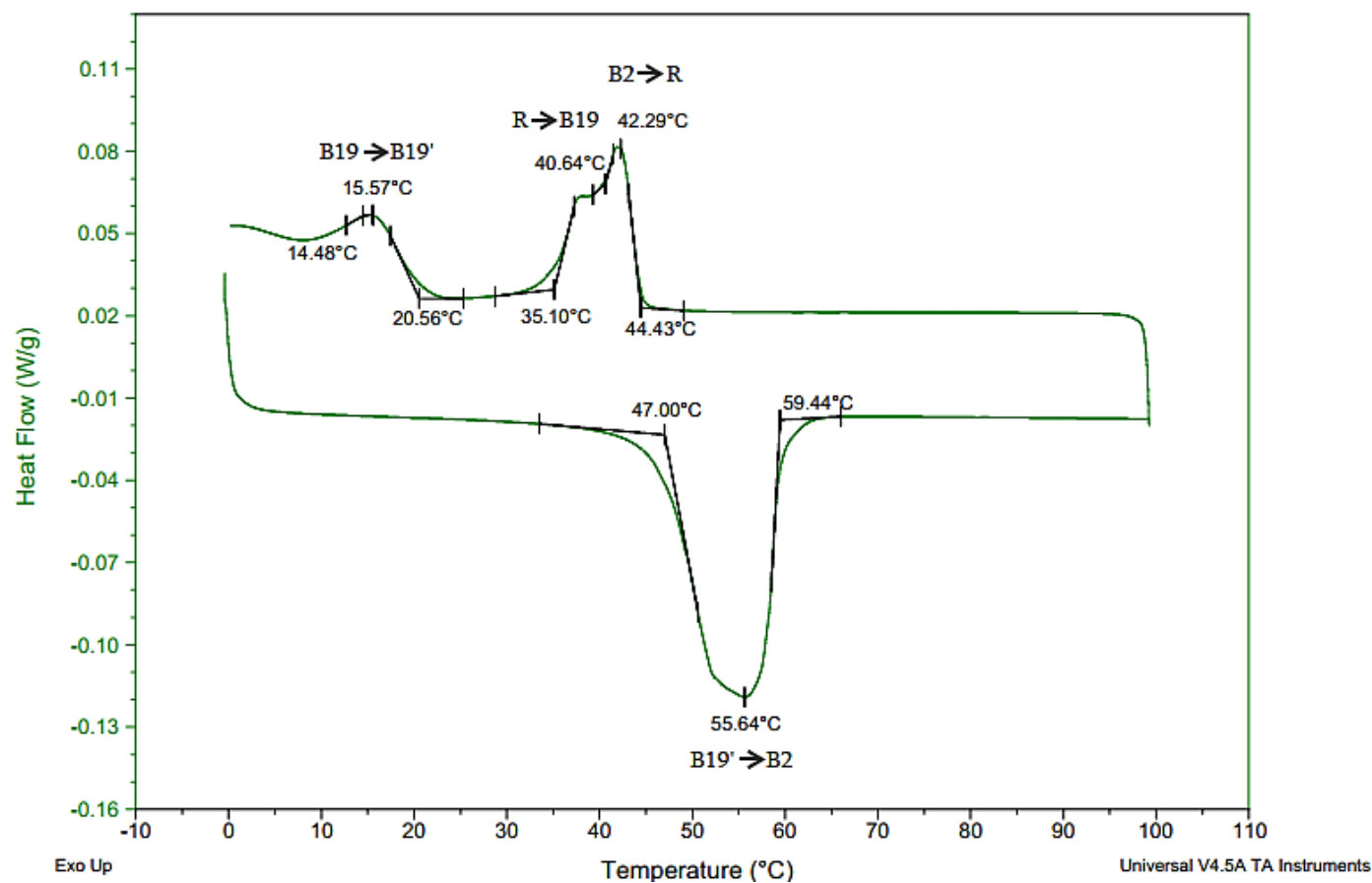


Appendix F2: DSC 25 Thermogram of Sample 2

Sample: 2_450
Size: 12.7000 mg

DSC

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Operator: Thilini
Run Date: 07-Dec-2018 11:03

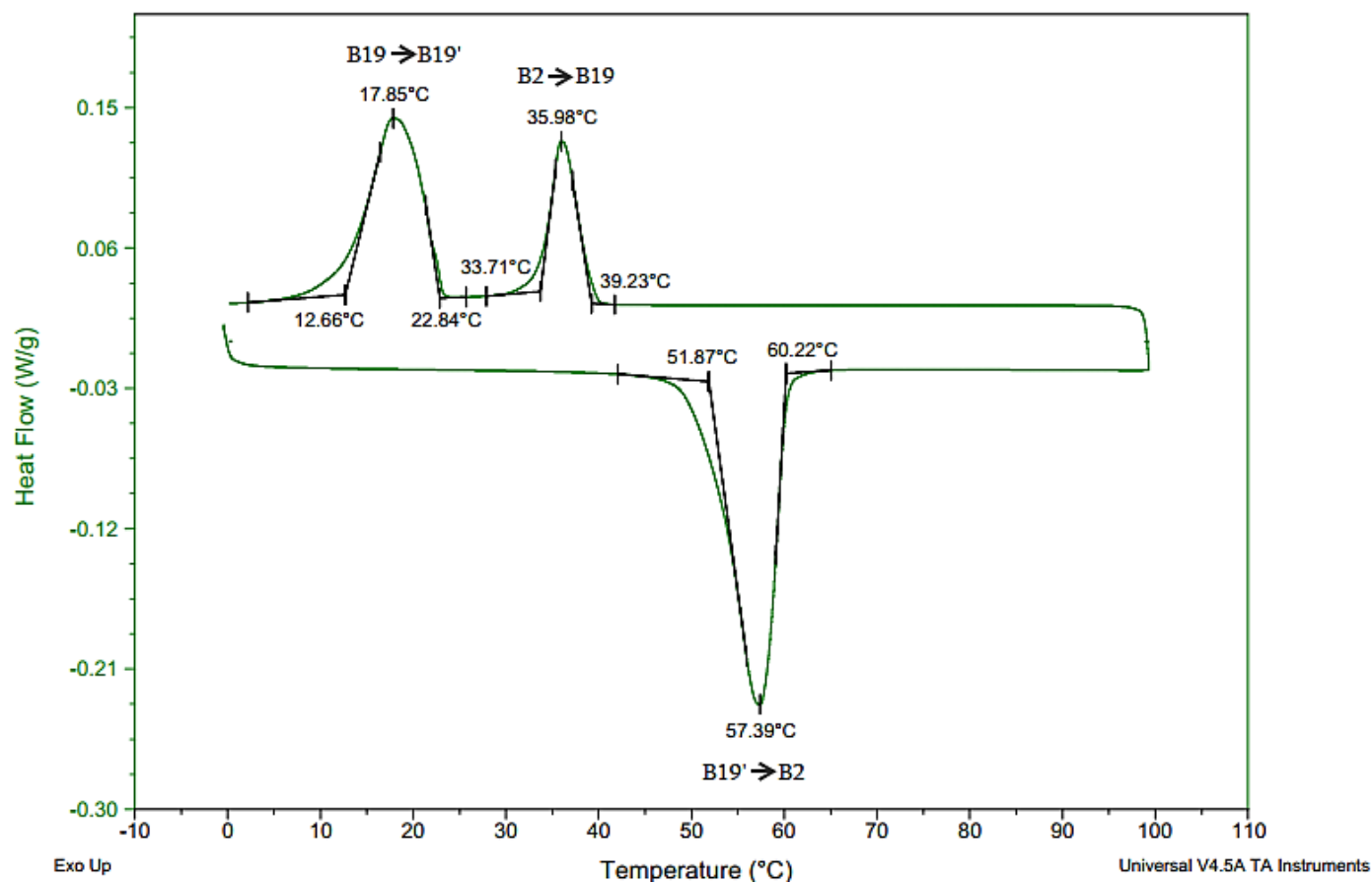


Appendix F3: DSC 25 Thermogram of Sample 3

Sample: 2_500
Size: 13.2000 mg

DSC

File: E:\UoM\Results\Source files\2_500.UA
Operator: Thilini
Run Date: 23-Nov-2018 14:31

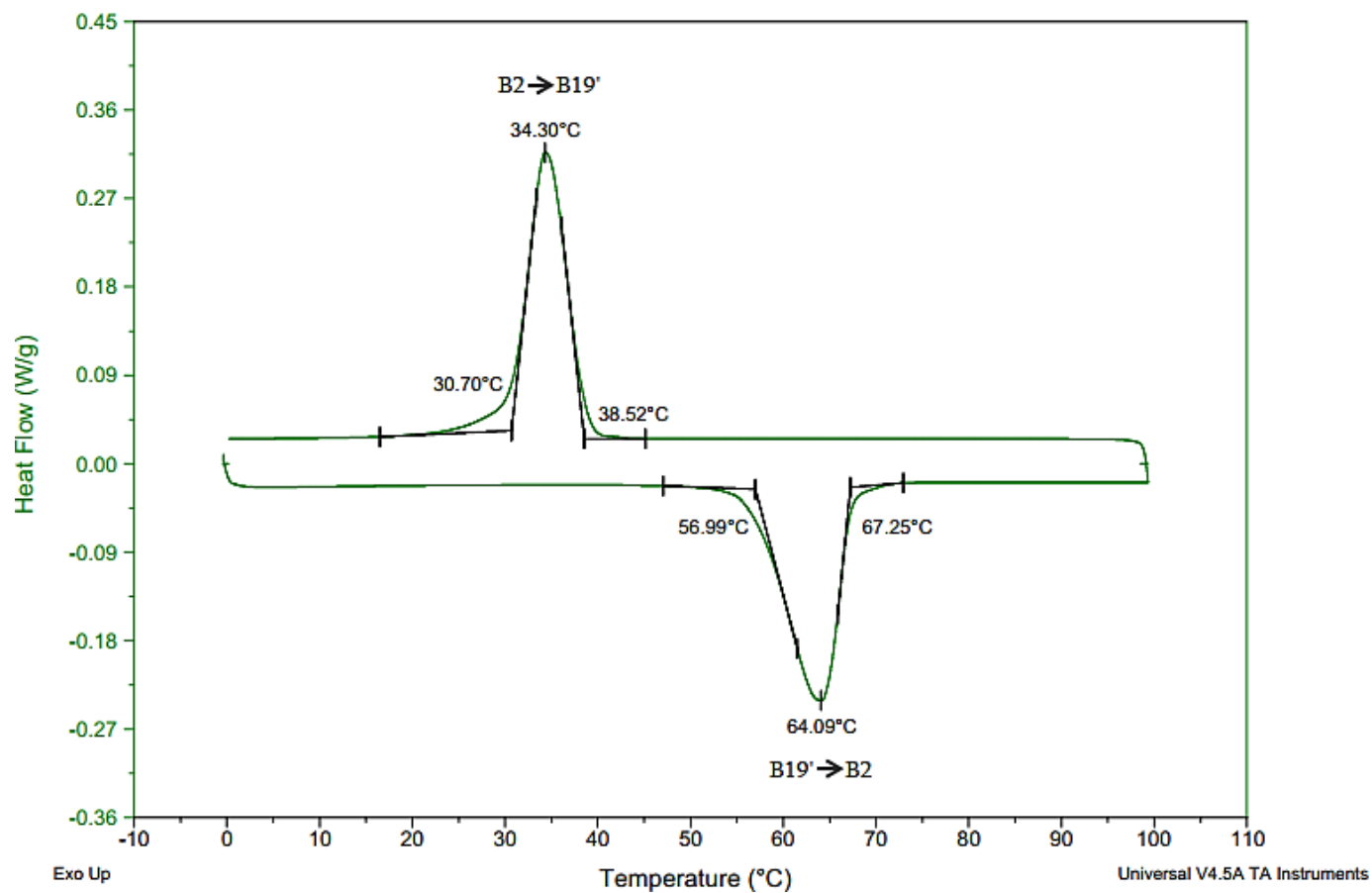


Appendix F4: DSC 25 Thermogram of Sample 4

Sample: 2_550
Size: 12.0000 mg

DSC

File: E:\...\Results\Source files\2_550(1).UA
Operator: Thilini
Run Date: 23-Nov-2018 11:46

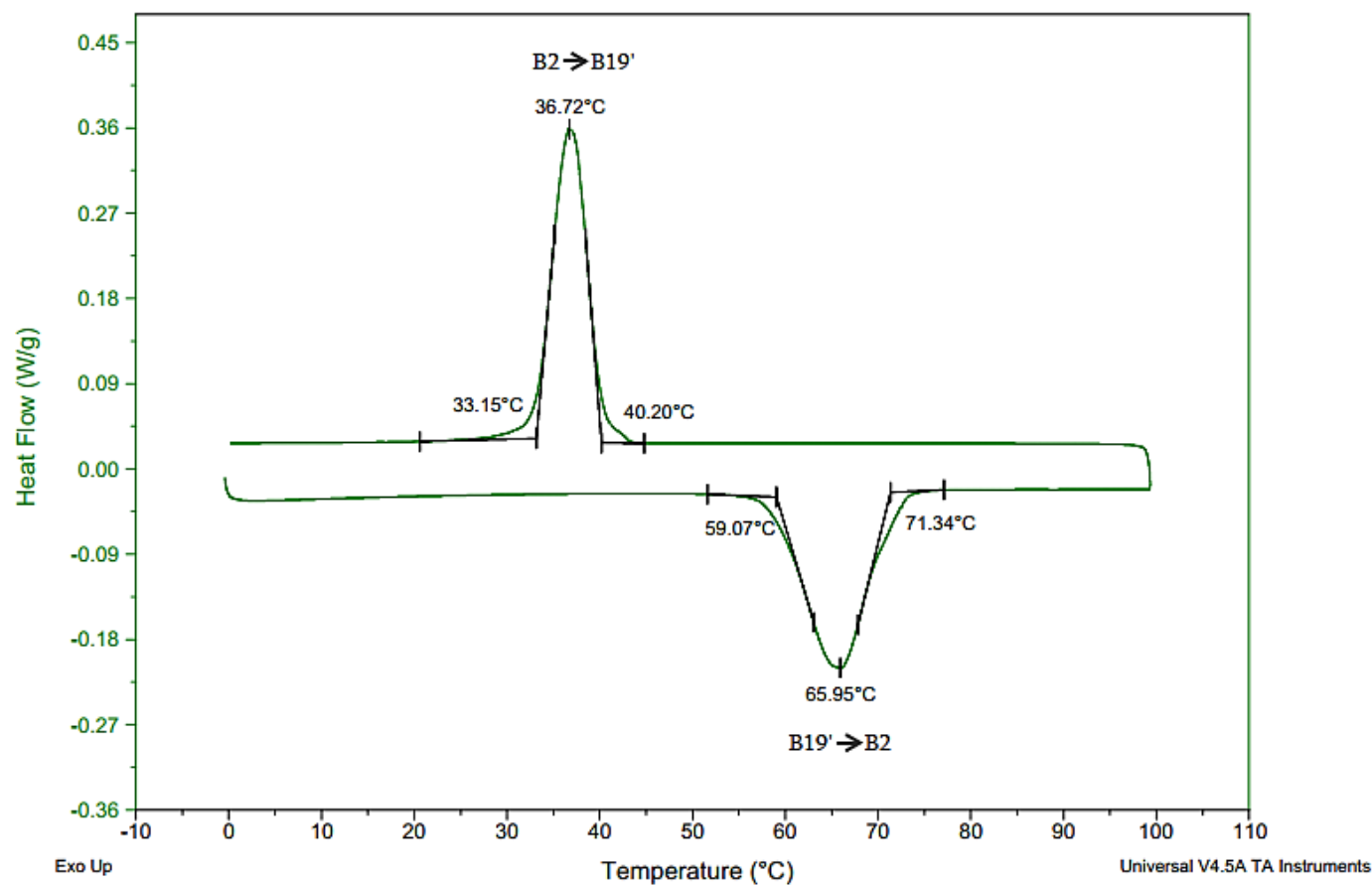


Appendix F5: DSC 25 Thermogram of Sample 5

Sample: 2_600
Size: 13.0000 mg

DSC

File: E:\...\Results\Source files\2_600(new).UA
Operator: Thilini
Run Date: 21-Nov-2018 11:51

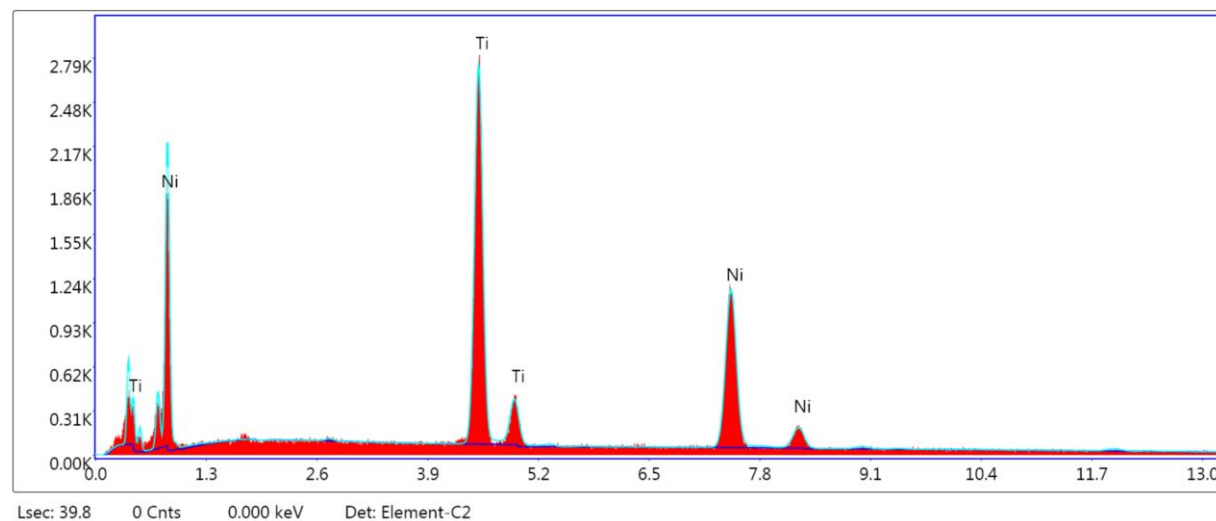


Appendix G: SEM EDX Results

Full Area 1

kV: 20 Mag:1000 Takeoff: 36.1 Live Time(s): 39.8 Amp Time(μs):7.68 Resolution:(eV)

Full Area 1 - Det 1



Lsec: 39.8 0 Cnts 0.000 keV Det: Element-C2

eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	A	F
TiK	46.92	52.01	842.13	2.35	0.4645	0.9982	0.9709	1.0214
NiK	53.08	47.99	447.20	3.19	0.5155	1.0006	0.9651	1.0058

Appendix H: Hardware Specification of 8-bit Microcontroller (Device – PIC18F452)



PIC18FXX2

28/40-pin High Performance, Enhanced FLASH Microcontrollers with 10-Bit A/D

High Performance RISC CPU:

- C compiler optimized architecture/instruction set
 - Source code compatible with the PIC16 and PIC17 instruction sets
- Linear program memory addressing to 32 Kbytes
- Linear data memory addressing to 1.5 Kbytes

Device	On-Chip Program Memory		On-Chip RAM (bytes)	Data EEPROM (bytes)
	FLASH (bytes)	# Single Word Instructions		
PIC18F242	16K	8192	768	256
PIC18F252	32K	16384	1536	256
PIC18F442	16K	8192	768	256
PIC18F452	32K	16384	1536	256

- Up to 10 MIPS operation:
 - DC - 40 MHz osc./clock input
 - 4 MHz - 10 MHz osc./clock input with PLL active
- 16-bit wide instructions, 8-bit wide data path
- Priority levels for interrupts
- 8 x 8 Single Cycle Hardware Multiplier

Peripheral Features:

- High current sink/source 25 mA/25 mA
- Three external interrupt pins
- Timer0 module: 8-bit/16-bit timer/counter with 8-bit programmable prescaler
- Timer1 module: 16-bit timer/counter
- Timer2 module: 8-bit timer/counter with 8-bit period register (time-base for PWM)
- Timer3 module: 16-bit timer/counter
- Secondary oscillator clock option - Timer1/Timer3
- Two Capture/Compare/PWM (CCP) modules. CCP pins that can be configured as:
 - Capture input: capture is 16-bit, max. resolution 6.25 ns ($T_{CY}/16$)
 - Compare is 16-bit, max. resolution 100 ns (T_{CY})
 - PWM output: PWM resolution is 1- to 10-bit, max. PWM freq. @: 8-bit resolution = 156 kHz
10-bit resolution = 39 kHz
- Master Synchronous Serial Port (MSSP) module, Two modes of operation:
 - 3-wire SPI™ (supports all 4 SPI modes)
 - I²C™ Master and Slave mode

Peripheral Features (Continued):

- Addressable USART module:
 - Supports RS-485 and RS-232
- Parallel Slave Port (PSP) module

Analog Features:

- Compatible 10-bit Analog-to-Digital Converter module (A/D) with:
 - Fast sampling rate
 - Conversion available during SLEEP
 - Linearity ≤ 1 LSB
- Programmable Low Voltage Detection (PLVD)
 - Supports interrupt on-Low Voltage Detection
- Programmable Brown-out Reset (BOR)

Special Microcontroller Features:

- 100,000 erase/write cycle Enhanced FLASH program memory typical
- 1,000,000 erase/write cycle Data EEPROM memory
- FLASH/Data EEPROM Retention: > 40 years
- Self-reprogrammable under software control
- Power-on Reset (POR), Power-up Timer (PWRT) and Oscillator Start-up Timer (OST)
- Watchdog Timer (WDT) with its own On-Chip RC Oscillator for reliable operation
- Programmable code protection
- Power saving SLEEP mode
- Selectable oscillator options including:
 - 4X Phase Lock Loop (of primary oscillator)
 - Secondary Oscillator (32 kHz) clock input
- Single supply 5V In-Circuit Serial Programming™ (ICSP™) via two pins
- In-Circuit Debug (ICD) via two pins

CMOS Technology:

- Low power, high speed FLASH/EEPROM technology
- Fully static design
- Wide operating voltage range (2.0V to 5.5V)
- Industrial and Extended temperature ranges
- Low power consumption:
 - < 1.6 mA typical @ 5V, 4 MHz
 - 25 μ A typical @ 3V, 32 kHz
 - < 0.2 μ A typical standby current

Appendix I: Hardware Specification of 8-bit Microcontroller (Device – ATmega2560)



Atmel ATmega640/V-1280/V-1281/V-2560/V-2561/V

8-bit Atmel Microcontroller with 16/32/64KB In-System Programmable Flash

Features

- High Performance, Low Power Atmel® AVR® 8-Bit Microcontroller
- Advanced RISC Architecture
 - 135 Powerful Instructions – Most Single Clock Cycle Execution
 - 32 x 8 General Purpose Working Registers
 - Fully Static Operation
 - Up to 16 MIPS Throughput at 16MHz
 - On-Chip 2-cycle Multiplier
- High Endurance Non-volatile Memory Segments
 - 64K/128K/256KBytes of In-System Self-Programmable Flash
 - 4Kbytes EEPROM
 - 8Kbytes Internal SRAM
 - Write/Erase Cycles: 10,000 Flash/100,000 EEPROM
 - Data retention: 20 years at 85°C/ 100 years at 25°C
 - Optional Boot Code Section with Independent Lock Bits
 - In-System Programming by On-chip Boot Program
 - True Read-While-Write Operation
 - Programming Lock for Software Security
 - Endurance: Up to 64Kbytes Optional External Memory Space
- Atmel® QTouch® library support
 - Capacitive touch buttons, sliders and wheels
 - QTouch and QMatrix acquisition
 - Up to 64 sense channels
- JTAG (IEEE® std. 1149.1 compliant) Interface
 - Boundary-scan Capabilities According to the JTAG Standard
 - Extensive On-chip Debug Support
 - Programming of Flash, EEPROM, Fuses, and Lock Bits through the JTAG Interface
- Peripheral Features
 - Two 8-bit Timer/Counters with Separate Prescaler and Compare Mode
 - Four 16-bit Timer/Counter with Separate Prescaler, Compare- and Capture Mode
 - Real Time Counter with Separate Oscillator
 - Four 8-bit PWM Channels
 - Six/Twelve PWM Channels with Programmable Resolution from 2 to 16 Bits (ATmega1281/2561, ATmega640/1280/2560)
 - Output Compare Modulator
 - 8/16-channel, 10-bit ADC (ATmega1281/2561, ATmega640/1280/2560)
 - Two/Four Programmable Serial USART (ATmega1281/2561, ATmega640/1280/2560)
 - Master/Slave SPI Serial Interface
 - Byte Oriented 2-wire Serial Interface
 - Programmable Watchdog Timer with Separate On-chip Oscillator
 - On-chip Analog Comparator
 - Interrupt and Wake-up on Pin Change
- Special Microcontroller Features
 - Power-on Reset and Programmable Brown-out Detection
 - Internal Calibrated Oscillator
 - External and Internal Interrupt Sources
 - Six Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, Standby, and Extended Standby
- I/O and Packages
 - 54/86 Programmable I/O Lines (ATmega1281/2561, ATmega640/1280/2560)
 - 64-pad QFN/MLF, 64-lead TQFP (ATmega1281/2561)
 - 100-lead TQFP, 100-ball CBGA (ATmega640/1280/2560)
 - RoHS/Fully Green
- Temperature Range:
 - -40°C to 85°C Industrial
- Ultra-Low Power Consumption
 - Active Mode: 1MHz, 1.8V: 500µA
 - Power-down Mode: 0.1µA at 1.8V
- Speed Grade:
 - ATmega640V/ATmega1280V/ATmega1281V:
 - 0 - 4MHz @ 1.8V - 5.5V, 0 - 8MHz @ 2.7V - 5.5V
 - ATmega2560V/ATmega2561V:
 - 0 - 2MHz @ 1.8V - 5.5V, 0 - 8MHz @ 2.7V - 5.5V
 - ATmega640/ATmega1280/ATmega1281:
 - 0 - 8MHz @ 2.7V - 5.5V, 0 - 16MHz @ 4.5V - 5.5V
 - ATmega2560/ATmega2561:
 - 0 - 16MHz @ 4.5V - 5.5V

