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Design and Characterization of a Novel Hybrid Actuator using Shape Memory Alloy and D.C Motor for Minimally Invasive Surgery Applications

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***Abstract* - Recent developments in the field of robotics, smart materials, micro actuators and mechatronics have opened a new frontier for innovation and development in millimeter scale actuators for use in medical robotics. In this paper a novel design idea for developing a millimeter scale actuator is presented for actuating the end effector of a robot performing minimally invasive surgery (MIS). This actuator is designed by combining D.C motor and shape memory alloy (SMA) actuator in series. The designed actuator is 5mm in diameter and 40mm in length and is used to actuate 10mm long needle driver jaws, while generating a force of 15N and a gripping force of 5.5N.**

Index Terms* — *Medical robotics, millimeter scale actuators, minimally invasive surgery, shape memory alloy actuator.

I. INTRODUCTION

Medical robotics is a new and promising field for innovation and development of new tools for enhancing the capabilities of surgeons**.** In this paper the design and characterization of a millimeter scale actuator for use with an end effector in MIS are discussed. This hybrid actuator can be used to improve the number of degrees of freedom for the robot performing MIS.

A. Laparoscopic surgery

Laparoscopic surgery is a revolutionary technique [1] that is minimally invasive, and the surgery is performed with instruments inserted through small incisions (less than 10 mm in diameter) rather than by making a large incision to expose the operation site. The main advantage of this technique is the reduced trauma to the healthy tissue, which is the leading cause of post-operative pain and long hospital stay of the patient. The hospital stay and rest periods, and the resulting procedure's cost, are significantly reduced with MIS, at the expense of more difficult techniques currently performed by surgeons. Adoption of laparoscopic techniques has been slower in more complex procedures, largely because of the greater difficulty due to the surgeon's reduced dexterity and perception of the operation.

B. Surgical Robots

There are two commercially available telemanipulation systems that are currently in use for cardiac surgery: the da Vinci Robotic System (Intuitive Surgical, Inc., Sunnyvale, CA) and the Zeus Robotic System (formerly Computer Motion, Inc., now part of Intuitive Surgical). In order to generate high gripping force for the end effector while maintaining small instruments size, the power transmission mechanisms are designed in such a way that the motors can be placed outside the human body. The da Vinci Robotic system uses a tendon driven mechanism and the Zeus Robotic system uses a serial linkage mechanism for transmitting the power from the motors to the end effector. The da Vinci system has an 8mm instrument diameter and includes a robotic wrist at the end of the instruments that provide articulated motions with 6 degrees of freedom (DOF) of movement inside the chest cavity, in contrast to the Zeus system which has a 5mm instrument diameter but lacks an articulated wrist allowing only 5 DOF inside the chest cavity. The Zeus system on the other hand requires a significantly smaller incision to be made on the body over the da Vinci system

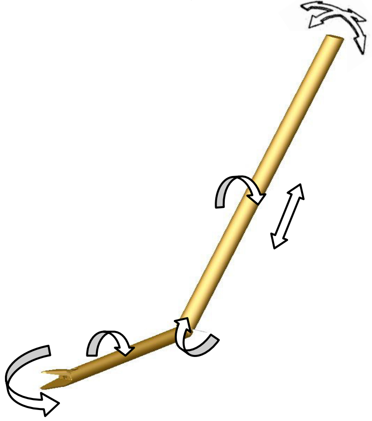

Figure 1. 7 DOF for an end effector having multi DOF wrist and local actution system.

If the robot has a multi DOF wrist then the number of DOF for the end effector can be increased, which allows the surgeon to perform the surgery with more dexterity. A conflicting objective is to reduce the diameter of the multi DOF robotic surgical instruments to allow their use in variety of applications, including minimally invasive pediatric, neonatal and fetal surgery. Due to the present actuating mechanisms for the end effector and power transmission for orienting the end effector, it is hard to design a multi DOF wrist for orienting the end effector of a 5mm diameter robotic instrument for MIS. If we can integrate a local actuating system with the end effector itself, this would simplify the wrist design, facilitating construction of wrists with higher DOF, as we can eliminate the transmission of the mechanical power through the wrist to the end effector.

