DEVELOPMENT OF A SHAPE MEMORY ALLOY ACTUATED ROBOTIC HAND

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Abstract:
This paper presents the ideology of this research, which is to utilize advanced actuators to design and develop innovative, lightweight, powerful, compact, and dexterous robotic technology. The key to satisfying these objectives is the use of advanced or smart materials, such as Shape Memory Alloys (SMAs) to power the joints of a prosthetic hand, and other dexterous robotic hands. The mechanical design of a dexterous robotic hand, which utilizes non-classical types of actuation and information obtained from the study of biological systems, is presented in this paper. Two experimental prototypes, emulating human skeletal structures and actuated by SMA artificial muscles, one fabricated by traditional means and another currently being fabricated by rapid prototyping, are described. The type of robotic hand described in this paper can be utilized for applications requiring low weight, power, compactness, and dexterity such as prosthetic devices, and space and planetary exploration.

Introduction

The mechanical design of a dexterous robotic hand, which utilizes non-classical types of actuation and information obtained from the study of biological systems, is presented in this paper. Several unique and fascinating multi-degree-of-freedom robotic hands have been developed over the past twenty years, primarily using traditional means of actuation. Though there are many robotic hands, there are only a few using a new approach to classical robotic hand power. These hands that utilize advanced or smart actuators are listed below. The Hitachi Ltd. Hand (1984) uses Shape Memory Alloy (SMA) wires. This four fingered (three fingers and a thumb) hand weighs 9.9 lbs. and is 27.5 inches long, which includes the forearm. It has a 4.4 lb. load capacity. Possible applications for this hand include maintenance work in hostile environments, medical micro-manipulators, and undersea operations [1].

Two other SMA actuated hands are a biomechanic robot hand and a Fingerspelling Hand. The biomechanic hand is a prototype that imitates the human hand in shape. 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. The purpose of this hand is for flexible manipulation [2]. The Fingerspelling Hand was developed by Oaktree Automation in 1989. The hand presents data from a computer one character at a time using a finger-spelling alphabet, which is read by the user placing their hands on the device. 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. This hand serves as a tactile communication aid for deaf-blind individuals [3].

Though there has been much research accomplished on SMAs, there is still a need for new design methodologies and paradigms for lightweight, practical hands for robotic systems. It is believed that the key to satisfying these objectives is via the use of smart materials, such as, Shape Memory Alloy artificial muscles. The advantages of Shape Memory Alloys include, their incredibly small size, volume and weight; their high force to weight ratio; their low cost; and their anthropomorphic behavior. Their limitations include: the large length of wire required to create significant motion, limited life cycle, non-linear effects such as hysteresis phenomena, and bandwidth and efficiency restrictions. It is proposed that the novel design methodology and prototype fabrication discussed in this paper will aid in the advancement and the development of human-like muscle actuators for assistive robotic devices and practical robotic systems.

Mechanical Design

The mechanical design of a four fingered, fourteen degree-of-freedom dexterous robotic hand, patterned

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after human anatomy, is currently being developed. To date, a lightweight aluminum four degree-of-freedom finger prototype has been made (Figure 1). The robotic hand concept presented here is based on the use of Shape Memory Alloy artificial muscles, composed of an equal ratio of nickel and titanium, to power the joints. However, it anticipated that other smart materials, such as electrostrictive polymers, electrostatic devices, piezoelectrics, mechano-chemical polymer/gels, shape memory polymers and shape memory alloys will be used either alone or in conjunction with the SMAs.

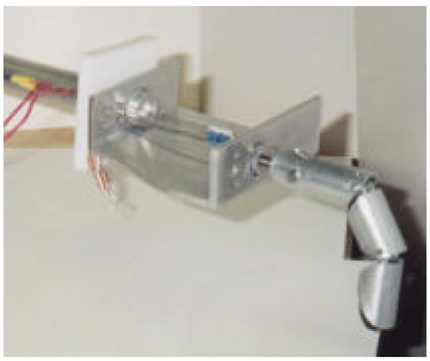

Fig. 1: Aluminum Finger Prototype

The entire finger prototype was fabricated using stock aluminum (Figure 2). The links are made of aluminum pipe, the outer diameter measuring 5/8-inch. The distal and middle links are each one-inch in length and the proximal link is 1 ½ inches long. Custom designed and fabricated pivot brackets connect the links. These pivot brackets are placed inside the distal and middle links allowing revolute movement of the following link. 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 110^{O} extension. A ball-and-socket will be used for the thumb proximal joint, as the concept of actuation of this joint has been successfully tested previously [4]. The mechanical measurements for the maximum joint deflections for this prototype are as follows:

First joint	77^{O}
Second joint	73^{O}
Third joint	88^{O}
Fingertip total workspace	110^{O}

Further machining is required to obtain the full 90^{O} range for the first two joints. The palm currently consists of two 3” x 3” aluminum channels placed together for mounting of the finger. The forearm shaft serves as the mounting brace for the SMAs. The final assembly weighs 0.546 pounds and the finger weighs 0.08 pounds. The total hand (three fingers, thumb, palm and shaft) weight is estimated that it will be less than three pounds.

This anthropomorphic prototype is actuated by a set of cables and Shape Memory Alloy artificial muscle wires routed within the structure of the finger. This was done to protect the cable and allow for an external synthetic covering to be placed over the exoskeleton. Thin braided Teflon coated cables, or tendons, are connected distal to each joint (forward of the axis), and run through the pivot brackets along the length of the finger. Figure 3 shows the internal routing of the tendons within the finger. An interesting feature with this design is that all the cables run on top of the joints except for the last joint closest to the palm. By routing the tendons above these successive joints, any reaction to the force applied to the desired joint will only cause the successive joints to lock in extension. Additionally, the pivot bracket design is such that different routing schemes can be accomplished, for example, routing can be done so joints are coupled thus decreasing the degrees-of-freedom. The cables are crimped to six-inch SMA muscle wires, placed parallel to each other three inches from the finger, which is in relative position of the radius and ulna in a human arm. This type of assembly shows the placement of the tendons and muscle wires in relation to the fingers, palm and forearm for direct application to a below-the-elbow prosthetic device.

Fig. 2: Finger Prototype Assembly Drawing

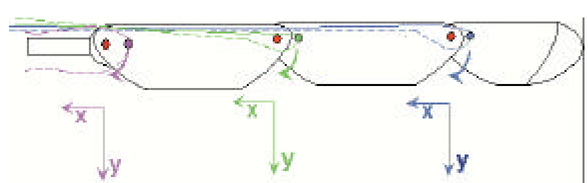

Fig. 3: Tendon Routing in Finger Prototype

This actuation scheme allows for uncoupled antagonistic articulation of the finger joints. In the future, the distal and middle links will be coupled so that actuation of the distal link also moves the middle link similar to the natural movement of a human finger. This also reduces the number of SMA wires required and the power consumed. There are three SMAs attached to the distal joint; one for flexion and two for the recovery force needed to reposition the finger to its original configuration. Two cables at the ball rod end joint provide the extension and flexion of this joint. Currently, passive movement of the ball rod end joint provides the abduction and adduction of the finger.

The NiTi 150 micron diameter Shape Memory Alloy artificial muscle wires are used here. Shape Memory Alloy wires have the characteristic of contracting when a voltage is applied to them. Shape Memory Alloys possess the ability to undergo shape change at low temperature and retain this deformation until they are heated; at which point they return to their original shape. This shape change occurs as the result of a change in the atomic crystal structure of the alloy. These properties allow the wire to be heated and cooled repeatedly to provide a usable amount of force for actuation of the hand.

Rapid Prototyping

In addition to the aluminum prototype, a rapidly prototyped robotic hand with five fingers and a palm will be used to demonstrate the actuation schemes and designs. This complex system is currently being designed and fabricated; entirely constructed as one non-assembly type mechanism. To date, a rapid prototyping technique called "Selective Laser Sintering" (SLS) has been used for the rapid fabrication of several fingers. The initial step of the Rapid Prototyping process toward fabricating a robotic hand was successful in building the non-assembly type finger prototype. Because this rapid prototype process produced joints that exhibit good mobility through the desired ranges of motion, the entire hand (Figure 4) can now be fabricated. Furthermore, since the Rapid Prototyping process has provided a means to acquire a prototype quickly, the next step of investigating motion capabilities and actuation schemes using Shape Memory Alloy muscle wires for incorporation into this design can begin. This robotic hand is designed with the future purpose of using a Rapidly Prototyped robotic hand as a possible replacement for mechanically driven prosthetic hand or other dexterous robotic system.