Appendix J: Hardware Specification of 8-bit Microcontroller (Device – ATmega328p)



ATmega328P

8-bit AVR Microcontroller with 32K Bytes In-System
Programmable Flash

Features

- High performance, low power AVR® 8-bit microcontroller
- Advanced RISC architecture
 - 131 powerful instructions – most single clock cycle execution
 - 32 × 8 general purpose working registers
 - Fully static operation
 - Up to 16MIPS throughput at 16MHz
 - On-chip 2-cycle multiplier
- High endurance non-volatile memory segments
 - 32K bytes of in-system self-programmable flash program memory
 - 1Kbytes EEPROM
 - 2Kbytes internal SRAM
 - Write/erase cycles: 10,000 flash/100,000 EEPROM
 - Optional boot code section with independent lock bits
 - In-system programming by on-chip boot program
 - True read-while-write operation
 - Programming lock for software security
- Peripheral features
 - Two 8-bit Timer/Counters with separate prescaler and compare mode
 - One 16-bit Timer/Counter with separate prescaler, compare mode, and capture mode
 - Real time counter with separate oscillator
 - Six PWM channels
 - 8-channel 10-bit ADC in TQFP and QFN/MLF package
 - Temperature measurement
 - Programmable serial USART
 - Master/slave SPI serial interface
 - Byte-oriented 2-wire serial interface (Phillips I²C compatible)
 - Programmable watchdog timer with separate on-chip oscillator
 - On-chip analog comparator
 - Interrupt and wake-up on pin change
- Special microcontroller features
 - Power-on reset and programmable brown-out detection
 - Internal calibrated oscillator
 - External and internal interrupt sources
 - Six sleep modes: Idle, ADC noise reduction, power-save, power-down, standby, and extended standby
- I/O and packages
 - 23 programmable I/O lines
 - 32-lead TQFP, and 32-pad QFN/MLF
- Operating voltage:
 - 2.7V to 5.5V for ATmega328P
- Temperature range:
 - Automotive temperature range: –40°C to +125°C
- Speed grade:
 - 0 to 8MHz at 2.7 to 5.5V (automotive temperature range: –40°C to +125°C)
 - 0 to 16MHz at 4.5 to 5.5V (automotive temperature range: –40°C to +125°C)
- Low power consumption
 - Active mode: 1.5mA at 3V - 4MHz
 - Power-down mode: 1µA at 3V

Appendix K: Hardware Specification of 24-bit ADC (Device – HX711)



HX711

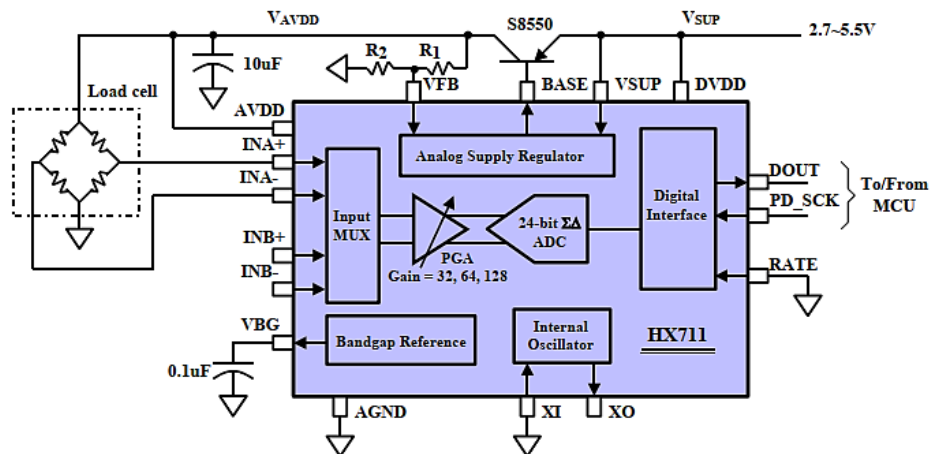
24-Bit Analog-to-Digital Converter (ADC) for Weigh Scales

FEATURES

- Two selectable differential input channels
- On-chip active low noise PGA with selectable gain of 32, 64 and 128
- On-chip power supply regulator for load-cell and ADC analog power supply
- On-chip oscillator requiring no external component with optional external crystal
- On-chip power-on-reset
- Simple digital control and serial interface: pin-driven controls, no programming needed
- Selectable 10SPS or 80SPS output data rate
- Simultaneous 50 and 60Hz supply rejection
- Current consumption including on-chip analog power supply regulator:
normal operation < 1.5mA, power down < 1uA
- Operation supply voltage range: 2.6 ~ 5.5V
- Operation temperature range: -40 ~ +85°C
- 16 pin SOP-16 package

APPLICATIONS

- Weigh Scales
- Industrial Process Control



Appendix L: Hardware Specifications of Cold-Junction-Compensated K- Thermocouple to-Digital Converter (0°C to +1024°C) (Device – MAX6675)

MAX6675

Cold-Junction-Compensated K-Thermocouple-
to-Digital Converter (0°C to +1024°C)

General Description

The MAX6675 performs cold-junction compensation and digitizes the signal from a type-K thermocouple. The data is output in a 12-bit resolution, SPI™-compatible, read-only format.

This converter resolves temperatures to 0.25°C, allows readings as high as +1024°C, and exhibits thermocouple accuracy of 8LSBs for temperatures ranging from 0°C to +700°C.

The MAX6675 is available in a small, 8-pin SO package.

Applications

- Industrial
- Appliances
- HVAC

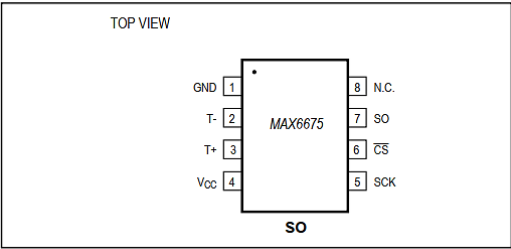
Features

- Direct Digital Conversion of Type -K Thermocouple Output
- Cold-Junction Compensation
- Simple SPI-Compatible Serial Interface
- 12-Bit, 0.25°C Resolution
- Open Thermocouple Detection

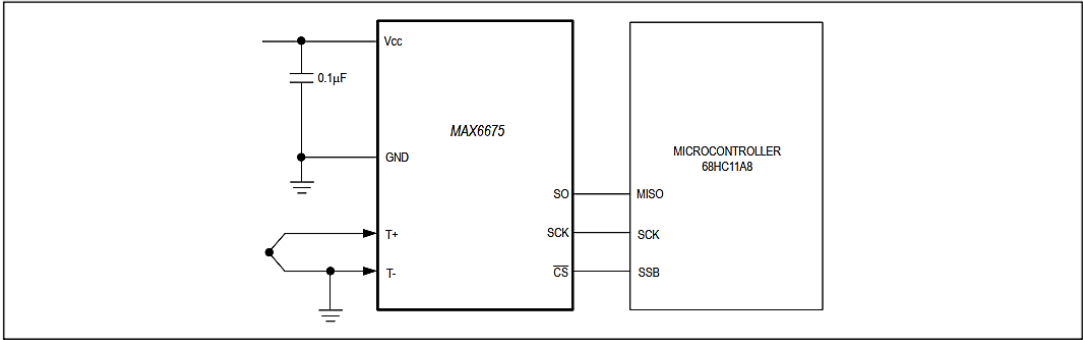
Ordering Information

PART	TEMP RANGE	PIN-PACKAGE
MAX6675ISA	-20°C to +85°C	8 SO

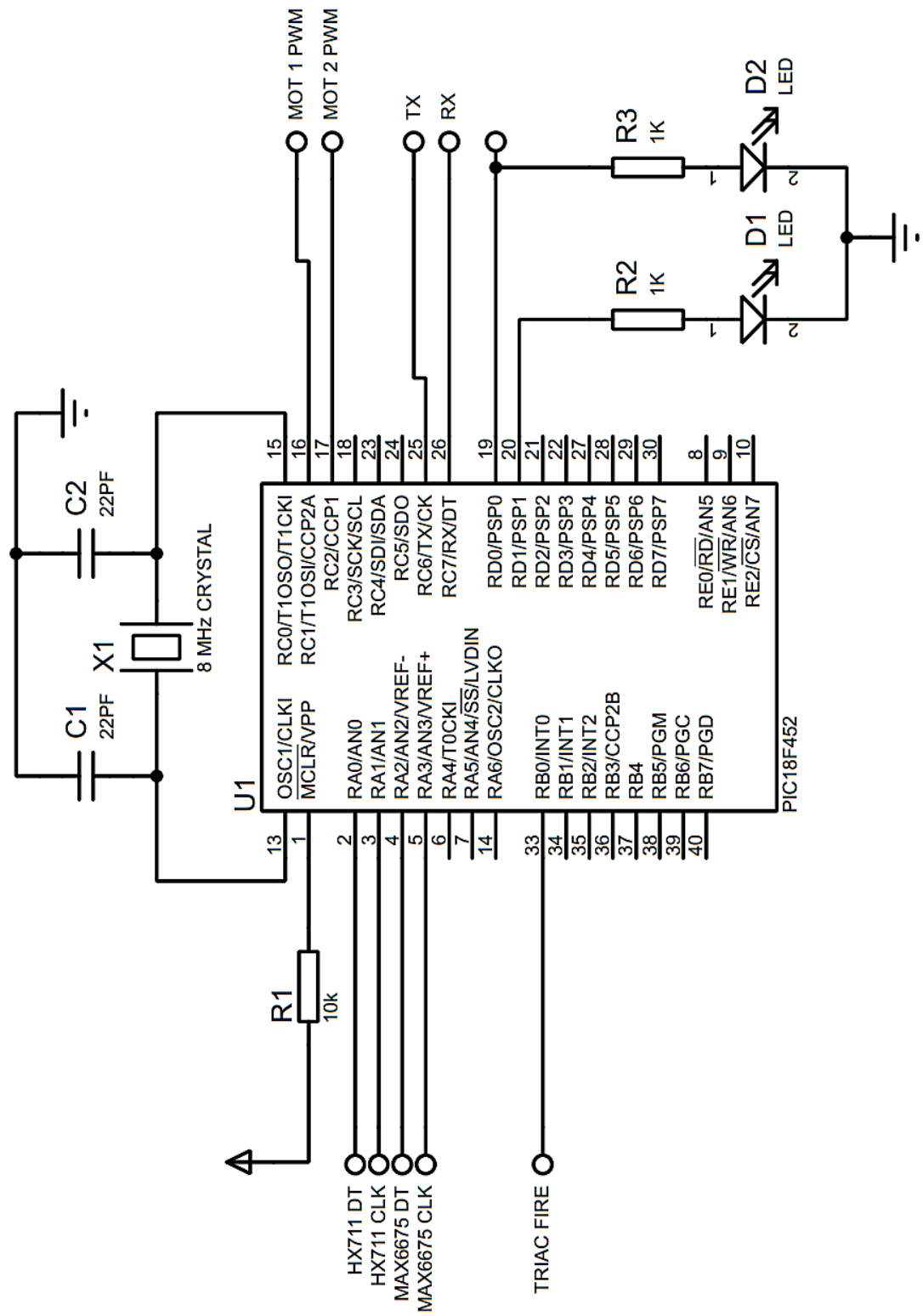
Pin Configuration



Typical Application Circuit

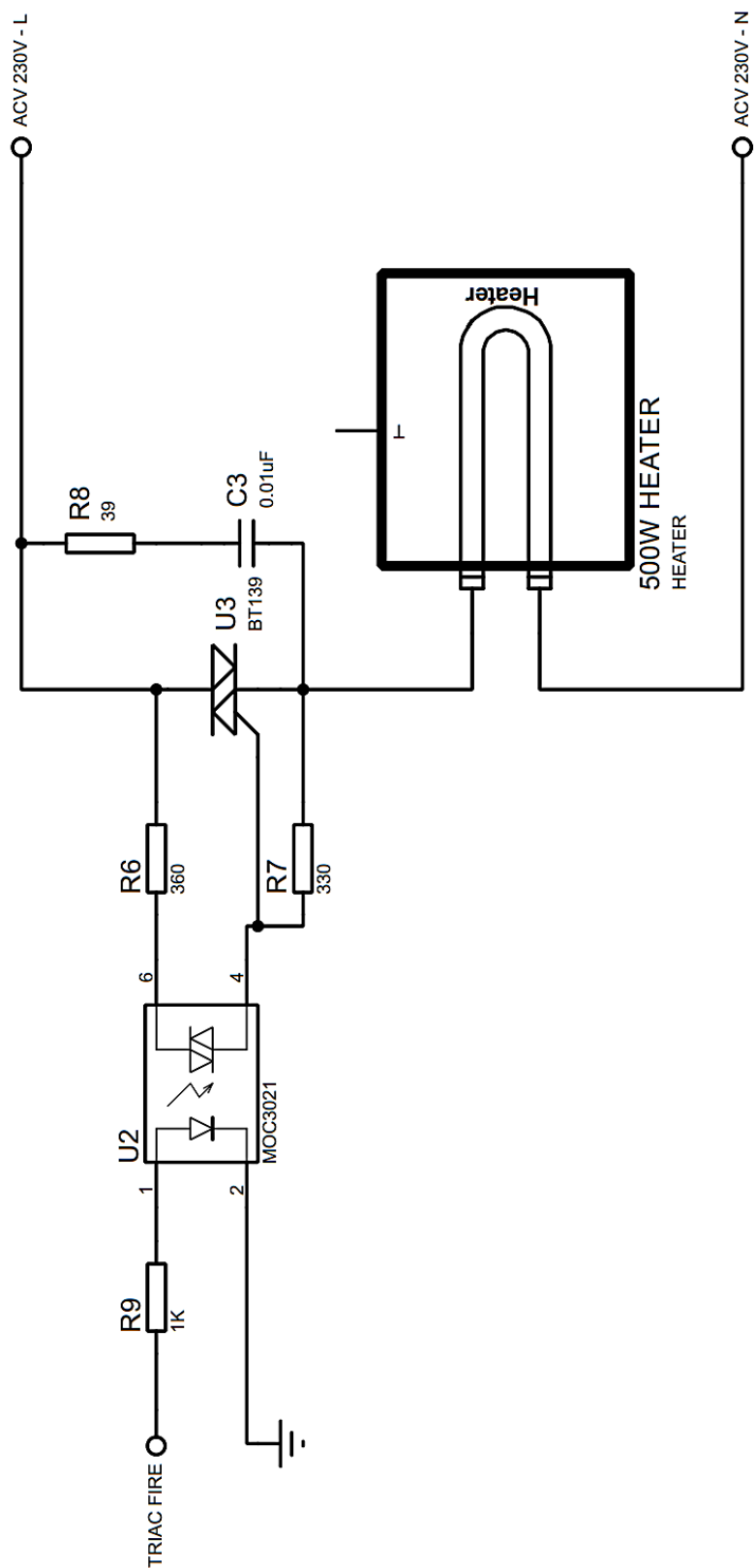


Appendix M1: Schematic Diagram of the Multi-Function Controller - Microcontroller Input / Output Signal Interface

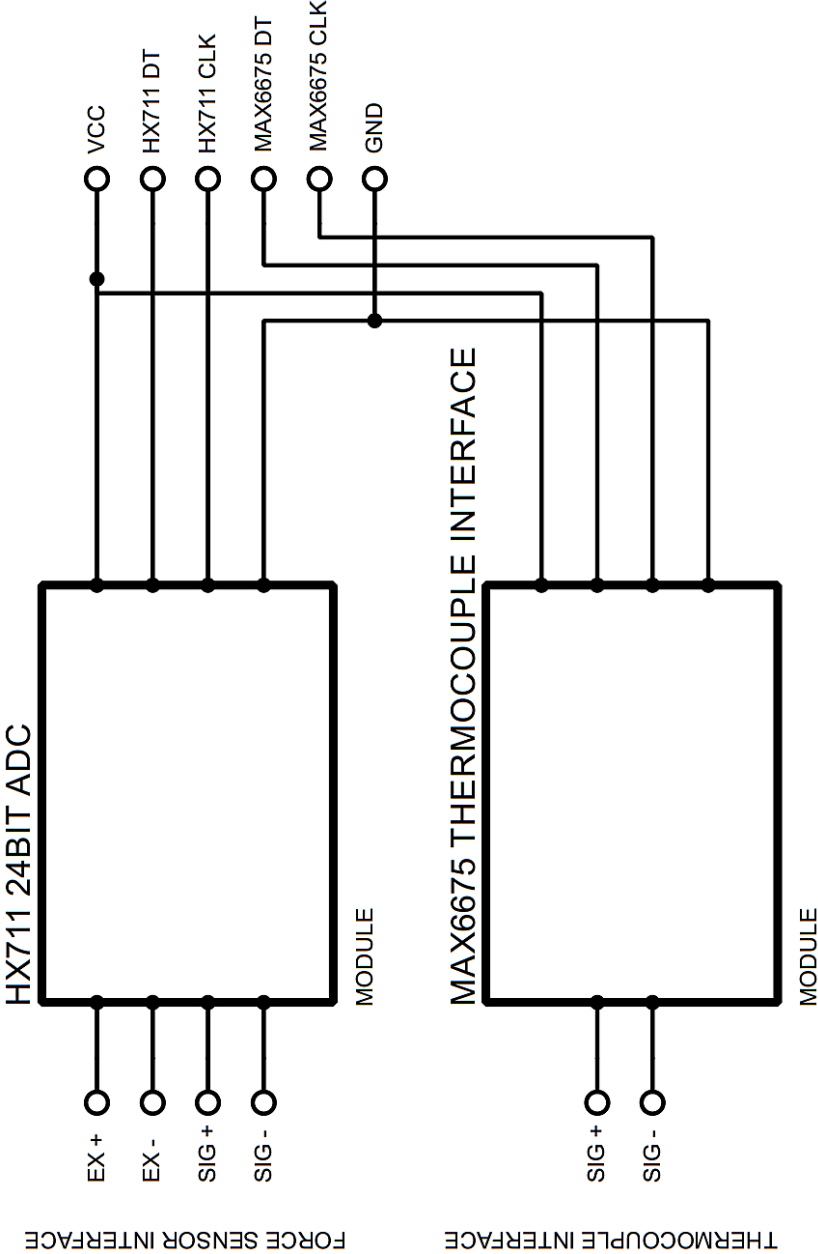


Appendix M2: Schematic Diagram of the Multi-Function Controller - 230V

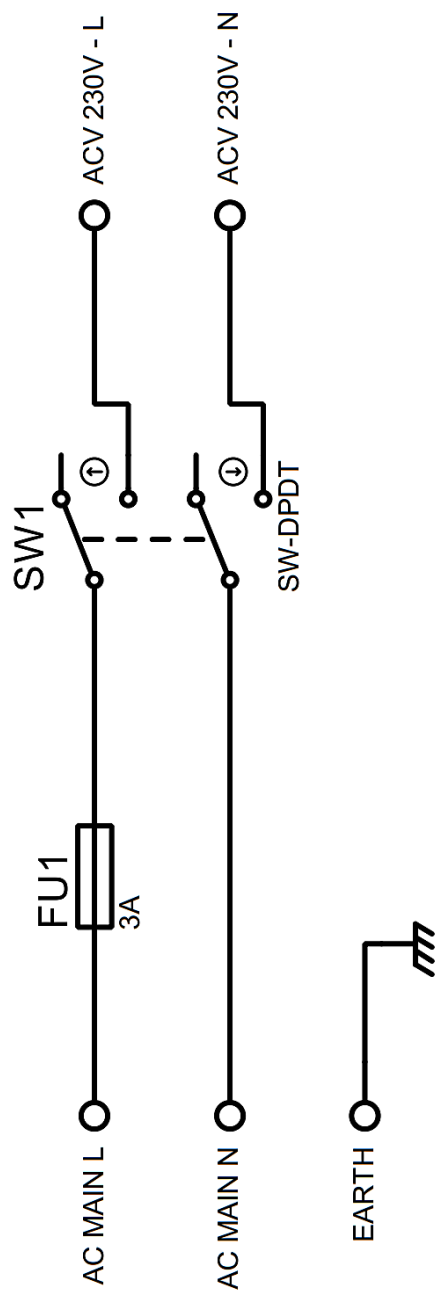
Heater Driver with Optical Isolator



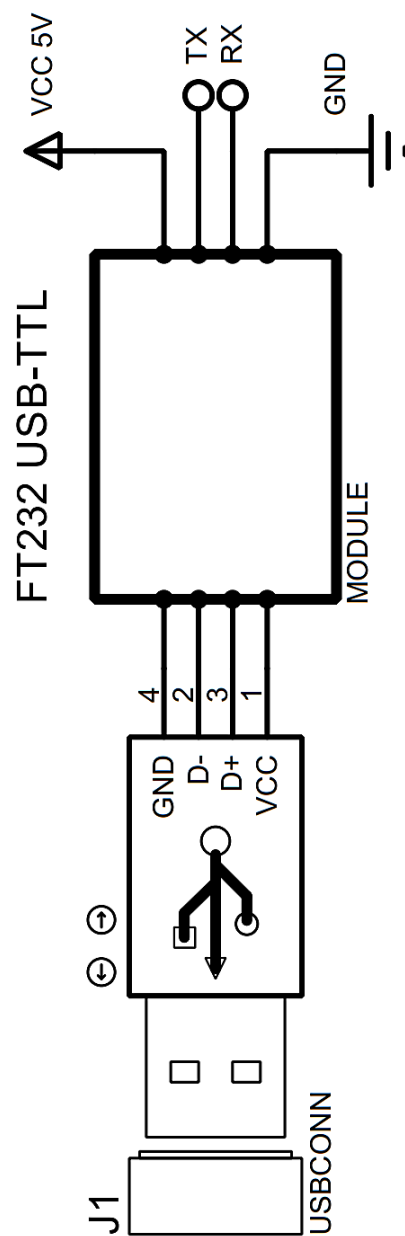
**Appendix M3: Schematic Diagram of the Multi-Function Controller -
Sensor Interface Modules**



