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Characterization of SMA Actuator for Applications in Robotic Neurosurgery

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Abstract— **Shape memory alloy has been proven to be MRI compatible and due to its unique microstructure and molecular characteristics, it possesses many unique properties. Additionally, internal resistive heating of the wires eliminates the need for bulky external heating mechanisms. These advantages make SMA actuators good candidates for a wide range of applications in robotic surgical systems when compared to conventional actuators. In this paper, we present our preliminary work towards the development of a SMA based miniature robot for neurosurgery which can be operated under MRI. In this robot, we use two antagonistic SMA wires as actuators for each joint, so that each joint can be operated separately. We also designed an experimental setup to test the SMA wires. The goal of this experiment is to develop a systematic test especially for this robot and to collect sufficient data to estimate the performance of the robot. This setup can also be used to test SMA wires themselves. The data from this experiment will be used to determine important material parameters that are required for analytical models, and then use those models to develop a control strategy to manipulate the SMA actuators.**

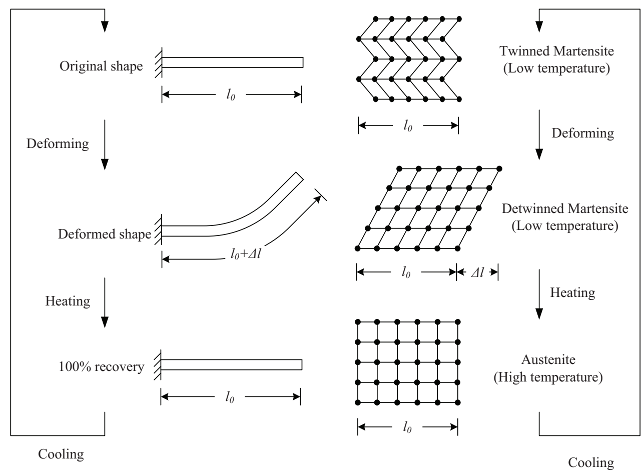

Fig. 1. Shape Memory Effect of Bending.

I. INTRODUCTION

Shape memory alloys (SMAs) have a special ability to memorize their shape at a low temperature, and recover large deformations on thermal activation. The recovery of strains imparted to the material at a lower temperature, as a result of heating, is called the Shape Memory Effect (SME). The shape memory effect is caused by a transformation between Martensite phase and Austenite phase in the material as shown in Fig.1. Furthermore, the properties of the material also depend on temperature. These phenomena can be traced to the lattice structure and associated deformation mechanisms inside the material. The most common shape memory material is an alloy of nickel and titanium called Nitinol (Nickel Titanium alloy developed at the Naval Ordinance Lab) which was discovered by Buehler and Wiley [1], [2]. This alloy has very good electrical and mechanical properties, long fatigue life, and high corrosion resistance. It also exhibits a much greater shape memory effect than any other materials. This material is a binary alloy of Nickel and Titanium in a ratio of 55% to 45% respectively. The recoverable strain up to a maximum of about 8% is achieved in this alloy. Another interesting feature is an over 200% increase in Young's modulus at high temperature phase as compared to low temperature phase. If the SMA encounters any external loads during the phase transformation, it can generate extremely large forces. This phenomenon provides a unique mechanism for actuation.

In our previous work, we have developed a preliminary prototype of a minimally invasive neurosurgical intracranial robot (MINIR) using SMA wires as actuators for possible application in neurosurgery [3]. Our goal for MINIR is able to resect tumor by positioning it such that it liquefies tissue and washes out the debris. MINIR will be fully MRI compatible, so that frequently-updated MRI can be used to provide virtual visualization of the target by the human operator as the target's 3-dimensional shape changes during resection. Because of such a special application, conventional actuators cannot be used for MINIR. Shape memory alloys, due to their unique microstructure and molecular characteristics, possess interesting properties such as large force to mass ratio, biocompatibility, light weight, and noiseless operation when compared to conventional actuators motors. Additionally, the internal resistive heating of SMA wires eliminates the need for bulky external heating mechanisms. These advantages make SMA actuators good candidates for MINIR as well as a wide range of applications in robotic surgical systems [3]–[7]. In this paper, we will propose a new design of MINIR

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which improves several disadvantages of our previous work. The new MINIR will have individual actuation for each joint and the SMA actuators are put antagonistically so that each joint can be moved back and forth independently. These designs give MINIR a larger motion range and better controllability. Further, the new design keeps all the joints on the outside surface of the robot which gives us more space inside for wiring and cooling system.

