Mechanical Design of a Shape Memory Alloy Actuated Prosthetic Hand

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ABSTRACT

This paper presents the mechanical design for a new five fingered, twenty degree-of-freedom dexterous hand patterned after human anatomy and actuated by Shape Memory Alloy artificial muscles. Two experimental prototypes of a finger, one fabricated by traditional means and another fabricated by rapid prototyping techniques, are described and used to evaluate the design. An important aspect of the Rapid Prototype technique used here is that this multi-articulated hand will be fabricated in one step, without requiring assembly, while maintaining its desired mobility. The use of Shape Memory Alloy actuators combined with the rapid fabrication of the non-assembly type hand, reduce considerably its weight and fabrication time. Therefore, the focus of this paper is the mechanical design of a dexterous hand that combines Rapid Prototype techniques and smart actuators. The type of robotic hand described in this paper can be utilized for applications requiring low weight, compactness, and dexterity such as prosthetic devices, space and planetary exploration.

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1   INTRODUCTION

It has been estimated that major amputations occur in one out of 300 individuals in the United States, and that 23% of these are upper extremity amputations [33]. The primary causes of upper extremity amputation include trauma, tumor, and congenital absence [17]. A large number of amputees are candidates for prosthetic limb replacement that will restore a certain degree of autonomy and improve their quality of life. In contrast to the dexterous manipulations performed by computer-controlled robotic arms with many-degrees of freedom (DOF), human-operated prosthetic arms function much as they did over a century ago, by single-jointed grasping [4]. This dichotomy underscores the urgent and unmet challenge of applying modern robotic technologies to prosthetic devices [8]. Lighter, dexterous, powerful and quieter prostheses, improved control of multiple degrees of freedom, along with sensory feedback, may greatly improve the function of upper extremity prostheses, thereby enhancing productivity and options of amputees and those with congenital limb absences [3].

In an effort to advance this technology, several unique and fascinating multi-fingered multi-degree-of-freedom anthropomorphic hands have been developed over the past twenty years. A good review of dexterous robotic hands can be found in [30, 31]. Some of the most notable recent hands that are using state-of-the-art robotic technologies are the NTU Hand, the DLR hand and the Robonaut hand [5, 18, 19, 20]. Existing dexterous artificial hands are primarily using conventional means of actuation and fabrication, which result in high system complexity and large weight, volume and fabrication time. In most cases, the actuators used do not have a biomimetic behavior and this creates human interface control problems. Finally, the actuators and transmission elements that are used in existing artificial hands are noisy and this creates discomfort to the human operator.

The potential of using a new generation of small, smart material based, high powered, biomimetic, artificial muscle actuators for robotic and biomedical applications is becoming increasingly evident [6, 16]. These technologies include electro-magnetics, mechano-chemical polymers, electro-chemo-mechanical polymers (conducting polymers), piezoelectric and magneto-strictive materials, Shape Memory Alloys and polymers. Of these actuators, only Shape Memory Alloys (SMA) have been used extensively in a vast number of applications including robotics and medicine.

Shape Memory Alloys, such as Nickel-Titanium (Ni-Ti) wires, belong to a group of metallic materials that demonstrate the ability to return to a predetermined shape or size when they are subjected to heating. These properties allow the wire to be heated and cooled repeatedly to provide a usable amount of force. This phenomenon, called the Shape Memory Effect (SME), occurs when the material is heated above a certain transition temperature changing its crystalline phase from Martensite to Austenite. Heating, and thus actuation, of an SMA wire is easily accomplished by applying a voltage drop across the wire causing current to flow through the material, resulting in joule heating. Ease of actuation is not the only advantage of SMA actuators. Other advantages are their incredibly small size, volume, and weight, their high force to weight ratio, and their low cost. Their limitations include the need for a large length of wire to create sizeable linear motion, the small amount of absolute force obtained from one SMA wire, a relatively small bandwidth and low energy efficiency. A more detailed description of the SMA effect is presented in Section 2.

Since 1983, SMA artificial muscles have been used in micro-robotics. It was discovered, that artificial muscle motion could be controlled and that their small size and displacement was ideal for micro-robots, i.e. robots smaller than 1mm. In this context, SMA has been used in

many different robotic systems as micro-actuators [6, 13-15]. SMAs have been proposed as actuators for dexterous hands [34] and several of these works are briefly described here.

The most famous SMA actuated hand is the Hitachi Ltd. Hand [41]. This four-fingered (three fingers and a thumb) hand weighs 4.49 kgs (9.9 lbs) and is 69.85 cm (27.5 inches) long, which includes the forearm. It has a 1.995 kgf (4.4 lbf) load capacity. The fingers each have a number of SMA 0.02 mm diameter wires that are set around the tube housings of its spring actuators. Each wrist axis (pitch and yaw) has four SMA 0.035 mm diameter wires set around pulleys and housed in the forearm. The joint travel speed is 90 degrees per second. A biomechanic SMA hand that imitates the human hand in shape has been proposed in [25]. This is a five-fingered hand utilizing four Flexinol NiTi wires per finger, which are connected on the upper and lower part of the finger's body on both sides. A Fingerspelling Hand, developed by Oaktree Automation in 1989, presents data from a computer one character at a time using a fingerspelling alphabet, which is read by the user placing their hands on the device [12]. The hand has a forearm attached that houses the 108, 250 micron Flexinol wires acting in parallel, providing flexion and extension, and abduction and adduction antagonistically. The mechanical design of a SMA direct driven five finger robotic hand has been described in a recent US Patent [32].