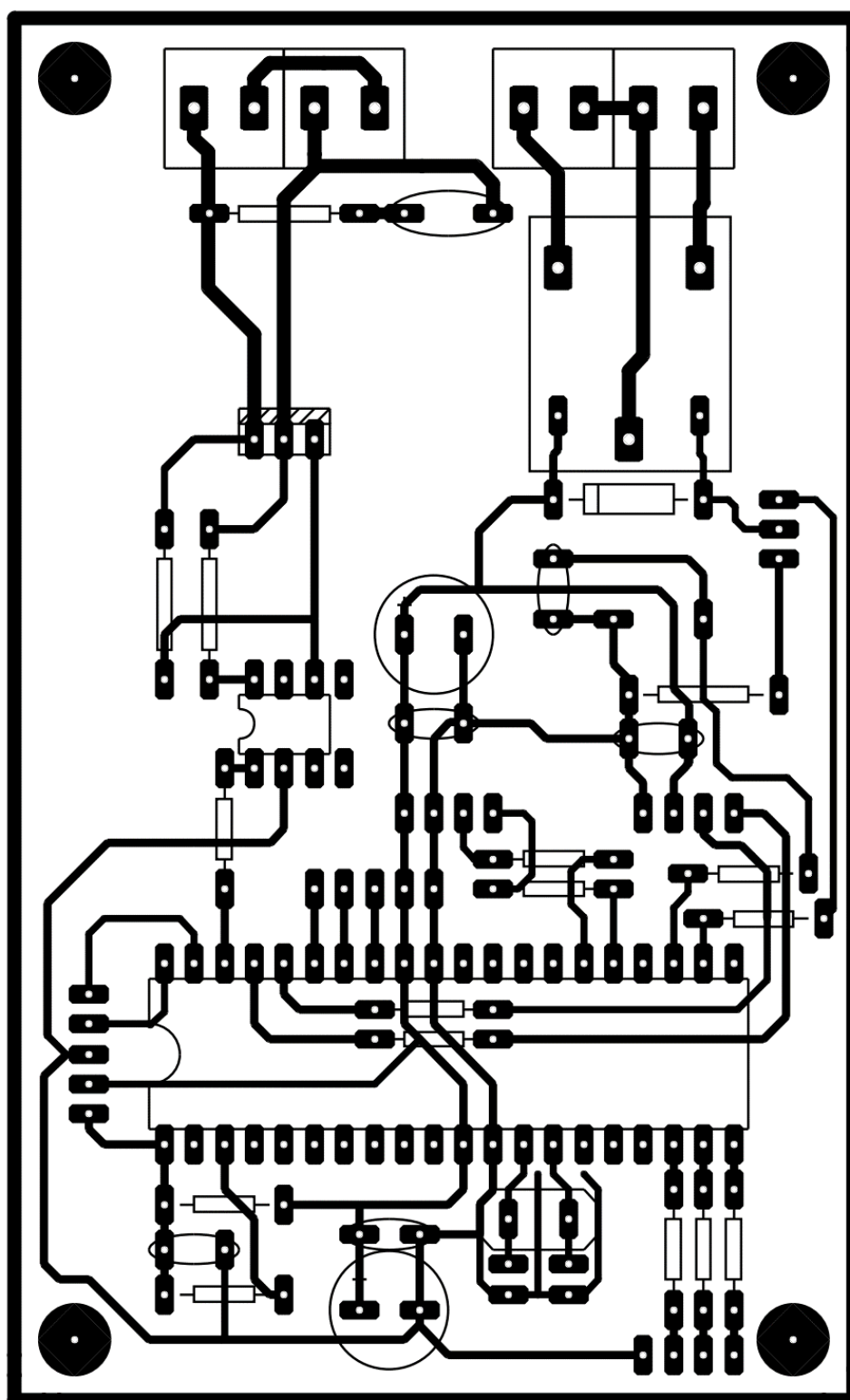
**Appendix M4: Schematic Diagram of the Multi-Function Controller -
Main Supply Distribution**



**Appendix M5: Schematic Diagram of the Multi-Function Controller –
USB Powered USB to TTL Converter**



Appendix M6: PCB Layout of the Multi-Function Controller



Appendix M7: Microcontroller Firmware Implementation for Multifunctional Controller

```
1: sbit maxso at portb.b2;
2: sbit maxsck at portb.b0;
3: sbit maxce at portb.b1;
4: sbit buzzer at latc.b4;
5: sbit relay at latd.b3;
6:
7: sbit green at latd.b1;
8: sbit red1 at latd.b0;
9: sbit red2 at latc.b3;
10:
11: unsigned short temp_read_l=0;
12: unsigned short temp_read_h=0;
13: unsigned int temprature_read, cal_temp;
14: int temp;
15: char txt[5];
16:
17: // PID Controller
18: int p_val,i_val,d_val,kp,ki,kd,out,sp,pv,error;
19:
20: e_tone(){
21:   buzzer=1;
22:   delay_ms(20);
23:   buzzer=0;
24:   delay_ms(30);
25:   buzzer=1;
26:   delay_ms(30);
27:   buzzer=0;
28: }
29:
30: del_tc(){
31:   delay_us(5);
32: }
33:
34: tc_read(){
35:
36:   maxce=0;
37:   delay_ms(1);
38:   maxce=1;
39:   delay_ms(250);
40:
41:   maxce=0;
42:   del_tc();
43:
44:   temp_read_l=0;
45:   temp_read_h=0;
46:
47:   // frist byte
48:
49:   maxsck=1;
50:   del_tc();
51:   maxsck=0;
52:   temp_read_h.b3=maxso;
53:   del_tc();
54:
55:   maxsck=1;
56:   del_tc();
```



```

57:  maxsck=0;
58:  temp_read_h.b2=maxso;
59:  del_tc();
60:
61:  maxsck=1;
62:  del_tc();
63:  maxsck=0;
64:  temp_read_h.b1=maxso;
65:  del_tc();
66:
67:  maxsck=1;
68:  del_tc();
69:  maxsck=0;
70:  temp_read_h.b0=maxso;
71:  del_tc();
72:
73:  // second byte
74:
75:  maxsck=1;
76:  del_tc();
77:  maxsck=0;
78:  temp_read_l.b7=maxso;
79:  del_tc();
80:
81:  maxsck=1;
82:  del_tc();
83:  maxsck=0;
84:  temp_read_l.b6=maxso;
85:  del_tc();
86:
87:  maxsck=1;
88:  del_tc();
89:  maxsck=0;
90:  temp_read_l.b5=maxso;
91:  del_tc();
92:
93:  maxsck=1;
94:  del_tc();
95:  maxsck=0;
96:  temp_read_l.b4=maxso;
97:  del_tc();
98:
99:  maxsck=1;
100: del_tc();
101: maxsck=0;
102: temp_read_l.b3=maxso;
103: del_tc();
104:
105: maxsck=1;
106: del_tc();
107: maxsck=0;
108: temp_read_l.b2=maxso;
109: del_tc();
110:
111: maxsck=1;
112: del_tc();

```

```

113:    maxsck=0;
114:    temp_read_l.b1=maxso;
115:    del_tc();
116:
117:    maxsck=1;
118:    del_tc();
119:    maxsck=0;
120:    temp_read_l.b0=maxso;
121:    del_tc();
122:
123:    // Done
124:    maxsck=1;
125:    del_tc();
126:    maxsck=0;
127:    del_tc();
128:
129:    maxsck=1;
130:    del_tc();
131:    maxsck=0;
132:    del_tc();
133:
134:    maxsck=1;
135:    del_tc();
136:    maxsck=0;
137:    del_tc();
138:
139:    cal_temp=temp_read_h ;
140:    temprature_read=cal_temp * 256;
141:    cal_temp=temp_read_l ;
142:    temprature_read=temprature_read + cal_temp;
143:    return temprature_read;
144:
145: }
146:
147: void main() {
148:
149:     trisb.b2=1;
150:     trisb.b0=0;
151:     trisb.b1=0;
152:
153:     trisc.b3=0;
154:     trisc.b4=0;
155:     trisd.b0=0;
156:     trisd.b1=0;
157:     trisd.b3=0;
158:
159:
160:     trisd=0;
161:
162:     intcon2.b7=0;
163:
164:     UART1_Init(9600);
165:     Delay_ms(100);
166:
167:     UART1_Write_Text("SMA Controller");
168:     UART1_Write(10);

```

```

169:     UART1_Write(13);
170:
171:     buzzer=1;
172:     green=1;
173:     red1=1;
174:     red2=1;
175:     delay_ms(200);
176:     latd=0;
177:     latc=0;
178:
179:     maxce=1;
180:     maxsck=0;
181:
182:     sp=150;
183:     kp=5;
184:
185:
186:     while(1){
187:         tc_read();
188:         temp=tc_read();
189:
190:         if(temp==4095){
191:             e_tone();
192:         }
193:
194:         pv=temp;
195:         error=sp-pv;
196:         p_val=error * kp;
197:
198:         out= p_val;
199:
200:
201:         inttostr(out,txt);
202:         UART1_Write_Text(txt);
203:         UART1_Write(10);
204:         UART1_Write(13);
205:
206:     }
207:
208: }

```

Appendix M8: Software Code of the Human Machine Interface

...SMA Interface\Temprature Meter and Data Logger\Form1.vb

1

Imports System.Drawing

Public Class Form1

Private comBuffer As Byte()

Private Delegate Sub UpdateFormDelegate()

Private UpdateFormDelegate1 As UpdateFormDelegate

Dim word_length As Integer

Dim count As Integer

Dim Read_temp As Char

Dim packet As Integer = 0

Dim data_string As String

Dim plotx As Double

Dim ploty As Double

'sp contol list

Dim sp_array(100)

Dim time_array(100)

Dim index As Integer

Private Sub SerialPort1_DataReceived1(sender As Object, e As

IO.Ports.SerialDataReceivedEventArgs) Handles SerialPort1.DataReceived

UpdateFormDelegate1 = New UpdateFormDelegate(AddressOf UpdateDisplay)

Dim n As Integer = SerialPort1.BytesToRead 'find number of bytes in buf

comBuffer = New Byte(n - 1) {} 're dimension storage buffer

SerialPort1.Read(comBuffer, 0, n) 'read data from the buffer

Me.Invoke(UpdateFormDelegate1) 'call the delegate

End Sub

Private Sub UpdateDisplay()

word_length = comBuffer.Length

count = 0

While count < word_length

Read_temp = Chr(comBuffer(count))

If Read_temp = "," Then

Read_temp = ""

Try

Dim prob_temp As Double = data_string

prob_temp = prob_temp / 10

Label12.Text = Format(prob_temp, "0.0")

data_string = ""

ploty = prob_temp

Chart1.Series("Temperature").Points.AddXY(plotx, ploty)

plotx = plotx + 1

Catch ex As Exception

data_string = ""

End Try

If plotx >= 500 Then

Button4.PerformClick()

```

        End If

        Else
            data_string = data_string + (Read_temp)
        End If
        count = count + 1
    End While

End Sub

Private Sub Button5_Click(sender As Object, e As EventArgs) Handles
    Button5.Click
        ControlBmpToFile(Chart1, "test")
End Sub

Private Sub ComboBox1_Click(sender As Object, e As EventArgs) Handles
    ComboBox1.Click
        If SerialPort1.IsOpen Then
        Else
            ComboBox1.Items.Clear()
            For Each sp As String In My.Computer.Ports.SerialPortNames
                ComboBox1.Items.Add(sp)
            Next
        End If
    End Sub

Public Sub ControlBmpToFile(control As Control, file As String)
    Dim bmp As New Bitmap(control.Width, control.Height)
    control.DrawToBitmap(bmp, control.DisplayRectangle)
    bmp.Save(file, System.Drawing.Imaging.ImageFormat.Jpeg)
End Sub

Private Sub Button1_Click(sender As Object, e As EventArgs) Handles
    Button1.Click
        If SerialPort1.IsOpen Then

        Else
            Try
                SerialPort1.PortName = ComboBox1.Text
                SerialPort1.BaudRate = 19200

                SerialPort1.Open()
                SerialPort1.DiscardInBuffer()
                Button1.BackColor = Color.Lime
            Catch ex As Exception
                MessageBox.Show(ex.Message)
                Button1.BackColor = Color.LightGray
            End Try
        End If
    End Sub

Private Sub Button6_Click(sender As Object, e As EventArgs)
    End
End Sub

```

```

Private Sub Button2_Click(sender As Object, e As EventArgs) Handles Button2.Click
    Try
        SerialPort1.DiscardInBuffer()
        SerialPort1.Close()
        Button1.BackColor = Color.LightGray
    Catch ex As Exception

    End Try
End Sub

Private Sub Button3_Click(sender As Object, e As EventArgs) Handles Button3.Click
    Timer1.Interval = Val(ComboBox2.Text)
    Timer1.Enabled = True
    Button3.BackColor = Color.Lime

    Chart1.Series("Temprature").Points.Clear()
    Chart1.ChartAreas("ChartArea1").AxisY.ScaleView.Size = 200
    Chart1.ChartAreas("ChartArea1").AxisX.Minimum = 0
    Chart1.ChartAreas("ChartArea1").AxisX.ScaleView.Size = 500

    plotx = 0
    ploty = 0

    Button8.Enabled = False

End Sub

Private Sub Timer1_Tick(sender As Object, e As EventArgs) Handles Timer1.Tick
    Try
        SerialPort1.Write("?")
    Catch ex As Exception
        Timer1.Enabled = False
        Button1.BackColor = Color.LightGray
        MessageBox.Show(ex.Message)
    End Try
End Sub

Private Sub Button4_Click(sender As Object, e As EventArgs) Handles Button4.Click
    Timer1.Enabled = False
    Button3.BackColor = Color.LightGray
    Button8.Enabled = True
End Sub

Private Sub Button8_Click(sender As Object, e As EventArgs) Handles Button8.Click
    Chart1.Series("Temprature").Points.Clear()
    Chart1.ChartAreas("ChartArea1").AxisY.ScaleView.Size = 5
    Chart1.ChartAreas("ChartArea1").AxisX.Minimum = 0
    Chart1.ChartAreas("ChartArea1").AxisX.ScaleView.Size = 300
End Sub

Private Sub Form1_Load(sender As Object, e As EventArgs) Handles MyBase.Load

```

```

        Button10.PerformClick()
    End Sub

    Private Sub Button9_Click(sender As Object, e As EventArgs) Handles
        Button9.Click
            Try
                Dim x As Integer = Val(input_sp.Text)
                Dim y As Integer = Val(input_time.Text)

                sp_array(index) = x
                time_array(index) = y

                If x = 0 Or y = 0 Then
                Else
                    index = index + 1

                    Dim txt As String = Str(index) +
                        Microsoft.VisualBasic.ControlChars.Tab + Str(x) +
                        Microsoft.VisualBasic.ControlChars.Tab + Str(y)

                    setpoint_list.Items.Add(txt)
                End If

                Catch ex As Exception
                    MessageBox.Show(ex.Message)
                End Try

            End Sub

    Private Sub Button10_Click(sender As Object, e As EventArgs) Handles
        Button10.Click
            index = 0
            While index < 100
                sp_array(index) = 0
                time_array(index) = 0
                index = index + 1
            End While

            index = 0
            setpoint_list.Items.Clear()

        End Sub

    Private Sub Button12_Click(sender As Object, e As EventArgs) Handles
        temp_mode.Click
            If (temp_mode.BackColor = Color.LightGray) Then
                temp_mode.BackColor = Color.Lime
                force_mode.BackColor = Color.LightGray
            Else
                temp_mode.BackColor = Color.LightGray
            End If
        End Sub

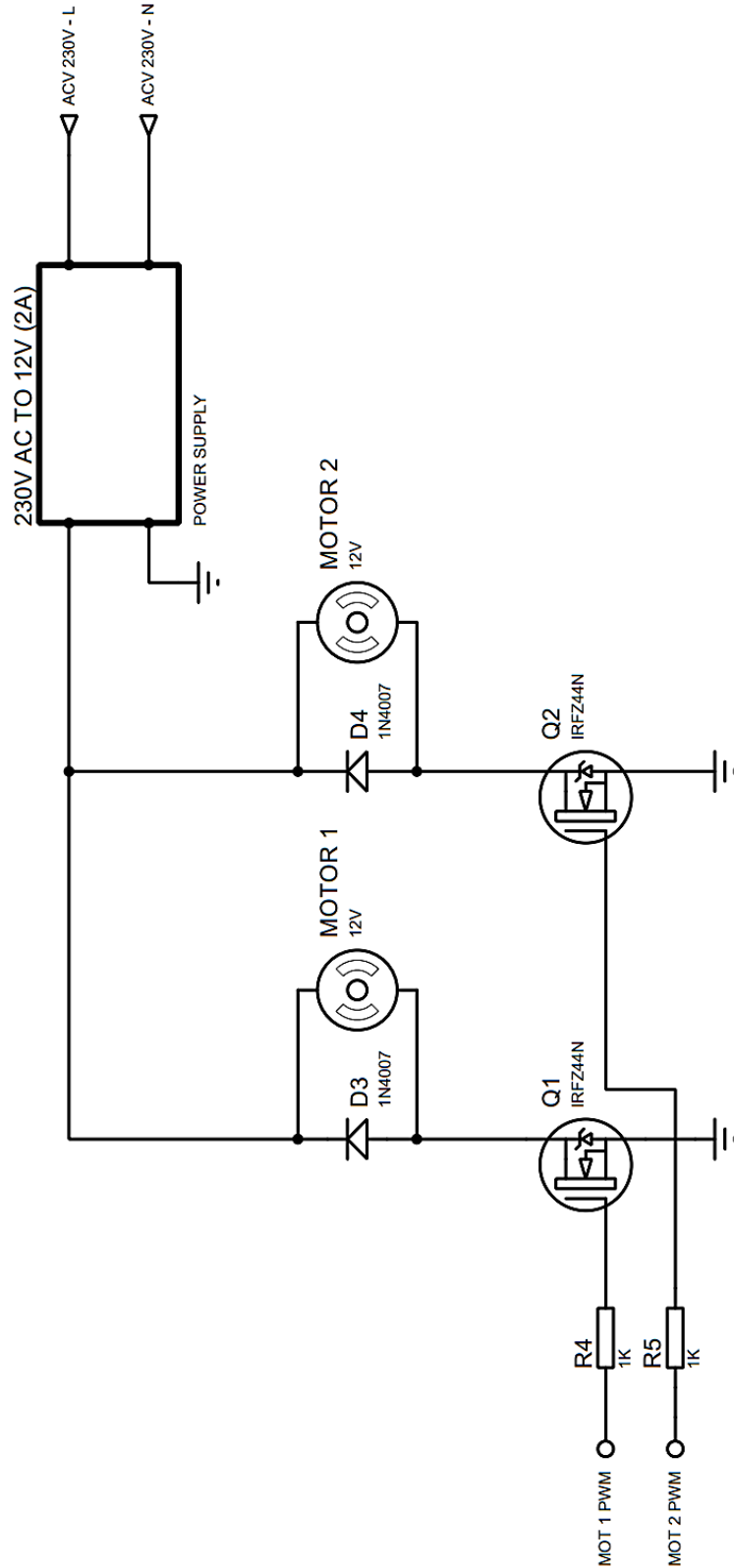
    Private Sub force_mode_Click(sender As Object, e As EventArgs) Handles
        force_mode.Click

```

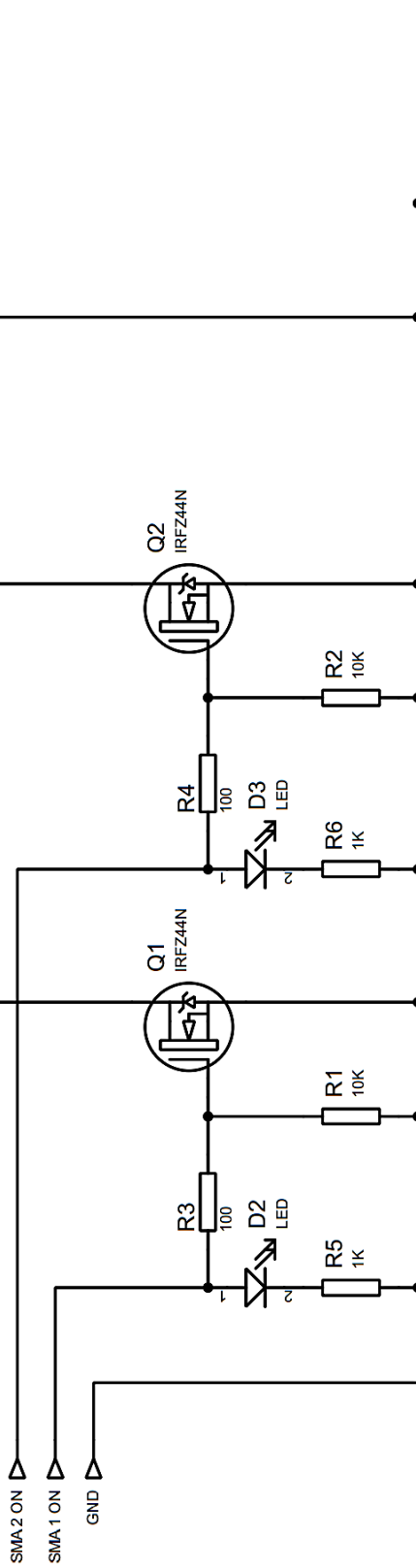
```
    If (force_mode.BackColor = Color.LightGray) Then
        temp_mode.BackColor = Color.LightGray
        force_mode.BackColor = Color.Lime
    Else
        force_mode.BackColor = Color.LightGray
    End If
End Sub

End Class
```

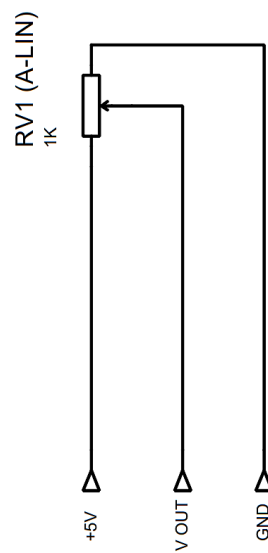

**Appendix M9: Schematic Diagram of the Multi-Function Controller –
Pump Motor Driver**



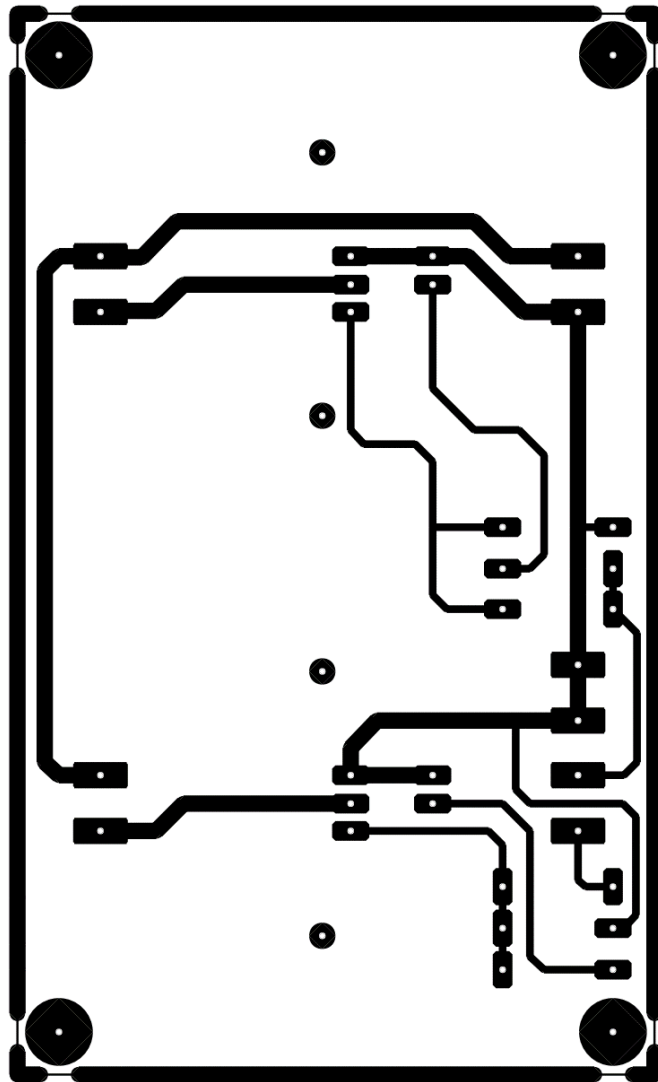
Based SMA Heating Element Driving Circuit



Appendix N2: Schematic Diagram of the Current Controller – Potentiometer Based Linear Position Sensing System



Appendix N3: PCB Layout of the Current Controller



Appendix O1: Hardware Specifications of Intelligent Digital Multimeter (Device – TENMA 72 - 7730A)

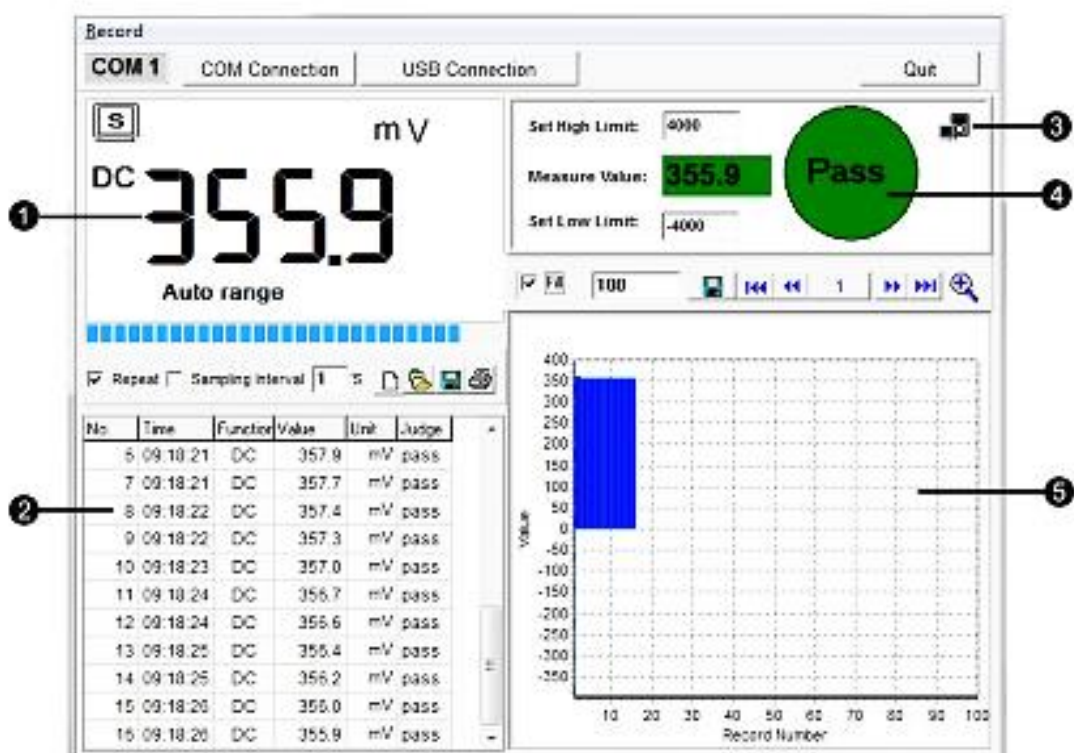


Basic Specifications

Function	Ranges / Description
DC Voltage	0 to 1000V
AC Voltage, True RMS	0 to 1000V, 100kHz bandwidth
Basic Accuracy	DC Voltage: 72-7730A/72-7732A: 0.05% AC Voltage: 72-7730A/72-7732A: 0.6%
DC Current	0 to 10A (5~10A for ≤ 10 seconds, interval ≥ 15 minutes)
AC Current, True RMS	0 to 10A (5~10A for ≤ 10 seconds, interval ≥ 15 minutes)
Resistance	0 to 40M Ω
Capacitance	0 to 40mF
Frequency	0~400MHz
Temperature	-40°C~1000°C (-40°F~1832°F)
STORE Readings	Up to 100 readings or 9999 reading for 72-7732A may be saved by the user in a memory. These readings may be viewed by using Recall feature.

