DESIGN AND CHARACTERIZATION OF A NOVEL HYBRID ACTUATOR USING SHAPE MEMORY ALLOY AND D.C MOTOR FOR MINIMALLY INVASIVE SURGERY APPLICATIONS

by

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Dedicated to my Dad, Mom, Sister and Brother-in-law

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Abbreviations

ARTEMIS	-	Advanced Robot and Telemanipulator System for Minimal Invasive Surgery
DOF	-	Degrees of freedom
MIRS	-	Minimally Invasive Robotic Surgery
MIS	-	Minimally Invasive Surgery
SMA	-	Shape Memory Alloy

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Abstract

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Current end effectors used in Minimally Invasive Robotic Surgery are actuated by a motor pack that is located outside the patient's body and the power to this end effector is transmitted by means of sliding link or tendon driven mechanisms. This method of power transmission to the end effector results in less number of degrees of freedom to the end effector, as the design of a spherical wrist gets complicated. But if there is a local actuation system for the end effector, then the design of the spherical wrist is simplified and its number of degrees of freedom can be increased. In this thesis, a novel design idea for developing a millimeter scale actuator is presented for locally actuating the end effector for a robot performing minimally invasive surgery. This actuator is designed by combining micro D.C motor and shape memory alloy (SMA) actuator in series. The designed actuator is 5.14mm in diameter and 40mm in length and is used to actuate 20mm long needle driver assembly, while generating a force of 24N (approximately) and a gripping force of 8N. The total stroke length of the actuator is 1mm (approximately) which corresponds to a 45° (approximately) opening of the needle driver jaw with a gap of 8mm in between the jaws.

Chapter 1

Introduction

Recent developments in the field of robotics, smart materials, micro actuators and mechatronics have opened a new frontier for innovation and development of millimeter scale actuators for use in Minimally Invasive Surgery (MIS) applications. Medical robotics is a new and promising field for innovation and development of new tools for enhancing the capabilities of surgeons.

In this thesis, I study and develop the design of a new class of actuator for actuating a needle holder which will be employed in robotic tools for MIS. The goal is to simplify the actuation mechanism of the end effector of the robot and therefore facilitate the increase of the degrees of freedom of the mechanism by simplifying the design of the robotic wrist. This would ease the design of higher degrees of freedom (DOF) medical robotic manipulators that can be used to perform the procedures which are currently impossible or complex to perform and by doing so to enhance the capability of the surgeon and reduce the overall cost of these procedures.

1.1 Minimally Invasive Surgery

Minimally Invasive Surgery (MIS) is the practice of performing surgery through small incisions or “ports” using specialized surgical instruments in order to reduce the size of incisions required to access the internal tissues during surgery. During conventional “open” surgery, a significant trauma is created at the incision site, which is the reason for much of the post operational pain and discomfort. Therefore it is argued that procedures performed using MIS techniques will have reduced bleeding, discomfort, patient recovery time, and cost.

However, MIS is technically more difficult for the surgeon. Surgeons must train extensively due to the lack of advanced tools and instruments for performing MIS. MIS is therefore limited to a number of relatively simple procedures such as cholecystecomy [1] (gall bladder removal) for which there seems to be a consensus within the medical community that it is in fact beneficial. Due in part to the changing landscape of medical reimbursement in the United States, there is a substantial push from medical payer organizations (insurance companies, health maintenance organizations and hospitals) to introduce MIS to other procedures in order to reduce hospital stays and therefore costs. Recoveries are typically faster and less painful which also means patients are asking for these procedures.

Perhaps the most common form of MIS is laparascopy [2], which is minimally invasive surgery within the abdominal cavity. A rapidly emerging field is MIS cardiac surgery for coronary artery bypass graft surgery. During laparoscopy, a patients abdomen is insufflated with CO_2, and cannulas (essentially metal tubes) with pneumatic check valves are passed through small (approximately 1-2 cm) incisions to provide entry ports for laparoscopic surgical instruments. The instruments include an endoscope for viewing the surgical site (a CCD camera/lens combination with slender shaft), and tools such as needle driver, graspers, scissors, clamps, staplers, and electrocauteries. The instruments differ from conventional instruments in that the working end is separated from its handle by an approximately 30cm long, 4-13 mm diameter shaft. As shown in Figure 1-1, needle driver instrument is used to hold the needle and drive it through the tissue while suturing.

FIGURE 1.1: Commonly used needle driver for minimally invasive surgery [3]

The surgeon passes these instruments through the cannula and manipulates them inside the abdomen by sliding them in and out, rotating them about their long axis and pivoting them about centers of rotation defined roughly by their incision site in the abdominal wall. Typically a one-degree-of-freedom device (gripper, scissors, etc.) can be actuated with a handle via a tension rod running the length of the instrument. The surgeon monitors the procedure by means of a television monitor which displays the abdominal worksite image provided by the laparoscopic camera.

There are several disadvantages to the current MIS technology.

1. Visualization of the surgical site is reduced. The operating site is viewed on an upright, two dimensional video monitor placed somewhere in the operating room. The surgeon is deprived of three-dimensional depth cues and must learn the appropriate geometric transformations to properly correlate hand motions to the tool tip motions.
2. The surgeon’s ability to orient the instrument tip is reduced. The incision point/cannula restricts the motions of the instrument from six DOF to four. As a result, the surgeon can no longer approach tissue from an arbitrary angle and is often forced to use secondary instruments to manipulate the tissue in order to access it properly or to use additional incision sites. Suturing becomes particularly difficult.
3. The surgeon’s ability to feel the instrument/tissue interaction is nearly eliminated. The instruments are somewhat constrained from rotating and sliding within the cannula due to sliding friction from the air seal, and the body wall constraints pivoting motions of the instrument shaft. The mechanical advantage designed into MIS instruments reduces the ability to feel grasping / cutting forces at the handle.

Despite surgeons considerable skill and ability to work within the constrains of the current MIS technology, the expansion of minimally invasive medical practice remains limited by the lack of dexterity with which surgeons can operate while using current MIS instruments.

1.2 Minimally Invasive Robotic Surgery

In order to avoid the drawbacks of manual MIS, Minimally Invasive Robotic Surgery (MIRS) is introduced. MIRS systems use telerobotics technologies to help the surgeon to overcome the physical barriers, such as patient's chest and abdominal wall, which separate him from the operating area. Furthermore, it is possible to perform the surgery from a remote location, i.e. the surgeon and the patient do not have to be in the same room.

As shown in figure 1.2, the main components of a medical robot performing MIS are:

1. Slave
2. Master
3. Communication between slave and master

The slave system consists of sensors, actuators and transmission mechanisms to control the position of the instrument tip and to provide tactile feedback to the surgeon performing MIS. The minimally invasive instrument should be small (diameter should be less than 10 mm) in order to reduce pain and trauma to minimum. The slave system can also scale the surgeon's motions and filter the surgeon's hand tremor to increase the safety and reliability of the MIRS system.

The master system has to provide high quality feedback, both tactile and kinesthetic. The tactile information helps the surgeon to use palpation, as in open surgery. This is necessary to find invisible structures (e.g. blood vessels below fat layer). The kinesthetic information gives the surgeon direct access to the forces at the operating area and therefore increases the quality of the operation.

The communication between master and slave has to be flexible to allow the connection of different master stations (not necessarily located in the same operating room) to get support by an additional expert or to enhance training of surgeons. The communication network has to be safe (guaranteed bandwidth and communication delay) and secure, so that an inexperienced surgeon can get immediate support from an experienced colleague.

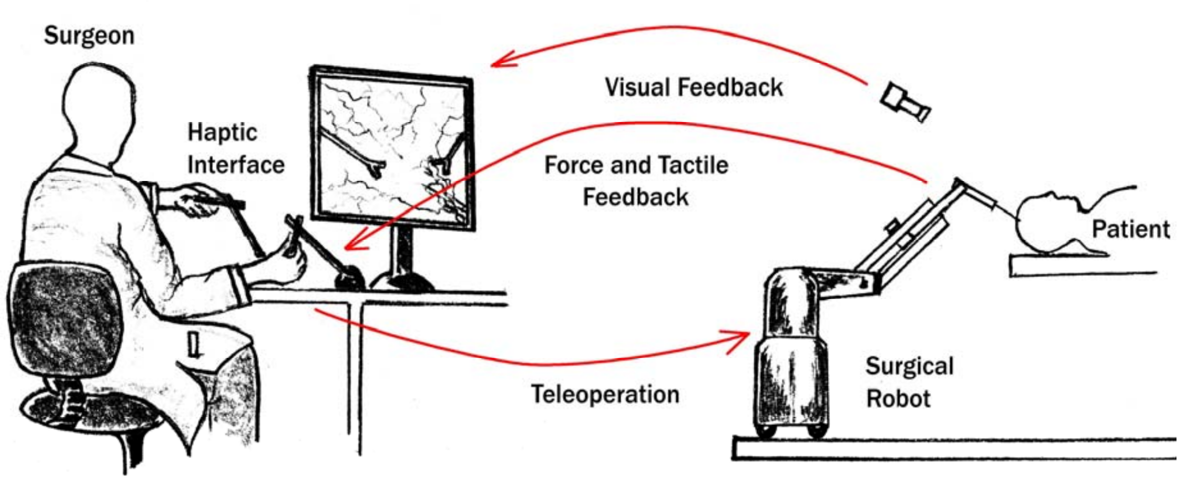


FIGURE 1.2: Concept of teleoperated MIS

1.3 Thesis Organization

Chapter 2 presents an overview about the Minimally Invasive Robotic Surgical (MIRS) Systems developed at various research institutes and companies. The actuation mechanisms presently used in the MIRS systems are also discussed in this chapter. Chapter 3 investigates into the need for local actuation in MIRS systems to actuate the end effector. The minimum design requirements for a local actuation system are discussed and is followed by literature review for selecting an actuation technology. Chapter 4 discusses the design idea for the hybrid actuator and characterization of the shape memory alloy (SMA) wire used in the final design. The design's of the prototype, first generation and second generation hybrid actuators are explained in detail with results. Finally, in Chapter 5, we summarize our work and present further improvements to this hybrid actuator.

1.4 Contributions

The objective is to investigate the need for a local actuation system in MIRS system and come up with a design solution in this thesis. In this thesis a novel concept of hybrid actuation is presented to design a hybrid actuator using SMA wire and a micro DC motor for actuating the needle driver jaws during minimally invasive surgery.

