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The SDM Hand as a Prosthetic Terminal Device: A Feasibility Study

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Abstract— **In this paper we discuss the potential of applying our concept for a robotic hand fabricated via Shape Deposition Manufacturing (SDM) as a prosthetic terminal device. Experimental results with the hand have shown a level of robustness, adaptability, and other performance properties as yet unseen in a robotic hand. Besides reliable performance, the hand is durable, is produced using a molding process that allows both for inexpensive mass production as well as a realistic appearance without the need for a cosmetic glove, and incorporates a simple design that requires only a single actuator for the eight active degrees of freedom. All of these factors make it a good candidate as a basis for either a body-powered or externally-powered prosthetic terminal device that is realistic, functional, robust, and inexpensive.**

I. Introduction

OVER 10,000 major amputations of the upper extremities occur every year in the United States alone [1]. However, while technology has improved drastically, very few advances in prosthetic devices have been adopted by the amputee community in the last century. Most patients still choose hooks or other simple mechanisms as terminal devices for functionality during their every day lives, switching to a less functional, more cosmetic terminal device for social activities [1-4].

Much of the research in prosthetic hands in the past few decades has focused on externally powered, multifunctional anthropomorphic devices (e.g. [5-12]). In order to capture the dominant performance characteristics of the human hand, some of these devices can incorporate 17 or more actuators, placed in the body of the forearm and sometimes upper arm of the prosthesis. For this reason they are therefore not purely terminal devices and are limited in application to amputees requiring the respective level of prosthesis. Additionally, current limitations with interfacing these devices and their operator do not permit nearly the same number of independent control signals required to operate them.

A few of these devices have been designed with a smaller number of actuators that are in fact modular as a terminal device and can therefore be used by the largest number of individuals (e.g. [10]). However, size, weight, and power requirements as well as current limitations with both myoelectric and body-powered methods of actuation limit the number of degrees of actuation that can reasonably be incorporated into a prosthesis. Indeed, current state-of-the-art commercial products are limited to 1 or 2 degrees of actuation.

For these reasons and others, there will always be a desire to maximize functionality of the terminal device while keeping the degrees of actuation small. In this paper, we describe the design of a robot hand that requires only a single actuator yet is able to reliably grasp target objects spanning a wide range of size, shape, and mass. The most interesting properties of the current implementation of the robot hand include:

- Molded from polyurethanes that are lightweight and tough
- Robust to impacts, other large loads
- Hand is compliant when unactuated, rigid when actuated
- Fingers are actuated via tendon cables
- Only a single actuator is needed
- Performs reliably *without* the need for sensory feedback
- Passively adaptable to a wide range of target objects

Besides good performance, the above properties lead to the following desirable attributes if constructed as a prosthetic terminal device:

- Cable actuation fits naturally with body-powered methods of actuation
- Single actuator can easily be incorporated into the palm of the hand for an externally-powered modular device
- Fabrication via polymer molding allows for realistic appearance and no need for a cosmetic glove
- Molding allows for easy, inexpensive mass production
- Reduced number of actuators while retaining performance decreases the mass of the hand

We begin this paper by describing the design of our four-fingered robot hand (Fig. 1) built using Shape Deposition Manufacturing (SDM) [13,14]. This process uses polymeric materials to simultaneously create the rigid links and

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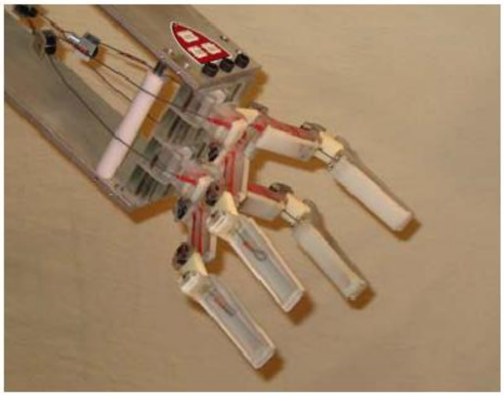

