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Simplifying Robot Hands using Recursively Scaled Power Grasps

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***Abstract*—This paper presents a concept for extending the functionality of robot hands so that they can better manipulate objects too small for an enveloping power grasp. Rather than pinching these objects between the fingertips of a hand, a miniature hand is embedded recursively on the end of a finger, enabling a power grasp on a smaller scale. The mechanics of designing such a gripper to operate without adding additional tendons are analyzed within the framework of underactuated elastic mechanisms. A simplified robot hand is demonstrated having a recursive gripper, and the process of picking up a pen and writing using a multi-scale grasp is demonstrated.**

I. INTRODUCTION

FOR traditional hands, which almost invariably have serial-link "fingers" placed around a palm, the choice of hand posture for grasping an object is often closely tied to the object's size. Large objects are generally secured using a "power" grasp that places a large number of hand contacts on the object by wrapping the fingers around the object, as well as generally involving contact with the palm, increasing the frictional contact with the object and allowing larger forces to be exerted or supported [1], [2]. For smaller objects, a "precision" grasp is typically utilized that places only the fingertips in contact with the object. While this type of grasp affords the ability to manipulate the object within the hand (due to the additional unconstrained degrees of freedom remaining in the fingers), the grasp is generally much less stable than a power grasp.

In this paper, we explore the concept of power grasping on multiple scales by employing a series of recursively structured grippers located at the distal ends of an arm or finger. As such, what would be typically considered a "finger" for one size scale, becomes an extension of the "arm" for a smaller size scale, as shown in Fig. 2. Using this approach, a power grasp can be achieved on objects spanning multiple size scales. This concept can be likened to "bi-manual" grasping and manipulation [3] of large objects using the arms as "fingers" (similar to how one would give a hug), while the hands are used for smaller objects.

The advantages of this recursive design are many. By achieving a power grasp on small objects, greater object stability is achieved due to a generally larger number of contact points and the ability to resist a larger range of forces that might otherwise dislodge the object. Grasp acquisition on small objects might be more easily and reliably achieved

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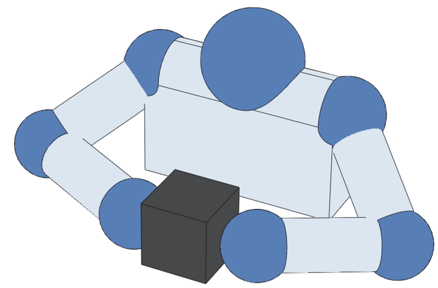

Fig. 1. Bi-manual manipulation is nearly identical to precision in-hand manipulation on a larger size scale.

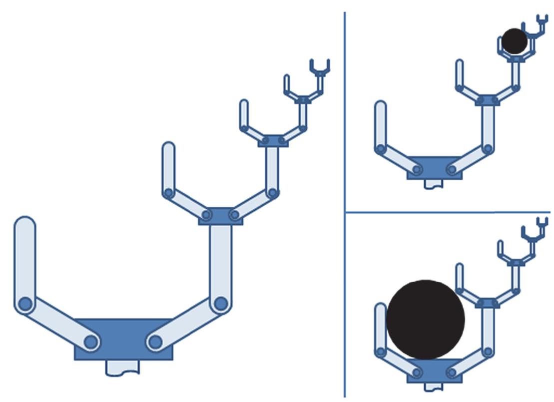

Fig. 2. Recursive manipulator showing different scales of manipulation. On one scale, the "fingers" grasping the object become part of the "arm" for a smaller scale grasp.

by using an appropriately-sized power grasper with fingers that can wrap around the object than with larger fingers and a pinch grasp. The mechanics of manipulation are simpler when using a recursively scaled gripper, because the problem of maintaining a force closure on the small object is decoupled from the problem of manipulating the object. As a side effect of this, the manipulable workspace of the grasped object depends only on the serial-chain kinematics of a single finger, instead of requiring an analysis of the hand and object as a parallel mechanism. Furthermore, the concept can be implemented without obstructing the more proximal "hand" by placing the successive links on the backside of the fingers.