Chapter 2

Minimally Invasive Robotic Surgical Systems

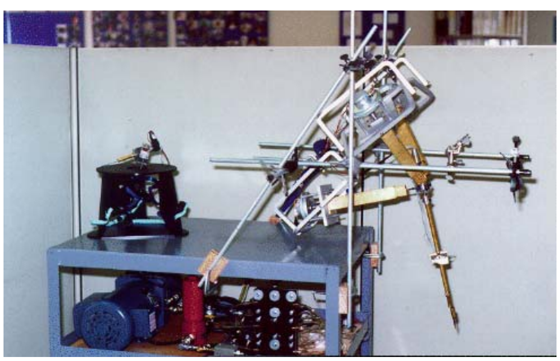
Modern Minimally Invasive Robotic Surgical (MIRS) systems should provide both realistic tactile and kinesthetic feedback, which gives the surgeon direct impression of tissue and embedded structures (e.g. blood vessels). Three dimensional visual feedback in combination with Cartesian control should allow correct hand-eye coordination as in open surgery. Actuated instruments are expected to provide full manipulability inside the body which is necessary to reduce surgery time as well as training time. Intelligent assistance functions, such as automatic positioning of instruments, automatic cutting, and grasping, as well as safety features are also desired. Robotic assistance systems are mainly used to hold the laparoscope or as flexible and intelligent tool holders [4]. Interaction with these assistance systems is either via voice, via tracking of a pointer or with force sensors.

This chapter presents an overview of the state of the art MIRS systems developed at research institutes and companies. Following this, the actuation mechanisms presently used in these systems to actuate the end effector are reviewed.

2.1 MIRS at the Research institutes

This section focuses on the development of MIRS systems at various research institutes around the world. This section gives an overview of the current research in MIRS systems and is not intended as a comprehensive list.

In a joint research project between the Robotics and Intelligent Machines Laboratory of the University of California, Berkeley (UCB) and the Department of Surgery of the University of California San Francisco (UCSF), a robotic telesurgical workstation for laparoscopy is developed [5] (see figure 2.1(a) for the prototype):



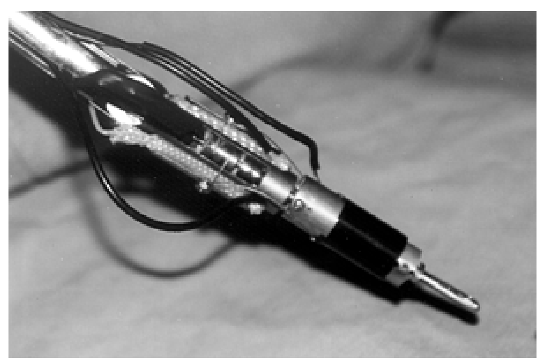


FIGURE 2.1 (a): First generation robotic telesurgical workstation [6] (b) Laparoscopic endeffector [6]

The slave manipulator of the first generation laparoscopic manipulator design is composed of two stages. The first stage is for gross positioning of the end effector and is a Stewart platform-like parallel manipulator, driven by electric motors, giving 4 DOF. The second stage is the 3 DOF millirobot and has a 2 DOF wrist and a gripper, driven by hydraulic actuators. The surgical master, which has 7 DOF, is the primary interface between the surgeon and the laparoscopic surgery platform, providing force and tactile feedback. In this design, a commercial 4 DOF force-reflecting joystick device (Immersion Systems [7] Impulse Engine 3000) is extended with additional degrees of freedom and a stylus-like handle to be grasped by the user.

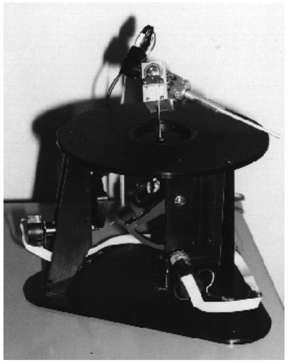


FIGURE 2.2 (a): Surgical master for the first generation system [6] (b) Close-up view of the surgical master [6]

In the second generation laparoscopic manipulator the design of the master device is based on a PHANToM [8] (see figure 2.3(a)). The millirobot (as shown in figure 2.3(b)) of the slave has a 2 DOF wrist, with yaw and roll axis rotations, and a gripper (on the right). It is 15 mm in diameter. The wrist-to-gripper length is 50 mm. The yaw and roll axes are coupled and actuated with tendons jointly by three DC servo motors located on the end of tool arm outside the body.

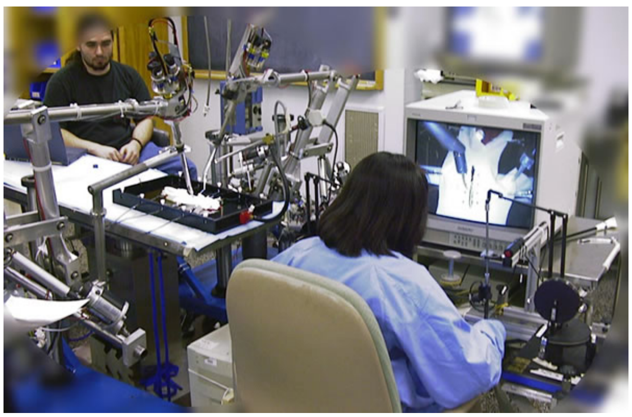


FIGURE 2.3(a): Surgical master for the second generation system [6] (b) Close-up view of the slave manipulator [6]

Advanced Robot and Telemanipulator System for Minimal Invasive Surgery [9] (ARTEMIS) is one of the first MIRS systems and was developed at the “Forschungszentrum Karlsruhe" in Germany. The master consists of various input devices: two haptic manipulators for the slave robots, voice recognition for the laparoscope, and foot pedals. The slave consists of three robots: two robots for holding and manipulating surgical instruments, while the other holds the laparoscope. The major drawback of the ARTEMIS system is that, it does not have force feedback at the master side and there are not any instruments with additional degrees of freedom at the slave side.

Korea Advanced Institute of Science and Technology (KAIST) has developed a teleoperation surgical system [10] for microsurgical tasks. It allows six DOF force/torque reaction at the master console. The master device consists of a five-bar parallel mechanism driven by harmonic DC servomotors. The slave consists of an industrial six DOF robot equipped with a modified six DOF Stewart platform for micro manipulation. Besides the fact that industrial robots are not designed for use in the operating room, the system does not allow full manipulability if used in laparoscopic surgery.

2.2 Commercially Available MIRS Systems

Currently there are two commercially available MIRS systems for performing cardiothoracic operations.

2.2.1 ZEUS™ Robotic Surgical System

Computer Motion, Inc. [11] manufactures the ZEUS™ Robotic Surgical System. Zeus Robotic Surgical system consists of three robotic arms as shown in figure 2.4(a). The surgeon controls these three robotic arms by a surgeon console as shown in figure 2.4(b). One of the three robotic arms is used to hold the endoscope – camera assembly and the remaining two robotic arms are used to manipulate the surgical instruments. The surgeon console consists of 3-D or 2-D visual feedback from the endoscope and controls the position of this instrument by his voice command. The surgeon controls the position of the surgical instruments inside the patient's body by controlling the two handles on the surgeon's console. The motion at the surgeons console is scaled and tremors of the surgeon hands are filtered to achieve a precise micro manipulation of the instruments inside the patient's body.

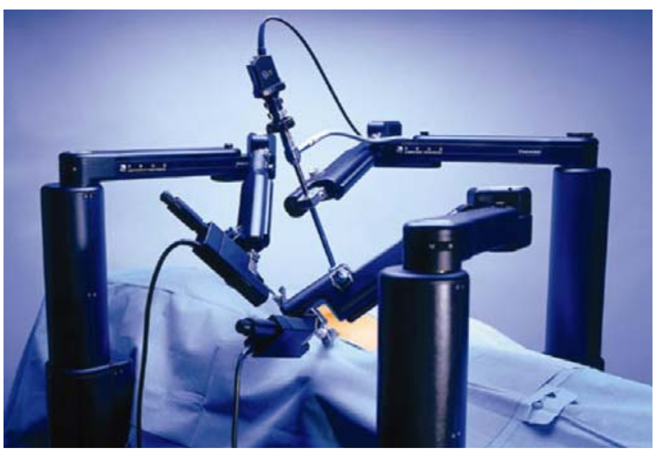


FIGURE 2.4(a): Slave manipulator for Zeus Surgical Robotic system [11] (b) Surgeon Consol for Zeus Robotic system [11]

Surgical instruments used with the Zeus Robotic system are 5mm or less in diameter and provide 5 DOF motion for the instrument tip to the surgeon. The articulating instruments are reusable and provide a one DOF articulation of the instrument jaws. The instrument tip is actuated by a detachable motor (as shown in figure 2.5) that is placed outside the patient's body. The motor controls the motion of instrument tip by controlling the metal rod that is used to push or pull the link at the instrument tip.

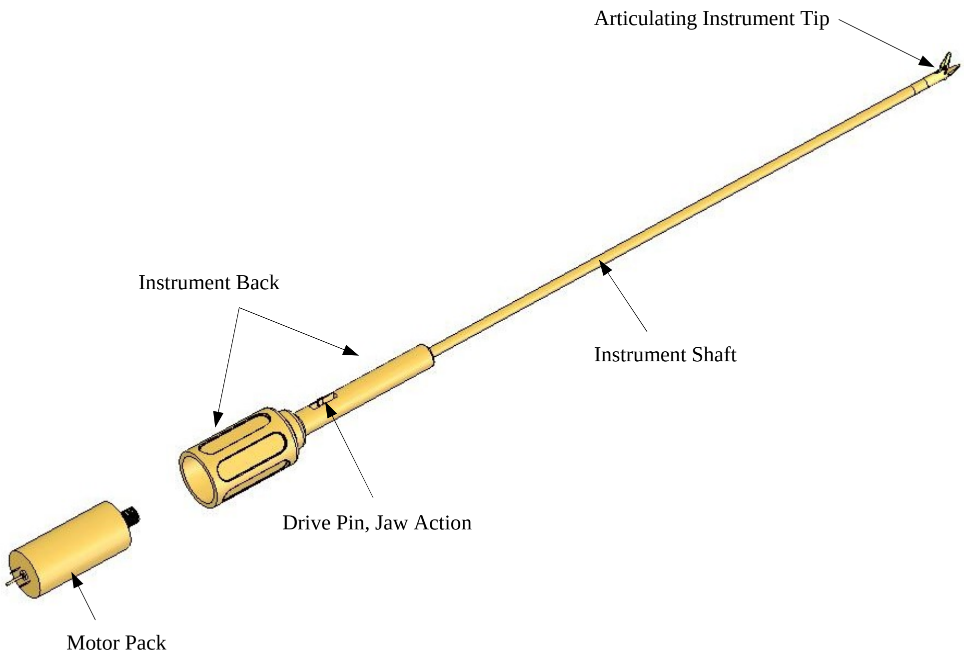


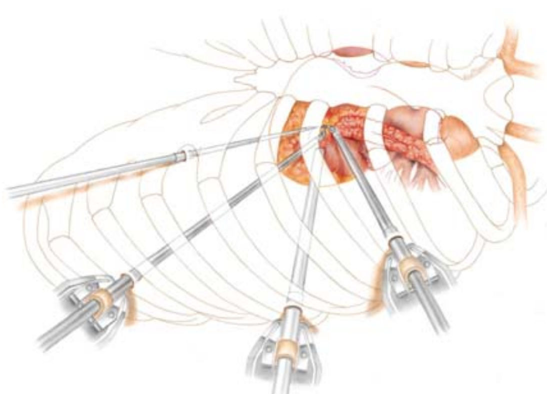
FIGURE 2.5: Zeus articulating instrument back assembly and motor pack

2.2.2 da Vinci™ Surgical System

Intuitive Surgical, Inc. [11] manufactures the da Vinci™ Surgical system. The da Vinci™ Surgical System consists of an ergonomically designed surgeon's console, a patient-side cart with four interactive robotic arms, a stereo endoscoping viewing system and proprietary EndoWrist® Instruments. During the surgical operation, the surgeon's hand movements are scaled, filtered and seamlessly translated into precise movements of the instruments. Surgeons console and the da Vinci™ Surgical system with four robotic arms are shown in the figure 2.6. The first two arms of the da Vinci™ Surgical system represent the surgeon's left and right hands, to hold the EndoWrist® instruments. A third arm positions the endoscope, allowing the surgeon to easily change, move, zoom and rotate his or her field of vision from the console. The optional 4th Arm extends surgical capabilities by enabling the surgeon to add a third EndoWrist® instrument and perform additional tasks like applying counter traction and following running sutures.