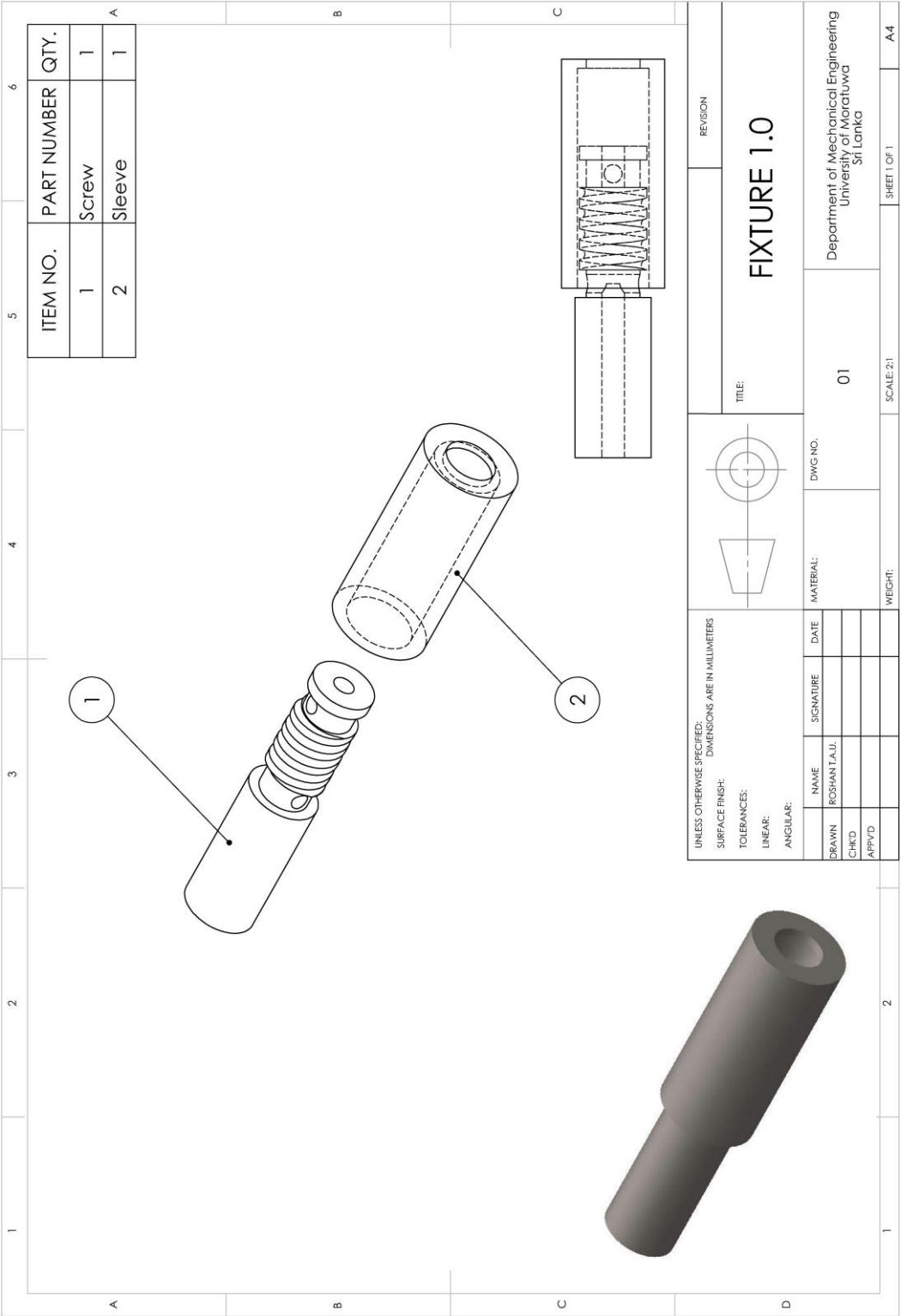
Appendix O2: Software Specifications of Intelligent Digital Multimeter (Device – TENMA 72 - 7730A)

Main Screen

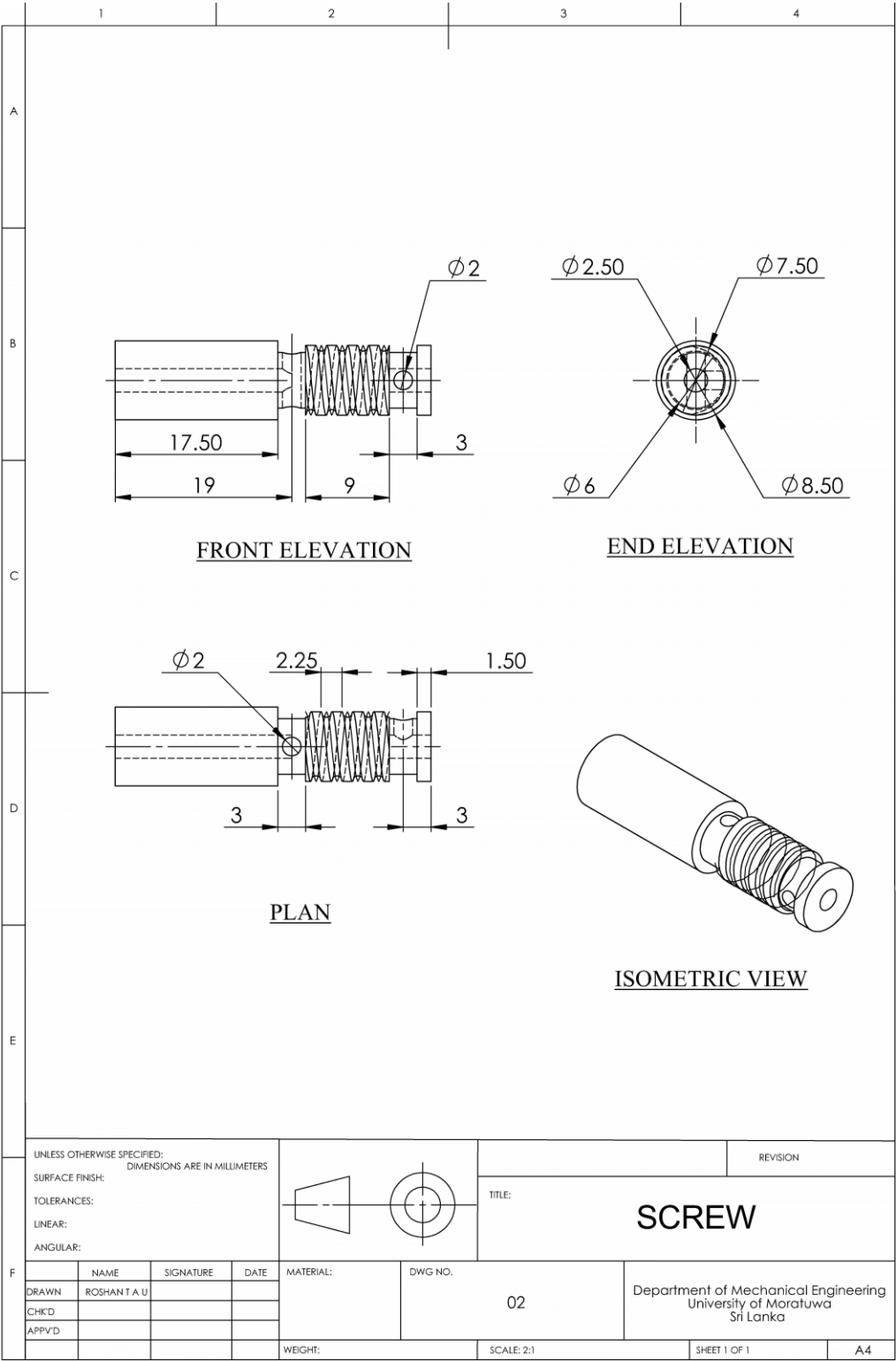


- ① Main display screen of measurement
- ② Secondary display screen for measurement
- ③  Blinking indicator: meter is connected to the software
- ④ Data Comparison
- ⑤ Measurement data in graph