We begin this paper by introducing the design of a three-fingered, simplified hand which has a recursive mini-gripper on the end of one finger. We explore the mechanics of actuating such a hand, showing that a stiffness scaling argument much like the one previously used for compliant underactuated hand design in [4] can be used to separate the motion of the recursive gripper from the motion of the finger as a whole. Finally, we will demonstrate how an added recursive gripper can be used to augment the ability of a simple hand to engage in a the complex task of picking up a pen, repositioning it within the hand, and writing with it.

II. A MULTI-SCALE SIMPLIFIED ROBOT HAND

A. Overview

Figure 3 depicts a prototype hand based on the design of HANDLE (hardened adaptive novel dexterous low-cost end-effector), a simplified robot hand developed in collaboration with several other research groups, and the official next-generation hand to be used by the DARPA Autonomous Robotic Manipulation (ARM) program. The primary goal of the HANDLE team was to develop a durable, low-cost robot hand which can perform a variety of grasping, regrasping and manipulation tasks. Like the authors' previous design, the SDM Hand, the distal joints of the fingers are monolithically molded flexures rather than traditional revolute joints, improving the durability of the hand and the stability of power grasps [5]. This new hand is also similar to the SDM Hand in that it is underactuated. Two symmetric fingers each have a single flexor tendon, attached at the distal link, so that the fingers close in a coupled, adaptive fashion common among simplified hands [5-9]. This pair of fingers rotates together, so that the hand can obtain pinch, spherical and cylindrical grasps on an object. The opposed digit, referred to as the thumb, shown at left in Fig. 3, is driven by two antagonistic tendons, which enable independent control of the proximal and distal joints.

B. Moving from Large-Scale to Small-Scale Objects

The primary functional requirements of this hand are to grasp and manipulate objects and tools on the scale of the hand, such as those shown in Fig. 4. The adaptive behavior of the underactuated fingers ensures that firm grasps on roughly palm-sized objects can be easily obtained despite the small number of actuators on the hand. Although the authors have shown that underactuated fingers can also be used for a range of in-hand grasping and manipulation tasks normally thought to require higher finger dexterity [10], [11], some human-inspired manipulation strategies, especially those used for small tools, are difficult to mimic with a limited set of actuators. Departing from the human-centric hand model, a recursive gripper was embedded in the distal link of the thumb, as shown on the left hand side of Fig. 3, and in a closer view in Fig. 5. Using this recursive gripper, a pencil-sized object can be attached to the thumb in a power grasp and moved around on the end of the thumb, rather than relying on multi-finger manipulation to achieve the same result.

C. Design Constraints

Cost and durability requirements impose significant design constraints on the recursive gripper. No additional actuators can be added to the hand to accommodate this feature, so the gripper must share the main flexor tendon of the thumb. A passive return spring keeps the gripper normally open. Because the primary functions of the hand should not be compromised, the gripper must not affect the kinematics of the thumb when it is not in use. Fortunately,

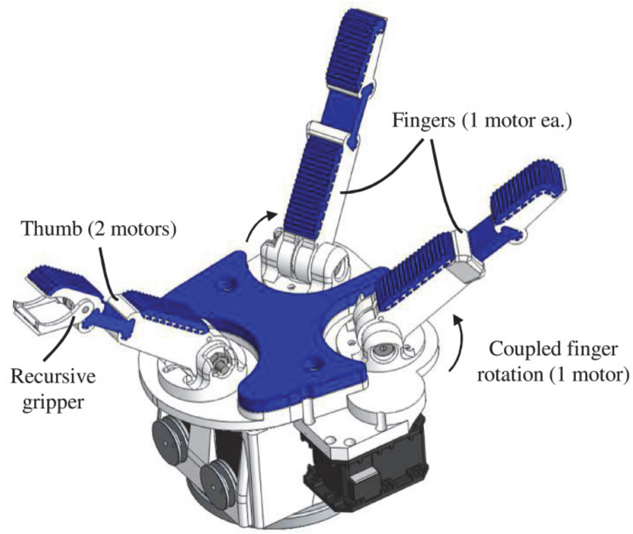

Fig. 3. A three-fingered robot hand having five actuators. The finger at left is actuated by two motors, while each finger at right has a single actuator controlling flexion. The fifth motor rotates the two right fingers.