Several SMA based actuator devices have been proposed specifically for use in robotic and prosthetic hands. One device that uses SMA springs in a push-pull configuration has been studied in [2]. Experiments were conducted in which two motor modules, each containing two SMA coil-type springs, were placed inside a finger phalanx. This actuator was able to exert a variable force at constant strain provided the SMA temperature does not exceed a limiting value. A SMA actuated micro-joint of a dexterous micro-gripper has been proposed in [36]. The developed micro-joint, which has been integrated in the gripper's phalanx, consists of a five link two

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degree of freedom planar mechanism that is actuated by two SMA wires. A novel SMA spring based actuator for force-feedback hand masters has been proposed in [11]. Finally, a novel wrist hand-orthosis system actuated by SMA artificial muscles has been presented in [21].

This paper presents the mechanical design for a new five fingered, twenty degree-of-freedom dexterous hand, which is based on information obtained from the study of human anatomy and actuated by our SMA artificial muscles. The developed hand has potential to be used in prosthetic and space robotic applications. The goal is to develop a biomimetic, ultra-lightweight hand, with a high number of degrees of freedom that will be able to apply substantial forces. Additional design requirements include fast fabrication times, noiseless operation and easy replacement of the components.

The lightweight requirement is achieved by using SMA artificial muscles as actuators of the system joints and by eliminating all transmission elements such as gears, pulleys or springs. The goal is to develop a hand that will weigh 1 kg. The dexterity requirement is achieved by developing a multi-degree of freedom hand with a high number of powered joints, following the geometry, dimensions and actuation patterns of a human hand. Each joint has a large range of motion that is achieved by attaching the SMA actuated tendons very close to the revolute joint axes. The high force requirement is achieved by using a series of SMA wire bundles as artificial muscles of the hand. The specific goal is to develop muscles that will apply forces of 50 N, resulting in fingertip forces of 10 N. The operation of SMA muscles is noiseless. The SMA muscles are placed outside the hand, in a forearm location. A modular design is proposed for the attachment of the artificial muscles on the hand so that the procedure of muscle replacement is very easy. This will allow the users of the hand, to easily replace the muscles if they break. It will also permit us to exchange easily the artificial muscles and conduct experiments with other

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types of smart material based artificial muscles. Finally, rapid prototyping techniques are used to develop the structure of the hand. These techniques allow the fabrication of the hand in a very short time as compared with conventional prototyping techniques. Because of the speed and ease of this type of fabrication, replacing part or even a complete hand is quite feasible. Because our rapid prototype assemblies use a lightweight material, the weight of the hand is reduced. A novel characteristic of the rapidly prototyped hand is that its multi-finger, multi-jointed structure is built in one step and no assembly is required.

It is important to note here that while the focus of this paper is purely mechanical design, such aspects as actuator control, speed, and heat dissipation; inclusion of sensors; and thermal isolation have not been neglected in the complete study of this problem. We have studied adaptive joint control algorithms for SMA actuated robotic systems [10]. Such algorithms, which allow accurate and fast joint control under varying payloads and configurations, will be used, in the future, for the control of the Rutgers hand. In addition, for the specific prosthetic device control the concepts of the biomimetic myo-pneumatic controller will be utilized as specified in papers [1, 7]. Heat dissipation, thermal isolation and sensor addition are the subjects of on going research at the Robotics and Mechatronics Laboratory at Rutgers University. While, all the above mentioned issues are important and quite practical concerns, they are outside the scope of this paper and are the subject of future papers.

Even though the applications of such a hand for robotics or prosthetics are different, the mechanical design problem is similar. The intent of this paper is to explore the use of Rapid Prototyping as a one-step, non-assembly, manufacturing process (not just a prototyping process) for this dexterous hand that provides advantages over traditional forms of manufacturing. In addition, a nontraditional form of actuation is explored and used that in part dictates the design.

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While there are many impressive hands, the purpose here is to improve the state-of-the-art. For example, the very successful Hitachi Hand is not direct drive, whereas the hand described herein is. There are other differences between the Hitachi Hand and the Rutgers Hand to be noted here: the Rutgers Hand decreases the number of components and is a less complex design; the Rutgers Hand does not use gears to increase the torque, rather it uses SMA bundles; and the Rutgers Hand is lighter with more DOF. As mentioned previously, the focus of this paper is the mechanical design of a dexterous hand that combines Rapid Prototyping and smart actuators.

2   PRINCIPLES OF SMA BEHAVIOR

Shape Memory Alloys consist of a group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure. This phenomenon is known as the Shape Memory Effect (SME). The SME occurs due to a temperature and stress dependent shift in the material's crystalline structure between two different phases called Martensite and Austenite. Martensite, the low temperature phase, is relatively soft whereas Austenite, the high temperature phase, is relatively hard. In order to understand this phenomenon, it is useful to consider the highly simplified two-dimensional representation of the material's crystalline arrangement shown in Figure 1.