To use SMAs as actuators, it is important to first characterize the SMA. Since SMAs are extremely sensitive to test conditions, one should be very careful when doing experiments as well as interpreting experiment data. Shaw and Churchill *et al*. [8], [9] have published a series of papers to introduce uninitiated engineers to the testing of SMAs. They introduced phenomena and subtleties that can lead to difficulties in testing SMA wire and also highlight pitfalls in the interpretation of results. Furthermore, they described special experimental techniques that help to illuminate and quantify the macroscopic thermomechanical behavior.

Although there are many previous works have been done [8]–[11], the testing of SMAs is not yet standardized and material property tables either are not available or provide incomplete, or even incorrect data. This is because SMA behavior is nonlinear, hysteretic, and extremely temperature dependent. Since each SMA is different, it is necessary for us to develop our own experimental setup to obtain a satisfactory characterization of the material. Besides, most previous works are based on uniaxial tensile tests. However, for our special application, bending deflection is the most important parameter which we are interested in characterizing. Thus, in this paper, in addition to discussing the design of our robot, we also present the design of our experimental setup which is used to determine the correlation between bending deflection and temperature as well as the correlation between generated force and temperature of the SMA.

II. ROBOT DESIGN

Recently, we have developed a new design for MINIR. We use rigid-link joints and connected them by relatively short links, so that they can be used as universal joints as shown in Fig.2(a). The robot consists of nine revolute joints, and the joints are actuated by 0.012” diameter SMA wires. One larger hole through the base disc allows for the passage of electrical wiring which is used to actuate individual SMA actuators as well as for the electrocautery wire to reach the two probe tips on the top. Two additional holes have also been milled in the base disc for fastening to a fixed frame. In this prototype we have not developed the bipolar electrocautery system since our primary goal was to develop the SMA actuation mechanism and choose the robot components that would not cause any artifact in the MRI image.

We also have a new design of the robot body. In this new design, we put all joints on the outside surface of the robot and kept it hollow in the center. Thus, all the wiring and tubes will be kept inside the robot body. This design makes the robot more compact, safer and easier to shield.

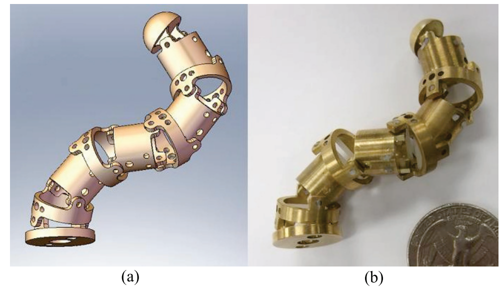


Fig. 2. (a) Schematic MINIR and (b) MINIR prototype

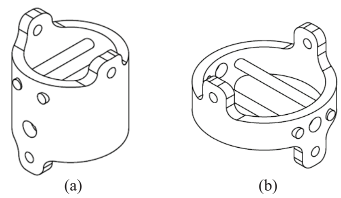


Fig. 3. Isometric View of (a) Body segment and (b) Ring connector.

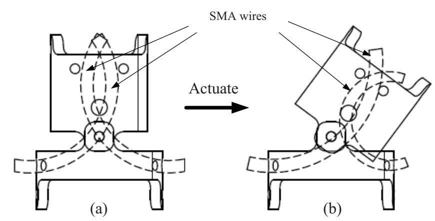


Fig. 4. Actuation mechanism (a) Stationary (b) Actuated.

The two major links are shown schematically in Fig.3. The dimensions of ring connector Fig.3(a) and body segment Fig.3(b) are 9mm in length, 13mm in diameter and 12mm in length, 10mm in diameter, respectively. The larger hole in Fig.3 was milled to allow for the passage of the SMA wire, and the remaining two small holes are for two columns to go through. These two columns are used for SMA actuators to push against during phase transformation and transmit necessary actuation force to each joint and resulting in joint motion. Fig.4 shows how this actuation mechanism works. In the stationary condition (see Fig.4(a)), SMA wires were bent to desired shapes in advance to keep the links straight. Since the maximum recoverable strain of the SMA wires is about 8%, it implies that the strain of SMA wires should not be over 4% in stationary condition. This is a very important design consideration for this robot. When we actuate the left side SMA wire, the wire will be heated up by electric current and thus goes back to its original straight shape. As a result, the body segment will be pushed by the wire and caused a clockwise rotation as shown in Fig.4(b). Furthermore, we use two antagonistic SMA wires as actuators for each joint, so that each joint can be moved back and forth and operated separately. These two new designs greatly increase the motion range and controllability of the robot.