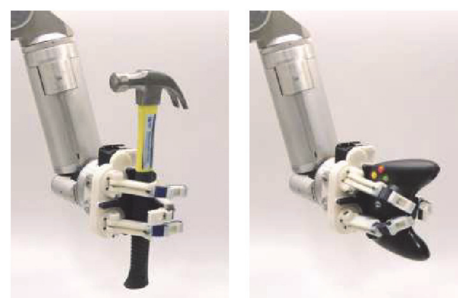

Fig. 4. A cylindrical power grasp (left) and a spherical power grasp (right) on two hand-scale objects.

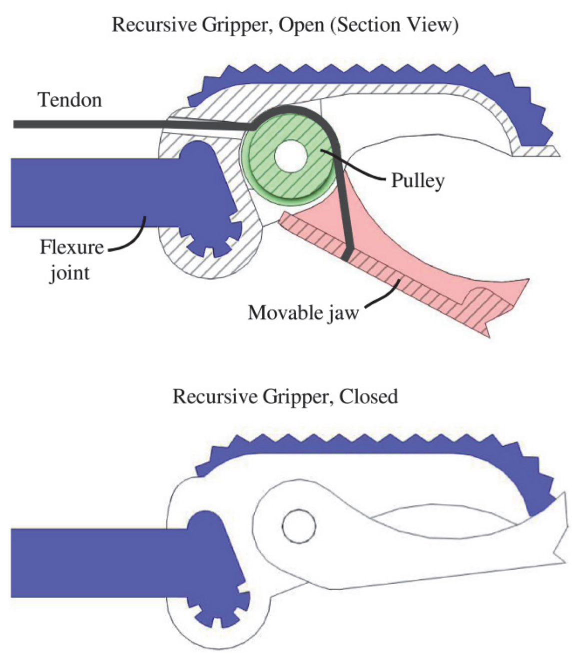

Fig. 5. A view of the small-scale gripper on the distal link of a finger, in open and closed configurations.

the problem of multiple passive joints sharing a single actuator is routinely solved in the design of underactuated fingers. By carefully choosing the relative stiffness of each joint in the thumb and the kinematics of the thumb tendons, the impact of adding the recursive gripper can be minimized. In the following section, these methods will be extended to the design of the recursive gripper.

III. Design of the Underactuated Recursive Gripper

A. Introduction

Underactuated systems, defined as systems possessing more degrees of freedom than can be actively controlled, are often employed in the design of mechanisms that must exhibit different behaviors depending on the conditions in their environment, such as the shape of an object grasped by a hand [12]. In particular, the design of underactuated robot fingers has been analyzed thoroughly [4], [9], [13]. In this section we will review the basic behaviors of a serial link underactuated finger actuated by a single tendon, and show how this analysis applies to the problem of a recursive gripper. The relative stiffness of each joint in the finger and the moment arms of the tendon at each joint are optimized so that the joints move in a preferential sequence. For example, Fig. 6 shows how a gripper might be designed to preferentially move the proximal joint on each hand while the fingers move freely, either by introducing a friction clutch at the distal joint, as in the UPenn/Barrett Hand [6] or by varying the relative stiffness of springs at each link, as in the SDM Hand [4]. We seek a similar property for the recursive gripper, so that it closes before the rest of the finger begins to move, ensuring that the behavior of the gripper does not affect the ability of the hand to obtain larger-scale power grasps.