Each box represents a grain of material with its corresponding grain boundaries. The grains form a heavily twinned structure, meaning they are oriented symmetrically across grain boundaries. The twinned structure allows the internal lattice of individual grains to change while still maintaining the same interface with adjacent grains. As a result, Shape Memory Alloy can experience large macroscopic deformations while maintaining remarkable order within its microscopic structure. For example, if a piece of SMA starts as Austenite (Figure 1a), the internal

atomic lattice of each grain is cubic creating grains with more or less right angles. If it is now allowed to cool below the phase transition temperature, the crystalline structure changes to Martensite (Figure 1b) and the grains collapse to the structure represented by the diamonds. Note that the grains lean in different directions for different layers. Now, if sufficient stress is applied, the Martensitic structure represented in Figure 1b will start to yield and "de-twin" as the grains reorient such that they are all aligned in the same direction (Figure 1c).

The change that occurs within a SMA's crystalline structure during the SME is not a thermodynamically reversible process. In other words there is energy dissipation due to internal friction and creation of structural defects. As a result, a temperature hysteresis occurs which is illustrated in Figure 2a. This temperature hysteresis translates directly into hysteresis in the strain/temperature relationship (see Figure 2b). The hysteresis behavior makes it challenging to develop modeling and control schemes for SMA actuators. Most Shape Memory Alloys have a hysteresis loop width of 27.8 to 67.8°C (50 to 122 °F), with the exception of some wide hysteresis alloys used for joining applications such as couplings. Additional information on SMA can be found in [9, 23, 35, 37].

3   MECHANICAL DESIGN OF THE HAND

A five fingered, twenty degree-of-freedom dexterous prosthetic hand patterned after human anatomy and actuated by our artificial muscles is presented in this section. Figure 3 shows the conceptual design of the hand. Figure 4 shows the detailed mechanical design of one finger. The links of the first prototype are made of aluminum pipe, the outer diameter measuring 0.246 cm (5/8-inch). The distal and middle links are each 2.54 cm (one-inch) in length and the proximal link is 3.81 cm (1 ½ inches) long. Custom designed pivot brackets connect the links. These pivot brackets are attached inside the distal and middle links allowing revolute movement of the

following link about the revolute pin. These brackets also serve as channels for routing the cables through the fingers. The proximal link is attached to the palm with a ball rod end joint that allows abduction and adduction of the fingers, as well as flexion and extension. The maximum deflection for each joint is approximately 80° in each direction. The range of motion for the rod-end joints for the four fingers is 90° in flexion and extension, and $\pm10°$ for lateral movement. The ball and socket joint for the thumb has $\pm30°$ deflection in all directions. The total hand (four fingers, thumb, palm and shaft) weight is estimated that it will be less than 1.36 kg.

The joints of the artificial hand are actuated by a set of cables or "tendons" routed within the structure of the finger. This is done to protect the cable and allow for an external synthetic covering to be placed over the exoskeleton. Thin braided Teflon coated tendons, are connected distal to each joint (forward of the axis), and run through the pivot brackets along the length of the finger. The pivot bracket design is such that different routing schemes can be accomplished. Figure 5 shows one routing scheme of the tendons within the finger. With this scheme all the cables run on top of the joints except for the last joint closest to the palm (and the joint where the cable is attached). By routing the tendons above these successive joints, any reaction to the force applied to the desired joint only cause the successive joints to lock in extension. Additionally, routing can be done so joints are coupled thus decreasing the degrees-of-freedom. The distal and middle links are coupled so that actuation of the distal link also moves the middle link similar to the natural movement of a human finger. This coupling is done by running the cables for the distal joint through the connecting channel of the middle joint, so that when the distal joint is actuated the middle follows. This also reduces the number of artificial muscles required and the power consumed. Confirmation of the effectiveness and pertinence to the desired application of both of these routing schemes is presently being undertaken. Figure 5 also shows the required

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displacement of the SMA to achieve a full 80° range of motion of the joints, which has been successfully tested.

The cables run through the middle of the wrist spherical joint and are attached to artificial muscles, placed parallel to each other in a position similar to the position of the radius and ulna in a human arm. For each finger, there are two artificial muscle bundles attached to the distal joint and two to the proximal joint: one muscle bundle for flexion and one for the recovery force needed to reposition the joint to its original configuration. The abduction and adduction motions of the proximal joint are passive. Because a ball rod end joint is used for the proximal joint, slight side-to-side movement occurs when the cables from the proximal joint are pulled. Three artificial muscle bundles at the thumb ball and socket joint provide the extension/flexion and abduction/adduction of this joint. In our previous work we have successfully achieved actuation of a ball and socket joint using three SMA artificial muscles placed symmetrically in an antagonistic actuation scheme [29]. The artificial muscles consist of bundles of SMA wires that are fabricated using the design considerations and techniques described in [24].

Simulations using the software package GraspIt!, from Columbia University, have been performed to test the grasping capabilities of the hand. GraspIt! is a versatile three-dimensional grasping simulator that allows a user to perform grasps with an artificial hand model and visualize the space of forces and torques that can be applied by each grasp [26, 27], which is directed by the hand's geometry and kinematics, and the CAD file information. This simulator is currently being used to test the Rutgers hand design for real-time collision detection, workspace analysis, and design evaluation based on grasping capabilities. Figure 6 illustrates the Rutgers hand in the simulator grasping a mug. Initial testing of the hand shows that all links are capable

of grasping the object. This verifies that the range of motion of the joints and finger link lengths are adequate, with few collisions detected.