FIGURE 2.6(a): Surgeon's consol for da Vinci system [12] (b) da vinci system's Master and slave manipulator with four arms [12]

The surgical instruments for da Vinci surgical system are 8mm in diameter. These instruments have 6 DOF at the instrument tip (as shown in the figure 2.7). The wrist design technology is based on a tendon driven mechanism. So the motors required for actuating the instrument tip are placed outside the patient's body as it was in the design of the Zeus Robotic Surgical system.



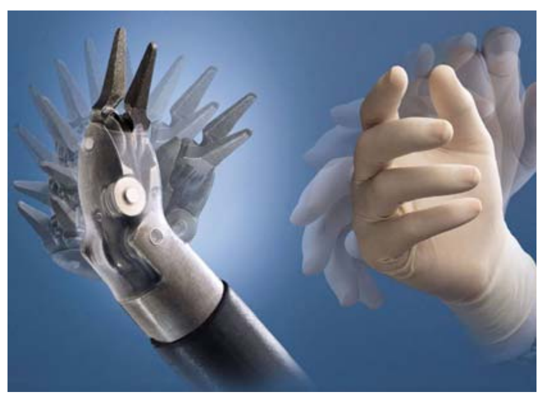


FIGURE 2.7(a): Placement of the three surgical instruments for manipulating the tissue and a fourth instrument, endoscope / camera unit for visual feedback. [12] (b) da Vinci Surgical Robot's Endo-Wrist [12]

Chapter 3

Local Actuation System for MIS / MIRS

3.1 Need for Local Actuation

Current needle holders, graspers, and other surgical tools for minimally invasive surgery transmit surgeon hand motions by passive mechanics. As the instruments slide, twist, and pivot through the point at which they enter the body wall, they are four DOF manipulators. Consequently, the surgeon can reach points within a three-dimensional volume but cannot fully control orientation. For simple tasks this is not a major hindrance, but it makes complex skills such as suturing and knot tying extremely difficult.

As discussed in the earlier section the number of DOF for the Zeus instrument tip is five when compared to six DOF for da Vinci's EndoWrist instrument tip. As da Vinci's wrist simulate's the motion of the human hand, it's much easier for a surgeon to perform the surgical task when compared to performing the same by Zeus Robotic instrument. But the advantage of the Zeus Robotic Surgical instrument over da Vinci's Surgical instrument is that the diameter of the Zeus instrument is 5 mm when compared to that of da Vinci's 8mm diameter instrument. The smaller the diameter of the instrument, the faster the recovery would be for the patient and in turn less expensive will be the overall procedure. So it's important to design a surgical system that has a smaller diameter instrument and more number of DOF.

In order to design a wrist mechanism in such a way that it would have more DOF, but still have a small diameter (5mm or smaller) the main constrain is the way in which the power is transmitted to the instrument tip. In Zeus robotic system, as shown in figure 2.8, the motor for actuating the instrument tip is placed outside the patients body and the power is transmitted though the push-pull of a long and thin metal rod. So in order to design additional degrees of freedom for the instrument tip it's very important to have a local actuation system that actuates the instrument tip (such as a needle holder). If we have a local actuation system then we can design a spherical wrist that can hold the local actuation system and the end effector, thereby giving more degrees of freedom. This thesis focuses only on the design of the local actuation system and does not specifically deal with the design of the wrist.

3.2 Requirements of the Local Actuation System

The actuator should be 5mm in diameter so that it can fit through the 5mm trocars, but still be able to apply sufficiently large forces required to hold the needle while suturing. The length of the end effector should be as short as possible so that it can be attached to a spherical wrist of a robot performing MIS. The design requirements that are adopted for the millimeter scale actuator are summarized in the Table I.

TABLE I. DESIGN REQUIREMENTS FOR THE ACTUATOR

Parameter	Value
Dimension: overall diameter	5mm max
Dimension: overall dimension	50mm max
Gripping force	5N min
Stroke length	1-3 mm min
Gripper closing time	2 seconds max

3.3 Review of Local Actuation Systems

Grant et al. [13]-[14] have designed an actuator (as shown in figure 3.1) using SMA wires that can generate high strain. This actuator is designed in such a way that it overcomes the inherent property of limited strain of the SMA actuators. The designed SMA actuator can generate 4N of force and is very light in weight. But the designed actuator is 17mm in diameter and 30mm in length, making it difficult to be implemented in MIS applications.

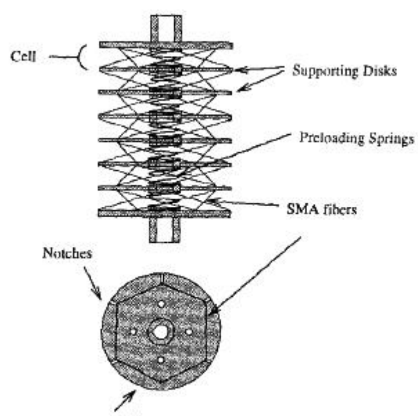
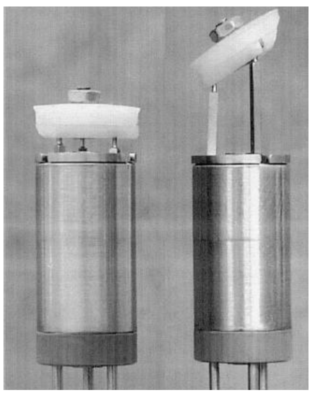


FIGURE 3.1: High strain Shape Memory Alloy Actuator [14]

J.Peirs et al. [15] have investigated the design of miniature manipulators for integration into a self propelling endoscope. The designed manipulators (as shown in figure 3.2) include a hydraulic actuator, electric stewart platform and electric serial manipulator. These actuators are designed to orient and position the tools and camera, which requires high force. But these actuators are more than 12mm in diameter and cannot be used with the standard 5mm trocars.



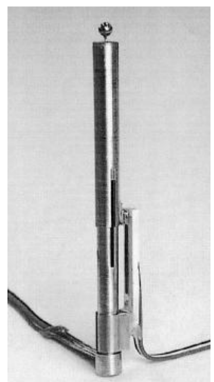


FIGURE 3.2 (a): Hydraulic actuator [15] (b) Linear actuator using micro motor [15] (c) Electric serial manipulator [15]

S.Ku et al. [16] have investigated the use of a solenoid in the design of micro gripper for MIS applications. The micro gripper is designed with flexural mechanisms and does not contain any hinges. In order to achieve bidirectional motions, the solenoid actuator is loaded with a return spring. The designed actuator is 5.4 grams in weight and is 12.5mm in diameter and 45mm in length. However, the amount of peak force generated by this actuator is only 0.2N.

Canfield et al. [17] have developed a single degree of freedom prototype to demonstrate the viability of smart materials, force feedback and compliant mechanisms for minimally invasive surgery. The prototype has a compliant gripper that is 7-mm by 17-mm, made from a single piece of titanium that is designed to function as a needle driver for small scale suturing. This compliant gripper is actuated by a 7mm-diameter actuator, designed by using piezo electric crystals to operate as an Inchworm actuator. The piezo electric actuator system can be used to measure the forces acting on the needle driver and can be fed back to the user. The main disadvantage of this system is that it can be fed only through an 8mm trocar as compared to the 5mm trocar in our present design. According to [18] this actuator design is somewhat complicated with respect to integration of the piezoelectric inch-worm actuator to the compliant end effector.

3.4 Selection of the Actuation Technology

TABLE II. COMPARISON OF DIFFERENT ACTUATION TECHNOLOGIES

(adapted from Kornbluh et al. 1998 [19])

Actuator type	**Maximum Strain**	**Maximum Pressure**	**Maximum Efficiency**	**Relative Speed (Full Cycle)**	**Power Density**
Shape Memory Alloy (TiNi)	>5	>200	<10	Slow	Very High
Electromagnetic *(voice Coil)*	50	0.10	>90	Fast	High
Piezoelectric Ceramic (PZT) Single Crystal (PZN-PT) Polymer (PVDF)	 0.2 1.7 0.1	 110 131 4.8	 >90 >90 n/a	 Fast Fast Fast	High
Electrostatic Devices (Integrated force array)	50	0.03	>90	Fast	Low
Shape Memory Polymer	100	4	<10	Slow	Medium
Thermal (expansion)	1	78	<10	Slow	Medium
Magnetostrictive (Terfenol- D. Etrema Products)	0.2	70	60	Fast	Very High

Table II [20]-[23] shows the comparison of different actuator technologies that were considered to achieve the design requirements. From the comparison chart shown in

Table II, it can be seen that the amount of force generated per unit volume is high for Piezoelectric and SMA actuators. But the amount of stroke produced by piezoelectric actuators is significantly lower than the other alternatives.

SMA wire was used in the design of different actuators [14, 24, 9] for many medical applications. Silent actuation is a positive attribute that allows the use of SMA in medical applications. So SMA is a good choice for use in miniature medical applications. But the major problem with the use of a SMA actuator is its low cycle speed and low stroke length. Its efficiency is low and also requires large power to actuate. In the present application power is not an issue.

On the other hand the DC motors have a good speed and large stroke, but a low output torque. With the advances in miniaturization and the production of miniature brushless DC motors with micro gearboxes, the feasibility of using DC motors in miniature applications has increased. Micro DC motors have been investigated in [15, 25, 26], as a linear actuator in the design of miniature medical devices.

Both the SMA and micro DC motor have positive attributes and drawbacks for designing the millimeter scale actuator. So the actuator design should be in such a way that the positive attributes of both SMA and DC micro motor can be utilized and the drawbacks of each technology are removed.