B. Quasi-Static Behavior of an Elastic Finger

Consider a multi-joint robot finger actuated by a single tendon and having springs attached to every joint, so that the restoring torque τ on each joint is related to the joint position by a full-rank stiffness matrix $\mathbf{K}$. The quasi-static mechanics of the finger can be written in terms of each joint's deflection from the equilibrium position, θ-θ_0, and the force on the tendon f scaled by the tendon Jacobian, $\mathbf{J}$:

$$\tau = \mathbf{K}(\theta - \theta_0) + \mathbf{J}^T f = 0 \tag{1}$$

The transpose of $\mathbf{J}$ is a column vector representing the

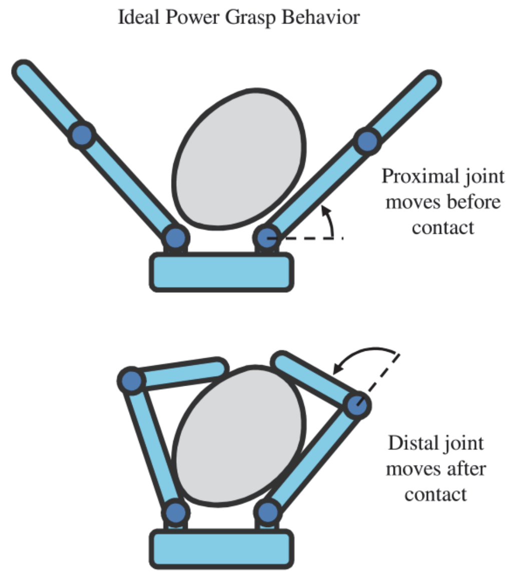

Fig. 6. The joint stiffnesses and pulley moment arms in an underactuated finger can be tuned so that the finger bends primarily at the proximal joint until contact with an object is made. After contact, the distal link bends to envelop the grasped object.

moment arm of each joint. When (1) is solved for the deflection of each joint, the rate of motion of each joint can be ascertained (if the stiffness and the Jacobian are assumed to vary little over the range of motion):

$$\theta \approx \theta_0 + (\mathbf{K}^{-1}\mathbf{J}^T)f \tag{2}$$

The column vector $\mathbf{K}^{-1}\mathbf{J}^T$ defines the relative rate of motion of the finger joints. For the example in Fig. 6 of a hand designed for power grasping, it would be advantageous to make the row of $\mathbf{K}^{-1}\mathbf{J}^T$ corresponding to the proximal joint larger than that of the distal joint by a reasonable ratio, so that the majority of the finger rotation occurs about the proximal joint. Previous work has found that a distal:proximal stiffness ratio of 5:1 was adequate for repeatable power grasping [4].

C. The Recursive Gripper

This elastic finger analysis can be applied to the recursive gripper, as shown in Fig. 7. Two tendons run through the thumb: an antagonist stopping at the proximal link, and a tendon which runs the entire length of the finger. The proximal joint and the gripper joint are made up of pulleys

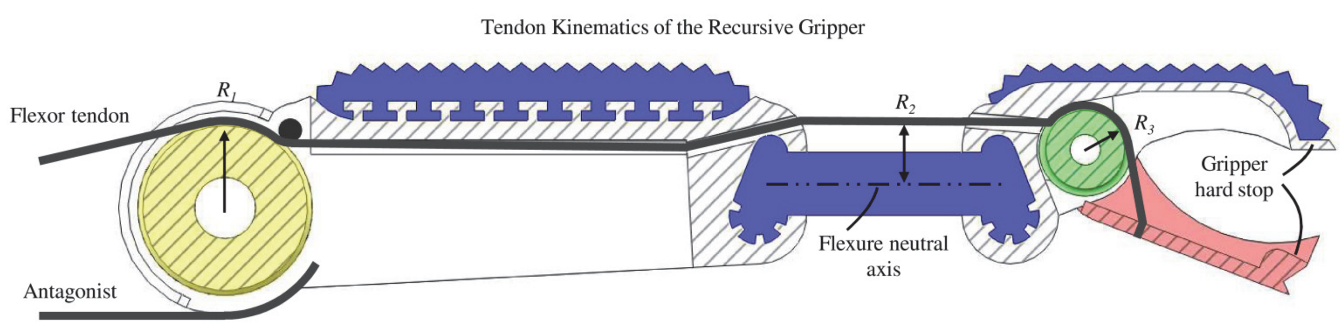

Fig. 7. A definition of the moment arms in the thumb and the recursive gripper.

having radii R_1 and R_3, with springs placed in parallel about the joints having stiffnesses K_1 and K_3. The distal thumb joint is a flexure whose stiffness K_2 can be calculated from the length L, elastic modulus E and bending moment I of the flexure,

$$K_2 = \frac{EI}{L} \tag{3}$$

The moment arm for small deflections is the distance from the tendon to the neutral plane of the flexure, as indicated on Fig. 7. The two joints on the thumb were designed to have equal moment arms $R_1 = R_2 = 9$ mm and a distal:proximal stiffness ratio of 5:1, but variability in the casting process resulted in a stiffness ratio of 4.4:1 on the prototype hand ($K_1 = 44$ mNm/rad, $K_2 = 195$ mNm/rad).