Fig. 1. SDM Hand

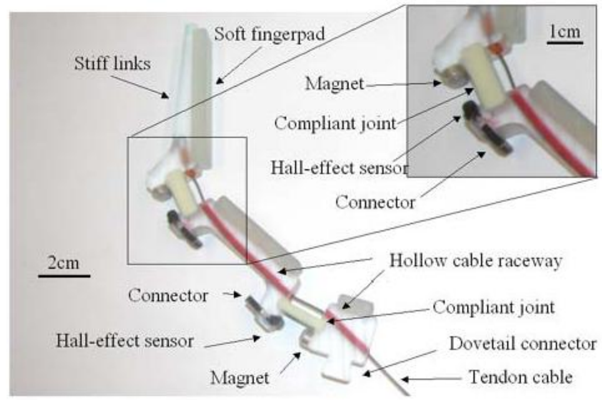

Fig. 2. Details of finger parts and placement of components. Note that the sensors shown are not currently in use.

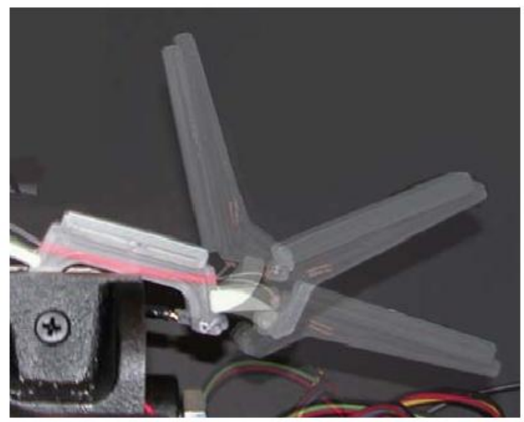

Fig. 3. Superimposed photograph of joint deflection and link motion for three positions across the travel range of the distal joint of the fingers. The center image is the rest position.

compliant joints of the gripper, with embedded actuation components. In addition to simplifying the construction process, the result is an extremely robust gripper, fully functional after impacts and other large loads due to unintended contact. We then describe the performance of the hand, including the ability to grasp a wide range of common target objects, and end with a discussion of modifications that might be made in order to realize the hand as an effective prosthetic terminal device.

II. SDM Hand Design

In this section we describe the architecture of our robot hand as it was designed for use as a *robot end-effector*. Note that some of the design choices such as the non-anthropomorphic finger placement might need to be modified to make it appropriate for use as a prosthetic terminal device. These modifications, addressed in section IV, are not expected to adversely affect the performance of the hand. As mentioned previously, this paper presents evidence of the *feasibility* of incorporating the main features of our hand concept as a prosthetic terminal device, and not the specific design of such a mechanism.

A. Finger design

To provide both adapatability and robustness, the fingers and base of our hand, featuring passively compliant joints, were fabricated using polymer-based Shape Deposition Manufacturing (SDM) [13,14] (Fig. 1). SDM is an emerging layered manufacturing technique with which the rigid links and compliant joints of the gripper are created simultaneously, with embedded sensing and actuation components. Elastomeric flexures create compliant joints, eliminating metal bearings, and tough rigid polymers fully encase the embedded components, eliminating the need for seams and fasteners that are often the source of mechanical failure.

Fig. 2 diagrams the parts of the SDM finger. (*Note that the joint angle sensors shown in the image are not currently being utilized – the SDM Hand is operated in an open-loop, feed-forward manner.) The concave side of each link contains a soft fingerpad to maximize friction and contact area, thereby increasing grasp stability [15,16]. Links are connected via elastomer joint flexures, designed to be compliant in the plane of finger motion and stiffer out of plane. Fig. 3 shows the behavior of the distal finger joint through its range of motion.