Developing a device for local actuation is the major challenge in designing new tools for MIS. In this paper, the design of a novel hybrid actuator driven by a miniature brushless D.C motor and SMA actuator is presented to overcome the present limitations of current MIS tools.

II. DESIGN CONSIDERATIONS

A. *Design requirements*

The goal of the design is to develop a millimeter scale actuator which can be used locally to actuate laparoscopic needle driver jaws, thereby facilitating development of a multi DOF wrist and developing a robot with more DOF for performing MIS. 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 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
Gripping force	5N min
Stroke length	1-3 mm max
Gripper closing time	2 seconds max

B. *Comparison of various design alternatives*

Table II [2]-[5] shows the comparison chart for different actuators 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. A 7mm in diameter actuator [6] is designed by using piezo electric crystals to operate as an Inchworm actuator to drive the laparoscopic needle driver. This actuator can be fed only through an 8mm trocar as compared to the 5mm trocar in our present design.

SMA wire was used in the design of different actuators [7]-[9] for many 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.

TABLE II. COMPARISON OF DIFFERENT ACTUATION TECHNOLOGIES *(adapted from Kornbluh et al. 1998 [8])*

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

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 gearbox, the feasibility of using DC motors in miniature applications has increased. Micro DC motors have been investigated in [10]-[12], 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. In this paper we propose a design solution to use the positive attributes and to overcome the drawbacks of both these actuators.

III. SHAPE MEMORY ALLOY CHARACTERISTICS

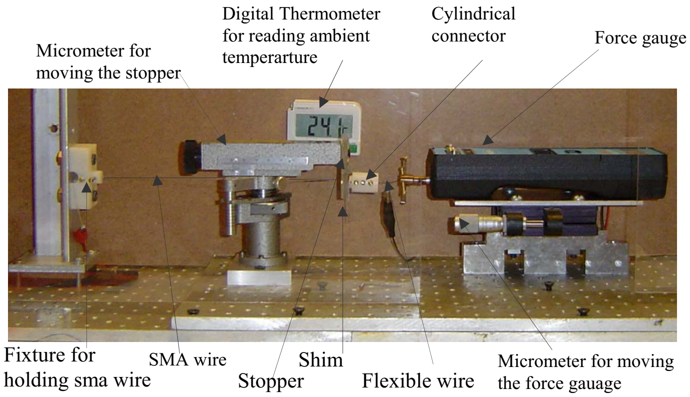

Figure 2. Experimental setup for determining SMA characteristics.

Flexinol SMA wire of 0.154mm diameter supplied by Dynalloy Inc [13] is used in our actuator prototype. The experimental setup shown in Fig. 2 is constructed to obtain the force vs 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. 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 [14]. 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 till the shim inserted in between the connector and the stopper falls, the force gauge reading is approximately equal to the force generated in the SMA wire. Corresponding value of the micrometer reading is taken down. In this way a set of force readings are taken for a set of known stroke length readings. From the readings of the force vs stroke length characteristics, Fig. 3, we can decide 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 (approximately).

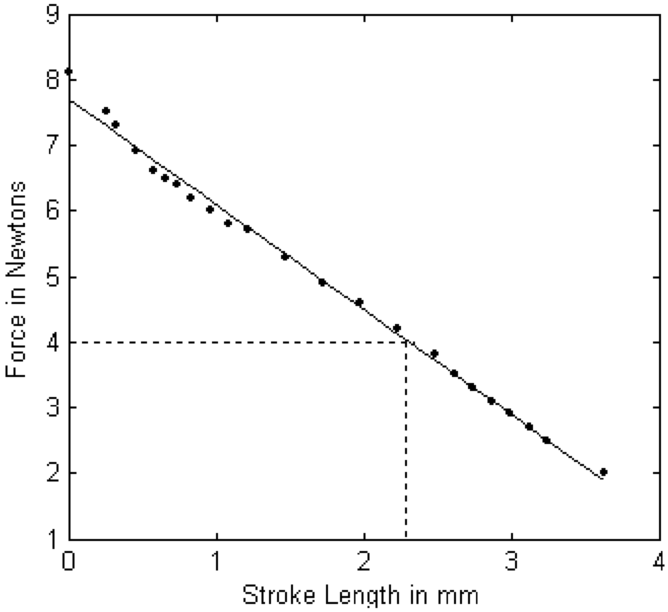

Figure 3. Force vs stroke length characteristics of the SMA wire (0.154mm diameter wire).