D. Gripper Parameter Choice

The joint moment arm of the recursive gripper, R_3, and the joint stiffness, K_3, can be chosen to satisfy two functional requirements: maximize the grip force that can be exerted on a small object, while minimally affecting the motion of the other two joints in the hand. The pulley radius is constrained by the packaging constraints inside the fingertip. In order to exert significant grip force, the largest possible pulley ($R_3 =$ 4 mm) that fit inside the fingertip profile was chosen to maximize the moment arm on the gripper. The joint stiffness was chosen to be 6.94 mNm/rad. Using the constant-moment arm approximation from (2), the relative motion of the proximal, distal, and gripper joints are coupled with respect to the flexor tendon force:

$$\begin{bmatrix} \theta_{prox} \\ \theta_{dist} \\ \theta_{gripper} \end{bmatrix} \approx \theta_0 + \begin{bmatrix} 44 & 0 & 0 \\ 0 & 195 & 0 \\ 0 & 0 & 6.94 \end{bmatrix}^{-1} \begin{bmatrix} 9 \\ 9 \\ 4 \end{bmatrix} f = \begin{bmatrix} .2045 \\ .0462 \\ 0.5764 \end{bmatrix} f \tag{4}$$

From this, one would expect that the gripper closes much more quickly than either of the other two joints when the flexor tendon is pulled. Unfortunately, friction is a major factor in determining the behavior of tendon-driven fingers. Due to the decrease in tendon force as the tendon passes each joint, initial testing showed that the recursive gripper closed too slowly relative to the proximal joint. However, because the proximal joint can be actuated independently of the distal joint, the gripper could be activated by locking the proximal joint when closing the gripper. Once an object is acquired, the joint can be unlocked and the object can be manipulated within the hand. Using the locking strategy, the motion of the distal flexure joint was acceptably small relative to the motion of the recursive gripper, as shown in Fig. 8. After the hard stop at the end of the gripper travel (illustrated in Fig. 7, right), the motion of the thumb was unchanged from its behavior without the gripper installed.

Figure 9 shows a pen grasped in the hand, manipulated to several points within the hand workspace. Unlike the more traditional approach of rolling an object between fingertips, the thumb alone can be used to position the object while the two opposed fingers can move independently – a feature that is especially useful considering the limited actuation capabilities of the hand.

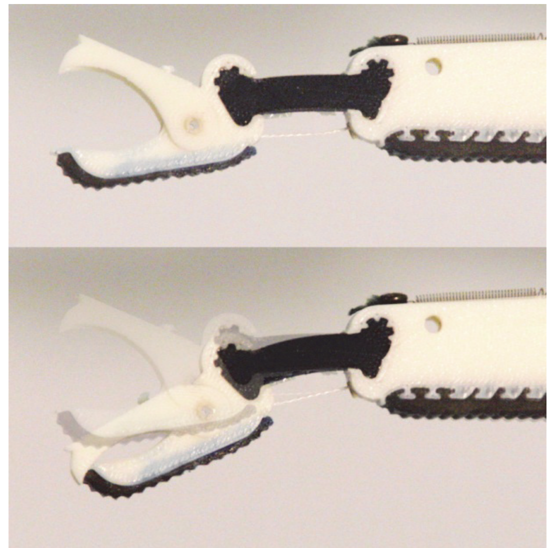

Fig. 8. The recursive gripper opening and closing. The motion of the fingertip over the gripper's working range can be seen from the overlay on the lower image.