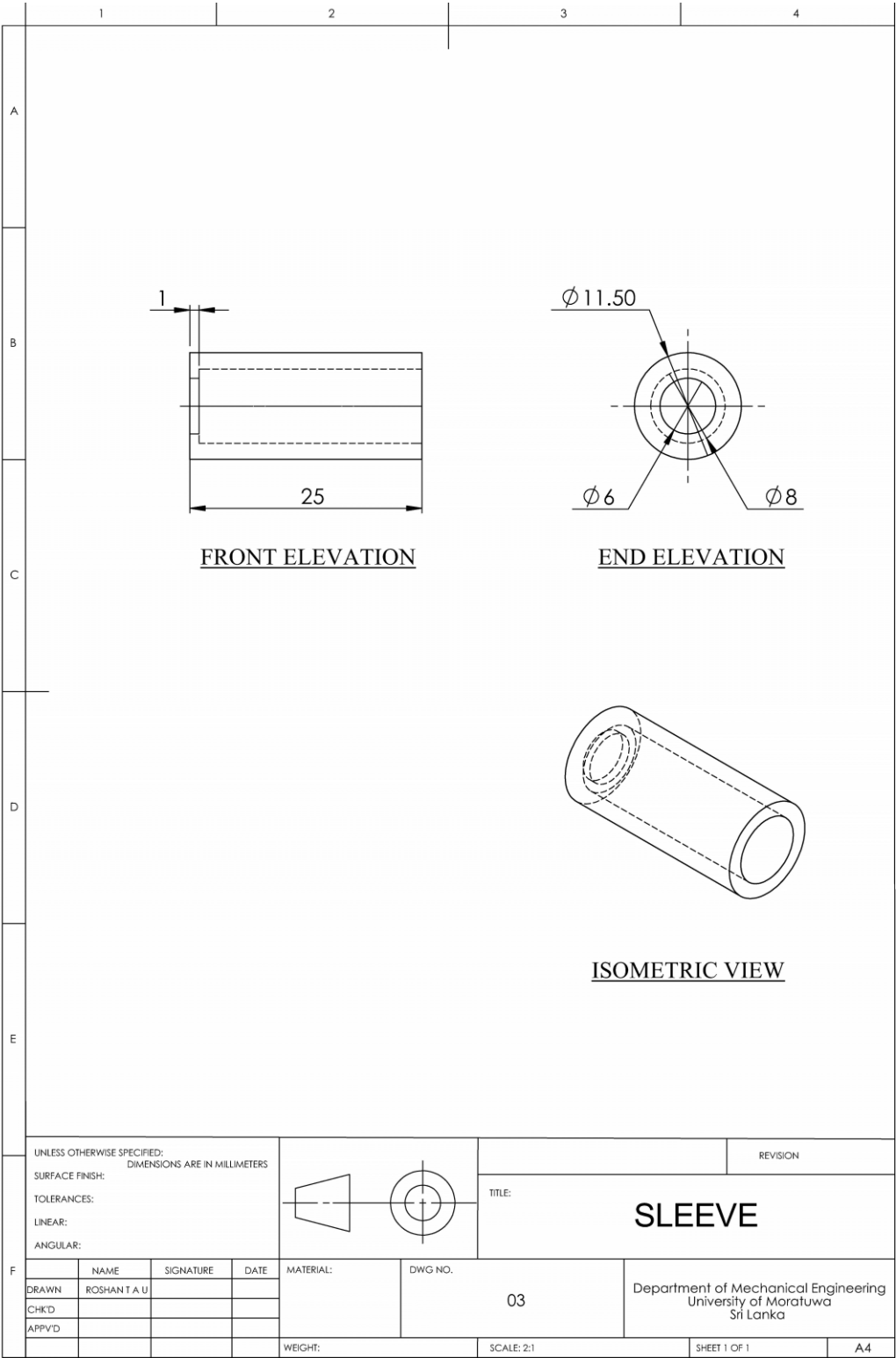
Appendix P1: Fixture 1.0



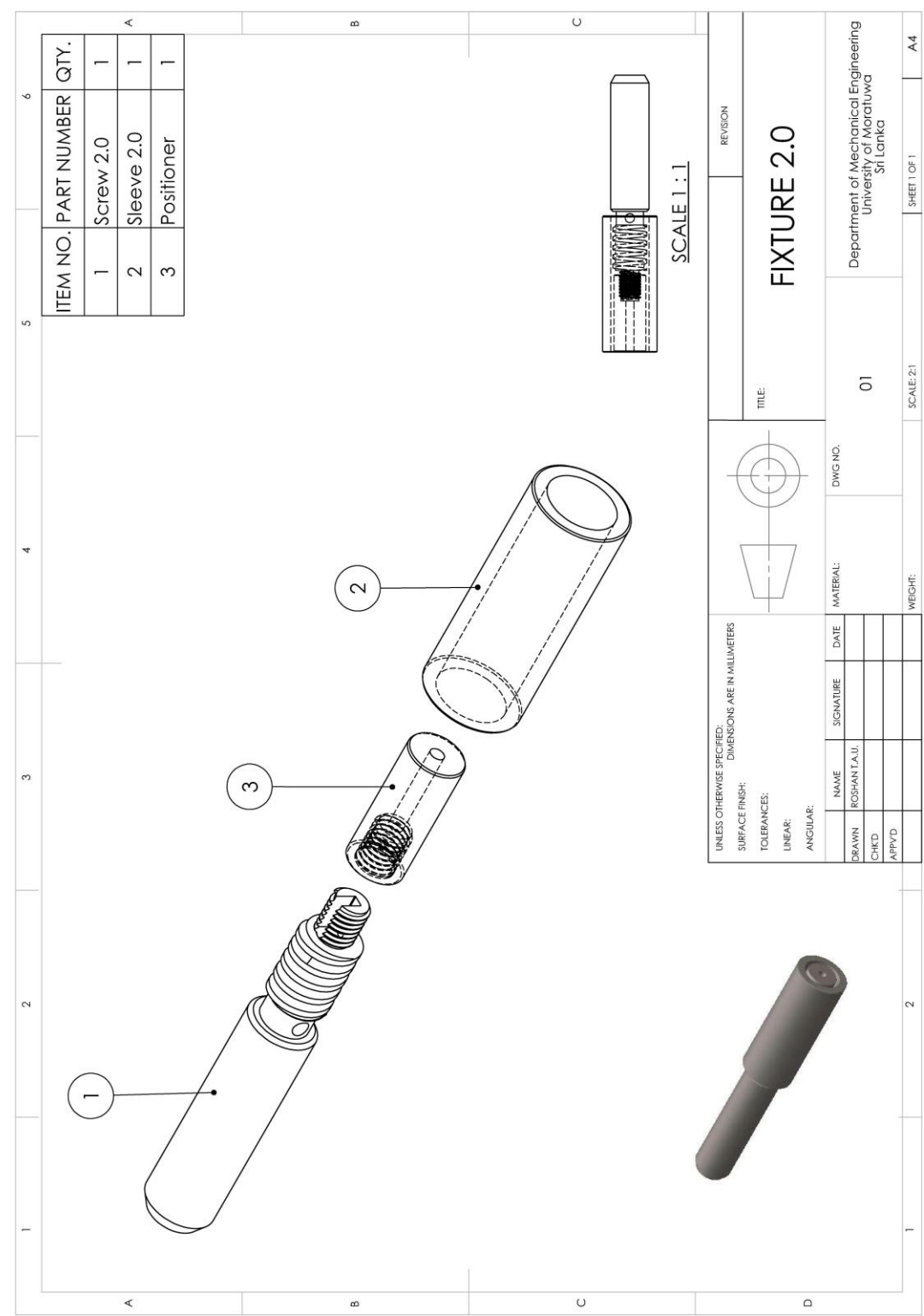
Appendix P2: Screw 1.0



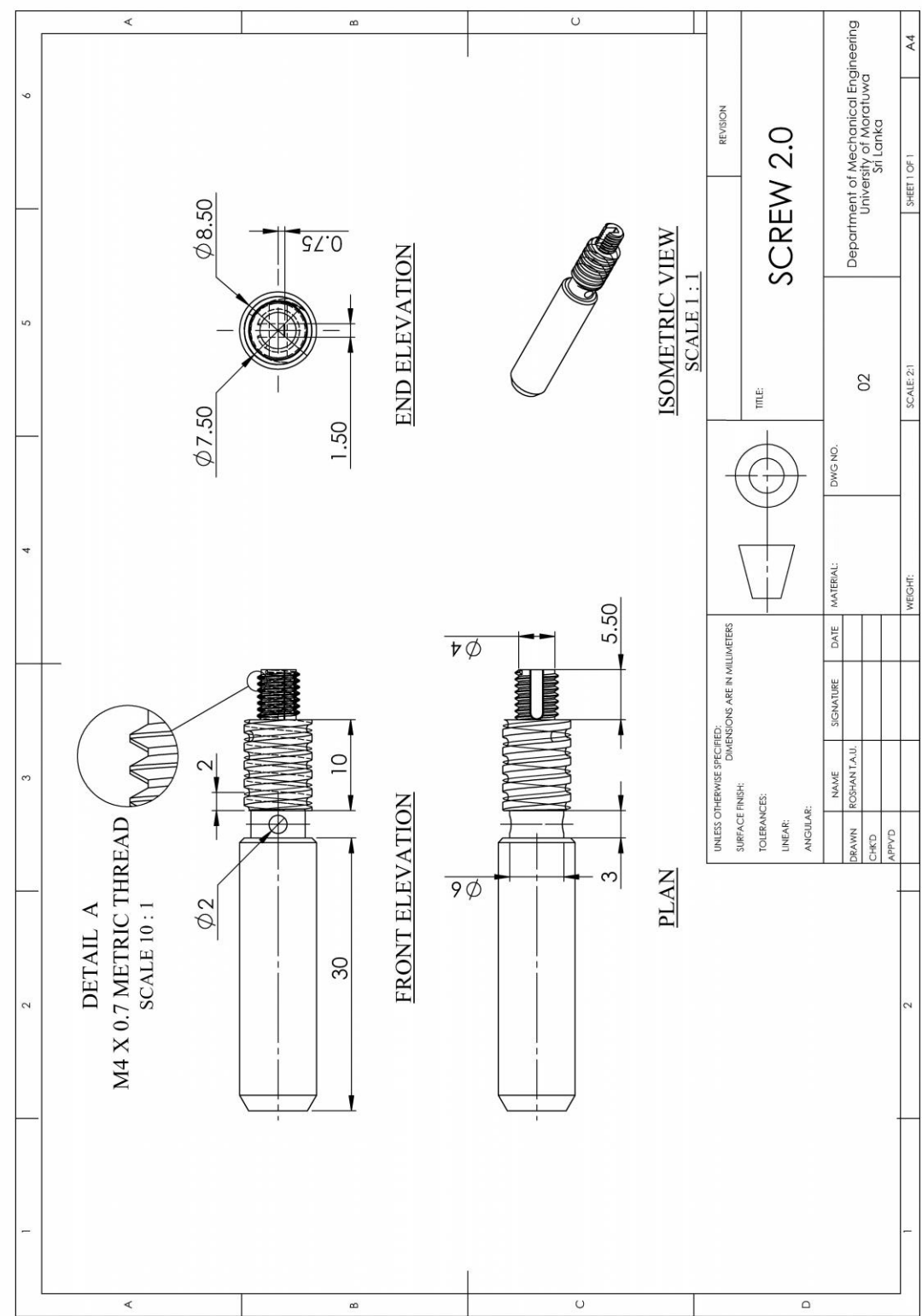
Appendix P3: Sleeve 1.0



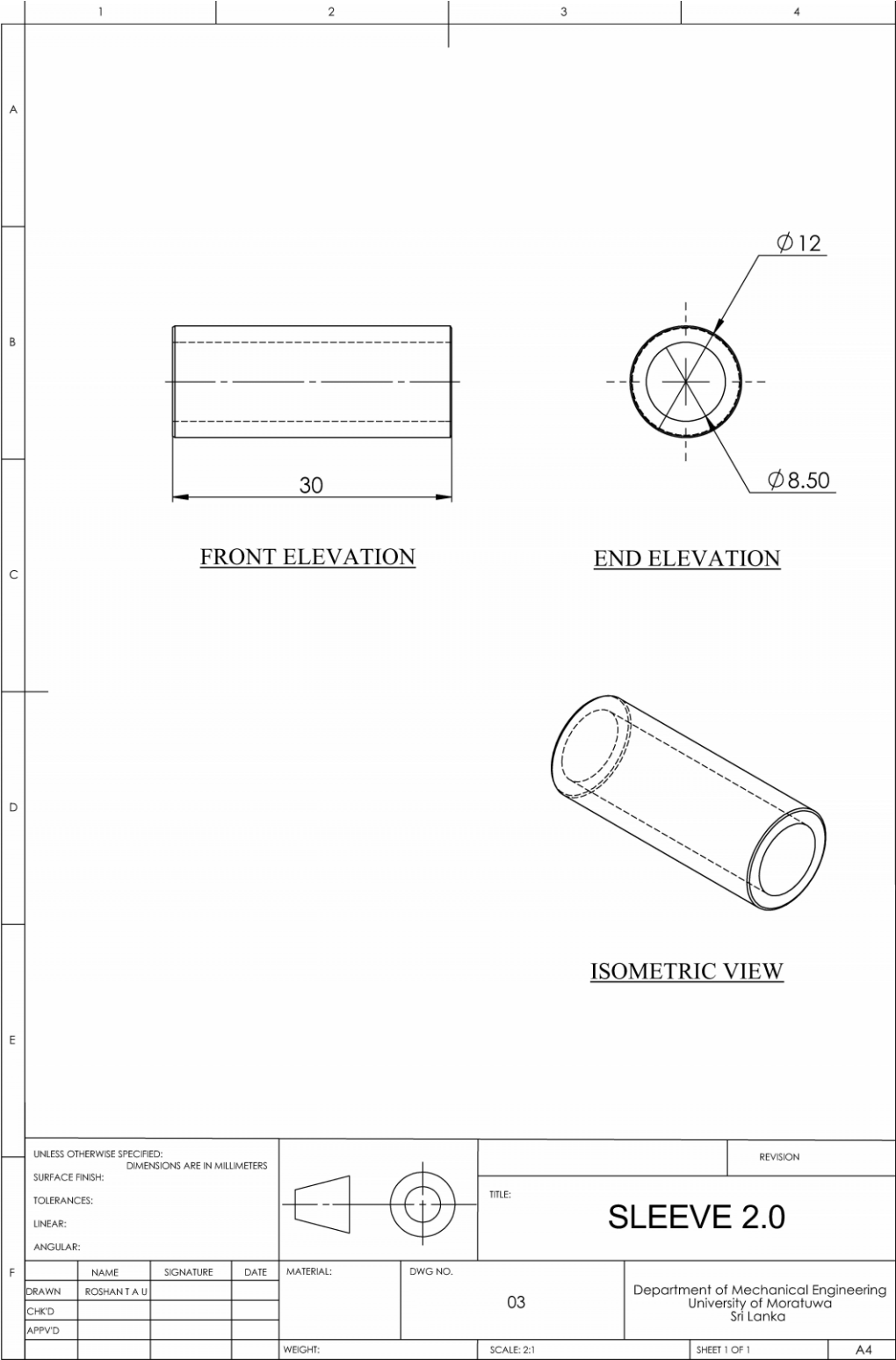
Appendix P4: Fixture 2.0



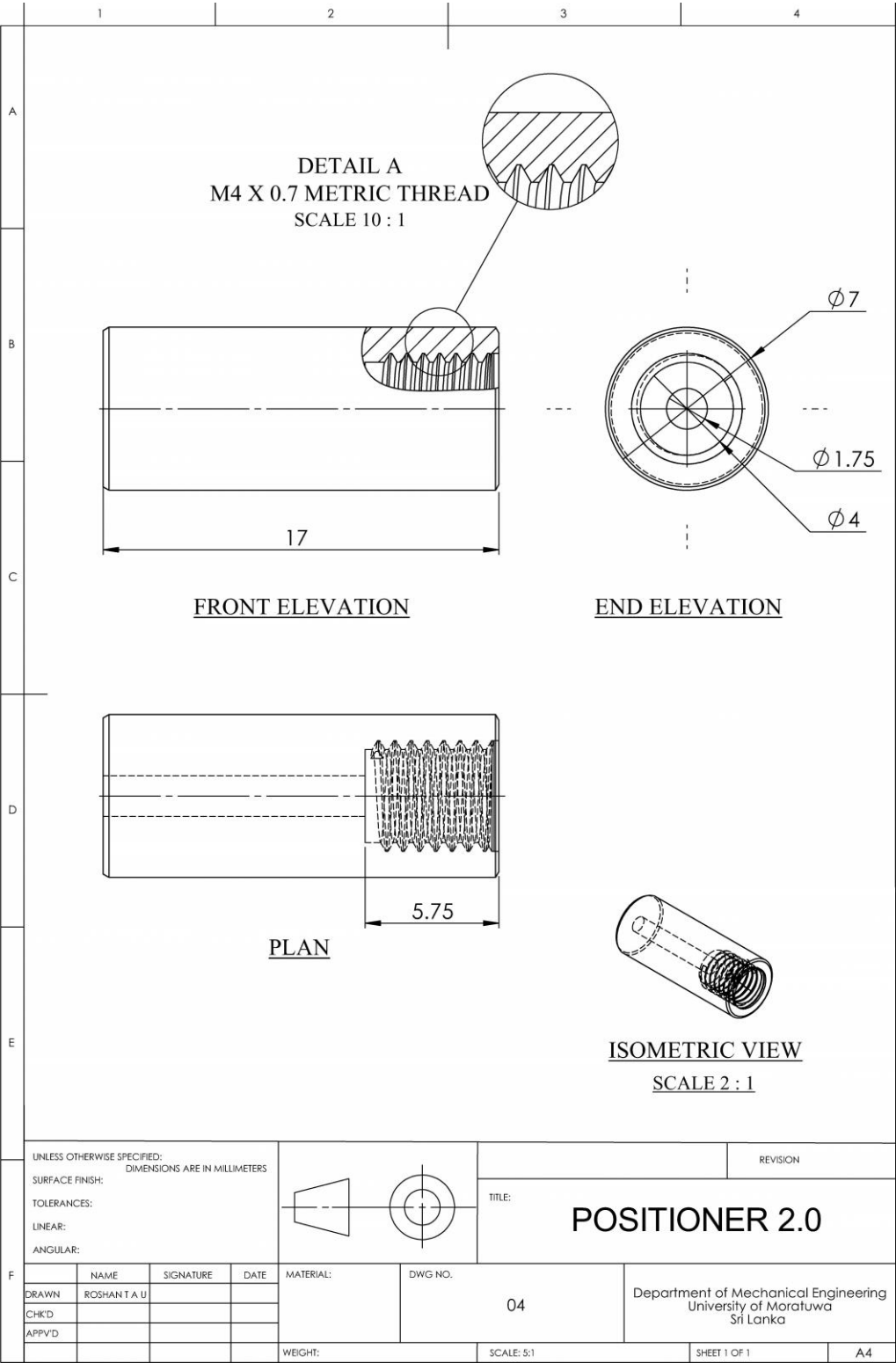
Appendix P5: Screw 2.0



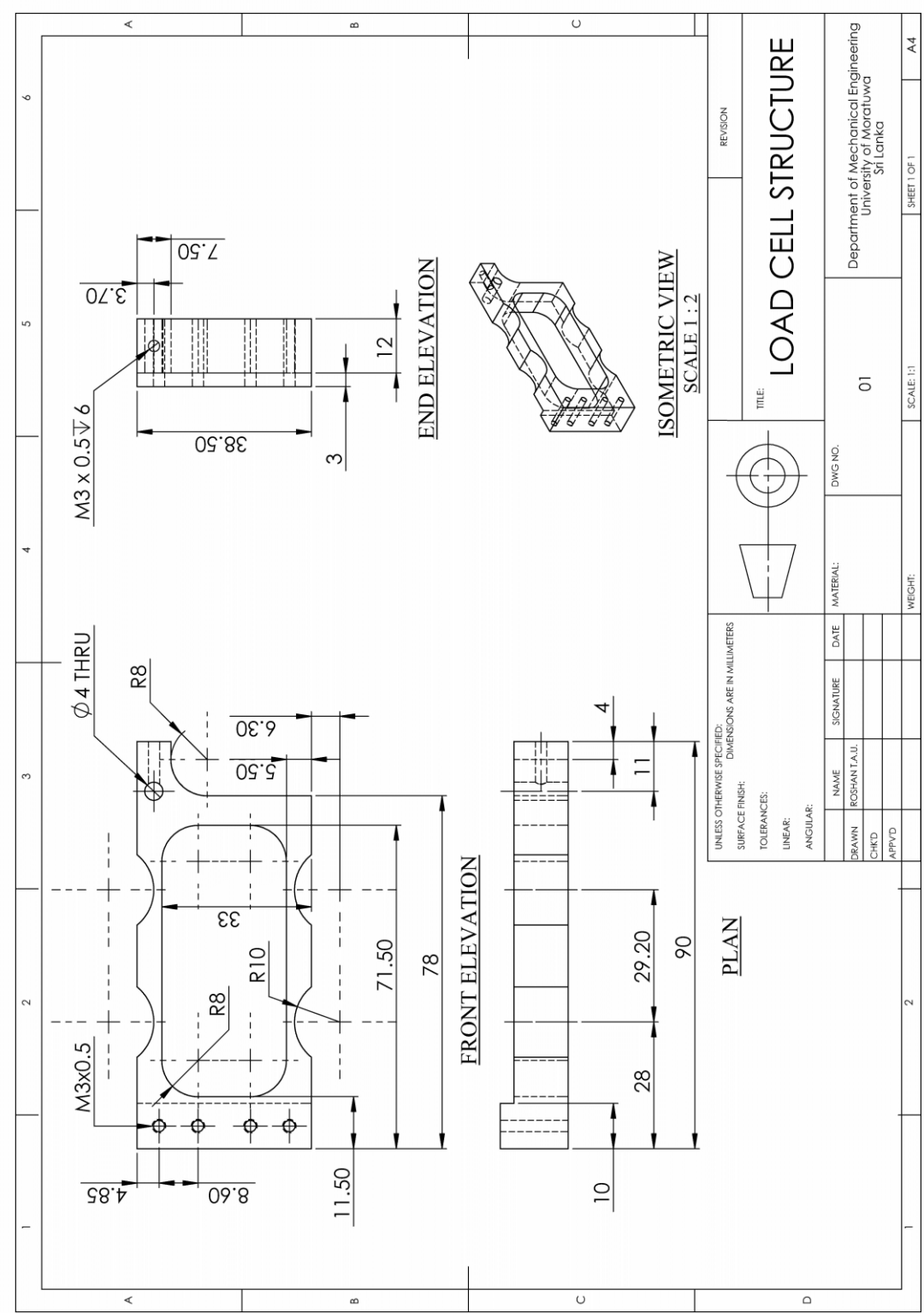
Appendix P6: Sleeve 2.0



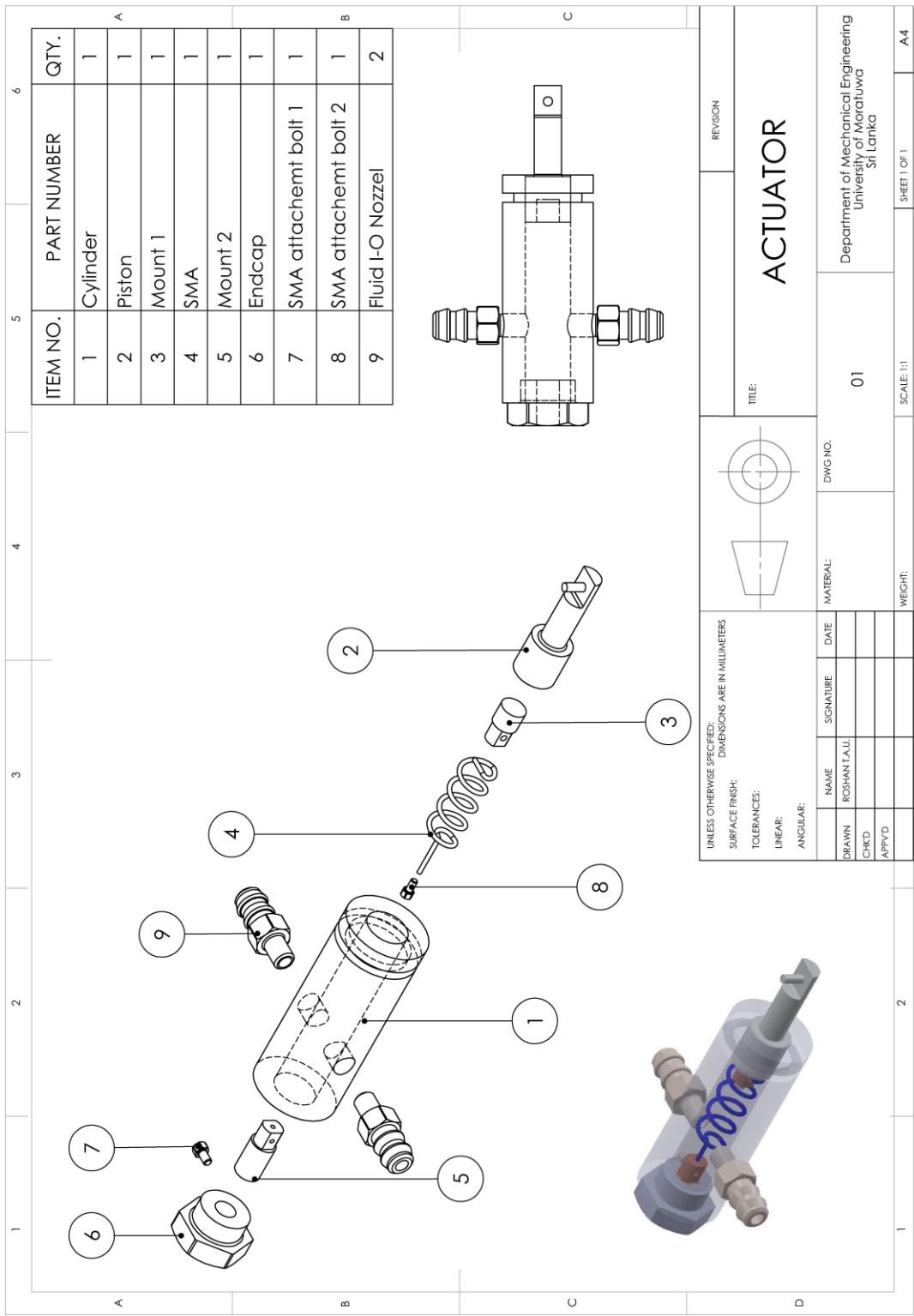
Appendix P7: Positioner 2.0



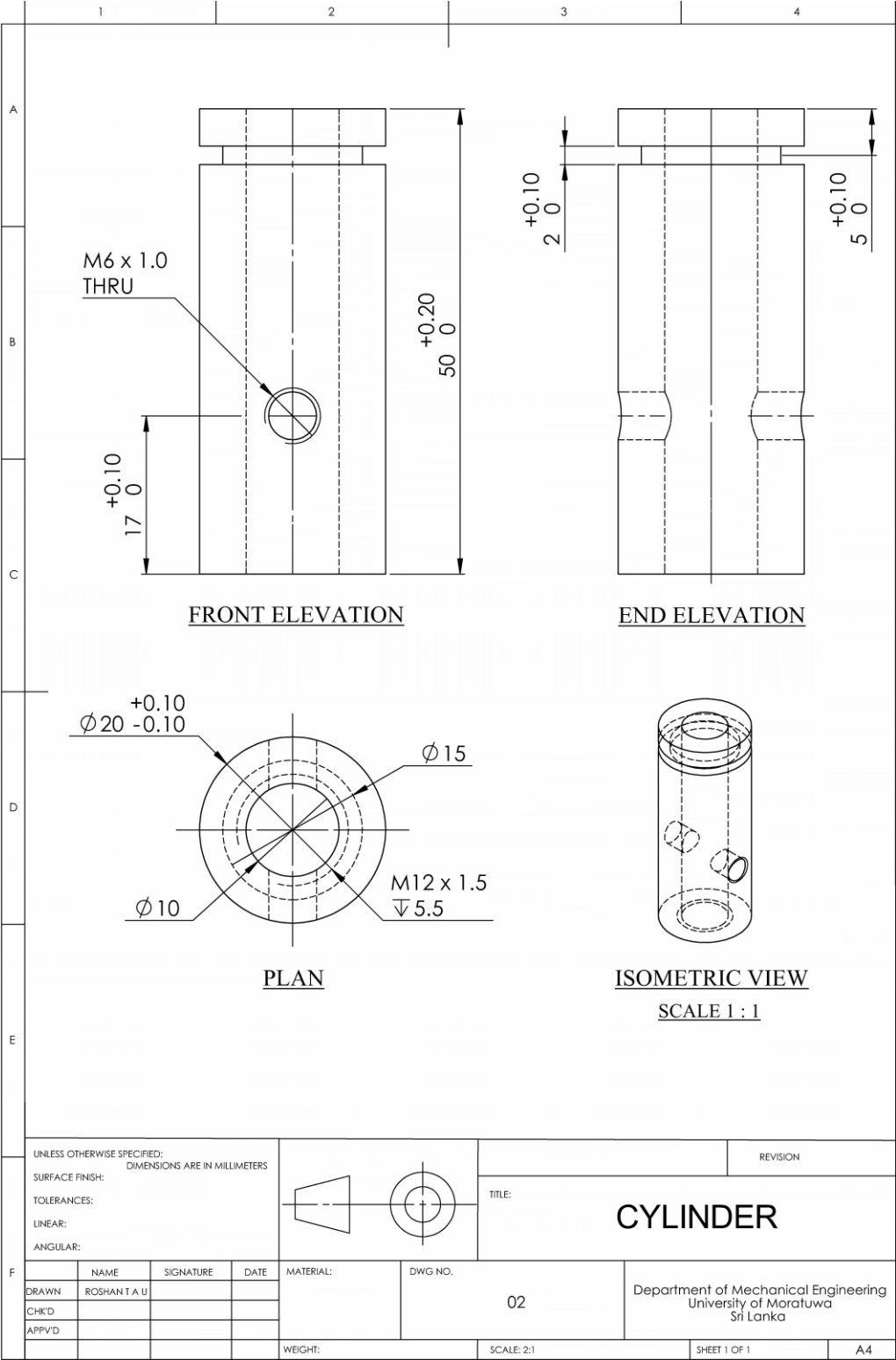