The polyurethane used for these joints demonstrates significant viscoelastic behavior, which is necessary to reduce the severity of joint oscillations and permit the use of low joint stiffness. Experimental results have shown that oscillations due to large step displacements are negligible after less than 1 second. In a conventionally-assembled grasper with metal springs, oscillations due to large step displacements were found to persist for tens of seconds after release [17].

Due to the molding process used to create them, the SDM fingers, including embedded cables and raceways, are a single part weighing 39 grams, with no fasteners or adhesives. This is in contrast to a grasper of similar size, structure, and actuation fabricated with conventional metal prototyping techniques used in our previous work, which had 60 parts total, 40 fasteners, and weighed 200 grams [17]. The total SDM hand (not including the DC motor and

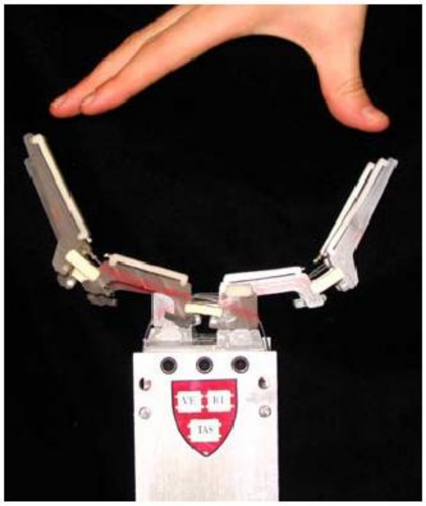

Fig. 4. Relative size of the SDM Hand

its base) currently weighs approximately 200g, and can likely be made much lighter with further engineering. The two links of each finger are 70mm long (measured from the center of the joint flexures), with a total hand aperture of 113mm in the current implementation, approximately the span of a larger size male hand, and slightly deeper (Fig. 4).

B. *Finger compliance and robustness*

The compliance in the finger joints, lack of fasteners, and the toughness of the polymers leads to a very robust robotic hand. The tip of the SDM fingers can be displaced more than 3.5 cm in the out-of-plane direction (normal to the page in Fig. 4, approximately 20 degrees) without any degradation of mechanical properties. The advantages of this property are clear when considering the usual result of unplanned contact during use of traditional research robotic hands. In a prosthetic hand, this property would allow for the removal of some of the bulk material, since the lower forces on the hand due to the compliance would allow for the use of components with less mechanical strength.

To give a sense of the robustness of the mechanism to impacts and other potentially harmful loads, a number of more informal tests were performed. An SDM finger was repeatedly dropped from a height of over 15m (50’) onto a stone floor, without significant damage. The fully-assembled hand has been hit repeatedly with a hammer, fingers jammed against objects, and used underwater, without any degradation of performance. Further details on the mechanical properties and design of the SDM *fingers* can be found in [18].

C. *Actuation*

As a terminal device, the SDM hand would be an ‘active-close’ device, with springs that tend to open the hand. For actuation, each finger has a pre-stretched, nylon-coated stainless steel cable anchored into the distal link, and running through low-friction nylon 11 tubing to the base

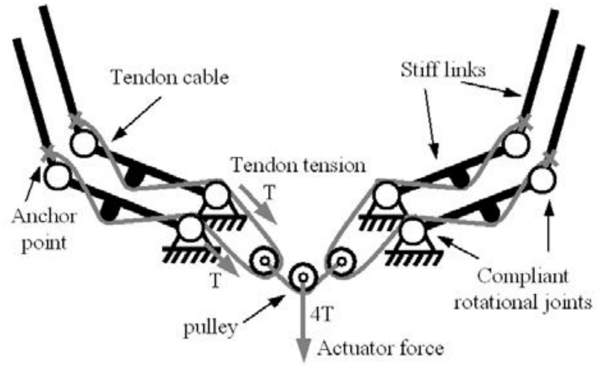

Fig. 5. Actuation schematic of the hand

(Fig. 2). Before actuation, the tendon cable, which is in *parallel* with the compliant joints, remains slack and the finger is in its most compliant state. This method permits the use of actuators that are not backdrivable and prevents the inertial load of the actuator from increasing the passive stiffness. After actuation, the stiffened tendon takes much of the compliance out of the fingers, resulting in a stiffer grasp with greater stability.