Figure 7 shows the aluminum four degree-of-freedom SMA actuated finger prototype that has been built to test the mechanical design of the hand and the SMA bundle actuators described. The palm currently consists of two 7.67 cm x 7.67 cm aluminum channels placed together for mounting of the finger. The forearm shaft serves as the mounting brace for the SMAs. The final assembly weighs 0.248 kg and the finger weighs 0.363 kg. The photographs in Figures 8 and 9 show the resulting uncoupled deflections from the first joint articulation. The results of these tests showed that while the SMA articulated the joint in full deflection of either extension or flexion, it was difficult to have the action performed consecutively in both directions. Though the SMAs are placed and perform in an antagonistic manner, they had to be adjusted to perform either motion precisely. The SMAs used for these tests were one bundle per joint of two linked 250 μm diameter wires. Recent tests of new SMA bundles have improved these results and added increased force capabilities for the bundles [28]. These new actuators are capable of providing a force of 53.4 N (at a power consumption of 14.5 W), which translates to at least a 6.67 N fingertip force. For further experiments, the successive joints would be tested first individually for maximum deflection, then various configurations and combinations of fingers, and finally, testing would be performed on the entire hand with full articulation.

4   HAND FABRICATION USING RAPID PROTOTYPING

In addition to the aluminum prototype, a rapidly prototyped robotic hand (Figure 3) with five fingers and a palm has been designed. The fingers are composed of three cylindrical links connected by two revolute joints. Each of the fingers is to be attached to the palm section by

modified spherical joints. This complex system is currently being fabricated; entirely constructed as one non-assembly type mechanism using a Rapid Prototyping (RP) technique. Thus far, two Rapid Prototyping techniques, StereoLithography (SL) and Selective Laser Sintering (SLS) have been used for the rapid fabrication of several fingers, a thumb, and palm.

4.1 Rapid Prototyping Techniques

Conventional manufacturing, such as CNC machining, fabricates a part by selectively taking away material from a work piece. However, Rapid Prototyping is a fabrication technique where three-dimensional solid models are constructed layer upon layer by the fusion of material under computer control. This process generally consists of a substance, such as fluids, waxes, powders or laminates, which serves as the basis for model construction as well as sophisticated computer-automated equipment to control the processing techniques such as deposition, sintering, lasing, etc. Also referred to as Solid Freeform Fabrication, Rapid Prototyping complements existing conventional manufacturing methods of material removing and forming. It is widely used for the rapid fabrication of physical prototypes of functional parts, patterns for molds, medical prototypes such as implants, bones and consumer products. Its main advantage is early verification of product designs. Through quick design and error elimination, Rapidly Prototyped parts show great cost savings over traditionally prototyped parts in the total product life cycle [38].

StereoLithography (SL) is a three-dimensional electro-mechanical building process, which produces a solid plastic model. In this process, a low-powered ultraviolet (UV) laser traces two-dimensional cross-sections on the surface of a photosensitive liquid plastic (resin). Successive 2-D slices are cured directly onto the previous layer as the entire part is built from bottom to top. The Department of Mechanical and Aerospace Engineering of Rutgers University

is equipped with a Stereolithography 190 machine from 3D Systems, of Valencia, CA. Available basis materials for this machine include photo-polymer resin epoxies with various physical properties. (Material data sheets for Cibatool® SL 5170 resin used here can be obtained from the developers: Ciba-Geigy Corporation, Formulated Systems Group, of East Lansing, MI.)

Selective Laser Sintering (SLS) is a three-dimensional building process based on the sintering (heating and fusing) of a metallic or non-metallic powder by a laser. The fabrication of prototype parts used in the present investigations was through a professional Rapid Prototyping service provider for SLS manufacturing. The machine used is the Selective Laser Sintering Sinterstation 2000 of DTM Corporation of Austin, TX.

The Rapid Prototyping process begins with the development of Computer Aided Designs (CAD) solid models. The solid models for this project were made using Pro/ENGINEER® and are shown here along with the actual prototype. Upon completion of the solid model, it is exported to the RP machine for fabrication.

4.2   Rapidly Prototyped Robotic Hand

The initial step toward fabricating a robotic hand is the successful fabrication of the joints. Additionally, an important design consideration in this robotic hand prototype is to have the same range of motion and similarity in size to that of an average human hand. The latter guiding design feature necessitated the use of modified joint designs to partially restrict some of the degrees of freedom. The spherical joint that meets the fingers with the palm is one such joint (Figure 10). The non-assembly type finger prototype shown here was built using the SLS process, with a glass-filled nylon material, and produced joints that exhibit good mobility through the desired ranges of motion. One of the challenges of using Rapid Prototyping in non-assembly

hand fabrication is the assurance of proper joint clearances. This SLS finger prototype is an example of this as the clearances are such that there is additional movement in the joints than desired. However, this movement is minimal still allowing very good finger mobility. Later prototypes eliminated this problem.

Additionally, no lubrication is needed due to the techniques used here for building the non-assembly type joints. Though the joints move freely with little friction, it is possible that over time some wearing may occur (metal inserts may be necessary in future joints). To date, this is not a problem and no maintenance is required. The lifetime of the RP hand material is expected to be similar to that of traditional plastic parts.