Appendix Q1: Load Cell Structure



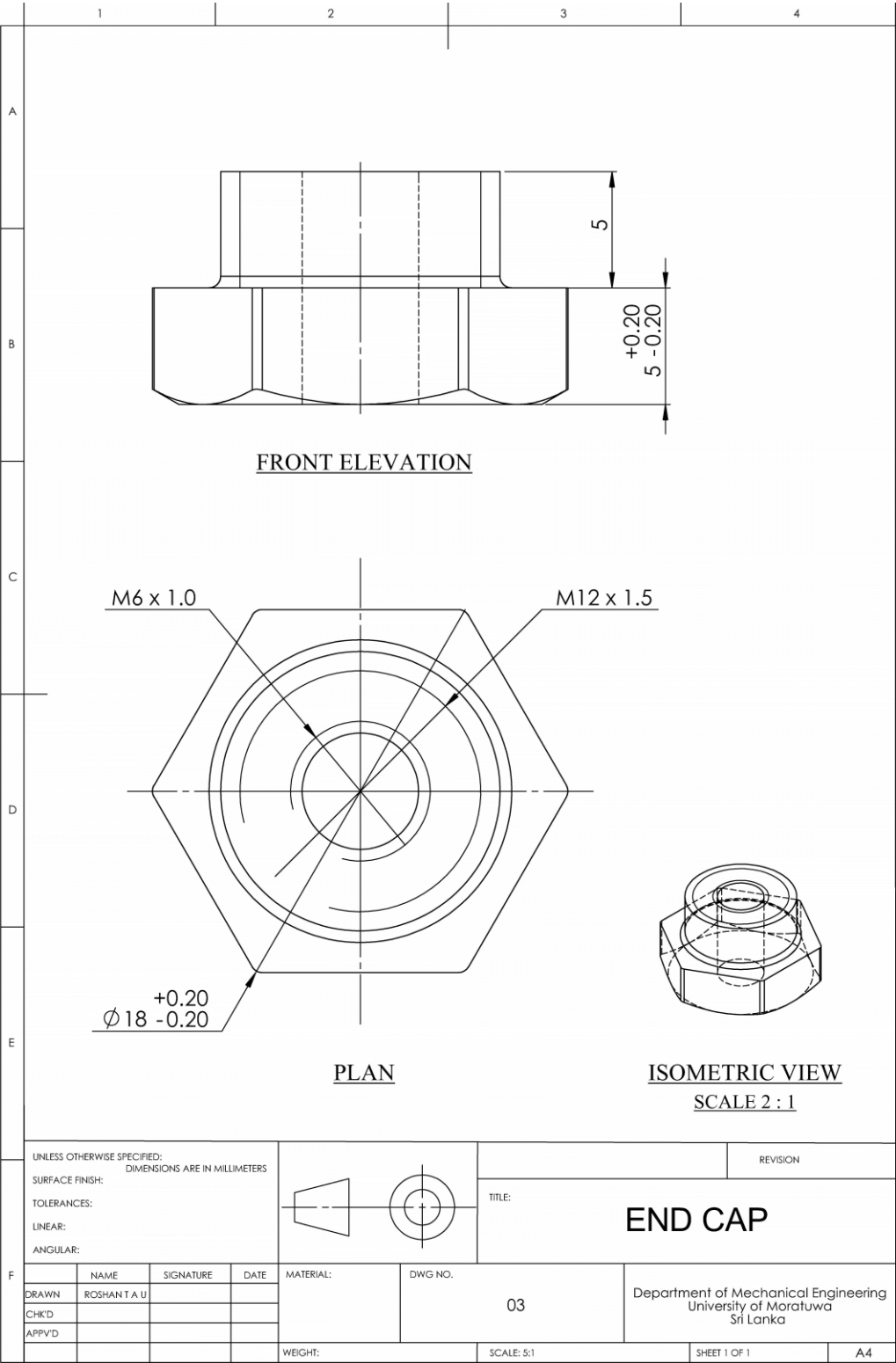
Appendix R1: Actuator 1.0



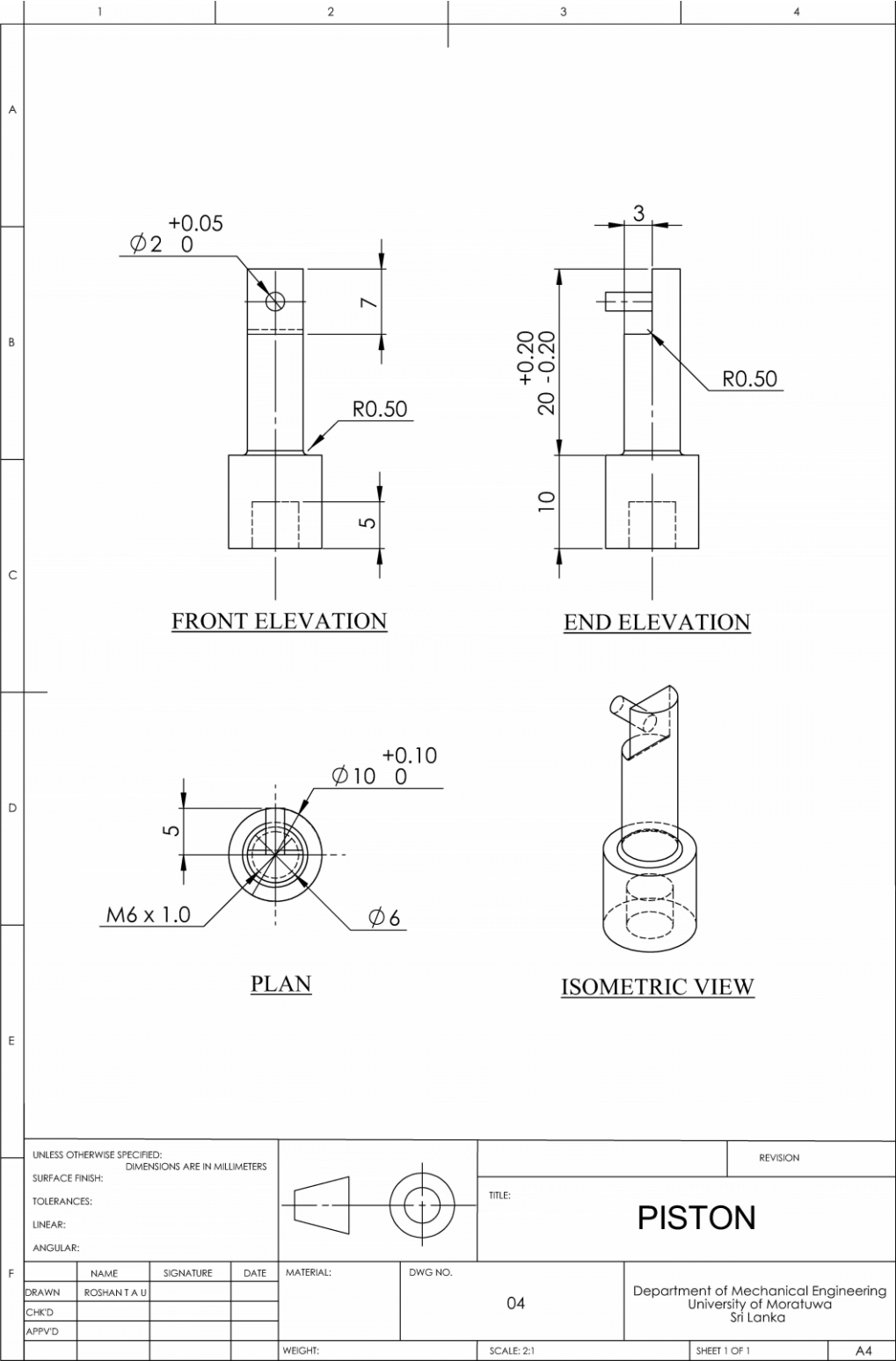
Appendix R2: Cylinder



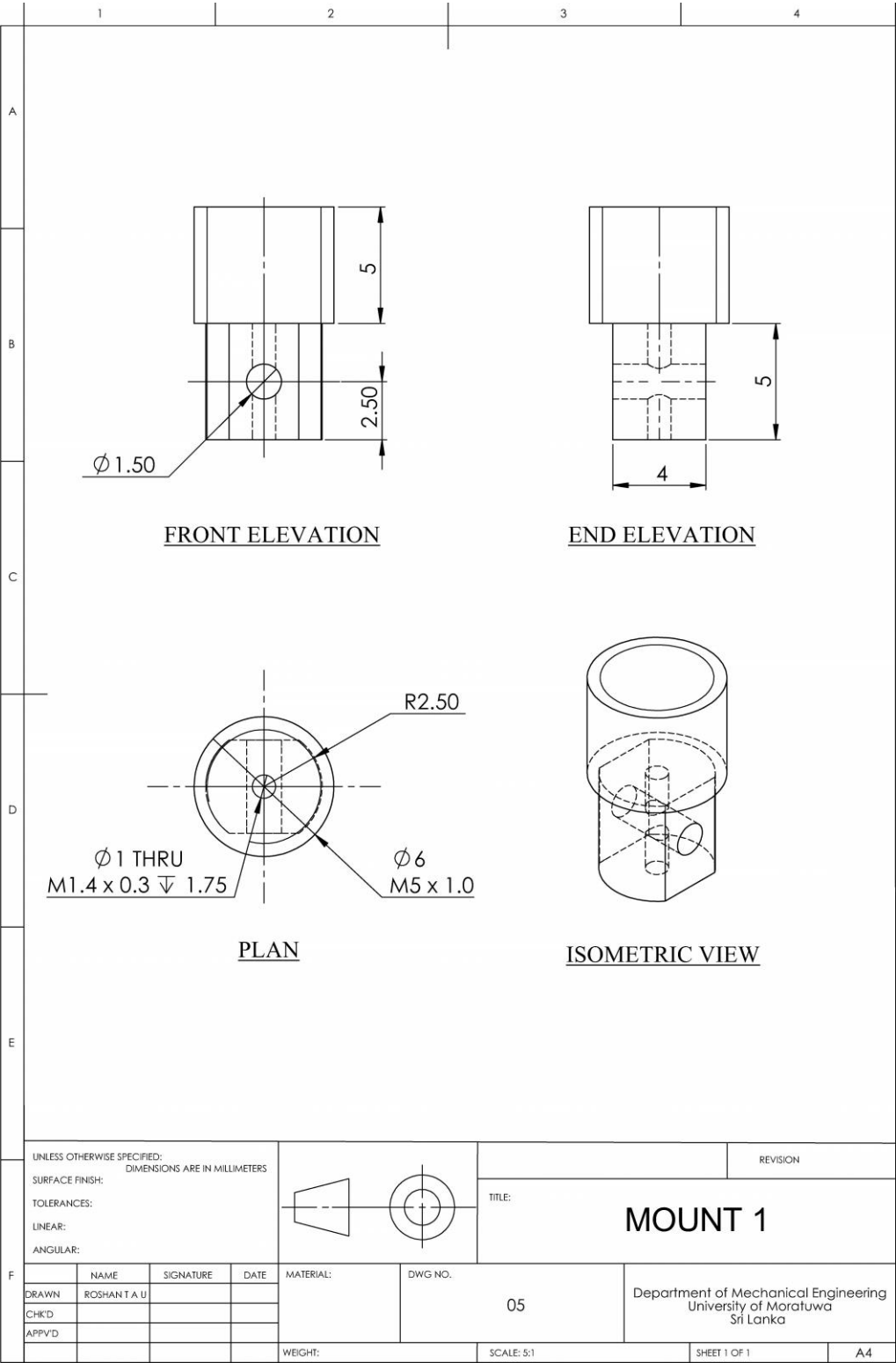
Appendix R3: End Nut



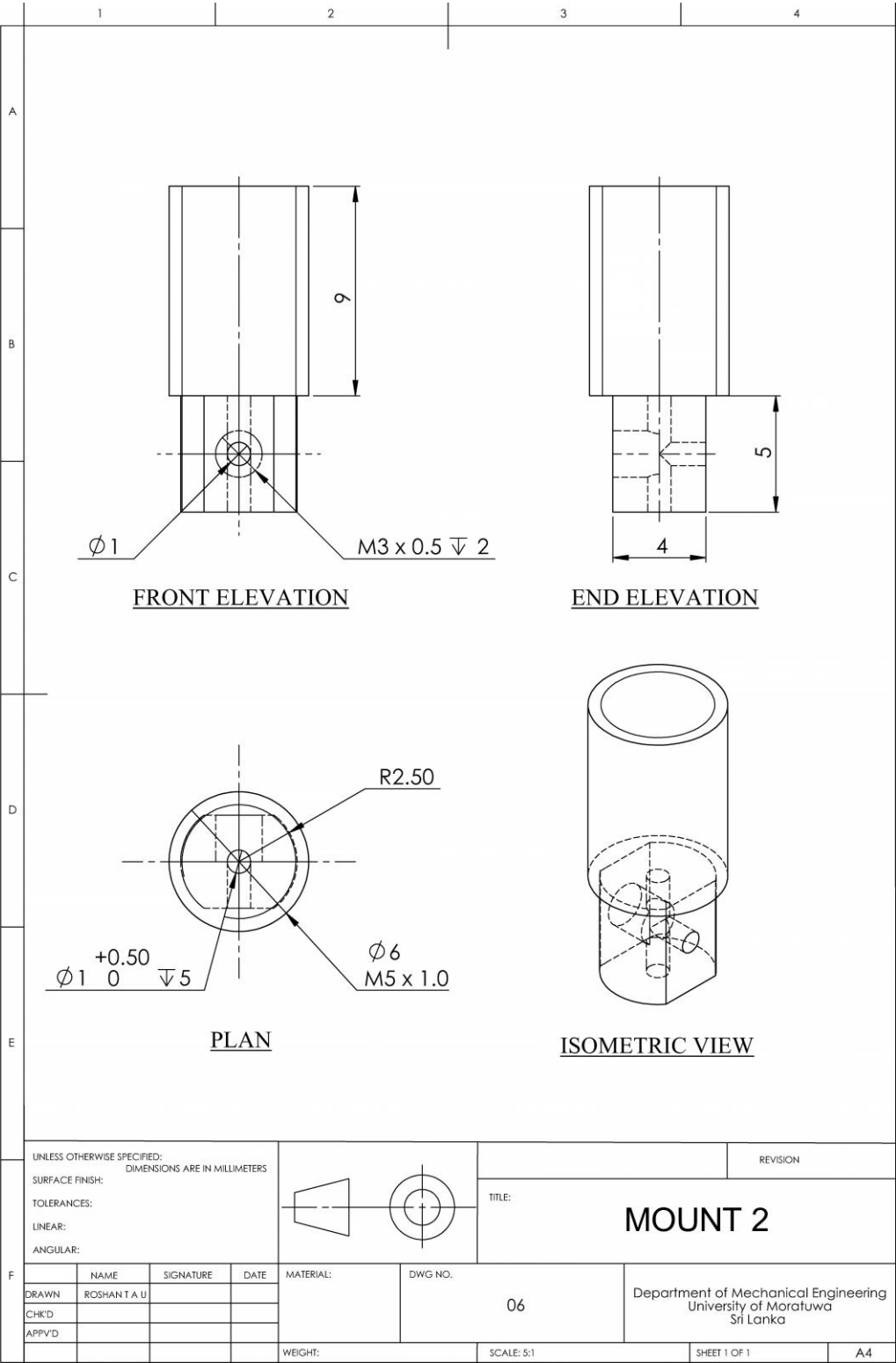
Appendix R4: Piston



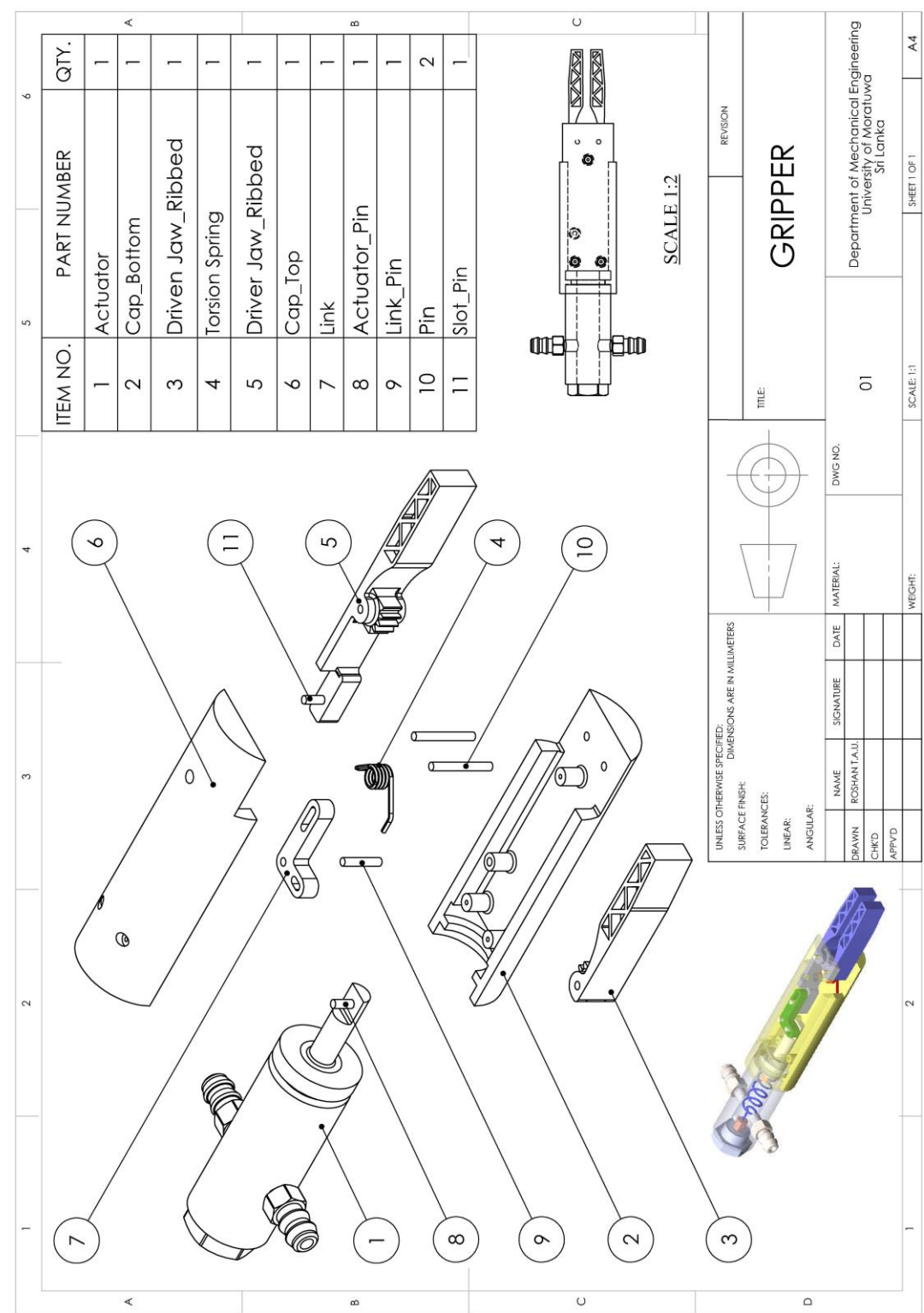
Appendix R5: Mount 1



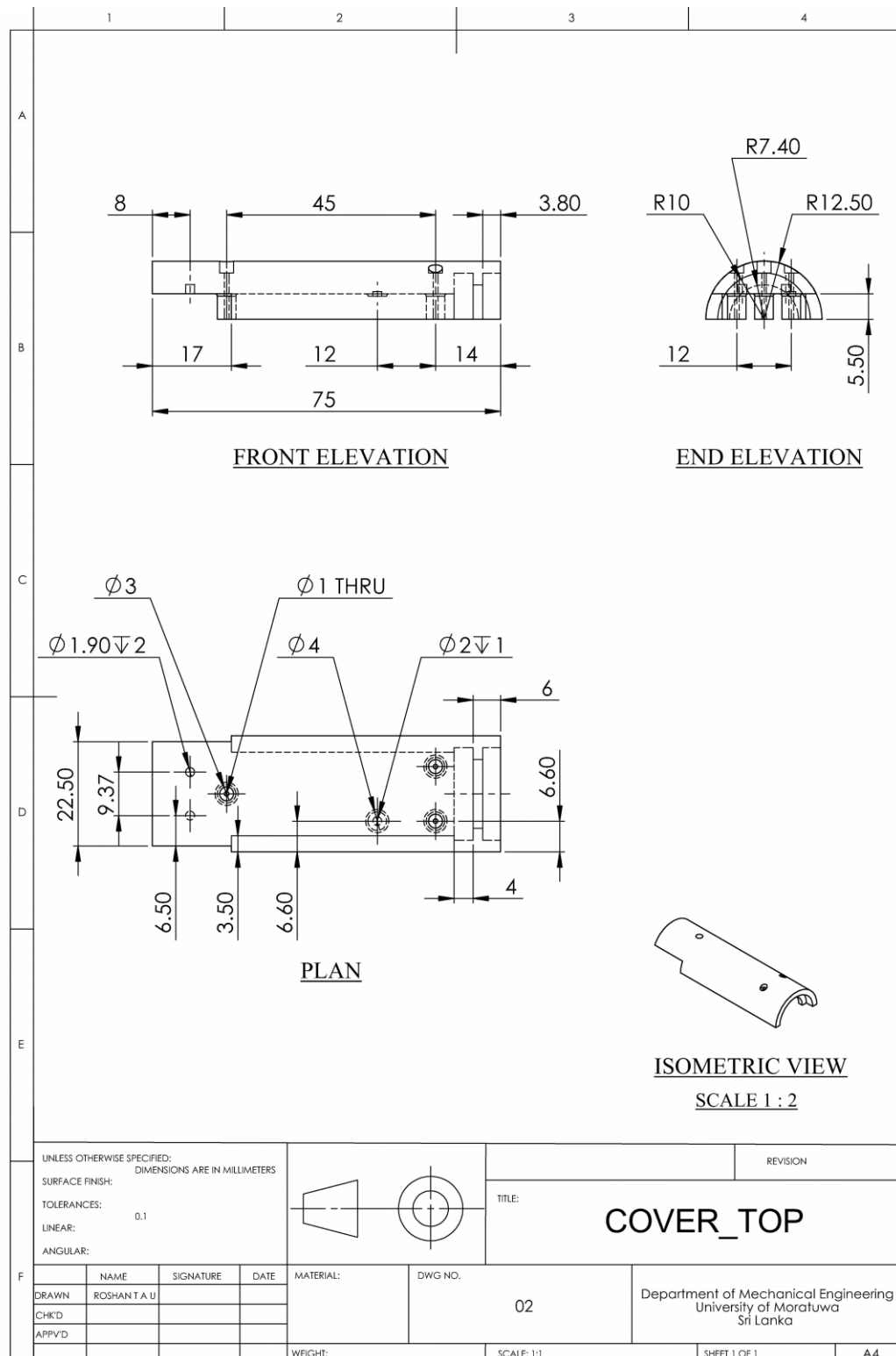
Appendix R6: Mount 2



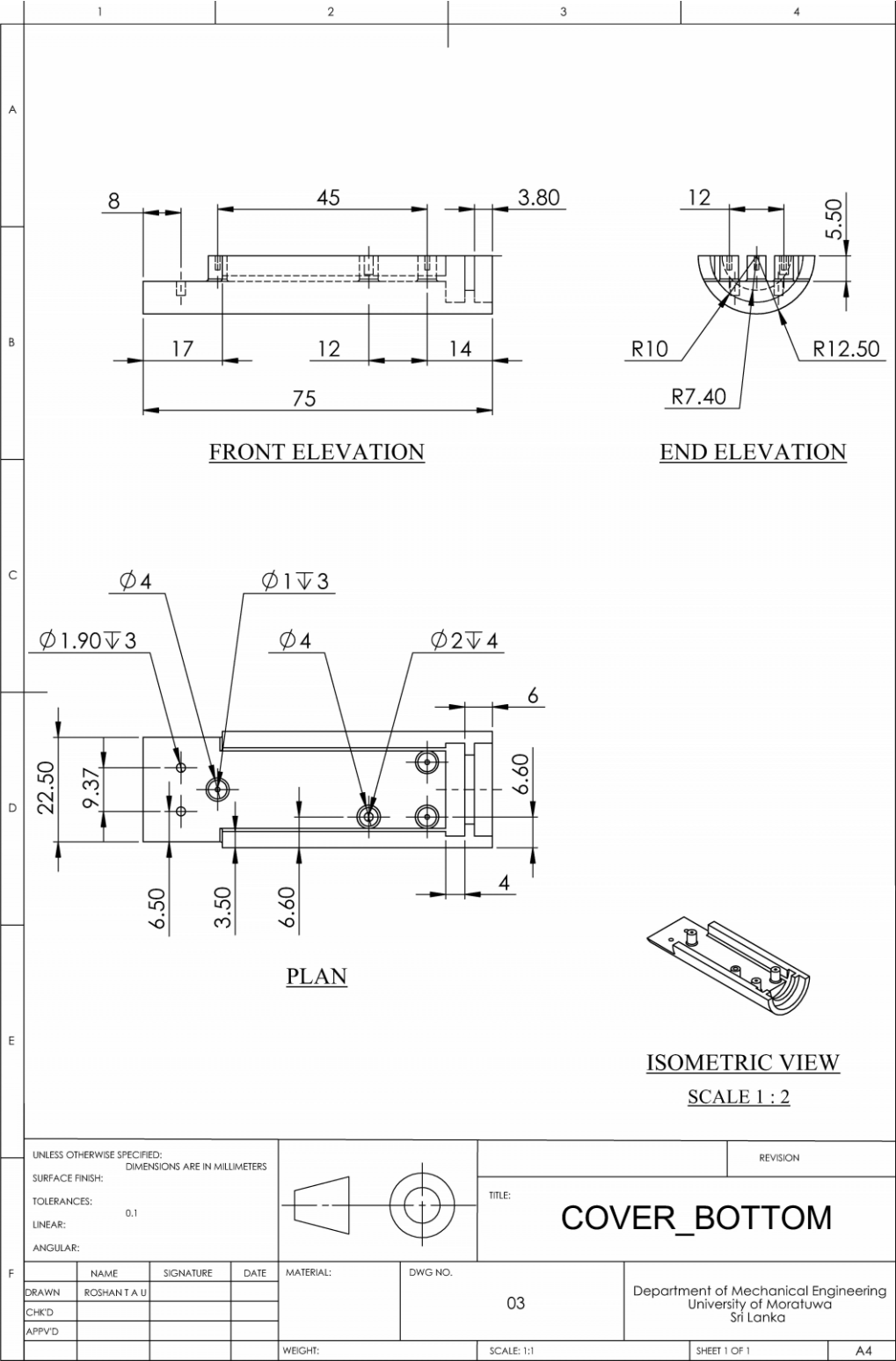
Appendix S1: Gripper