A single actuator drives the four fingers (eight joints) of the hand. This property not only makes the gripper simpler and lighter, but with the incorporation of an appropriate transmission it also allows the gripper to be self-adapting to the target object. Fig. 5 details a representation of the actuation scheme. Using this design, motion of the outer link (distal link) of a finger can continue even after contact on the coupled inner link (proximal link) occurs, allowing the finger to adapt to the object shape passively, without any active control. Additionally, the pulley transmission designed for the hand enforces that an equal amount of tension is present on all tendons, regardless of finger configuration or contact state and without affecting the position or ‘length’ of the tendon. This design therefore allows the remaining fingers to continue to enclose the object after the other fingers have been immobilized by contact.

In the current implementation, the four fingers (two on each side) are staggered on the palm to allow them to completely close without interfering with one another. The fingers are also overlapped on the base such that the proximal joints of the fingers of both sides are collinear. In this way, all areas of potential initial contact within the concave shape of the hand are compliant, with the stiffer base link not making contact until a certain level of deflection has occurred.

D. *Design optimization*

The kinematic configuration, joint stiffnesses, and actuation coupling scheme were determined based on the results of previous optimization studies, described in [17,19]. These studies sought to find the configuration of these properties for good performance in unstructured

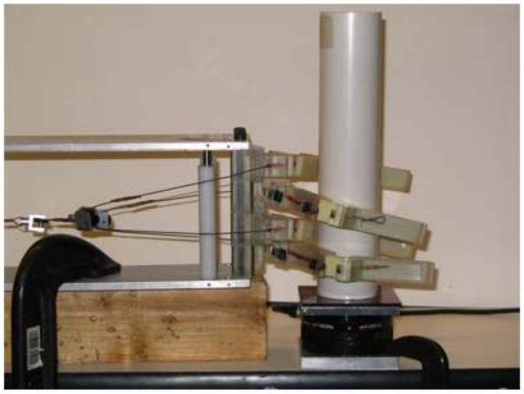

Fig. 6. Grip force experimental setup.

environments - the widest range of target object size could be grasped under the greatest amount of allowable positioning error while keeping contact forces low so as not to damage or displace the object. These results, particularly those of the kinematic configuration (i.e. joint angles), might need to be slightly varied for implementation in an anthropomorphic architecture.

III. HAND PERFORMANCE

There is a lack of universally accepted performance measures for a prosthetic hand. However, [3,4,20] provide a number of specifications that can be used as guidelines, particularly in the types of tasks that should be able to be performed using the terminal device. In this section we present the actuation capabilities of our hand, demonstrate the range of objects that can be easily grasped using the current configuration, and identify the class of tasks that require a change in the layout of the hand in order to be accomplished. However, note that almost all common objects can be stably held by positioning the fingers using the unaffected hand for unilateral amputees.

Fig. 6 shows the experimental setup used to determine the grasp force of the hand. Contact was made on the two fingers of the right side of the hand (the two closest to the reader in the figure) while the left side fingers were prevented from contacting the object, a 48mm diameter PVC tube. This object was securely mounted to a sensor measuring forces in the plane (Gamma model, ATI Industrial Automation, Inc, Apex, NC, USA). The object was contacted such that the center of the outer joints of the fingers was approximately centered between the two contact points.

In the current implementation of the hand, approximately 300N of actuator force (seen as 4T in Fig. 5) was found to produce 30N of grasp force. This transmission ratio, however, can be easily varied by changing the stiffness of the joints and/or the distance of the cable tendons from the flexure joints (i.e. the 'lever arm'). Additionally, a maximum of 2.5cm of travel on the actuated end of the cable is required in the current configuration to fully close the hand, regardless of contact state.