Actuation of the robotic hand is to be achieved through a combination of cables (tendons) and Shape Memory Alloy artificial muscle wires. The SMA wires to be used in this design have a wire diameter of approximately 150 microns (0.006"). The cables are connected close to the pivot points of the revolute joints and run through the incorporated "pathways" (Figure 11) within the length of the fingers. The cables are crimped to SMA muscle wires proximal to the palm. It is necessary to run the cables through the hand rather than the SMAs themselves as the activation temperature of the SMA is 70° - 90°C and the melting temperature of the SL material is 85°C. (The melting temperature is not a consideration with the SLS material as its melting temperature is 185°C.) The use of SMA wires will be the first attempt at actuating a Rapidly Prototyped system at Rutgers University.

Figure 11 shows a cutaway view of the channels within the finger for routing of the cables used for actuation. These pathways, 0.254 cm in diameter, were designed to guide the cables through the finger links so as to decrease stress on the cables while maintaining the required tension. One channel through the middle link appears in a diagonal pattern, as seen from this

side view, for the above-mentioned purpose. In addition, the cables intended for flexion and extension of the distal link travel over top of the revolute joint between the middle and proximal links. The channels through the proximal link fan out around the ball and socket (which could be seen from a dorsal view). Two cable pathways, one for flexion and one for extension of the modified spherical joint, run through the socket on the palmar and dorsal sides to allow for 90° rotation during actuation. Currently, abduction and adduction movement at the finger spherical joint is passive. This is due to the modified spherical joints natural side to side motion when the cables from the proximal joint are pulled.

Figure 12 shows the SLS fabricated finger with the tendons (cables) attached in a post-fabrication phase. As in the previous SLS constructions, the joints fully reach the designed range of motion. Additionally, all the pathways and cable assembly holes were clear of material. The Selective Laser Sintering process successfully fabricated this multi-joint, multi-degree-of-freedom robotic finger.

Other fabricated hand parts were done with the SL technique (SLA 190 with Cibatool® SL 5170 resin) and are shown in Figures 13 and 14. The thumb design (Figure 13) has been modified to a two link, two joint assembly to more closely resemble the size and "appearance" of the human thumb. Additionally, slots for sensors have been incorporated for strain gauges to measure all fingertip forces and the palmar grasp force. The position of each link will be measured with Hall effect magnetic position sensors placed in the links. Figure 14 shows the palm design and fabricated part. The palm is hollow to allow for passage of cables and sensors. Because fabrication of the separate structures of the robotic hand has been successful, the entire hand can now be built as one non-assembly prototype. Additional information on the application of rapid prototyping in the fabrication of robotic systems can be found in [39, 40].

5   CONCLUSIONS

The mechanical design of a dexterous hand that combines Rapid Prototyping techniques and smart actuators was presented. The concept of actuation for one finger with one cable routing scheme was successfully tested with the aluminum finger prototype. Rapid prototyping techniques have also been used to develop prototypes of a finger. Additionally, the mechanical design grasping ability for the Rapid Prototype hand has been confirmed. The prototype experimentation and the design finalization of the robotic hand described here are ongoing projects. Future work will involve the performance of closed loop computer control experiments with various control schemes such as adaptive and non-linear control. Electrical and thermal insulation of the actuators in the hand and electrical consumption of the prototype are also subjects of future work.

6   ACKNOWLEDGMENTS

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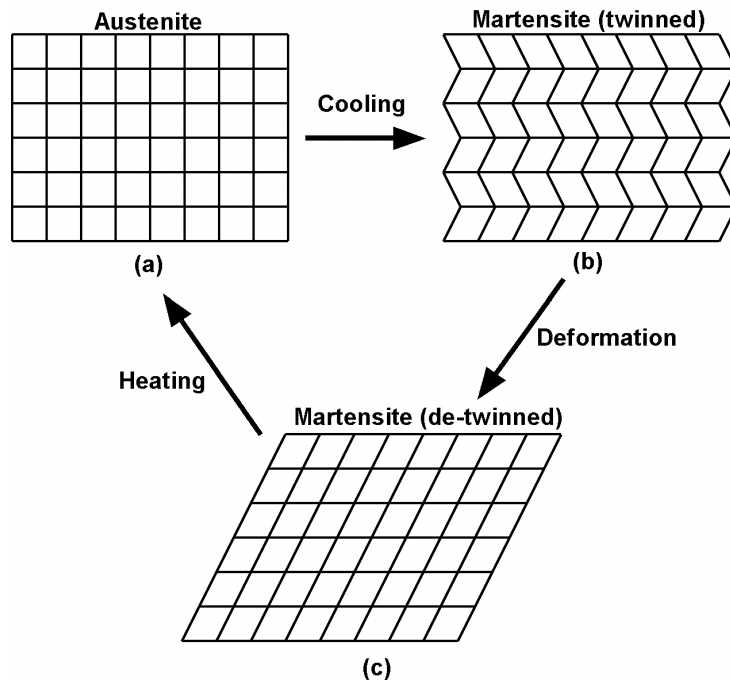
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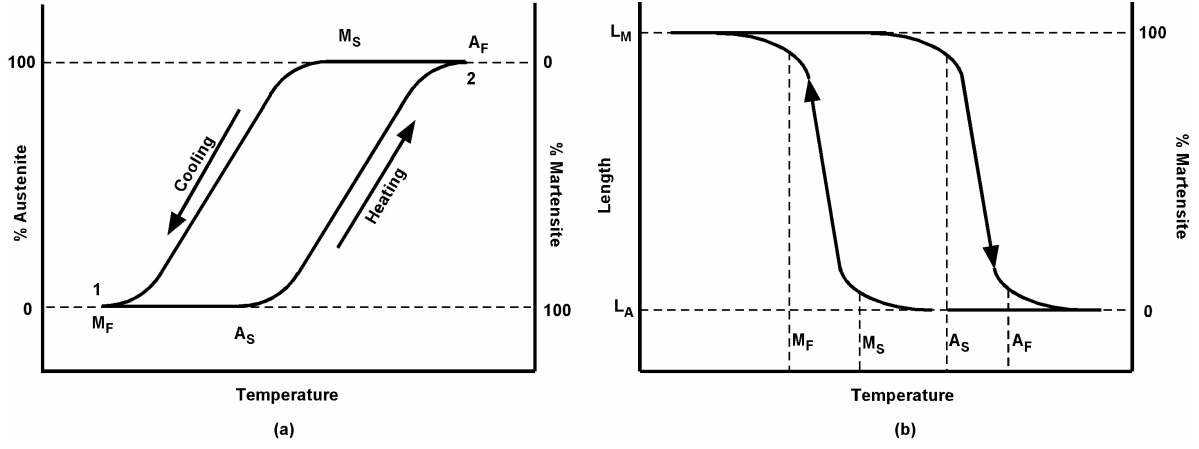**Figure 1.** Material Crystalline Arrangement During the Shape Memory Effect