III. SMA CHARACTERIZATION

The thermomechanical properties of SMAs depend on many variables, such as wire manufacturing process, wire diameter, pre-strain, stress level, temperature, annealing condition and thermo-mechanical history. The experiment in this part will only focus on the SMA wire we use for MINIR. The behavior of a SMA is a function of its three primary variables: stress, strain and temperature. To determine the correlation between any two of the above variables, we need to fix the other one when performing the experiment. For example, in our test, we would first like to correlate bending angle with temperature so that we can use temperature as a feedback signal to control the motion of the SMA wires as well as the end-effector position of the robot. The goal of this experiment is to develop a systematic test especially for MINIR and to collect sufficient data to estimate the performance of MINIR. Furthermore, it can also be used to determine important material parameters that are required for analytical models.

A. Apparatus design

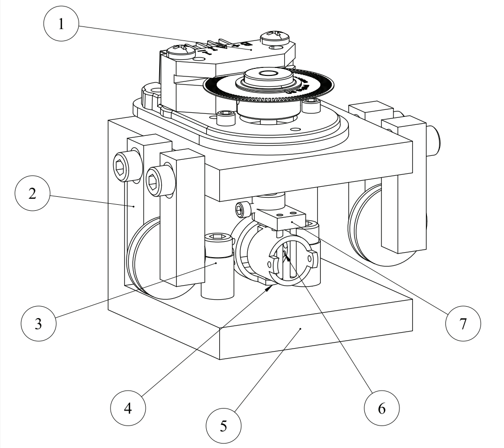
For the experimental apparatus design, we followed the suggestions of ASTM standard F2082-03. This standard is used for determination of transformation temperatures (TTRs) of NiTi shape memory alloy, however, it can be easily extended to perform the tests of temperature-strain and temperature-force relations by adding force sensors. The apparatus design is shown as Fig.5.

For our robot, the SMA actuators were distributed antagonistically to move the joints back and forth independently. Thus, the apparatus design should have similar configuration with the robot and be capable of testing two SMA wires at the same time. As a result, there are two pins, which act as the two columns in Fig.3, on the extension plate. There are also two larger columns (SMA wire fixer) on the main frame which are use to pinch/grasp the SMA wires - the SMA wires will be clamped between washers on a bolt and tightened down on a nut. It is important to note that knot-tying and coiling will yield poor results.

The apparatus also consists of a rotary encoder with a resolution up to 5000 pulses per revolution. In order to achieve minimal friction force in the encoder mechanism, we chose US digital optical kit encoder E5 which contains only a rotary disk and a reader. There are also two sets of pulley mounted on the main frame, which are used to apply different external loadings to the SMA wires. With this design, we are able to have the TTRs of the SMA wires under different stresses. We can also use it to evaluate the behavior of the robot under different external loadings. For temperature sensing, we use T-type thermocouples with resolution of 0.2 °C along with thermal conductive paste to attach the thermocouples to the SMA wires. Since SMAs are highly temperature sensitive, the whole device will be put in a chamber to isolate any external disturbance.

B. Experimental Procedure

The first step of this experiment is to define the TTRs of the SMA wires under zero stress. TTRs are essential parameters for most use of shape memory alloys. There are numerous ways of performing TTRs testing, but three



1. Rotary encoder	2. Pulley set	3. SMA wire fixer
4. MINIR segment	5. Main frame	6. Pin
7. Extension plate		

Fig. 5. Schematic of SMA characterization apparatus.

are in common use with Nitinol alloys. They are Constant Load, Differential Scanning Calorimeter (DSC), and Active A_f [12]. Constant Load test is to apply a load to the alloy and monitor its deformation and shape recovery simultaneously with temperature as the material is cooled and heated through the transformation range. DSC test is a precise method of determining the TTRs values at zero stress, but requires an expensive instrument. This DSC method measures the amount of heat given off or absorbed by a tiny sample of the alloy as it is cooled or heated through its phase transformations. The third method is called Active A_f test. This method is also known as a Water Bath or Alcohol Bath test, is conducted by merely bending a sample of the alloy, such as a wire, while it is below M_s and then monitoring the shape recovery while it is heated. For instance, if a wire is bent into a desired shape, then warmed slowly in a stirred liquid bath while monitoring bath temperature, one can measure the bend angle at specific temperatures. Using this method, the SMA wire should be carefully bent to prevent overstrain. The radius of curvature should not be smaller than 12.5 times the wire radius for 8% maximum recoverable strain. This method, while not very sophisticated, will yield surprisingly accurate, repeatable results if performed carefully, and it requires very little experimental apparatus. Since the bending deflection is what we are interested in, we choose the Active A_f method to perform the test of the SMA actuator. From this experiment, we envision to have the data of transformation temperature (A_s and A_f) and also temperature-bending angle relations.