In evaluating the performance of various harness configurations for body-powered terminal devices, Bertels found that a test subject with the most common harness configuration could apply 250N of tensile force and 12cm of cable travel [21]. Additionally, [8] specifies that a hand must apply a maximum of 68N of grip force, although the exact reason for this maximum value is somewhat unclear. Therefore, by modifying the transmission ratio of the current design, these two goals can be easily achieved in order to allow this device to be used with a body-powered method of actuation. Furthermore, the increased contact area due to the compliance in the joints and fingerpads of the SDM hand will reduce the "desired" grip force.

The images in Fig. 7 demonstrate the utility of the hand in grasping everyday objects. Many of these objects are involved in challenging tasks suggested by [3] as 'practice' objects on which a recent amputee should eventually learn to grasp as they train. Others were grasped to demonstrate the range of size, shape, and mass of objects that can be successfully grasped using the SDM Hand. These objects are grasped with only a single DC motor for actuation, without the aid of any sensory feedback. The motor is simply run to stall at one of three different current levels, and the passive adaptability designed into the hand and transmission drives the joints to a position that conforms to the given object shape. The method of achieving this passive adaptability was described in detail in section II.C.

IV. DISCUSSION

While a small number of compliant, underactuated hands have been previously proposed in the robotics literature (e.g. [22,23] – see [19] for a thorough review), none have demonstrated the level of robustness, adaptability, ease of use, and reliability that we demonstrate here. Furthermore, the very nature of our approach is well-suited for application to prosthetic terminal devices.

The SDM Hand is molded from polyurethanes that are lightweight and tough, making it robust to impacts and other large loads while remaining lightweight. The molding fabrication process allows for easy, inexpensive mass production with the potential of incorporating embedded sensors for sensory feedback to the operator or control system. Additionally, the device can be molded to give a realistic appearance with a soft external 'skin', avoiding the need for a cosmetic glove. Others have attempted a fully-molded device (e.g. [11,12]), however the performance of the underlying mechanism was not demonstrated to the level shown here.

The SDM Hand is compliant when unactuated, keeping contact forces low and maximizing conformability, but becomes rigid when actuated, resulting in a stiff, stable grasp. The use of only a single actuator gives excellent performance (although more may extend the capabilities even further), while enabling the device to be a truly modular prosthetic terminal device which can be actuated