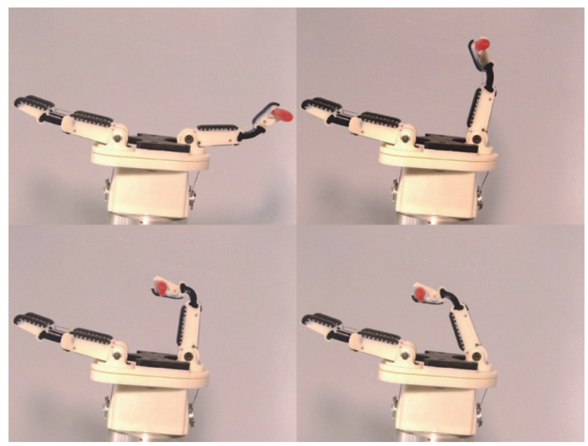

Fig. 9. A pen grasped in the recursive gripper can be manipulated in the hand workspace without the aid of the opposed fingers.

E. Summary

The process used to select the design of the recursive gripper is very similar to the process of designing an underactuated finger, with the added complication that the ratio of gripper forces to finger forces are much smaller than the force ratios in a more conventional multi-link underactuated finger. The exponentially decreasing stiffness of the springs required to achieve these multiple force scales would have been problematic if the gripper were not mounted on an otherwise fully actuated thumb.

IV. Experiment: Grasping a Pen and Writing

To demonstrate the degree of dexterity added to the hand by the recursive gripper, a prototypically hard task was chosen as an experiment: grasping a pen, repositioning it in hand into a writing grasp, and then writing on a piece of paper. This was a proof-of-concept test; the test hand used had no sensors and was controlled using kinematic playback of recorded joint trajectories. The results were extremely encouraging. Underactuated hands are typically limited to a small set of basic grasping and manipulation primitives. HANDLE has more actuators than most underactuated hands, and thus a wider range of primitives, but to perform a task this complex unaided by tactile feedback represents a remarkable improvement in hand capability.

A. Apparatus

The robot hand constructed for this experiment, shown in Figs. 10-12, was fabricated using a combination of fused deposition modeling on a Stratasys 3D printer and cast flexible parts made using Smooth-On Plastics urethane polymers. This hand was actuated using Robotis Dynamixel RX-28 servos. Tendons were made from Spectra 100 pound test fishing line, and tendon guides were made from PEEK tubing. The hand was mounted on a 7 DOF Barrett Whole Arm Manipulator.

B. Control

The WAM and the hand actuators were scripted using a python script that interfaced to all 7 arm and 5 hand joints. The trajectory for acquiring an pen, regrasping it, and writing was defined as a sequence of reference joint angles played back without replanning or tactile feedback. Because the fingers were compliant and underactuated, the playback trajectory did not need to be very accurate; the fingers deflected to accommodate any errors in table height or orientation.

C. Results

The video accompaniment to this paper and Figures 10-12 show the hand picking up the pen and writing on a piece of paper. The process of acquiring the writing grasp is demonstrated in the video. First, the proximal joint of the finger was fixed with the antagonistic tendon, and the flexor was used to close the recursive gripper around the pen. Then, the two actuators of the finger were used to position the pen in the center of the hand's workspace. Finally, the two opposed fingers were closed around the pen to provide a stable tripod grasp. To write, the pen was held at an angle with respect to the table top; this was done to increase the compliance of the pen tip in the direction normal to the table, much as human hands. The largest source of error in writing letters using the pen was the non-uniform lateral deflection of the pen tip as it was moved across the page. Pre-planning hand motions based on the non-uniform compliance of the tip, so that the pen is dragged in the orientation producing minimum deflection, would reduce these errors significantly.