IV. DESIGN OF MILLIMETER SCALE ACTUATOR PROTOTYPE

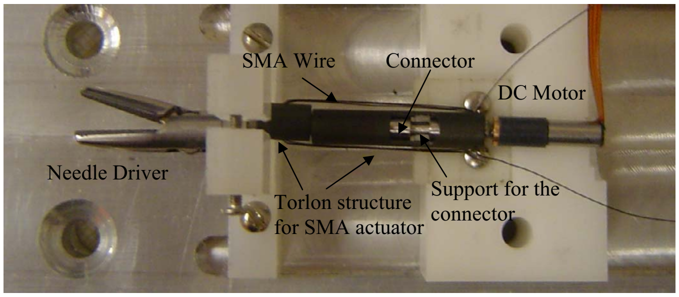

Figure 4. Photo of the design prototype.

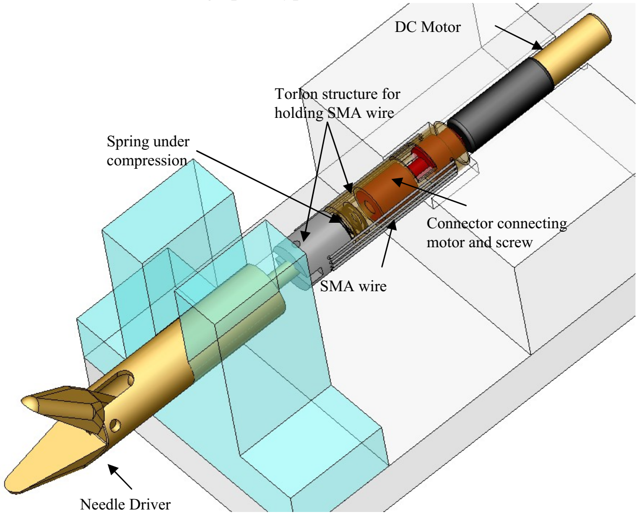

Figure 5. CAD model of the design prototype.

A. *Design principle*

The designed hybrid actuator works as a two phase actuator. 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.

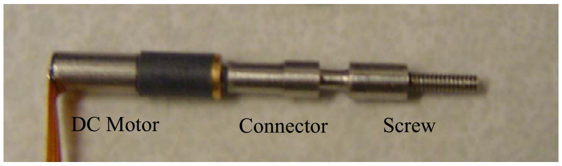

Figure 6. Linear actuator consisting of dc motor, connector and screw.

As shown in Fig. 6, the millimeter scale actuator prototype consists of a 3.4 mm diameter and 12.22 mm long smoovy [15] brushless DC motor (BL2S3.025.R.0) with a planetary gear reduction of 1:25. 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. The connector acts as a 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.

The SMA actuator consists of a 0.1524mm diameter SMA wire wound around the cylindrical torlon structure through holes, as shown in Fig. 4. Torlon is used to built the SMA actuator structure as it can withstand high temperatures, has good mechanical properties, and can be machined easily. This SMA wire 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 Fig 5. 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 150mm and the length of each individual wire connecting the SMA actuator is 25mm.

B. *Closing the needle driver jaws*

As shown in the Fig. 7, 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, Fig. 8, as the jaws reach the closed position, the DC motor is stopped and SMA actuator is actuated. SMA actuator is actuated by heating the array of parallel SMA wires by applying current. At this position the force exerted by the needle driver jaws on the needle is approximately 5.5 N. This force is enough for the needle driver jaws to hold the needle for performing suturing.