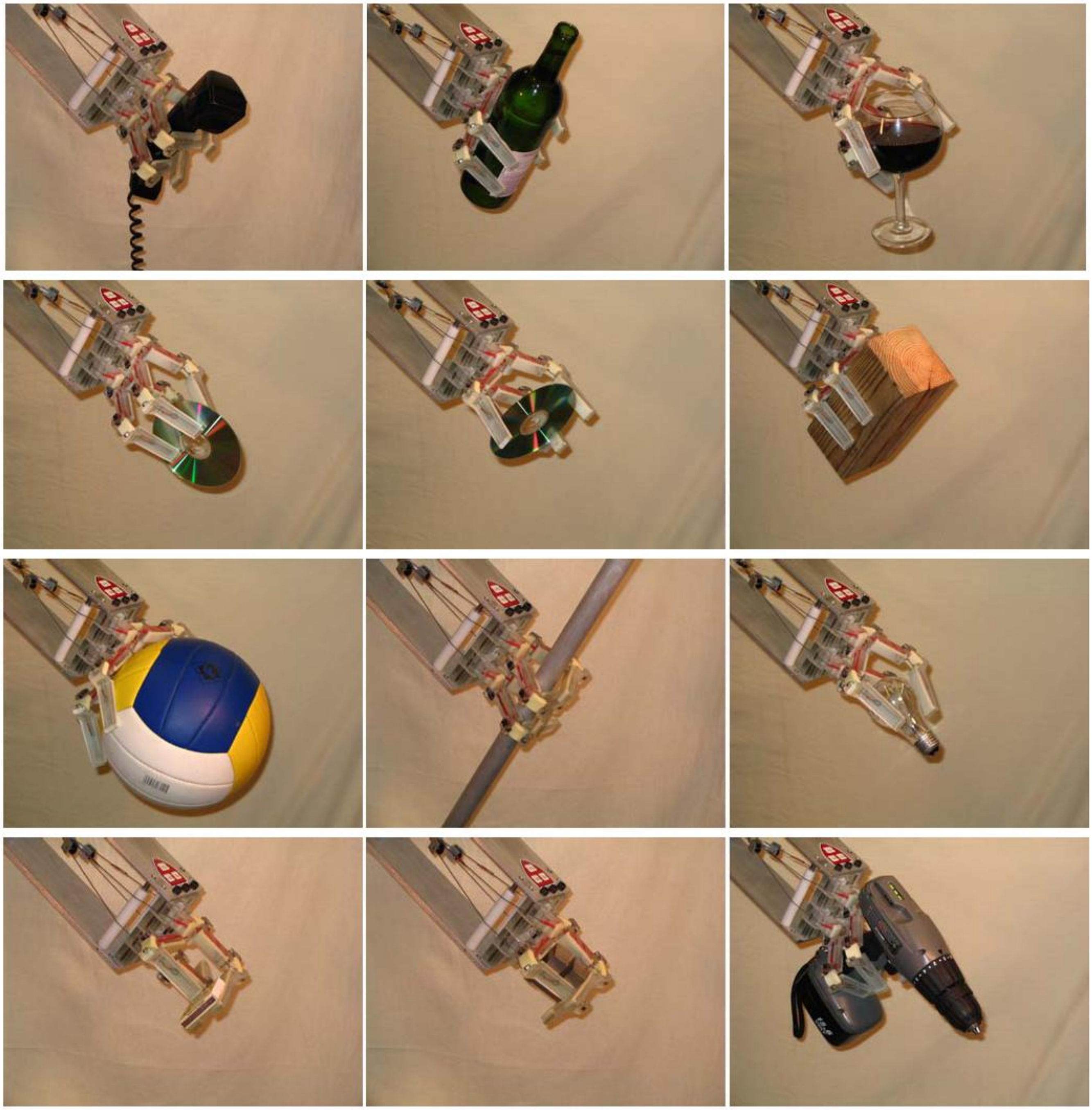

Fig. 9. SDM Hand grasping various household objects, many of which are suggested in [ref subs] as 'practice' objects. From top left, moving across: phone receiver, full wine bottle, full wine glass, compact disc grasped on faces, compact disc grasped on edges, wood block, volleyball, long rod (e.g. a broom), light bulb, book of matches (for striking), steel block approximating a padlock, and cordless drill.

with either body-powered or externally-powered methods of actuation. The fingers are actuated via tendon cables, which fit naturally with body-powered methods of actuation.

The biggest downfall to the current configuration of the SDM Hand as applied to a prosthetic terminal device is that no means of precision grasp is currently implemented except by manually positioning the fingers using the unaffected hand (for a unilateral amputee). This prevents bilateral amputees from being able to grasp very small objects as well as from picking up certain larger objects from flat surfaces that it might otherwise be able to grasp. However, configuring the hand in an anthropomorphic architecture with slight design modifications for a thumb digit should be able to solve this problem without sacrificing most of the performance capable with the current design. An additional degree of actuation would also facilitate a pinch grasp, regardless of whether an anthropomorphic architecture is adopted.

Despite these small limitations, we believe that a prosthetic terminal device implementing the major design features of the SDM Hand has potential as either a body-powered or externally-powered prosthetic terminal device that is realistic, functional, robust, and inexpensive.

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