2013 IEEE International Conference on Robotics and Automation (ICRA)
Karlsruhe, Germany, May 6-10, 2013

A Modular, Open-Source 3D Printed Underactuated Hand

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Abstract— **Commercially available robotic hands are often expensive, customized for specific platforms, and difficult to modify. In this paper, we present the design of an open-source, low-cost, single actuator underactuated hand that can be created through fast and commonly-accessible rapid-prototyping techniques and simple, off-the-shelf components. This project establishes the design of an adaptive, four-finger hand utilizing simple 3D-printed components, compliant flexure joints, and readily obtainable off-the-shelf parts. Modular and adjustable finger designs are provided, giving the user a range of options depending on the intended use of the hand. The design tradeoffs and decisions made to achieve the 3D-printable, compact and lightweight robotic gripper are discussed, as well as a preliminary discussion of the performance differences between the finger designs. The authors intend this work to be the first in a series of open-source designs to be released, and through the contributions of the open-source user community, result in a large number of design modifications and variations available to researchers.**

I. Introduction

Robotic hands often fall into two categories: simple and highly specialized grippers often used in manufacturing, and general and highly complicated grippers designed for a variety of tasks. Underactuated hands [1,2] have been shown to improve the generality of simple grippers by adaptively conforming to the surface of objects without the explicit need for sensors or complicated feedback systems. However, although many novel grasping mechanisms have been published in the literature, end-users of robot hands are still frequently limited to spending a substantial amount of time, effort, and money to fabricate their own hands, or purchasing one of the relatively expensive, commercially-available hands. Because of these two primary options, it is typically impractical to experiment with alternate end effector designs, or to significantly modify existing ones. This results in researchers needing to compensate in software for intrinsic and pervasive mechanical disadvantages, rather than allowing software and hardware research in manipulation to co-evolve.

Meanwhile, advances in rapid prototyping, such as 3D printing [3,4] and shape deposition manufacturing (SDM) [5], have made it increasingly tractable to make custom parts for robotic hands on demand expediently. In this paper, we present a simple adaptive robotic gripper, based on the SDM Hand [1,5], redesigned with rapid-prototyping methods in mind. This design seeks to provide performance adequate for general-purpose experimentation, while requiring only off-the-shelf components and minimal machining. The minimalist design and the low fabrication cost of this hand will allow researchers to modify and replace components on their own at low cost, without the need to wait for custom-machined replacement parts.

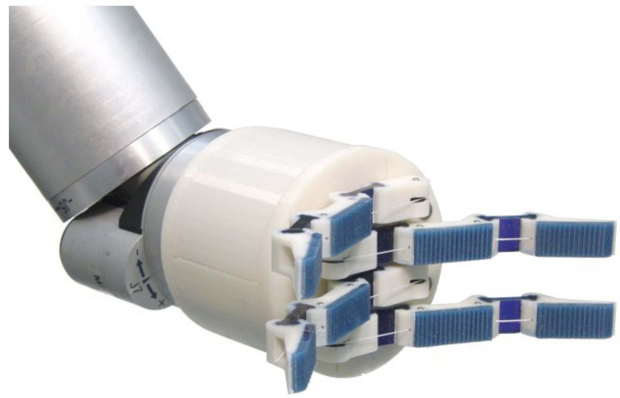

Fig. 1. Prototype of the low-cost underactuated robotic gripper based on the SDM hand

In terms of commercially available hands, a variety are used in research today [6-13], many of which are capable of adaptive behavior through novel linkage mechanisms or joint compliance. However, none are designed to accommodate extensive modifications, and they are typically designed for operation with specific arms. As a result, researchers may find their choice in robotic hands tied to their manipulator selection, limiting the types of research tasks they can accomplish.

In order to give researchers a hand option that is inexpensive, easily customizable, and fast to fabricate, the authors have developed a low-cost hand, shown in Fig. 1, utilizing a minimal number of 3D printed components and unmodified off-the-shelf parts, powered by a readily available, self-contained servo. The finger design is modular and monolithic and can be easily switched out to best accommodate the desired task. The whole hand can be fabricated for approximately 500 USD in material and parts and can be fully printed and assembled in less than one day and with only a few hours of user interaction.

The paper is organized as follows: Section II presents and overview of the characteristics of underactuated, compliant hands used in this design. Section III details the design considerations related to presenting an open-source and 3D-

This work was supported in part by National Science Foundation grant IIS-0952856 and by DARPA ARM-H, grant W91CRB-10-C-0141.