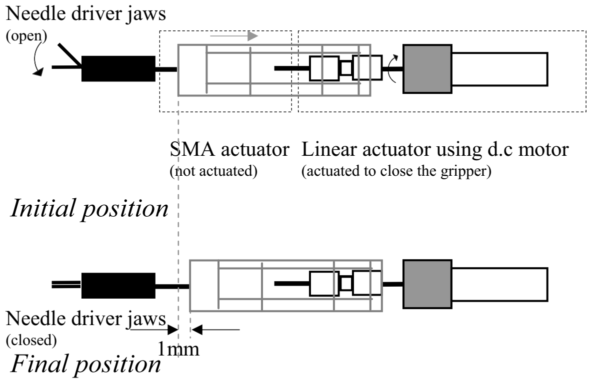

Figure 7. First phase of actuation in closing the needle driver jaws.

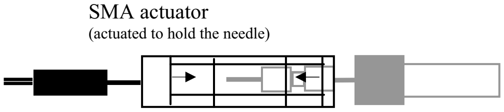

Figure 8. Second phase of actuation, SMA actuator generating the force required to hold the needle.

C. *Opening the needle driver jaws*

For opening the jaws of the needle driver, Fig. 9, first the SMA actuator is switched off. While the SMA actuator is cooling down, the DC motor is rotated in clockwise direction. The clockwise rotation of the screw causes the SMA actuator to move in the forward direction. As the SMA wires cannot transmit the compressive forces, the pre-loaded spring transmits the force generated by the DC motor to open the needle driver jaws. As the motor continues to rotate the needle driver jaws open up. The time taken to open the jaws of the needle holder from the closed position is 1.5 sec. The DC motor is switched off after the jaws open up.

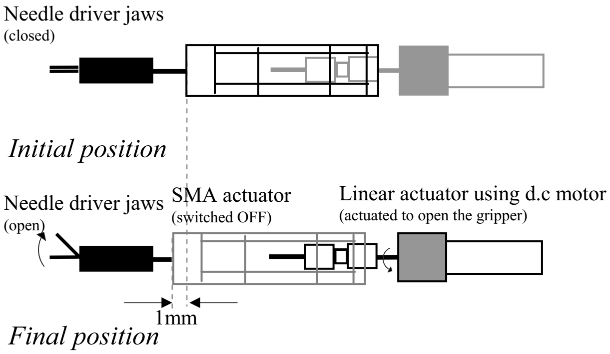

Figure 9. Actuation of dc motor for opening the needle driver jaws.

V. EXPERIMENTAL RESULTS

The designed prototype is interfaced to a computer through the printer port for controlling the motion of the gripper. The software code for generating the required signals is written in C++. The motor is controlled by a smoovy controller (BLCPS.000.2.8) and the required input signals for the controller are generated by the computer. The SMA actuator is controlled by switching an electro-mechanical relay ON and OFF through the computer. First the DC motor is actuated by giving a pulse signal to the input of the controller. Each pulse signal makes the DC motor to 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. The amount of gripping force generated by this setup at the end of the 10mm long needle driver jaw is 5.5N. This shows that the actual force generated by the SMA actuator is around 15N, as there is a reduction in the force applied to the force exerted by the needle driver.

VI. FINAL DESIGN

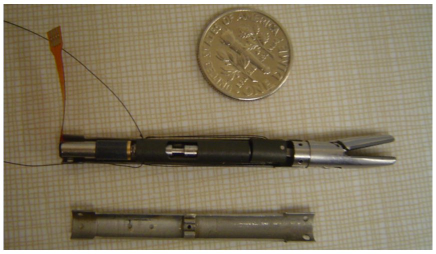

Figure 10. Assembly of the final design, that is under fabrication.

VII. CONCLUSION

This paper addressed the need for a local actuation system to actuate the end effector of a robot performing MIS. We discussed a novel design idea for developing a hybrid actuator, as a local actuation system. The force vs. stroke length characteristics are determined for the shape memory alloy wire used in the design of the actuator. We developed a prototype to test the feasibility of the design idea and tested it to determine the amount of gripping force generated.

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