Chapter 4

Design of a Hybrid Actuator

As described in the previous chapter, no single existing actuation technology can be employed to achieve the design specifications of the miniature actuator presented in the table I. In this chapter a novel method to combine both these actuator types is presented for developing a novel hybrid actuator which has the positive attributes of both of these actuation techniques

4.1 Design Principle

The design of the proposed hybrid actuator consists of a micro DC motor for opening and closing the gripper jaws and an SMA actuator for holding the needle. The hybrid actuator works as a two phase actuator for holding the needle. The first phase is the opening and closing action of the jaws of the gripper which requires large strokes. The second phase is the needle gripping action applying pressure on the suture needle which requires large forces. Both the SMA actuator and the DC motor are actuated in closing the needle driver jaws to hold the suture needle, and only the DC motor is actuated in opening the needle driver jaws.

4.1.1 Closing the Needle Driver Jaws

As shown in figure 4.1, in the first phase of actuation the DC motor rotates in anticlockwise direction and moves the needle driver jaws from the open position to the closed position.

In the second phase of the actuation, as shown in figure 4.2, as the jaws reach the closed position, the DC motor is stopped and the SMA actuator is actuated by heating the array of parallel SMA wires. The heating is achieved by passing high ampere current through the SMA wires. At this position the force exerted by the needle driver jaws on the needle is due to the force generated by the SMA actuator. This force is enough for the needle driver jaws to hold the needle for performing suturing.

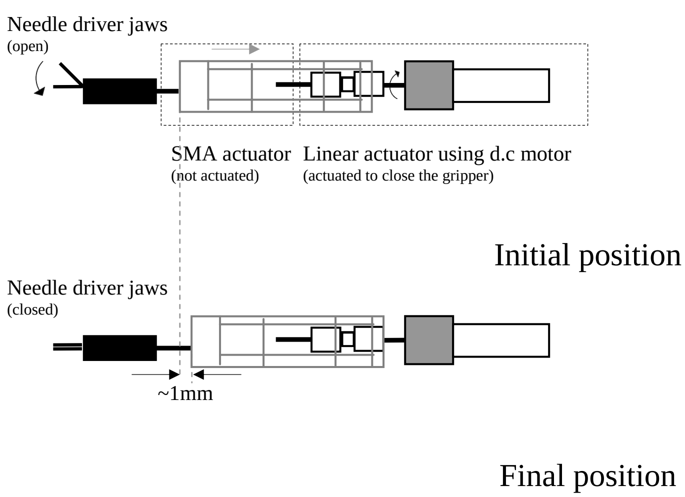


FIGURE 4.1: First phase of actuation in closing the needle driver jaws.

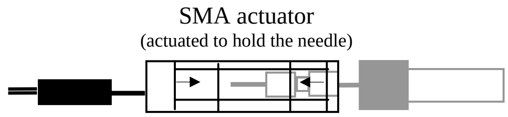


FIGURE 4.2: Second phase of actuation, SMA actuator generating the force required to hold the needle.

4.1.2 Opening the Needle Driver Jaws

For opening the jaws of the needle driver, as shown in figure 4.3, first the SMA actuator is switched off. While the SMA actuator is cooling down, the DC motor is rotated in the clockwise direction. The clockwise rotation of the screw causes the SMA actuator to move in the forward direction. As the SMA wires cannot transmit compressive forces, the pre-loaded spring transmits the force generated by the DC motor to open the needle driver jaws. The preloaded spring in the SMA actuator gives the necessary bias force for the SMA wires to reach its initial length. As the motor continues to rotate, the needle driver jaws open up. The DC motor is switched off after the jaws open up.

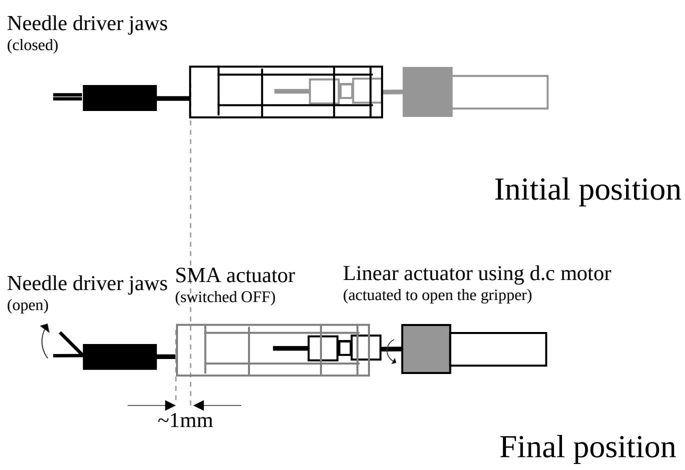


FIGURE 4.3: Actuation of DC motor for opening the needle driver jaws.

4.2 Characterization of the SMA actuator

4.2.1 Introduction

Shape Memory alloys are metals that exhibit two unique properties: pseudo-elasticity, and the shape memory effect. Shape memory effect is the unique ability of shape memory alloys to be severely deformed and then returned to their original shape simply by heating them. Arne Olander was the first to observe these unusual properties in 1938 (Oksuta and Wayman 1998). The most effective and widely used alloys include NiTi (Nickel - Titanium), CuZnAl, and CuAlNi.

The two unique properties of the SMA, pseudo-elasticity and shape memory effect, occur due to a solid state phase change. A solid state phase change in shape memory alloy materials is similar to that of a molecular rearrangement occurring during the transformation of a material from solid to liquid, but the molecules remain closely packed so that the substance remains a solid. The two phases that occur in shape memory alloys are Martensite and Austenite.

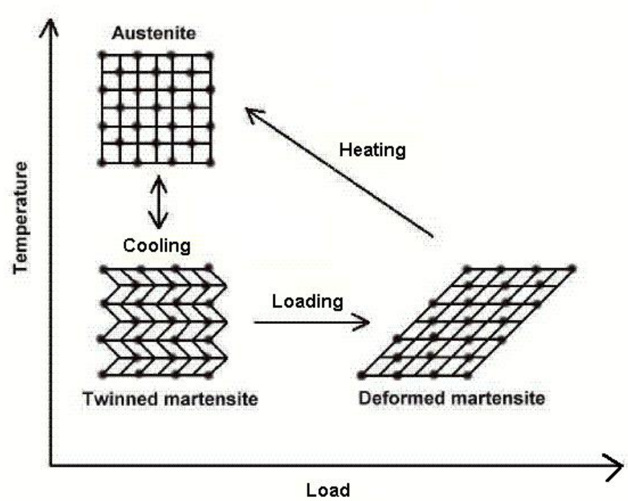


FIGURE 4.4: Shape Memory Effect [27]

Martensite is the relatively soft and easily deformed phase of shape memory alloys, which exists at lower temperatures. The molecular structure in this phase is twinned, as shown in figure 4.4. When the material is deformed in Martensite state, then the molecular structure changes as shown on the right side of the figure 4.4. Austenite, the stronger phase of shape memory alloys, occurs at higher temperatures. The shape of the Austenite structure is cubic, the structure shown on the left side of figure 4.4. The un-deformed Martensite phase is the same size and shape as the cubic Austenite phase on a macroscopic scale, so that no change in size or shape is visible in shape memory alloys until the Martensite is deformed.

4.2.2 Experimental Setup

Flexinol® SMA wire of 0.154mm diameter supplied by Dynalloy Inc [28] is used in our actuator. Flexinol® is a trade name for shape memory alloy actuator wires. Made of nickel-titanium, these wires contract when they are heated. The contraction of Flexinol® actuator wires when heated is opposite to ordinary thermal expansion, is larger by a hundredfold, and exerts tremendous force for its small size.

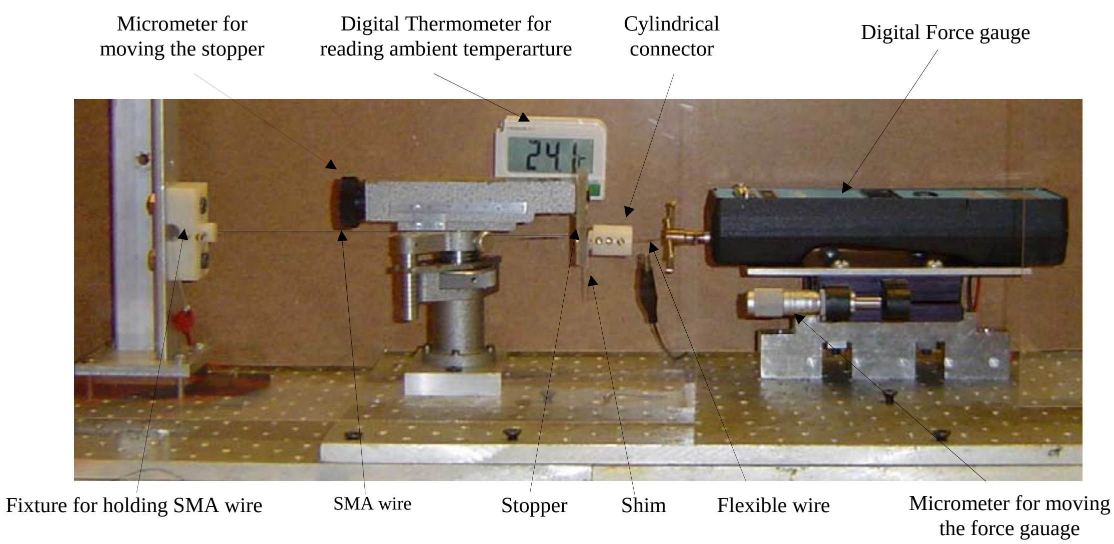


FIGURE 4.5: Experimental setup for determining SMA characteristics.

The experimental setup shown in figure 4.5 is constructed to obtain the force versus stroke length characteristics of the SMA wire. One end of the SMA wire is connected to a fixture which is firmly fixed to the base plate, and the other end of the SMA wire is connected to a force gauge through a cylindrical connector and a flexible wire. The stiffness of the supporting structure for holding the SMA fixture is measured before carrying the experiment and is found to be very high for the forces applied during the experiment. So the supporting structure is treated as a rigid structure as the deformation at this end is negligible. Initially the force gauge is moved with the help of a micrometer in a direction which increases the tensile force in the SMA wire. As soon as the force gauge reading shows 0.5N (to make the SMA wire taut) the movement is stopped and the movable stopper is moved to transfer the load from the force gauge. A shim is placed in between the connector and the stopper, and the stopper is moved towards the connector until the force gauge shows a reading of 0N. Then, the SMA wire is actuated by passing current through it and heating it to 75 to 80 degrees C. The temperature of the SMA wire is measured using a FLUKE 80TK temperature probe [29]. At this point, the SMA wire is actuated with both of its ends constrained, so the force generated in the SMA wire is approximately equal to the maximum force the SMA wire can generate with almost zero displacement. Then, the force gauge is slowly moved away from the stopper until the shim inserted in between the connector and the stopper falls, at which point the force gauge reading is approximately equal to the force generated in the SMA wire. Corresponding value of the micrometer reading is taken down. Once the initial reading is obtained for zero stroke length, the stopper is moved towards the fixture by a known displacement and the force gauge is moved towards the stopper until its reading becomes zero and the shim is placed in between the connector and the stopper. Then the force gauge is moved away from the stopper till the shim falls of and at this point the force reading and the displacement of the stopper from the initial position are noted down. It is repeated in this way to obtain a set of force readings for a set of known stroke length readings. For example from the figure 4.6, we can determine that the 270 mm length and 0.154mm diameter SMA wire can generate a force of 4 N for a stroke length of 2.25 mm. This means that a SMA actuator with 8 SMA wires, each one 30mm (aproximately) in length, connected mechanically parallel can generate a combined force of 32N if the SMA actuator structure allows a movement of 0.2mm (approximately).