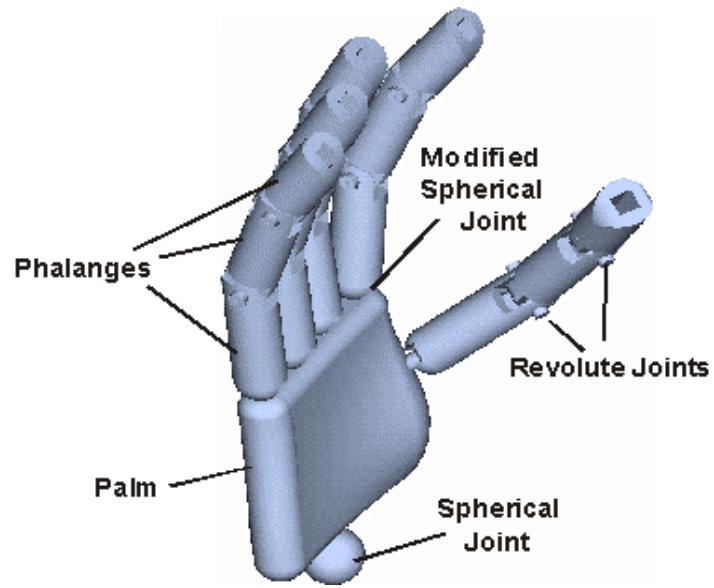**Figure 2.** Hysteresis Loops in Shape Memory Alloys

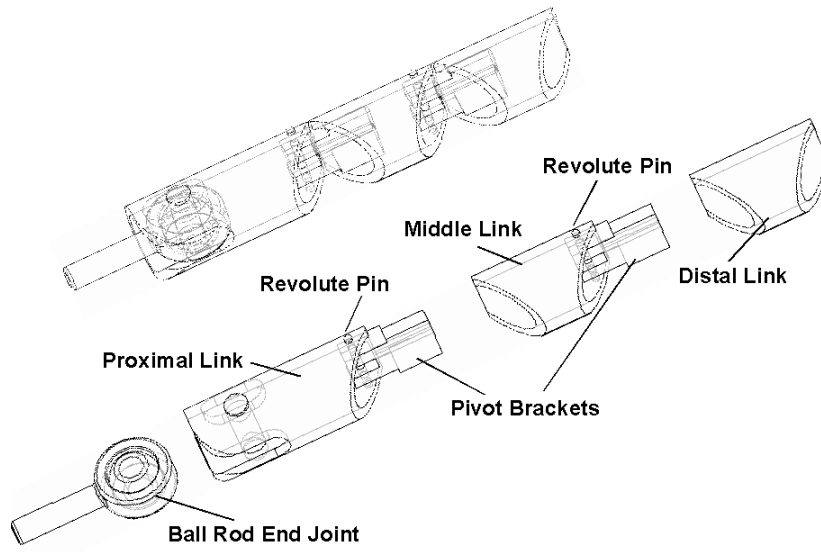**Figure 3.** Pro/ENGINEER® Rendering of a Robotic Hand