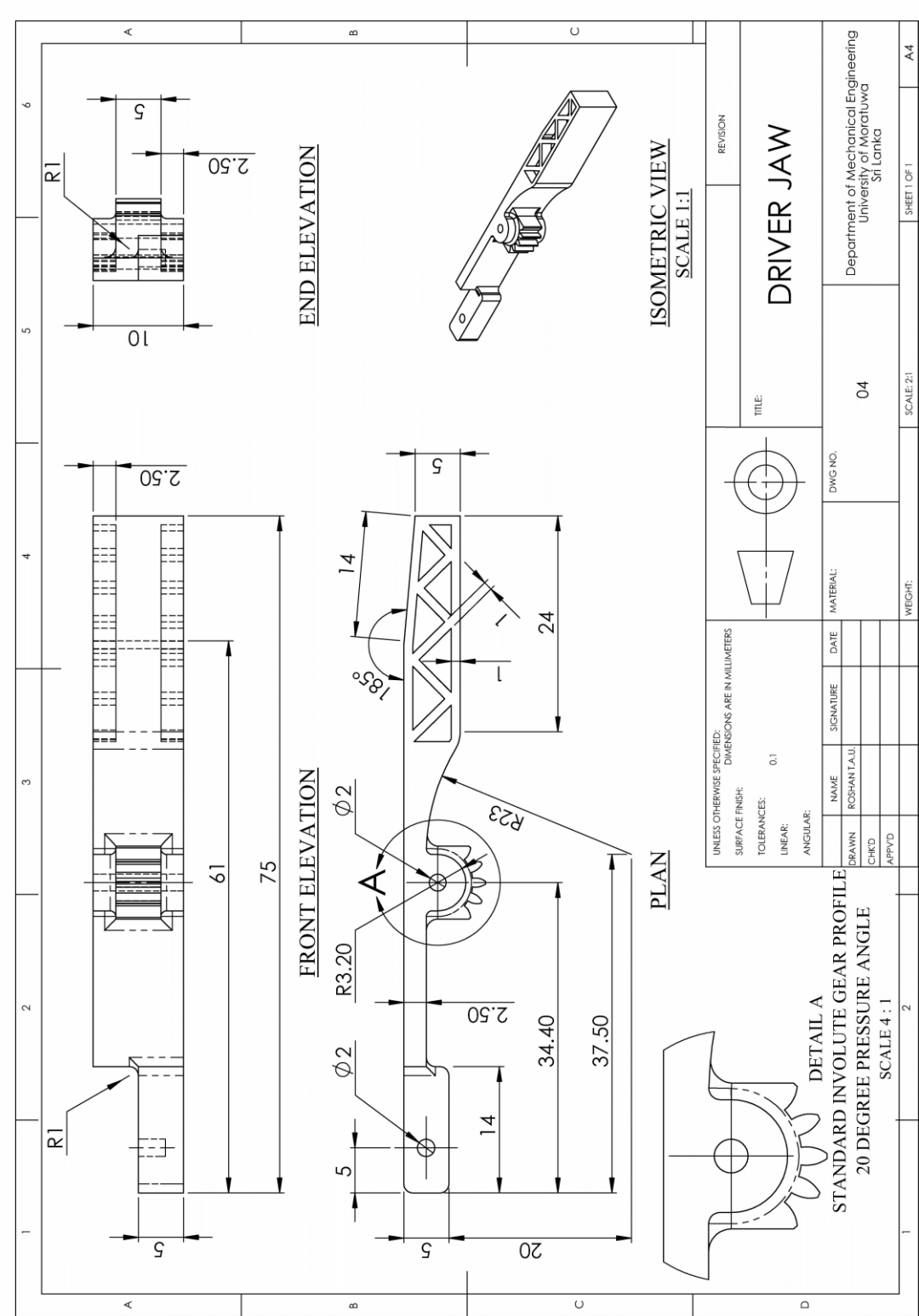
Appendix S2: Top Cover



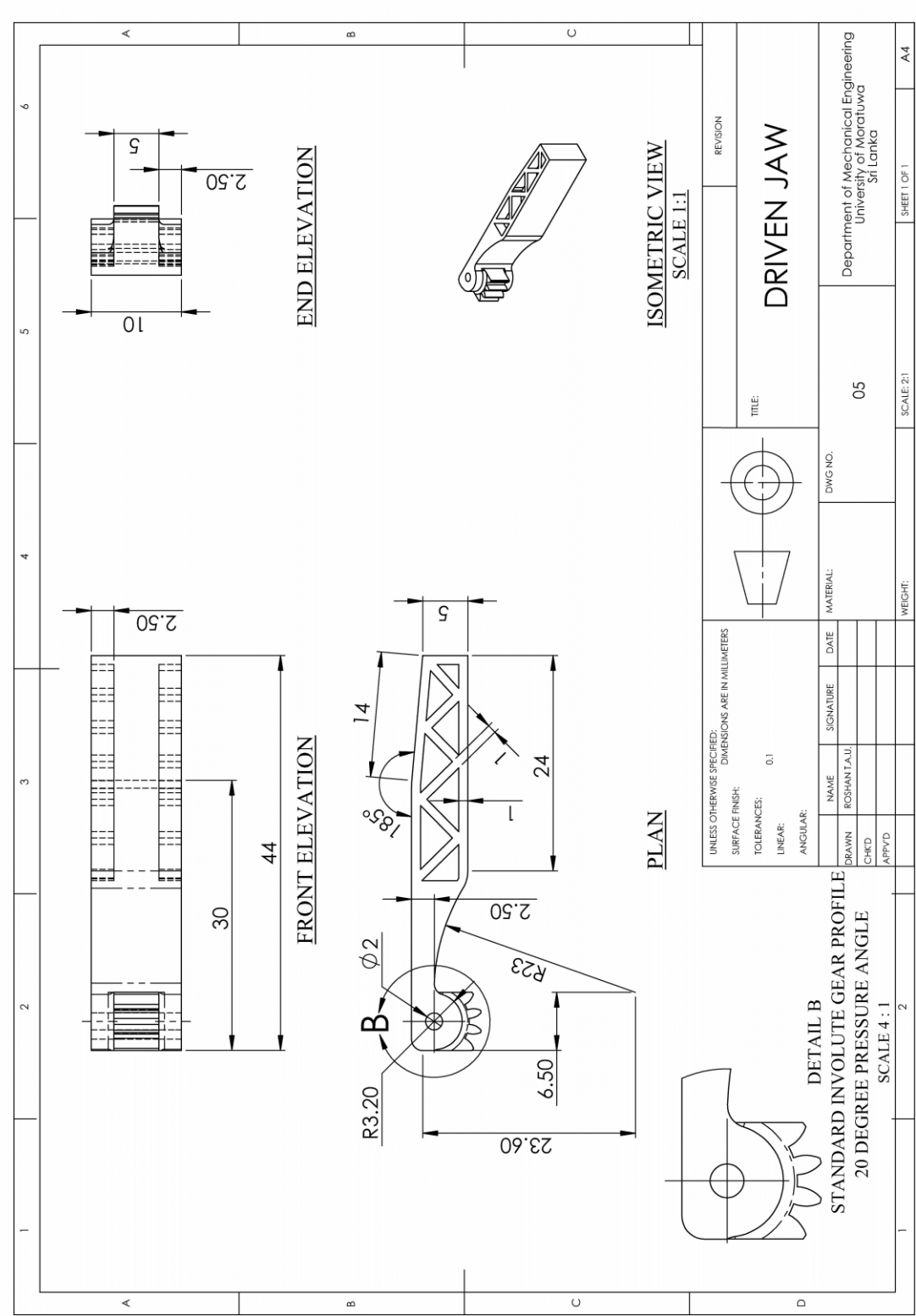
Appendix S3: Bottom Cover



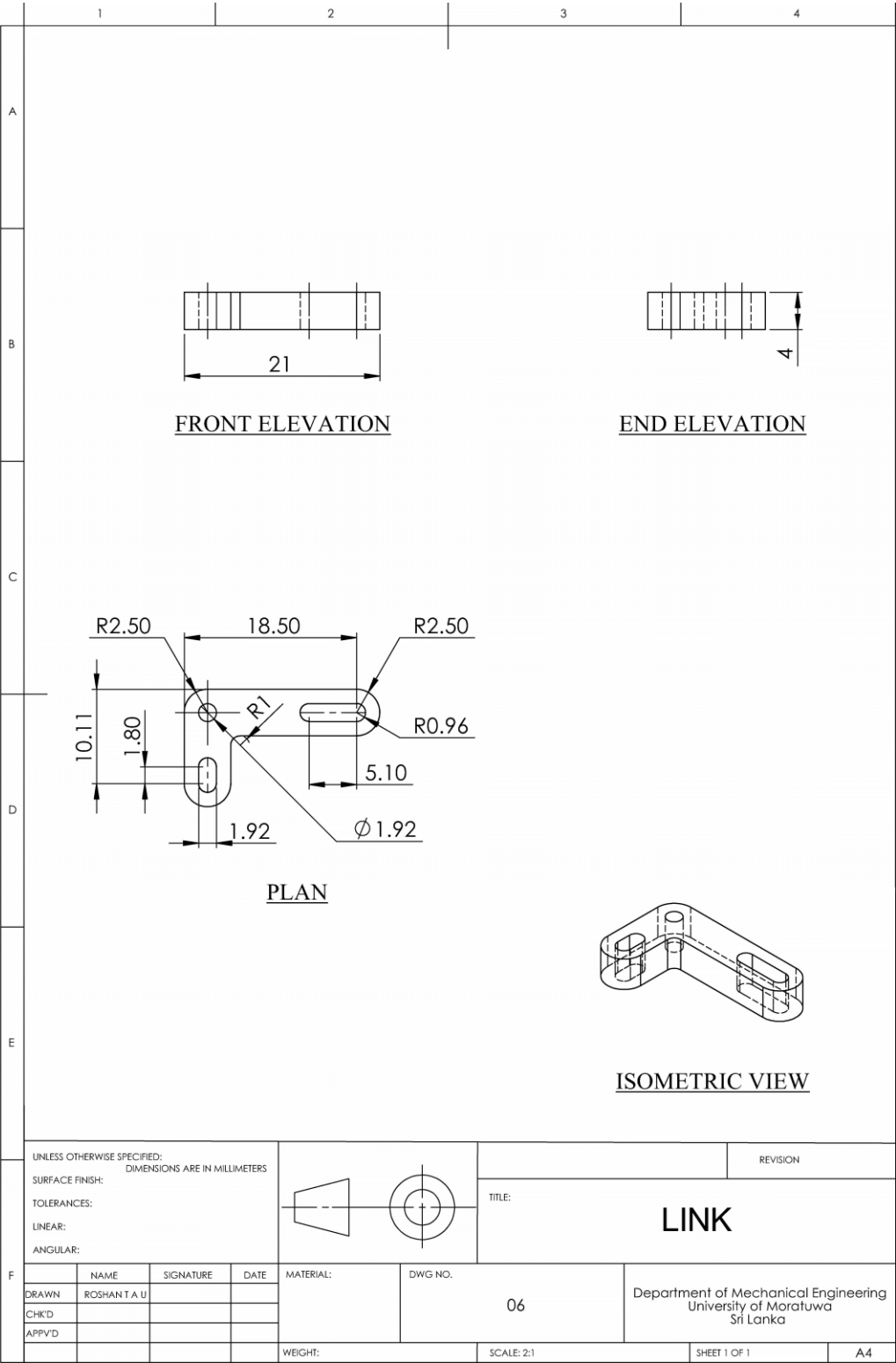
Appendix S4: Driver Jaw



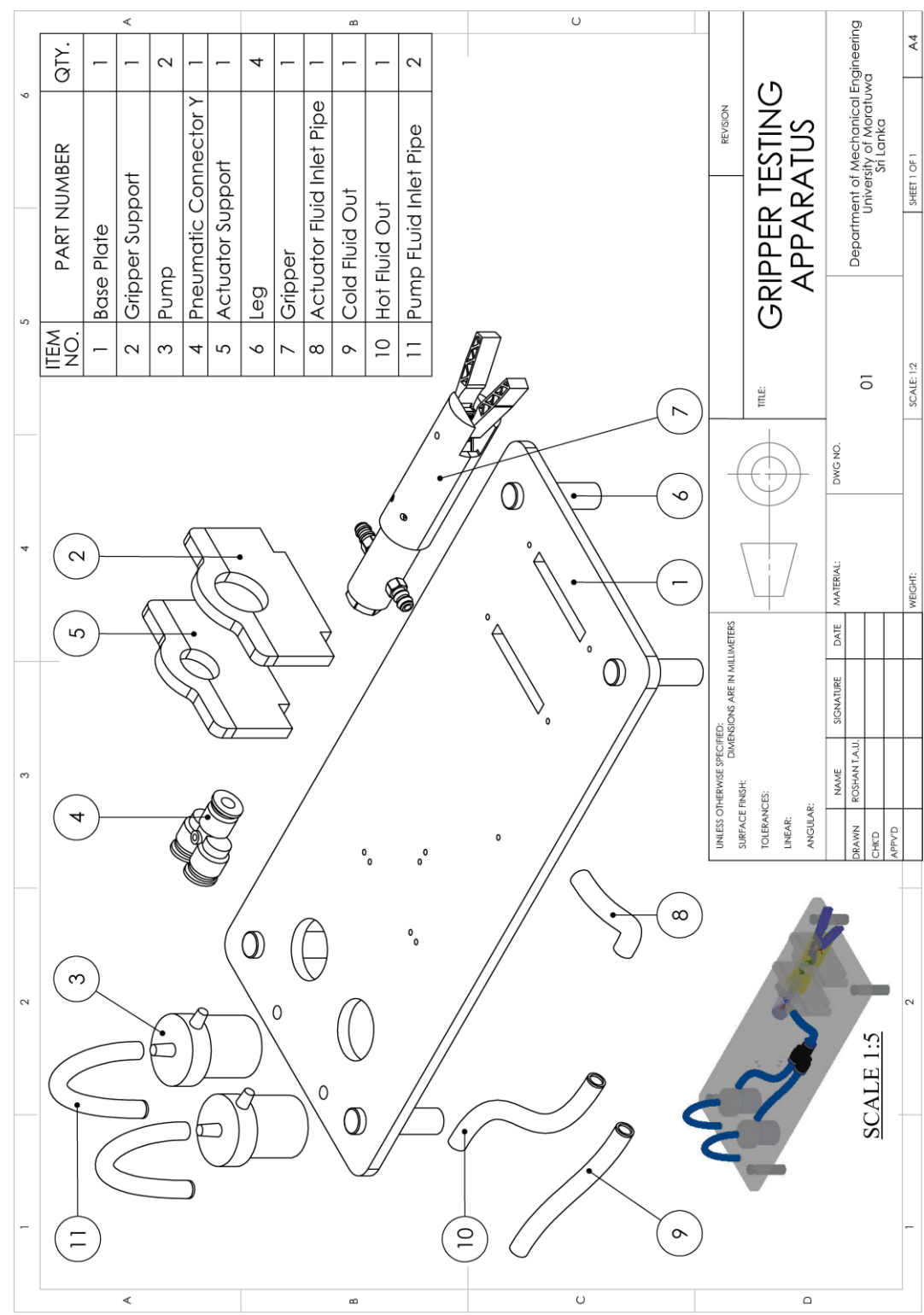
Appendix S5: Driven Jaw



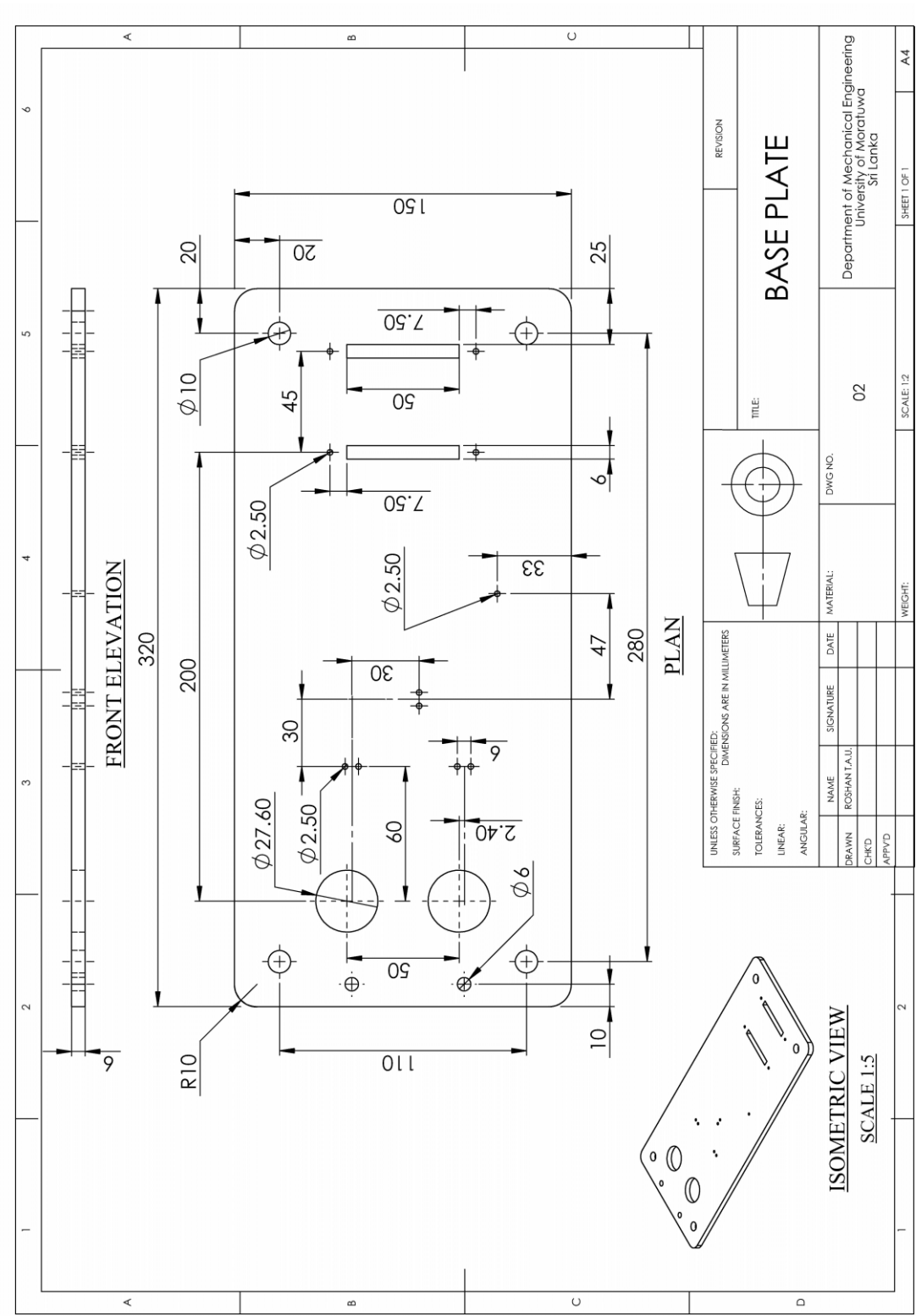
Appendix S6: Link



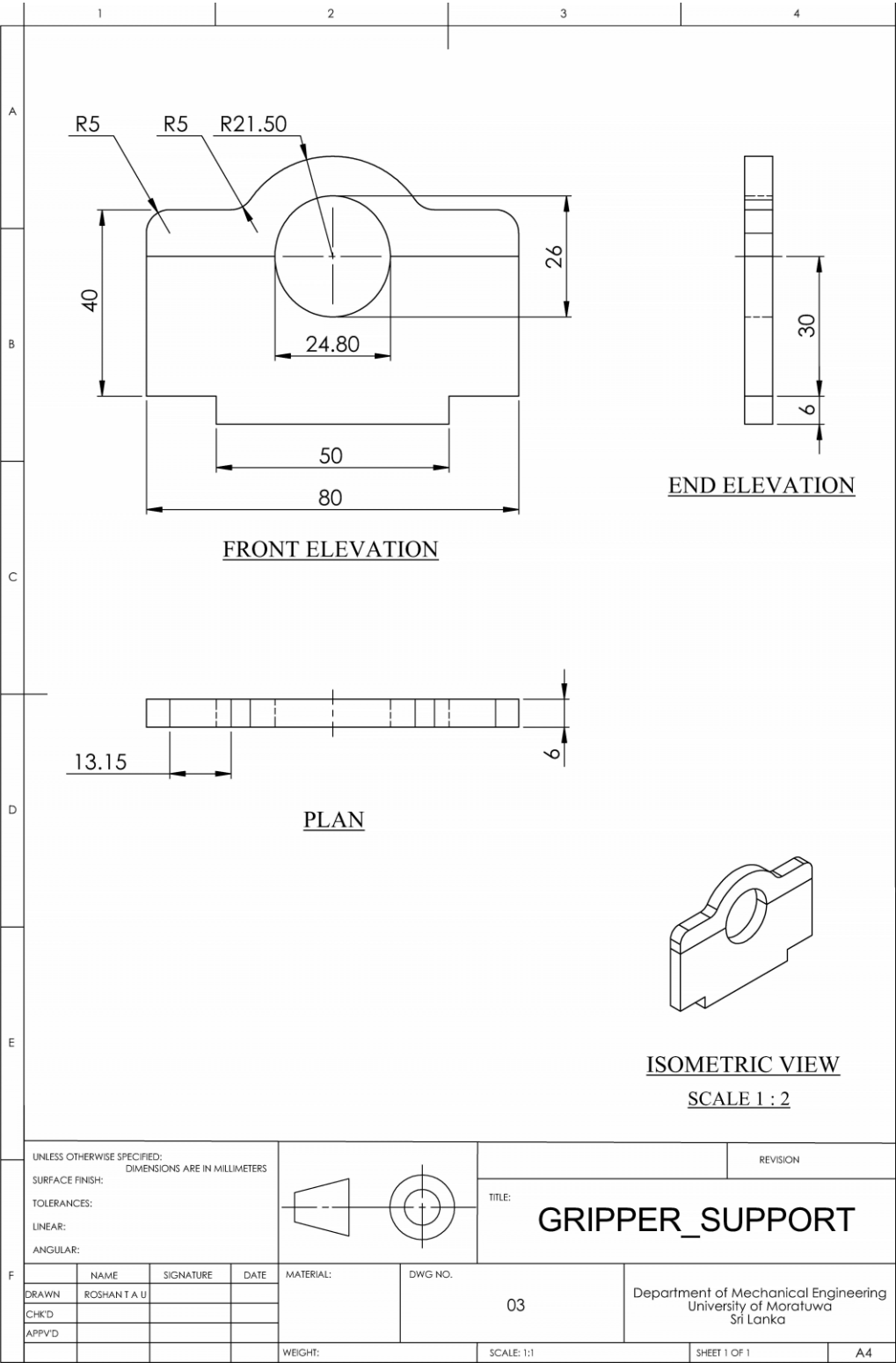
Appendix T1: Apparatus



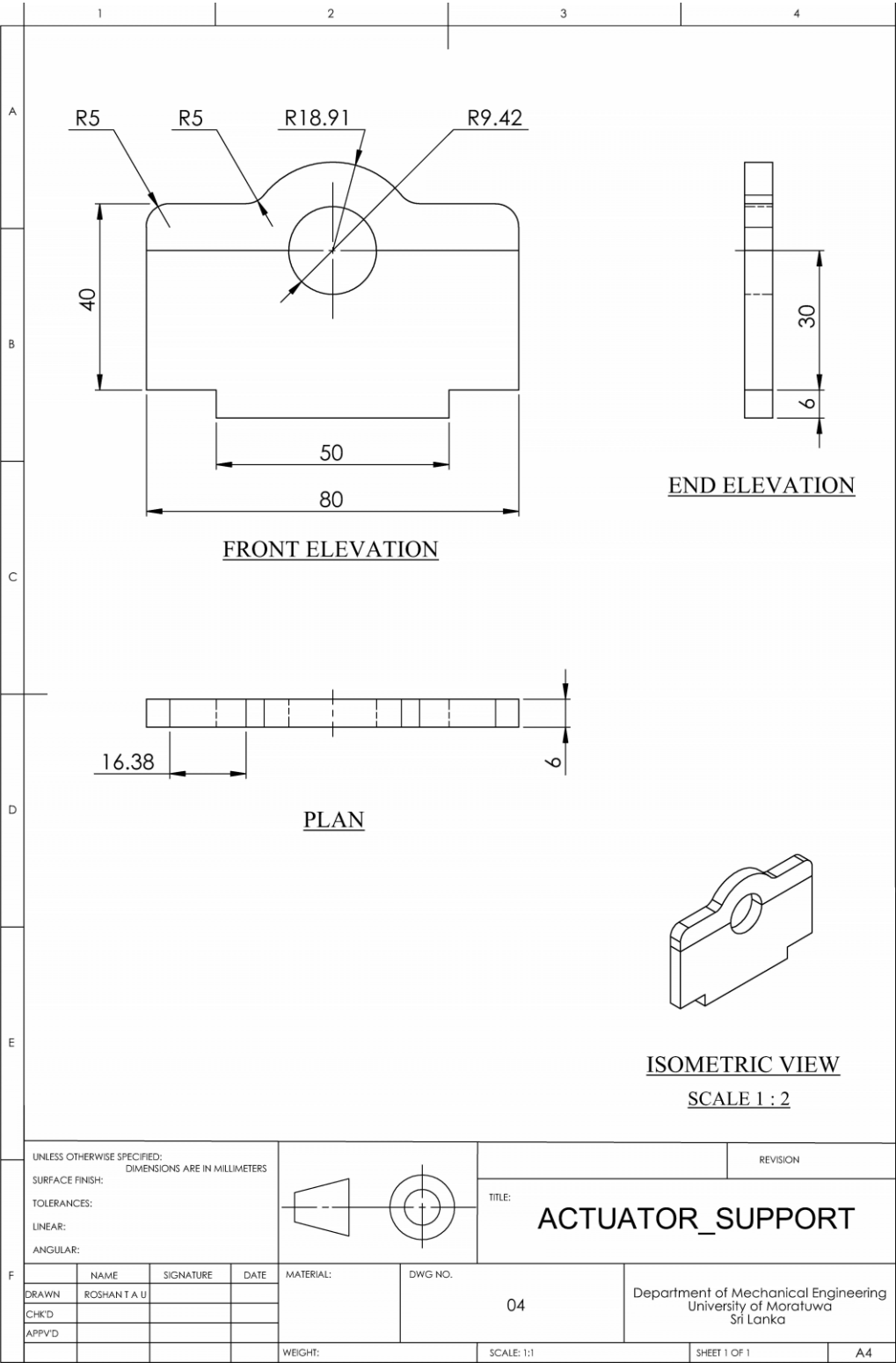
Appendix T2: Base Plate



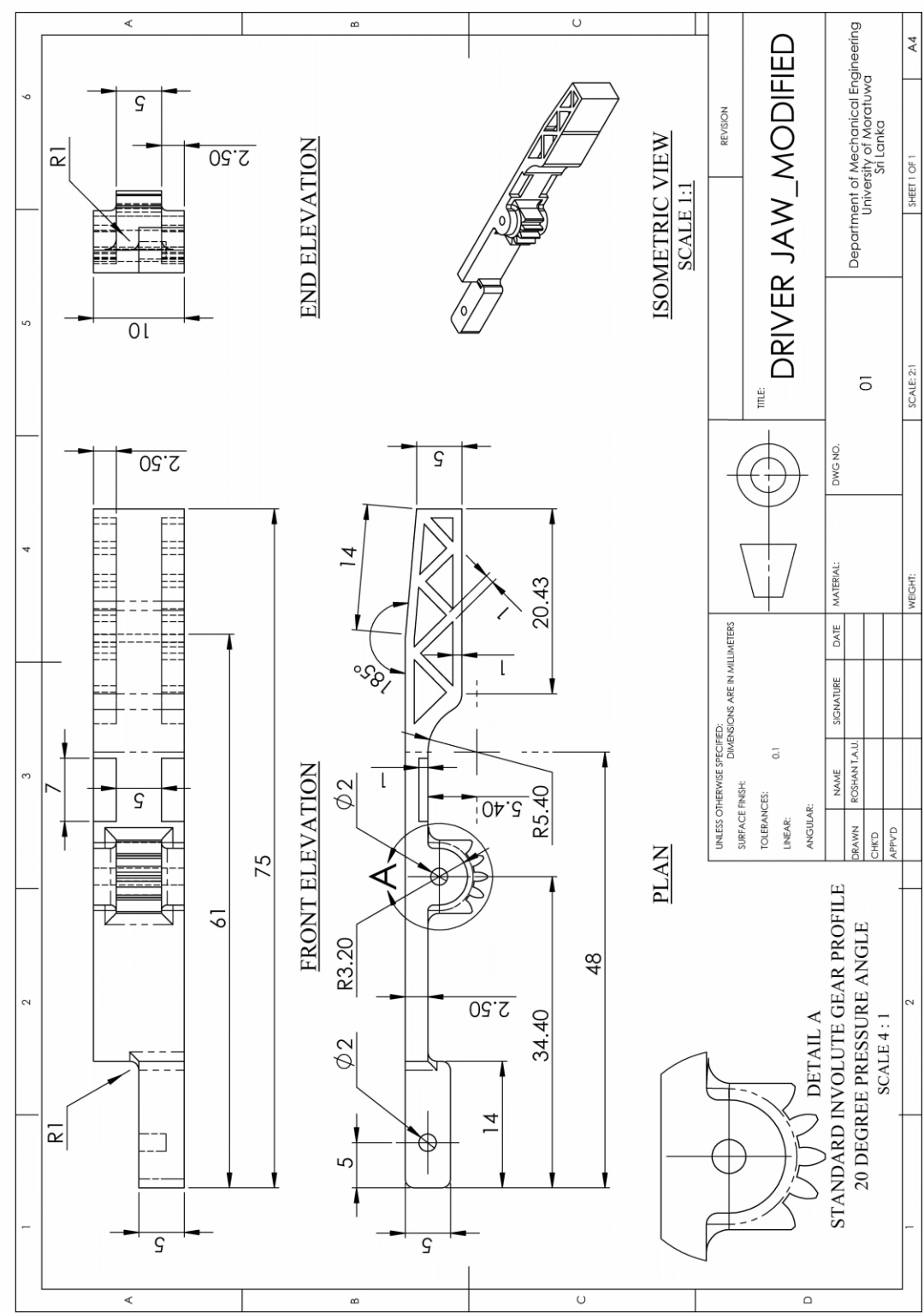
Appendix T3: Gripper Support