The second experiment will be to characterize the force-temperature behavior at constant strain. After obtaining the transformation temperatures of the material as described in the previous paragraph, we are also interested in investigating the constrained recovery behavior of the material, since in our application MINIR should be able to move in a tightly enclosed environment (human brain). Thus, we need to ensure that the force generated by the SMA wires is enough to move the robot and to resect the tumor. Constrained recovery means that the wire is kept at constant strain, and the testing involves measurement of generated force-temperature relations under different strain conditions, *i.e.*, different bending deflections. In this experiment, we need to put two force sensors beside the extension plate to measure how much force each SMA wire can generate.

For shape training of the SMA wires, we will use a high-temperature oven (up to 550 °C) to prepare several SMA wires with different curvatures and repeat the experiment described in the previous paragraph. As a result, we will have different data of generated force of SMA wires under different shapes. We envision that the generated force is a function of its original shape. With this data, it is possible to find out the optimal shape of the SMA wire which can generate maximum force under the same strain.

IV. RESULTS AND DISCUSSIONS

We have developed a new MINIR design with nine revolute joints and the SMA wires will be attached to each joint to serve as individual joint actuators, as shown in Fig.2(b). The current prototype is 13mm in diameter and 70mm in length. During the first trial, the bending angle is about $\pm 30^\circ$ for a single segment, as shown in Fig.6. In this preliminary experiment, constant current were applied to the SMA wires and the thermocouple readings and bending angles were recorded continuously. The measured bending angles and thermocouple readings are shown in Fig.7. Several interesting observations can be made from these experimental results. During heating, the response time (from 0° to 30°) ranges from 12 seconds to 20 seconds, depends on different applied current, which is much faster than cooling time (35 seconds under natural cooling). Thus, an active cooling system is necessary for MINIR in order to have a faster response, and this design consideration will be an important part in our future work.

Fig.7 shows the average bending angles under different temperatures, and the standard deviation of each point is smaller than 2°. This shows that the motion of SMA wires is repeatable, and proves that it is possible to use temperature feedback to control the motion of MINIR. In order to precisely control the motion of MINIR through temperature, a theoretical model which is able to describe the correlation between temperature and bending angle of SMA wires is also necessary. As mentioned before, the experimental setup presented in this paper is capable of measuring all parameters needed for developing analytical models. As a result, modeling process will be another important point for our future research. In this paper, we have investigated the behavior of single segment of MINIR and shown that the motion is repeatable. An experimental setup for obtaining parameters of analytical models is also presented. The experimental bending responses revealed that an active cooling system is necessary for practical applications. We are currently working on developing an analytical model for the actuation of SMA that can be used for MINIR.

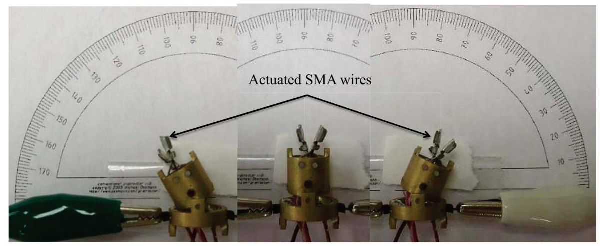


Fig. 6. One segment of MINIR actuated by SMA wires

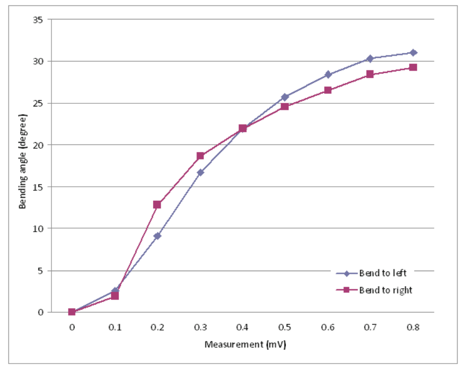


Fig. 7. Correlations between bending response and thermocouple readings

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