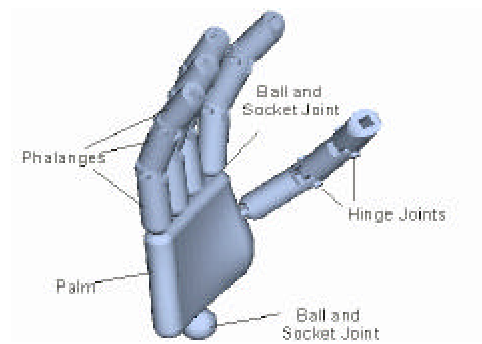

Fig. 4: CAD Rendering of a Robotic Hand

Discussion / Results

The fingertip force is estimated at two lbs., which is based on previous single SMA wire testing [4]. The total payload capacity specifications for the hand are required to be 8 lbs. This design calls for these minimum figures for the fingertip force and payload capacity, and is currently being verified.

Preliminary testing of the finger prototype with the preferred 150 micron wires was performed, by applying 7 volts and 300 mili-amps via a 300 MHz Dell Pentium PC. For the task of making a fist, for example, the power requirements for each finger are 4.2 Watts, and the total maximum power required for the four-finger hand is estimated at 16.8 Watts. The power requirements for various other tasks will be different. Experiments that involve varying the arrangement of the electrical wiring connections (series vs. parallel), changing the SMA wire bundling, coupling, and placement, and the inclusion of a joint braking system are currently being performed to minimize the power requirements and maximize motion.

These actuation tests of the finger have been done under open loop computer control. The SMA actuating results are unpredictable during open loop control. It has been shown that function of the SMA is better under closed loop computer control that produces fluctuations in the voltage to account for the SMA temperature and environmental changes [5]. In order to produce the fully functioning hand in this project, and perform further tests, sensors such as position sensors at the joints, force sensors at the fingertips, and touch sensors, will be incorporated. The finger design was kept simple with space inside the links for this purpose.

The photographs in Figures 5 and 6 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. The SMAs had to be adjusted to perform either motion.

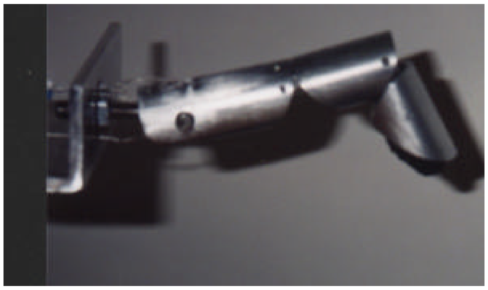

Fig. 5: First Joint in Flexion

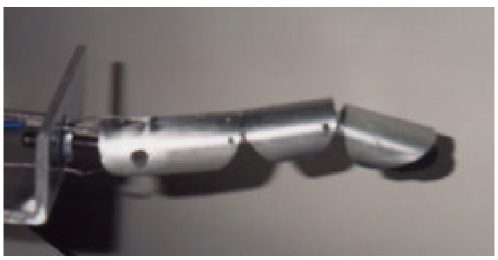

Fig. 6: First Joint in Extension

Additionally, because the pivot point is so close (1/16") to the axis of rotation for the first two joints a shorter wire (4") actually would provide better actuation. This is a significant accomplishment as one of the original goals of the hand design called for a self-contained actuation scheme. These results indicate that this is possible. 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.

Conclusions / Future Work

The mechanical design of a dexterous robotic hand, which utilizes non-classical types of actuation, was presented. The aluminum hand prototype, actuated with SMA artificial muscles, and that emulates human skeletal structures was described. The concept of actuation for the fingers was successfully tested with the aluminum finger prototype.

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 will be optimized. In addition, utilizing the proposed models to maximize joint angle location and link displacement, while increasing fingertip force, by the inclusion of mechanical advantage design features, it is expected that a fully functioning robotic hand can be accomplished.

Acknowledgments

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