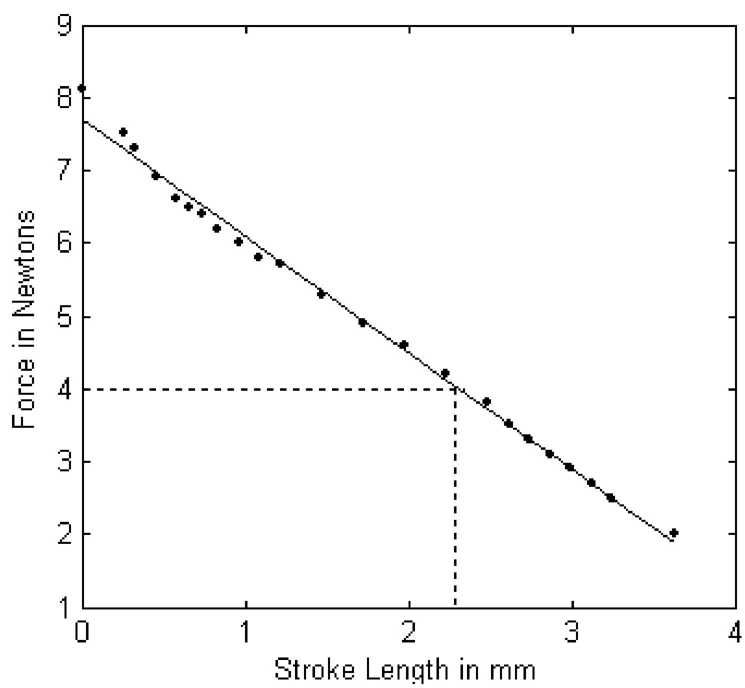


FIGURE 4.6: Force vs stroke length characteristics of the SMA wire (0.154mm diameter wire).

4.3 Design Prototype of Hybrid Actuator

In order to test the feasibility of the design idea, a prototype was designed, which is almost twice the size of the final actuator design. As shown in figure 4.7, the micro gripper actuator prototype consists of a 5.8 mm diameter and 21.7 mm long Smoovy [30] brushless DC motor (BL2S5.025.R.0) with a planetary gear reduction of 1:25. The needle driver gripper used in the prototype is cut from the Ethicon endoscopic needle driver instrument (E705R). The linear actuator consists of a 5.8 mm DC motor, which is connected to a 1.46 mm diameter screw (80 threads per inch) through a connector. The torque generated by the DC motor with 1:25 reduction gear train, as per the specifications provided in the Smoovy motor data sheets is 1.2mNm. As the main objective of this test setup was to show the feasibility of the design idea, we chosen a motor which is powerful for the given task

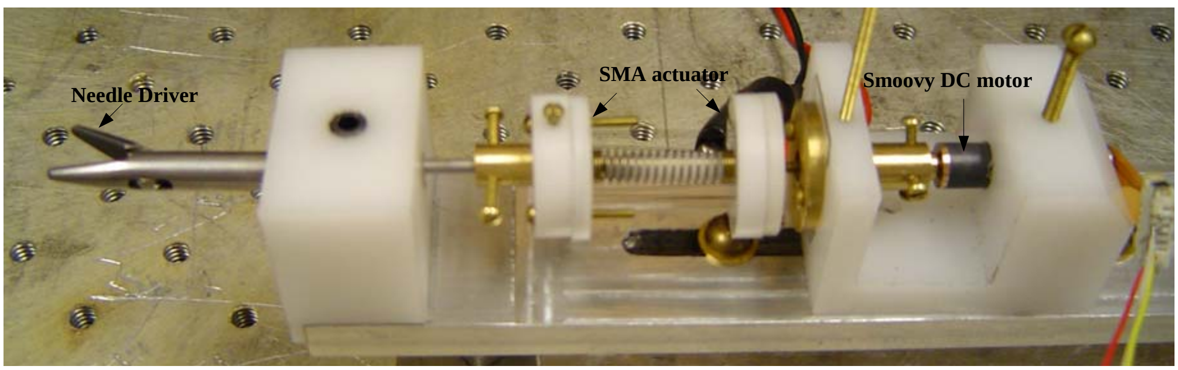


FIGURE 4.7: Design prototype of the hybrid actuator

The components of the SMA actuator are fabricated out of thermoplastic as they have to isolate the SMA wires electrically and can with stand high temperatures. Table III specifies the properties of different thermoplastics that are available commercially. The SMA actuator consists of a 0.1524mm diameter SMA wire wound around the cylindrical Derlin (Acetal) block through holes, as shown in figure 4.8. The main reason for selecting Derlin to make the SMA actuator components is that it is widely available and can be machined easily when compared to the other thermoplastics. Derlin has good mechanical properties and can withstand an operating temperature of 115 °C. The SMA wire weaved around the SMA actuator acts as eight individual SMA wires connected mechanically in parallel. The SMA actuator is pre loaded with a spring to provide necessary reverse bias force to the SMA wire. As the SMA wire cannot transmit compressive forces, the loaded spring transmits the compressive force required for opening of the gripper. The total length of the SMA wire used in the actuator is 380mm and the length of each individual wire is 22.5mm. The SMA actuator is driven electrically as if the eight SMA wires are connected in series with a total resistance of 19.6 ohms.

TABLE III. COMPARISON OF THE MECHANICAL PROPERTIES OF DIFFERENT THERMOPLASTICS [31]

Thermo Plastic	**Type**	**Tensile Strength (MPa)**	**Machinability (20=best)**	**Operating Temperature (°C)**
Celazole PBI	PBI Polybenzimidazole	140	16	310
Derlin	Acetal	68	20	115
Ertalon 4.6	Nylon	100	16	150
Ertalyte	PETP Polyester	90	20	115
Ertalyte TX	PETP Polyester	76	20	115
Nylatron GS	Nylon	92	16	95
Nylatron GSM	Nylon	78	16	105
Nylatron MC901	Nylon	81	16	105
PEI-1000	PEI Polyetherimide	105	15	170
Polystone 300	PE Polyethylene	23	16	80
Polystone Ultra	PE Polyethylene	20	18	90
PPSU-1000	Polyphenylenesulphone	76	15	180
PSU-1000	PSU Polysulphone	80	15	150
PVDF 1000	Polyviylidenefluoride	50	16	150
Safeguard	PC Polycarbonate	65	8	125
Techtron HPV PPS	Polyphenylene Sulphide	75	15	220
Tetco V	Polytetrafluoroethylene	36	19	260
Tetron B	Polytetrafluoroethylene	23	7	260
Torlon 4203 & 4503	PAI Polyamide-imide	120	16	250
Trovidur EN PVC	PVC Polyvinylchloride	55	12	60

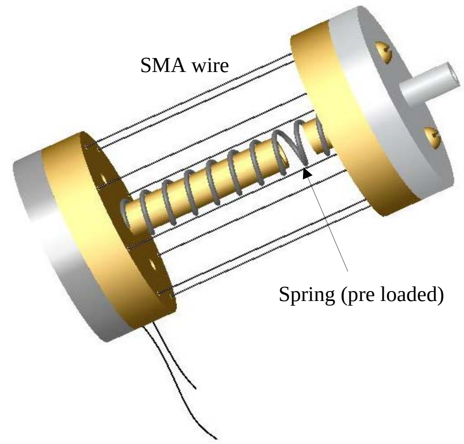


FIGURE 4.8: CAD model showing the SMA actuator.

4.3.1 Results

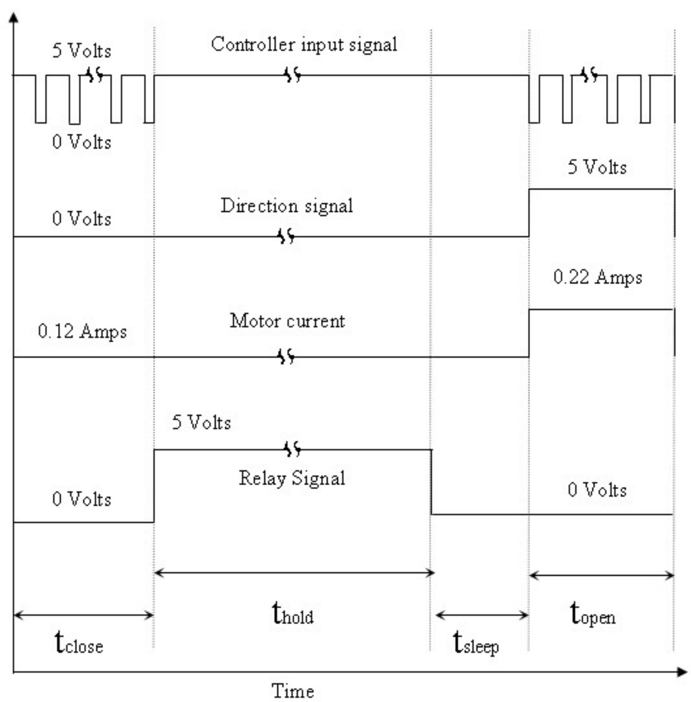


FIGURE 4.9: Waveform plot for controlling the hybrid actuator.

A plot of the signals required for one complete cycle of the hybrid actuator is as shown in figure 4.9. First the DC motor is actuated by giving a pulse signal to the input of the controller. Each pulse signal makes the DC motor rotate by 60˚, and a total of 520 pulses are required to close/open the gripper. The total time taken by the DC motor to close the gripper is 1.5 seconds (t_{close}). The direction of rotation of the DC motor depends on the direction signal. At the end of 1.5 seconds, after the gripper closes, the SMA actuator is actuated by switching the electro mechanical relay switch ON. The SMA actuator is actuated while the gripper needs to hold the needle, for a time of t_{hold} seconds. The amount of force applied by the gripper jaws on the needle is 8.5N. The DC motor is not actuated immediately after switching OFF the SMA actuator, it is actuated after a time delay of 1.7 seconds (t_{sleep}) and the amount of current is increased from 0.12 to 0.22 amperes. The time delay is necessary to make sure that the SMA actuator has relaxed and is not applying high axial force on the linear actuator. At the end of the t_{sleep} seconds, the DC motor is actuated to open the gripper jaws. The DC motor rotates clockwise as the direction signal changes from 0 volts to 5 volts. The total time required for the one complete cycle excluding the time required to hold the needle is 4.7 seconds.