V. Conclusions

In this paper, we have introduced the concept of a recursive robot hand, partially as a philosophical exercise and partially as a practical tool for robot design. While

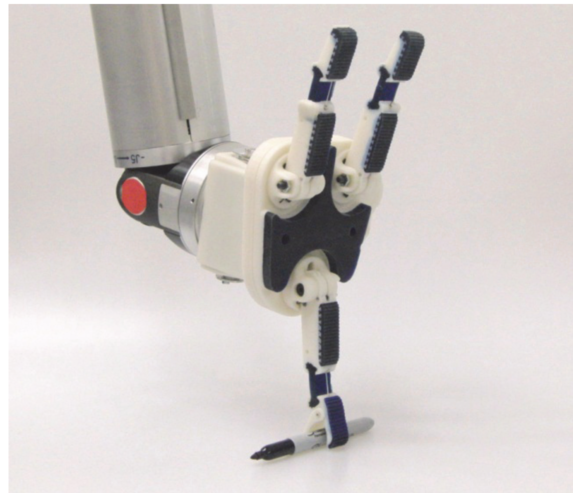

Fig. 10. Picking up a pen off the table with the recursive gripper. The thumb was lowered onto the pen and then the gripper was tightened with the proximal joint locked.

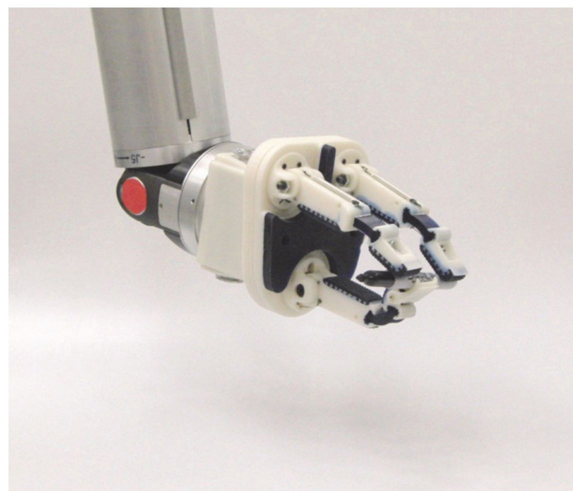

Fig. 11. Repositioning the pen into a stable grasp for writing. Holding the recursive gripper shut, the pen was moved up into the center of the hand workspace. The opposed fingers were then moved to brace the pen.

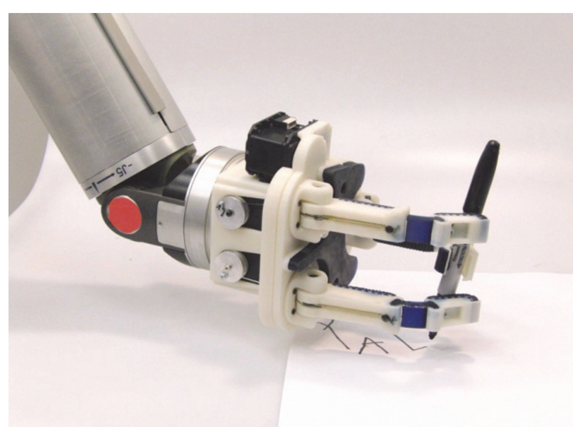

Fig. 12. Writing with the grasped pen. The pen was moved on a pre-recorded trajectory to write on a piece of paper affixed to the table.

human limbs are limited to a small number of scales (arms and fingers) on which objects can be manipulated while held in power grasps, an artificial system having no such limitations could have significant advantages over a strictly anthropomporhic hand. We have shown experimentally how the grasping and manipulation capabilities of a robot hand can be improved by enabling the hand to obtain a power grasp on smaller objects rather than relying on manipulation between the fingers. This scale-matching strategy is particularly effective at compensating for the lack of dexterity in a simplified robot hand, although friction limits the degree to which compliance scaling can be employed to reduce the number of actuators. Recursive scaling of grippers may also be desirable in a highly dexterous robot hand as well. It is not hard to imagine a manipulator capable of replicating this recursive scaling on several levels, so that objects from the size of centimeters to microns could be manipulated with the same system.

Several related directions of future inquiry are apparent from this point. It would be interesting to compare the range of motion that can be achieved in a recursive power grasp to the range of motion possible by rolling the same object between the fingers. This and other performance measures, such as grasp strength and stiffness, could easily lead to a set of design rules suggesting one strategy or the other depending on circumstance. It would also be interesting to implement a recursive gripper using an underactuated finger framework less susceptible to frictional losses than tendons are, such as a linkage-based hand.

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