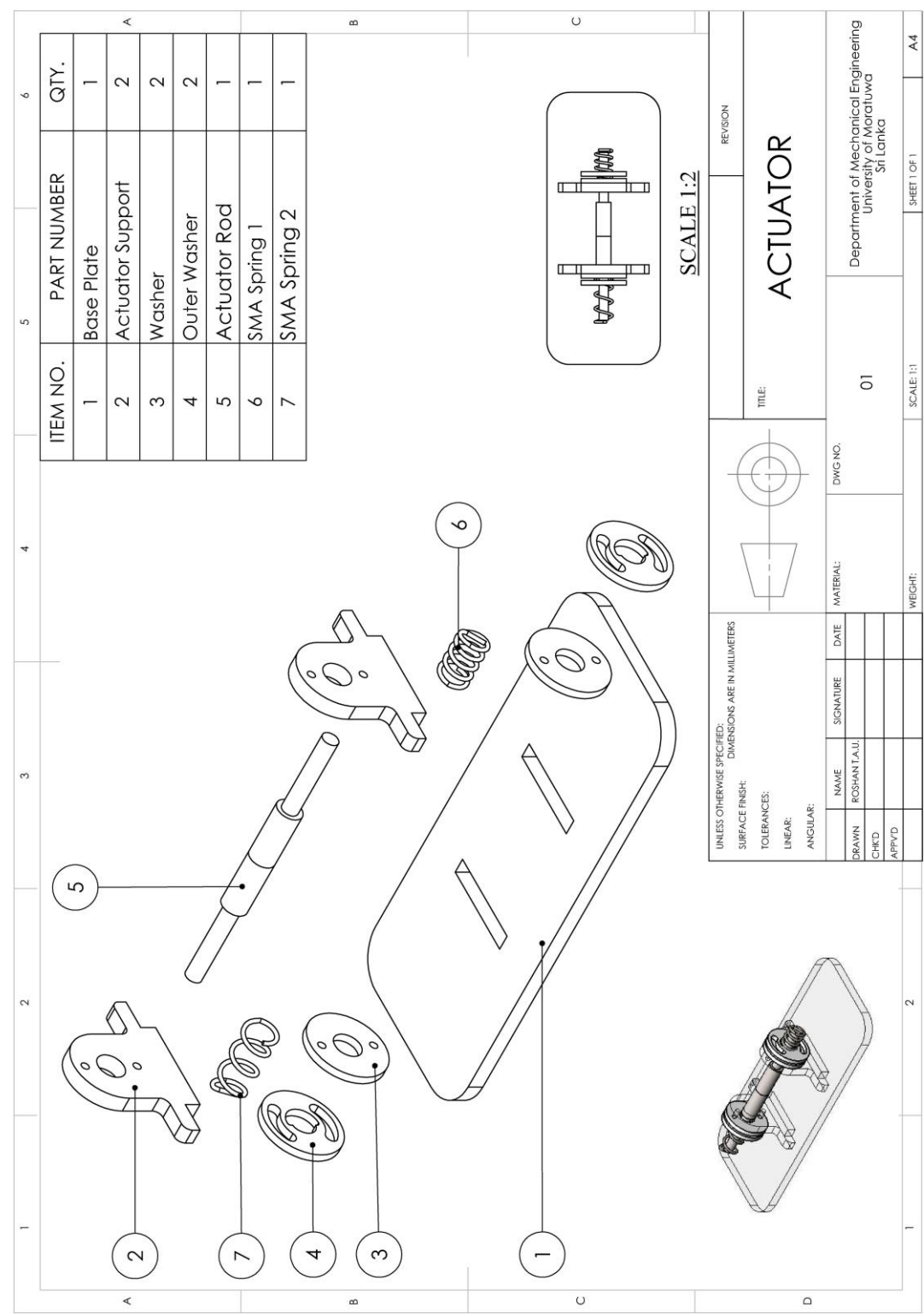
Appendix T4: Actuator Support



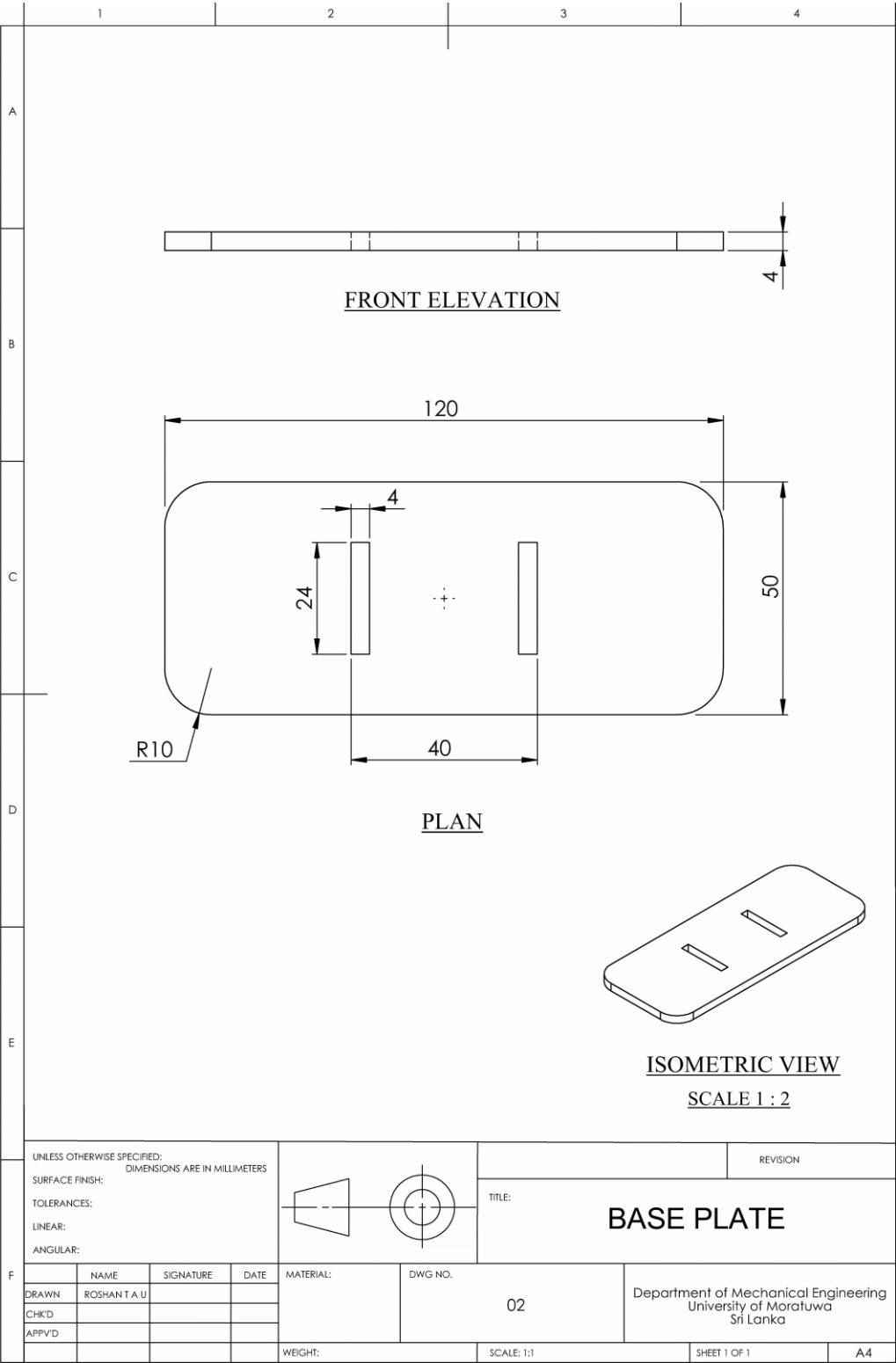
Appendix T5: Driver Jaw_Modified



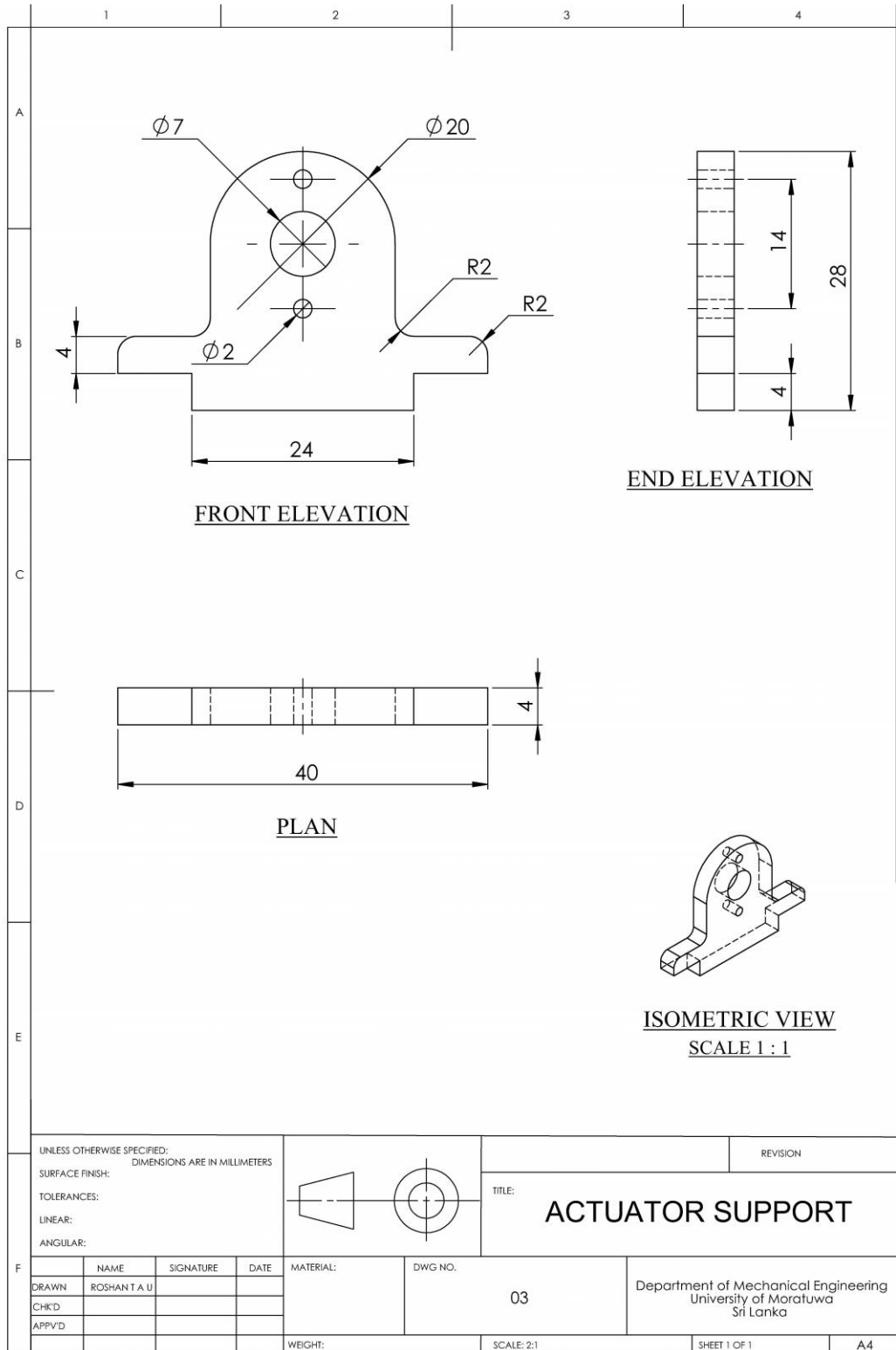
Appendix U1: Actuator 2.0



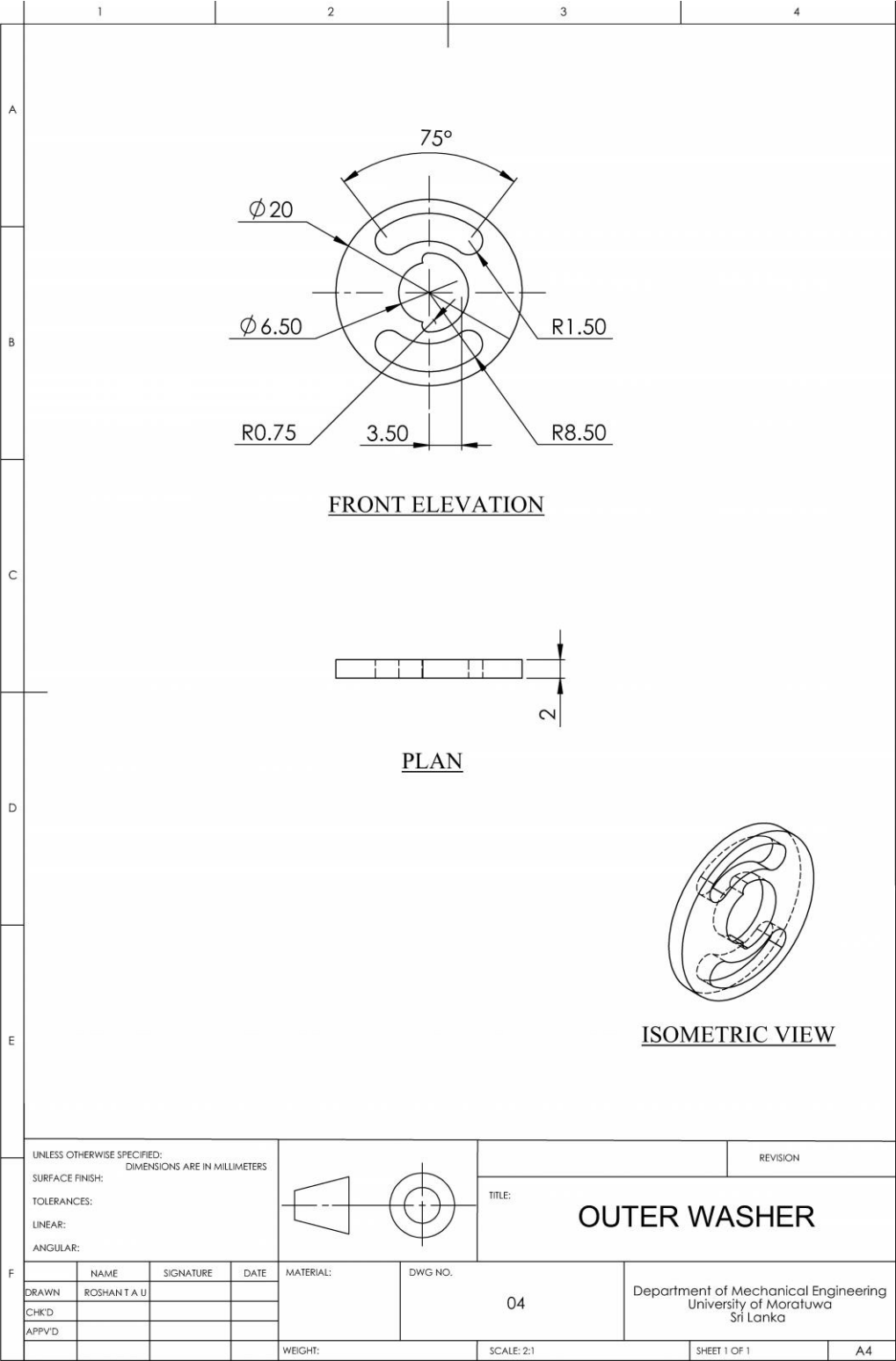
Appendix U2: Base Plate



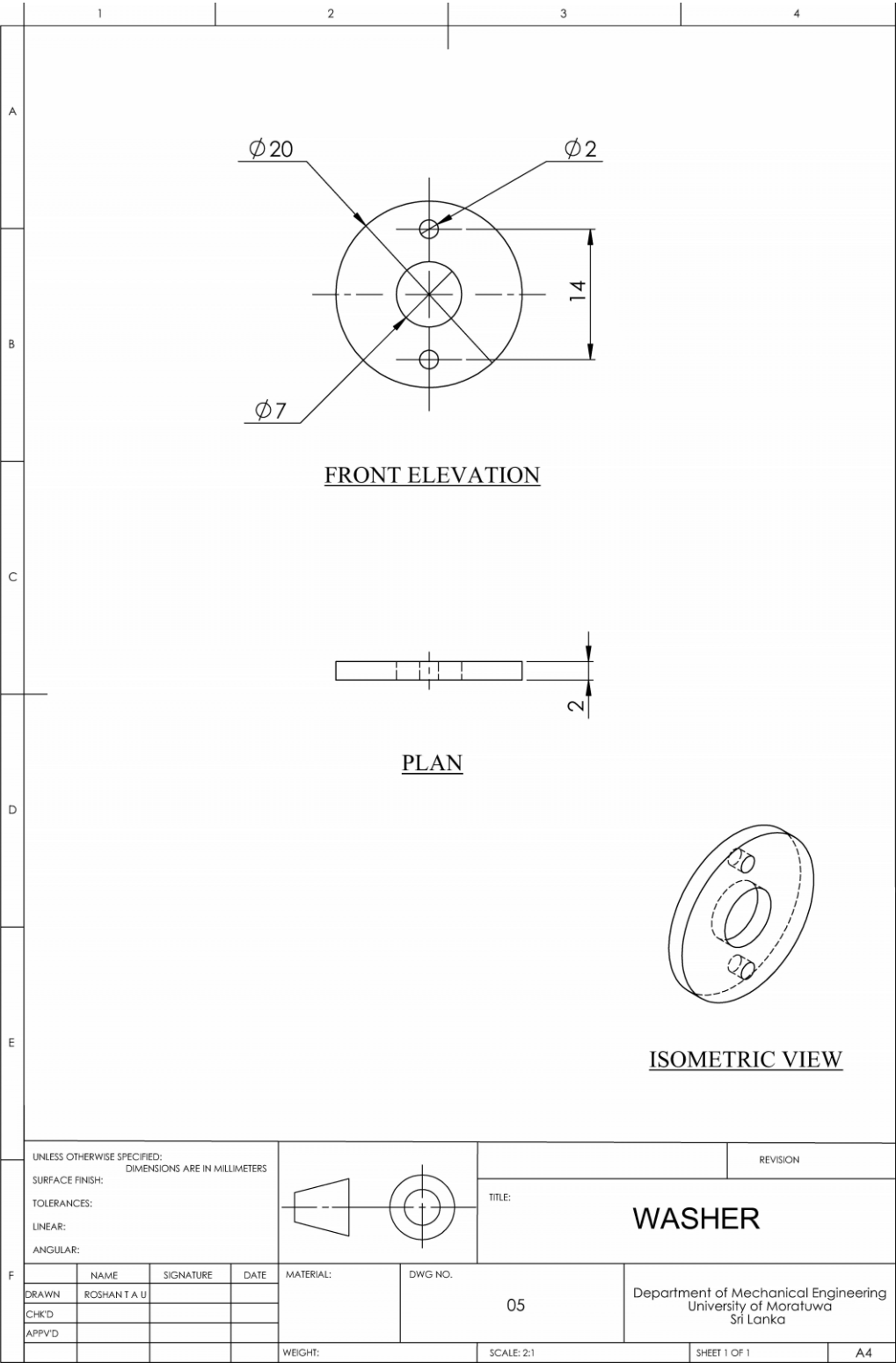
Appendix U3: Actuator Support



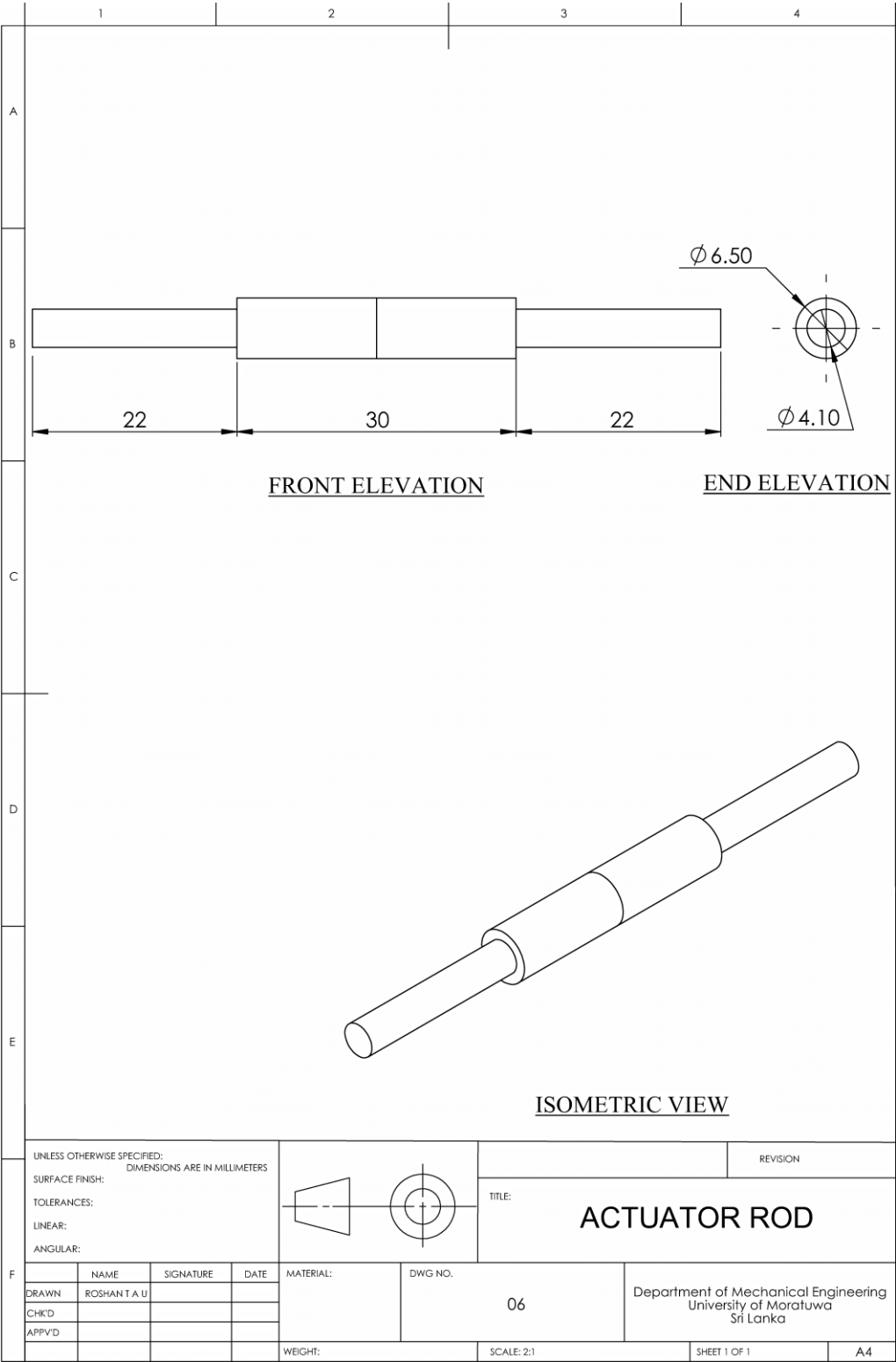
Appendix U4: Outer Washer



Appendix U5: Inner Washer



Appendix U6: Actuator Rod



Appendix V1: Retractor