4.4 Design of First Generation Hybrid Actuator

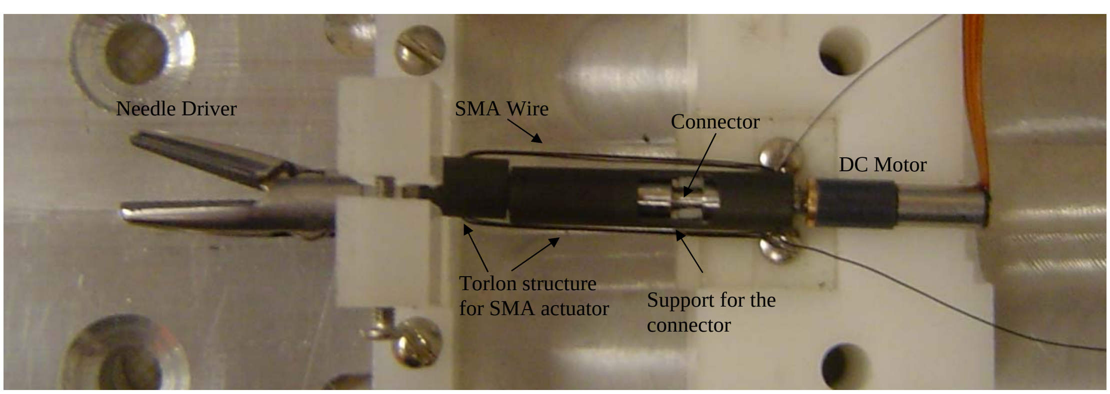


FIGURE 4.10: Design of First Generation Hybrid actuator.

As shown in figure 4.10, the millimeter scale actuator prototype consists of a SMA actuator made of Torlon and a 3.4 mm diameter and 12.22 mm long smoovy brushless DC motor (BL2S3.025.R.0) with a planetary gear reduction of 1:25. As shown in figure 4.11, the 3.4 mm motor is connected to a 1.46 mm diameter screw with a pitch of 80 threads per inch, through a connector that acts as a linear actuator for opening and closing the gripper. Instant adhesive is used to hold the connector and motor shaft together. The connector also acts as part of an axial bearing and isolates the motor from any axial forces that are produced when the SMA actuator is actuated. The torque generated by the DC motor with 1:25 reduction gear train, as per the specifications provided in the data sheets is 0.42mNm.

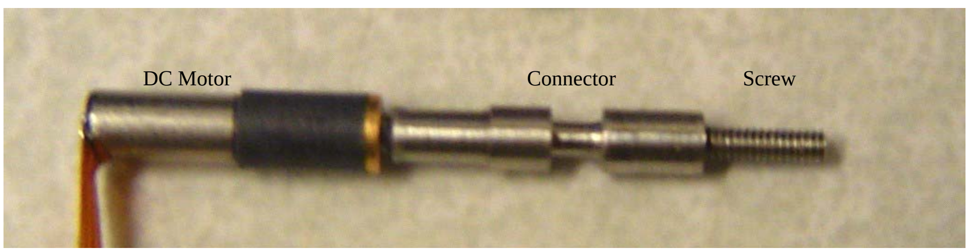


FIGURE 4.11: Linear actuator consisting of dc motor, connector and screw.

The SMA actuator consists of a 0.1524mm diameter SMA wire wound around the cylindrical Torlon structure through holes, as shown in figure 4.12. The main reason for selecting Torlon to fabricate the SMA actuator structure is that it can withstand high temperatures, has good mechanical properties when compared to Derlin, and can be machined easily when compared to Celazol. The structure made of Torlon consists of 0.3mm in diameter holes for weaving the SMA wire around it. The SMA wire weaved around the SMA actuator structure acts as six individual SMA wires connected mechanically in parallel. The SMA actuator is pre loaded with a spring to provide necessary reverse bias force to the SMA wire, as shown in figure 4.12. As the SMA wire cannot transmit compressive force, the loaded spring transmits the compressive force required for opening of the gripper. The total length of the SMA wire used in the actuator is 150mm and the length of each individual wire connecting the SMA actuator is 25mm.

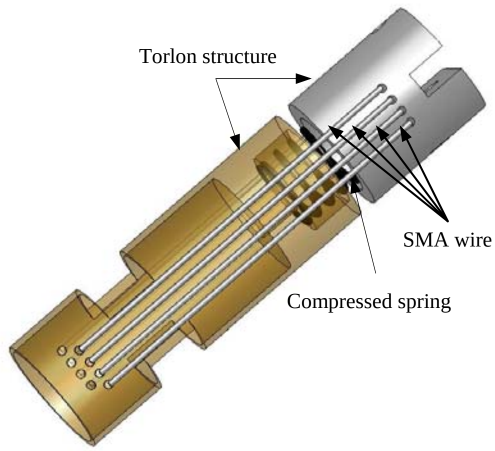


FIGURE 4.12: SMA actuator of the first generation hybrid actuator

4.4.1 Results

The testbed setup for testing the first generation hybrid actuator proved that the design concept tested with the design prototype can be achieved even by scaling the dimensions of the actuator components to fit within a 4.5mm inner diameter tube. The amount of gripping force generated by this hybrid actuator setup at the end of the 10mm long needle driver jaw is 5.5N. The pattern of signals required for the excitation of the hybrid actuator is similar to that of the plot of signals shown in figure 4.9. The total time taken by the DC motor to close the gripper is 1.5 seconds approximately and the total cycle time for opening and closing the gripper is 4 seconds, as it includes 1 second delay in opening the gripper after the SMA actuator is switched OFF. This delay is required to make sure that the SMA does not apply high force on the motor when it is switched ON.

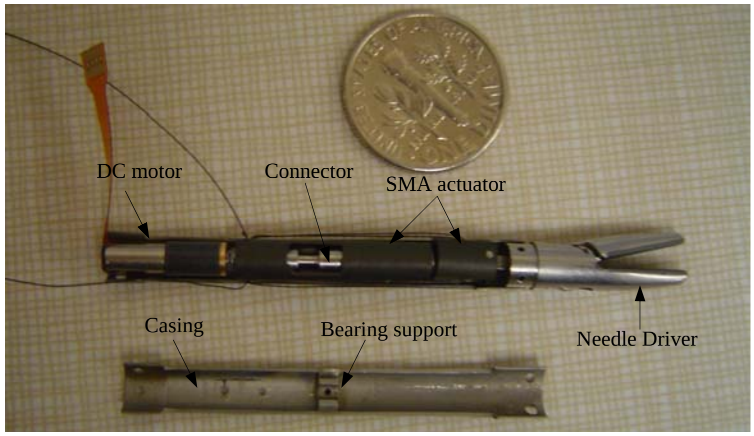


FIGURE 4.13: Assembly of the first generation hybrid actuator

As shown in figure 4.13, the casing for the hybrid actuator consists of a bearing support structure to hold the actuator assembly in place and protect the motor from axial forces. The casing is made out of steel, as the thickness of the casing needs to be very thin and it has to provide structural stability to the actuator assembly. The idea of Teflon coating on the inner side of the casing was pursued in order to electrically isolate the SMA wires from the casing. Given the tight tolerances of the parts, the Teflon coating can be only on the order of micron thickness. At this thickness it is very difficult to control the density and uniformity of the Teflon coating resulting in a significant manufacturing challenge. The major problem with this assembly is that the parts have close tolerances and the clearance between them is very low. So if the parts are not aligned properly then the performance of the actuator is not as expected. Therefore a second generation hybrid actuator was designed to overcome these problems.

4.5 Design of the Second Generation Hybrid Actuator

The second generation actuator is designed in such a way that the assembly of the various parts inside the actuator is simple and all the parts can be assembled inside a 4.6mm inner diameter casing. As shown in figure 4.14, the constructed final actuator is 5.14mm in diameter and approximately 60mm in length. The outer casing for the hybrid actuator is fabricated out of Celazol material. As shown in Table III, Celazol has better mechanical properties when compared to Torlon in terms of tensile strength and operating temperature. As the casing needs to be very thin and should provide structural support to the actuator assembly, Celazol is preferred to that of Torlon.

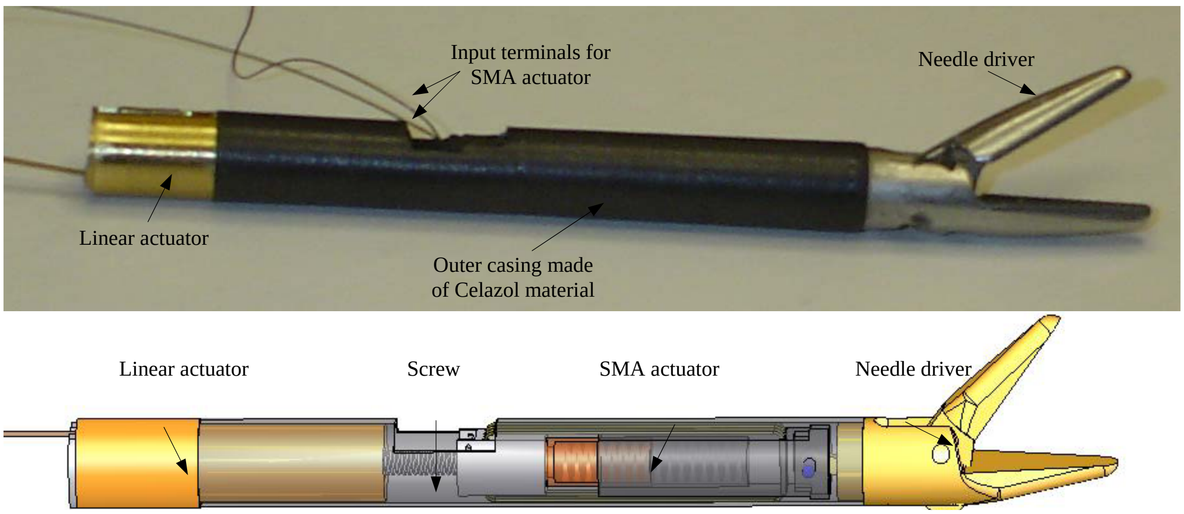


FIGURE 4.14 Second Generation Hybrid Actuator

4.5.1 Design of the SMA Actuator

The SMA actuator, as shown in figure 4.15, consists of a lower fixture, upper fixture, spring holder and a spring. The major and minor diameters of the lower fixture and upper fixture are 4.2mm and 3.2mm. Lower and upper fixtures for the SMA actuator are fabricated from Torlon material. Torlon was selected for fabricating the SMA actuator as it can withstand high temperatures, can be machined easily and isolates the SMA wires electrically. The lower fixture contains 0.3mm in diameter holes to hold the SMA wire and for tying a knot to secure the ends of the SMA actuator. The spring holder acts as a housing for the spring that is used to provide reverse bias force to the SMA wire. The end of the spring holder that goes into the lower fixture contains a threaded hole to move the SMA actuator linearly when the screw shaft on the linear actuator is rotated. The spring holder for the actuator is made of brass. The reason for using brass to fabricate the spring holder is that it acts as a heat sink for the SMA actuator and provides low friction between the screw and the threaded hole. There is a clearance between the spring holder casing and the inner diameter of the upper fixture, so that the spring holder can slide inside the upper fixture. Upper fixture is also fabricated from Torlon and it holds and connects the SMA actuator to the needle driver.