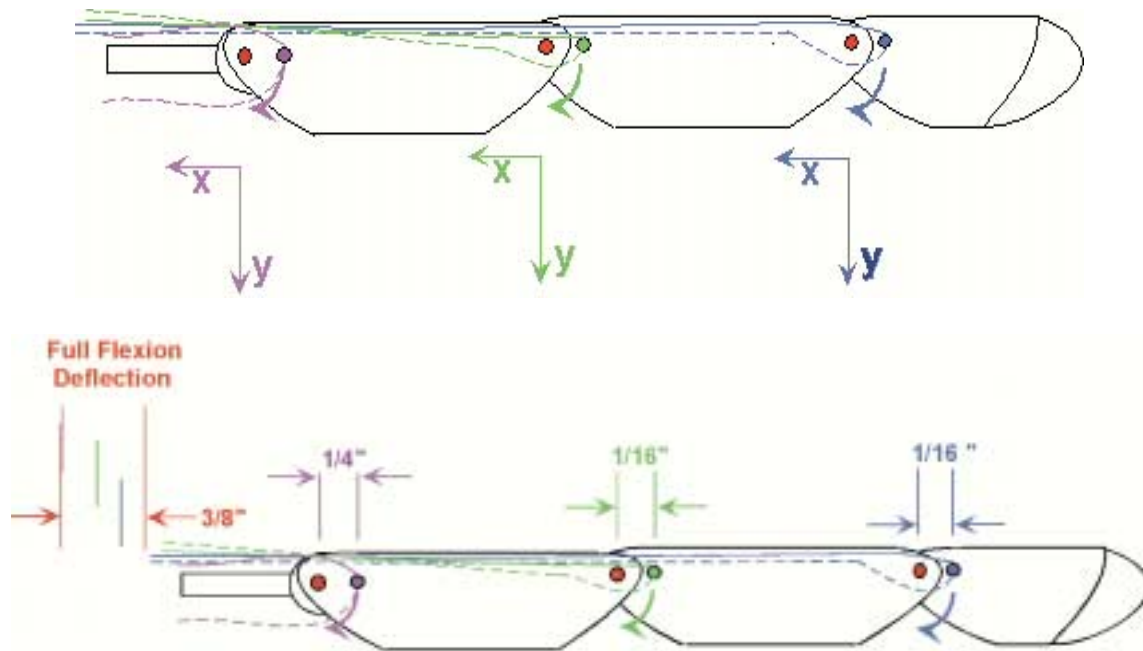**Figure 4.** Finger Prototype Assembly Drawing

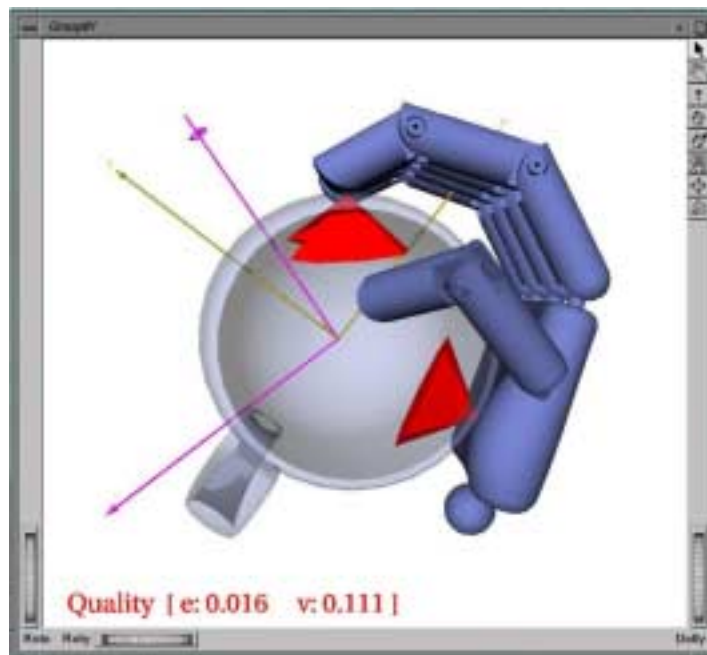**Figure 5.** Tendon Routing in Finger Prototype and Diagram Showing Full Flexion / Deflection

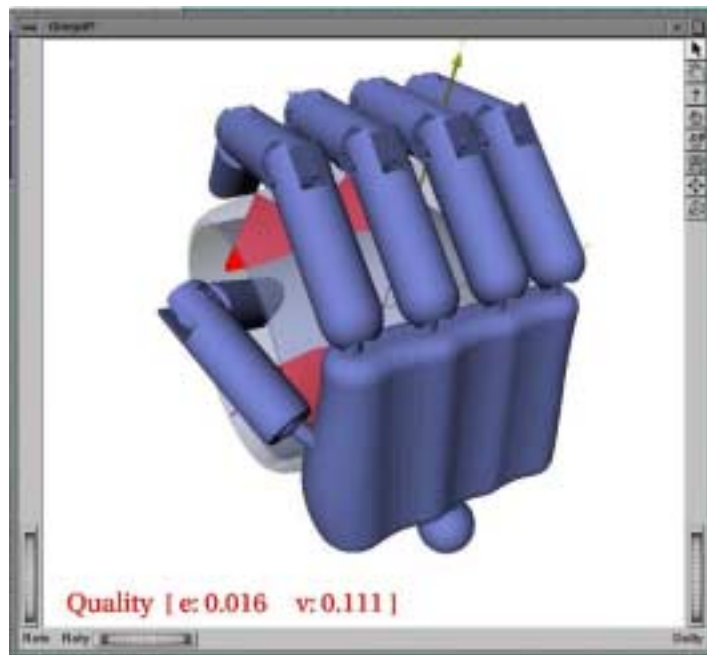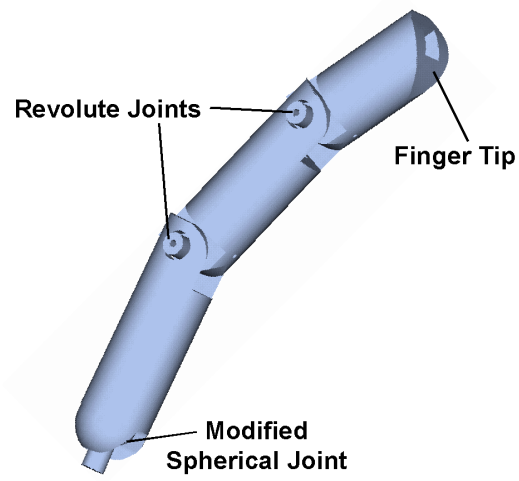**Figure 6.** Simulations of the Rutgers Hand Using GraspIt!