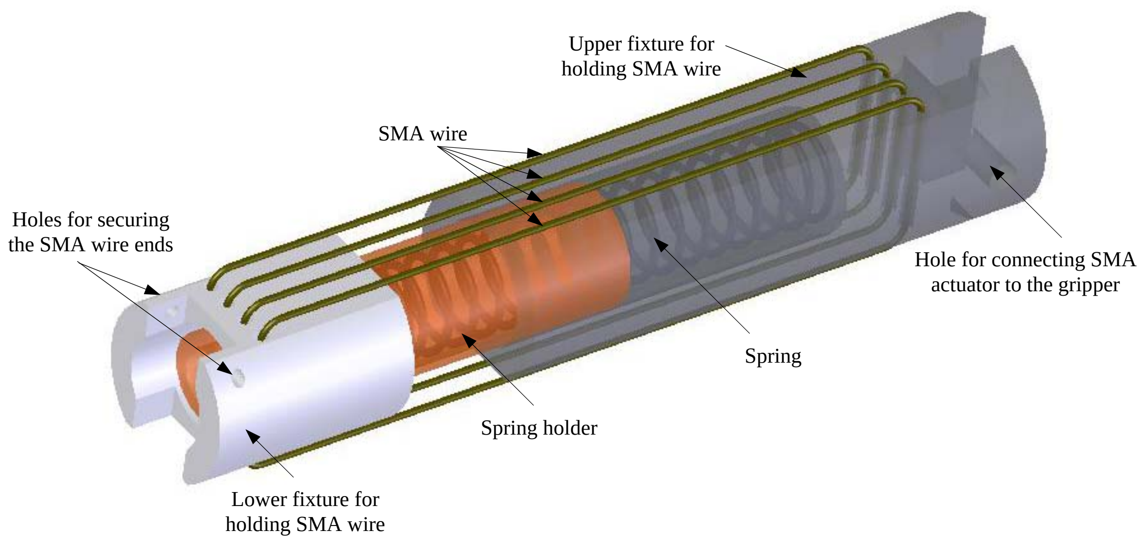


FIGURE 4.15 CAD model of the SMA actuator

Figure 4.16 shows an exploded view of the SMA actuator. During the assembly of the SMA actuator, first the spring holder and the lower fixture are joined together by applying instant adhesive. Then the assembly of the spring holder and lower fixture is loaded into the upper fixture with the spring in between them. This assembly is loaded into the SMA weaving instrument for holding the components of the SMA actuator in position, under the compressive force of the loaded spring, as shown in figure 4.17. The SMA weaving instrument is made of Torlon material. In order to provide the reverse bias force on the SMA wire, the assembly of the lower fixture, spring holder and the upper fixture are locked in a position, by a positioning pin, such that the spring is compressed in between the lower fixture and the upper fixture. Once the position of the assembly is secured in the SMA weaving instrument the SMA wire is weaved around the assembly as shown in figure 4.18. The two ends of the SMA wire are secured to the lower fixture by tying a knot through the two additional holes provided on the lower fixture. Thermal resistive adhesive from Loctite [32] (4211 PRISM®) is applied on the knot to make sure that the SMA wire remains in position once the positioning pin is removed. Thermal resistive adhesive is used, because the temperature of the SMA wire reaches approximately 80 degree C during the operation of the SMA actuator. Once the adhesive is cured, the positioning pin is removed and the SMA actuator is removed by pushing it from the bottom of the SMA weaving instrument with a long thin rod.

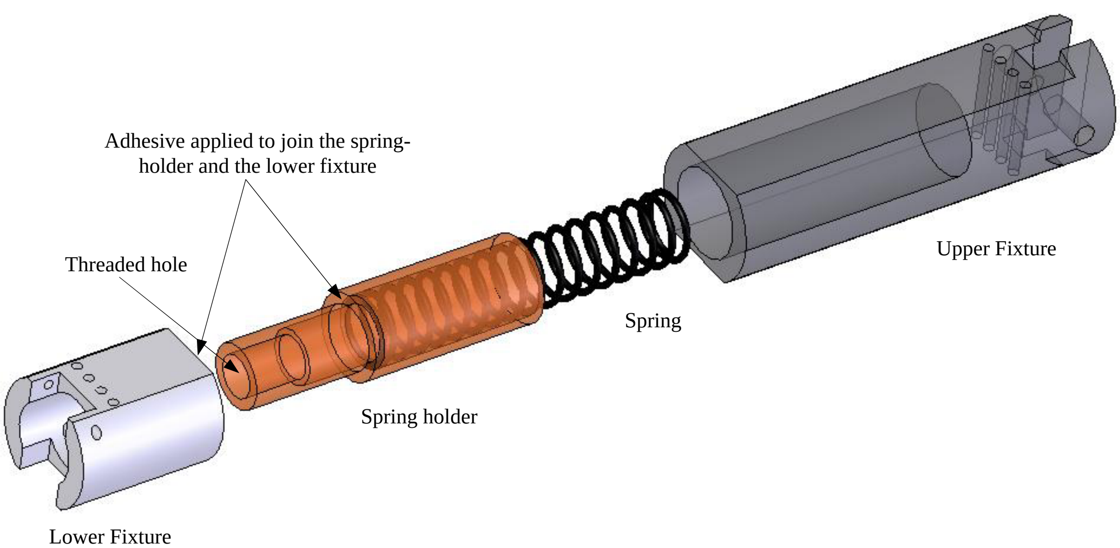


FIGURE 4.16 Exploded view of the SMA actuator

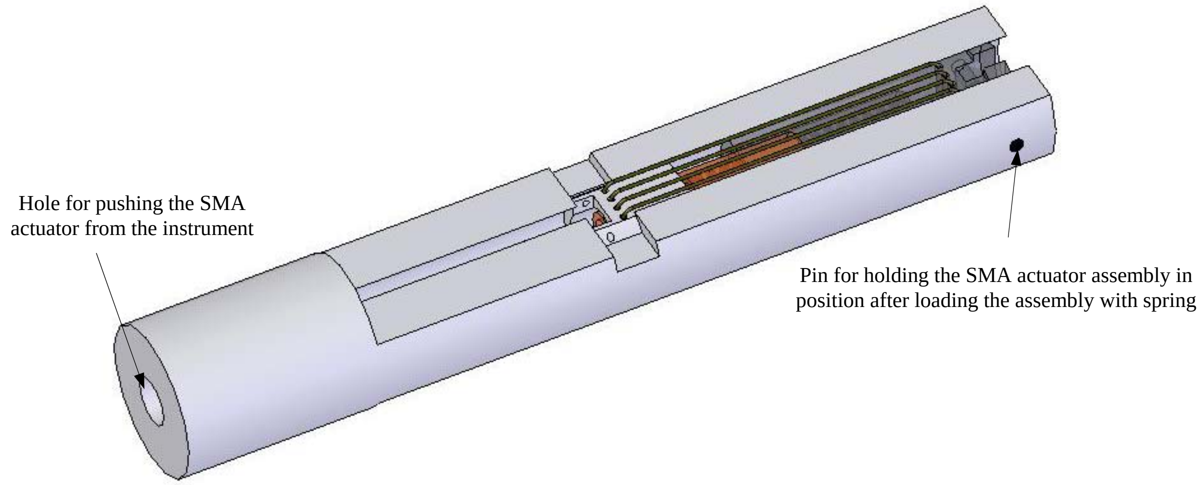


FIGURE 4.17 SMA weaving instrument

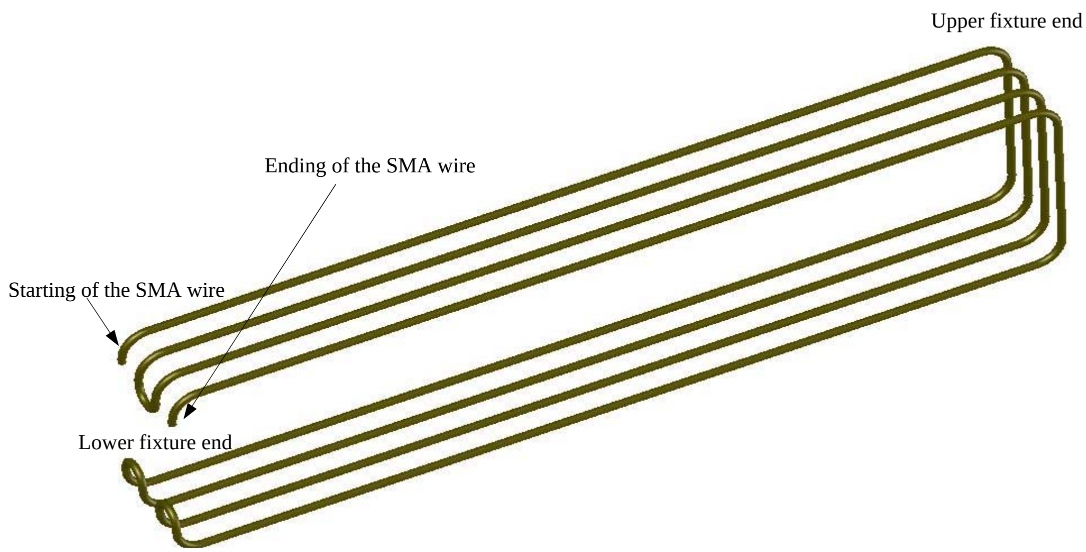


FIGURE 4.18 Weaving path of the SMA wire

4.5.2 Design of the Linear Actuator

The linear actuator part of the hybrid actuator consists of a 1.4mm diameter screw with a pitch of 0.3175mm that is rotated by a micro motor, as shown in figure 4.19. The micro motor used in this hybrid actuator is a 4mm outer diameter motor (SBL04-0829PG18) from Namiki [33] consisting of a 4mm diameter gearbox with a 1:18 reduction ratio. The reason for selecting Namiki motor over Smoovy motor is that the output speed and the amount of output torque generated by the Namiki motor are greater than Smoovy motor. The total length of the motor is 18mm including the length of the shaft. A hole of 0.8mm diameter and 3mm in length is drilled into the end containing the head of the screw. The motor shaft is slid through this hole and instant adhesive from Loctite (411 PRISM®) is applied to hold the motor shaft and the screw.

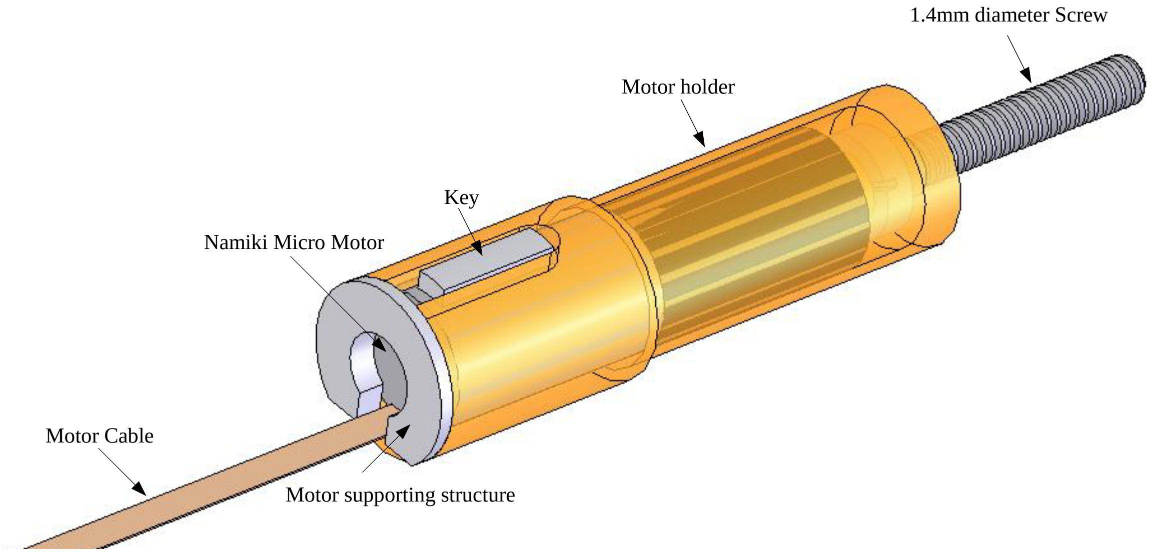
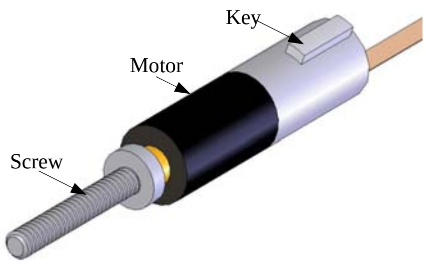


FIGURE 4.19 Design of Linear actuator

The linear actuator part of the hybrid actuator consists of a 1.4mm diameter screw with a pitch of 0.3175mm that is rotated by a micro motor, as shown in figure 4.19. The micro motor used in this hybrid actuator is a 4mm outer diameter motor (SBL04-0829PG18) from Namiki [33] consisting of a 4mm diameter gearbox with a 1:18 reduction ratio. The total length of the motor is 18mm including the length of the shaft. A hole of 0.8mm diameter and 3mm in length is drilled into the end containing the head of the screw. The motor shaft is slid through this hole and instant adhesive from Loctite (411 PRISM®) is applied to hold the motor shaft and the screw.



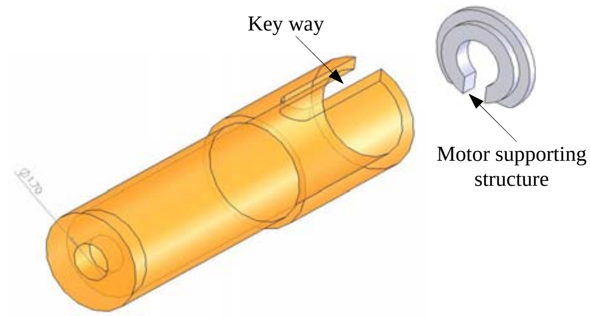


FIGURE 4.20 (a) Motor and screw assembly (b) Motor holder and supporting structure

As shown in figure 4.20, a key is attached to the casing of the motor. The screw and the motor assembly are slid into the motor holder such that the key on the motor casing is in between the key way of the motor holder. The key attached to the casing of the motor prevents the motor casing from rotating, but allows it to move linearly. The motor supporting structure is fixed to the end of the motor holder to fix the motor inside of the motor holder. A small clearance is left in between the motor and the supporting structure, so that the motor can slide by a fraction of a millimeter. The main advantage with this type of motor assembly is that the motor shaft is free from any high axial load that is generated during the operation of the SMA actuator, as the entire load is taken by the screw head.

4.5.3 Assembly Procedure

During assembly, first the SMA actuator is attached to the sliding link of the needle driver, as shown in figure 4.21. A connecting pin is used to connect the sliding link and the SMA actuator. There is clearance provided in between the sliding link and the connecting pin, so that the connecting pin can freely pivot over the sliding link. But there is a tight fit in between the SMA upper fixture and the connecting pin; as a result the connecting pin stays with the upper fixture of the SMA actuator.

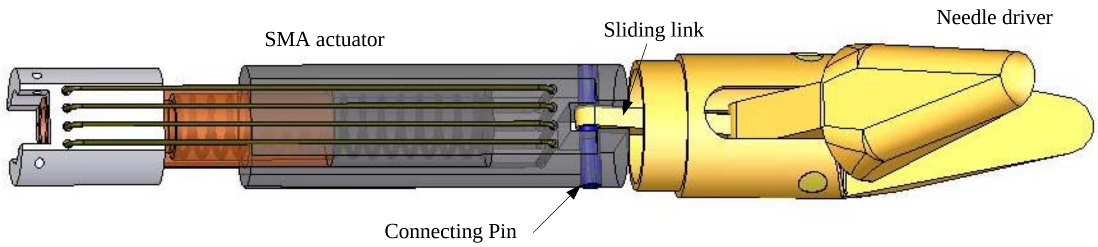


FIGURE 4.21: Assembly of SMA actuator and Needle driver

After assembling the SMA actuator and needle driver, the casing is assembled by applying adhesive between the needle driver and the inner surface of the casing. Then the linear actuator is connected to the drive circuit and is rotated in the anti-clockwise direction. Rotation of the linear actuator in the clockwise direction makes the screw advance in the forward direction into the SMA actuator. Once the linear actuator is inside the outer casing, adhesive is applied to attach the linear actuator to the casing firmly.

4.5.3 Results

A plot of the signals required for one complete cycle of the second generation hybrid actuator is as shown in figure 4.22. First the DC motor is actuated by giving an input signal to the input of the Namiki motor drive unit (SSD04). Namiki motor drive drives the motor in an open loop control method as the motor does not have any feedback sensors. The total time taken by the DC motor to close the gripper is 0.4 seconds (t_{close}). The direction of rotation of the DC motor depends on the direction signal. At the end of

0.4 seconds, after the gripper closes, the SMA actuator is actuated by switching the electro mechanical relay switch ON. The SMA actuator is actuated while the gripper needs to hold the needle, for a time of t_{hold} seconds. The amount of force applied by the gripper jaws on the needle is 8N. The DC motor is not actuated immediately after switching OFF the SMA actuator, it is actuated after a time delay of 1second (t_{sleep}). The time delay is necessary to make sure that the SMA actuator has relaxed and is not applying high axial force on the linear actuator. At the end of the t_{sleep} seconds, the DC motor is actuated to open the gripper jaws. The DC motor rotates in the clockwise direction as the direction signal changes from 0 volts to 5 volts. The total time required for one complete cycle excluding the time required to hold the needle is 1.8 seconds.

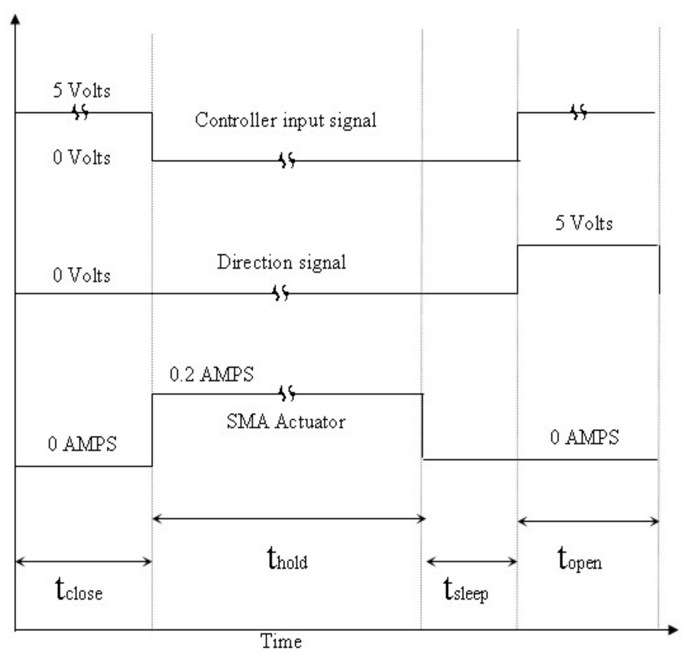


FIGURE 4.22: Waveform plot for controlling the second generation hybrid actuator.

Chapter 5

Conclusion

This thesis addresses the need for a local actuation system for the end effector used in MIS/MIRS and presents a novel design of a hybrid actuator for MIS/MIRS applications. This work is based on the premise that despite surgeons considerable skill and ability to perform within the constrains of current MIS/MIRS technology, the use of minimally invasive surgery remains limited by the lack of dexterity with which surgeons can operate while using current MIS/MIRS instruments.

The main focus of this thesis was on the design idea to actuate the needle driver locally, so that the design of a wrist for 5mm diameter MIRS instruments can be made possible. The hybrid actuator designed in this thesis meets the design requirements for the actuator that were laid out in chapter 3. The second generation hybrid actuator design is approximately 5mm in diameter and 60mm in length. The amount of force generated by the hybrid actuator is 24N and the force applied by the needle driver jaws to hold the needle is measured to be 8N. The designed hybrid actuator proved that it can generate sufficient force to be used in MIS/MIRS applications.

5.1 Future Work and Improvements

The present research work was only focused on the design of the local actuation system and did not look into the design of a spherical wrist for MIRS applications. Future research work will proceed towards the design of a spherical wrist.

This thesis is more focused on coming up with a design idea that works in the design constraints and still achieves the performance goals. There is a large scope of improvements for this hybrid actuator to increase its performance. Presently the actuator operates as a feed-forward device without any position feedback. One improvement that can be done in this area is to use micro position sensors to get feedback of the absolute position of the end effector jaw.

The amount of force required for holding the needle is different from the force required to hold the tissue. So if micro force sensors can be embedded on to the needle driver jaws, the SMA actuator can be controlled to generate appropriate amount of force based on whether it has to hold the needle or the tissue.

Presently the outer casing of the actuator is fabricated from Celazol, which is an electrical and thermal insulator. So the performance of the actuator can reduce if the SMA actuator is switched ON for long time, due to over heating of the internal parts of the actuator. But if we design the outer casing out of brass and coat the inside diameter with a very thin layer of Teflon, the performance of the actuator can be increased as the amount of heat dissipated to the surrounding environment will be more. Even the use of micro solid state coolers can be investigated to cool the SMA actuator rapidly and reduce the amount of time taken to open the needle driver jaws.

The present design uses the needle driver tip cut from an endoscopic needle driver instrument and is not designed to give optimum performance for use with the hybrid actuator. If a custom gripper is designed for the hybrid actuator, it can decrease the overall length of the actuator and can increase the amount of force applied.

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