Figure 7. Aluminum Finger Prototype

Figure 8. First Joint in Flexion

Figure 9. First Joint in Extension

(a) CAD Drawing

(b) SLS Prototype

Figure 10. Robotic Finger Built with SLS
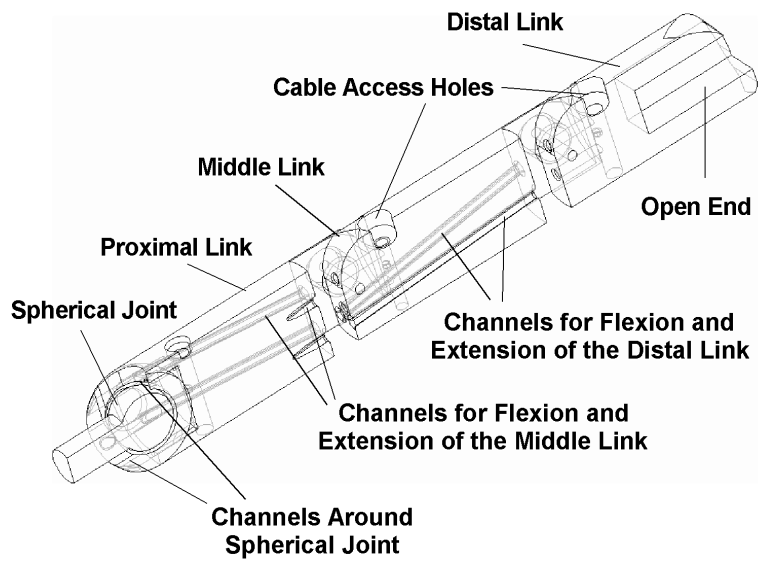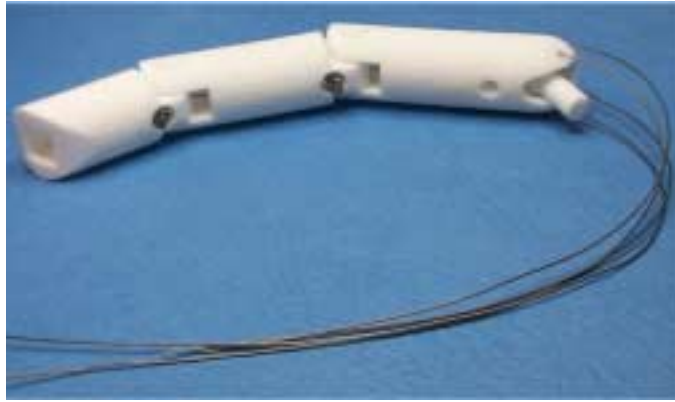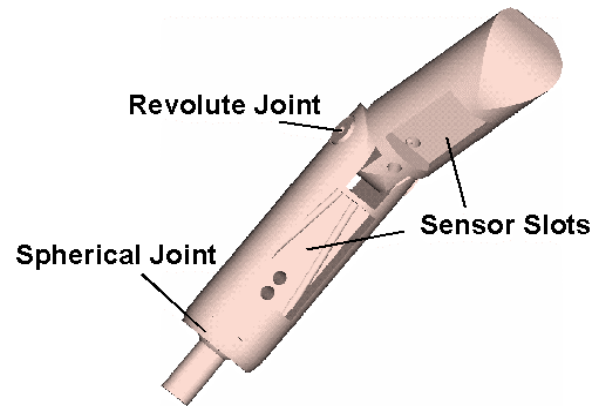
Figure 11. Cable Channels in SLS Finger

Figure 12. Robotic Finger Built with SLS and Actuated with SMA Wires
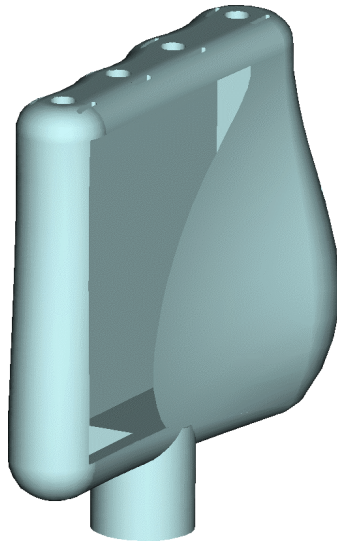
(a) CAD Drawing

(b) SL Prototype

Figure 13. Robotic Thumb Built with SL

(a) CAD Drawing

(b) SL Prototype

Figure 14. Robotic Palm Built with SL