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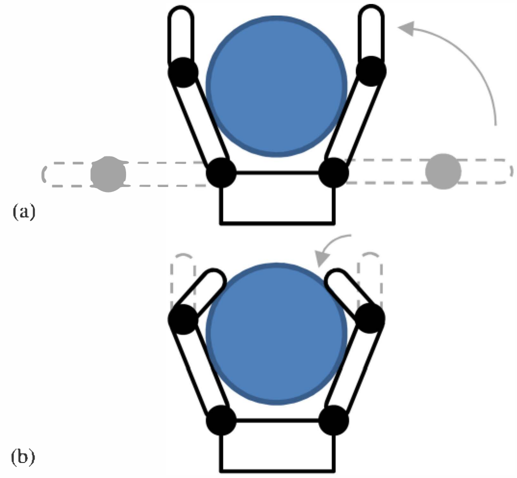

Fig. 2. Main phases of adaptive power grasping: (a) sweeping, (b) caging

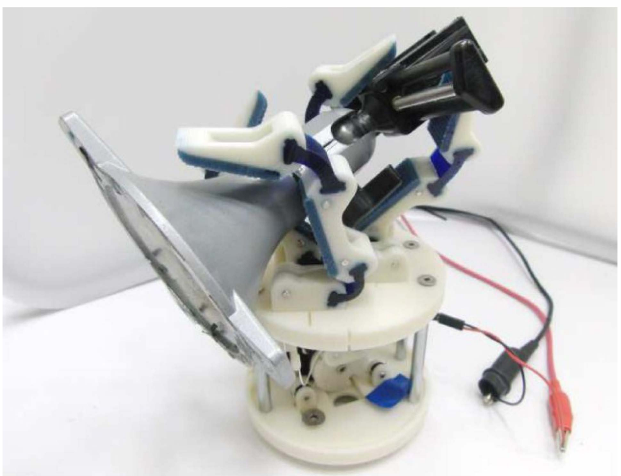
Fig. 3. Differential between fingers maximize the number of contact points

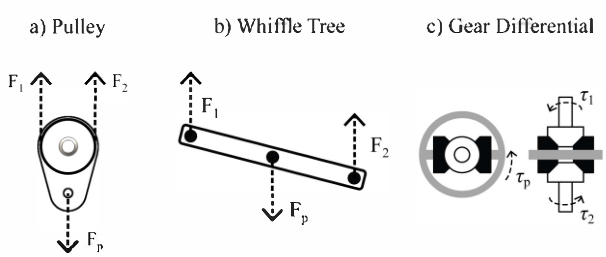

Fig. 4. Main types of actuation differentials used in grasping: a) floating pulley, b) seesaw linkage and whiffle tree, c) gear differential

printable hand. Section IV describes the build process for the prototype hand; in particular, the SDM process used to create in-molded elastomer pads and joints for the compliant fingers is detailed. Section V discusses the performance of this hand and compares it to similar commercial products, followed by a conclusion.

II. Underactuated Hand Design

The presented hand design reproduces the functionality of the SDM hand [1], an underactuated, four-finger hand with compliant flexure joints driven by a single actuator. Underactuated robotic hands have been shown to be proficient at grasping items of various sizes and shapes by passively adapting to the object geometry. Much past work has been done on the analysis of underactuated hands [1,2], and many existing hands [6,9,11,12] already leverage the benefits of underactuation. Fig. 2 shows the two primary phases of an underactuated power grasp: the sweeping phase, where the proximal finger links contact the object, and the caging phase, where the distal links make contact to fully encompass the object.

To achieve form closure with a single actuator, underactuation both between the fingers and within the individual fingers can aid in maximizing the grasp contact, such that if contact on any finger is obstructed, the others continue to move, until the hand fully envelopes the object in a power grasp. Fig. 3 shows the underactuated hand conforming to an irregularly shaped object. All fingers continue to move until they are fully constrained.

III. Design for Open-Source and 3D Printing

In order to present a set of open-source designs that are easy to fabricate on common 3D printing systems, a number of issues must be considered.

A. *Differentials for Adaptive Underactuation*

Birglen and Gosselin [14] provide a review of differential actuation mechanisms in the context of grasping. For practical applications, designs for between-finger differentials can utilize three types: gear differentials, linkage seesaw differentials, and pulley differentials. The basic components of these differential subsets are shown in Figure 4. Gear differentials, utilized automobiles, offer compactness at the expense of high complexity and friction, but can support large torques. However, it is difficult to 3D print gears, and the resultant resolution is often unacceptable.

Linkage seesaw differentials, also known as Whiffle-tree differentials, utilize the rotation of a bar about staggered pivots to accommodate the difference in outputs. The output travel of the pivoting bar, also referred to as the differential or equalizing lever, is limited by its length, limiting the packaging flexibility for this option. Nonetheless, the rigid and relatively simple components make rapid-prototyping and assembly more straightforward. Pulley differentials, where a floating or moving pulley is used, were implemented with the original SDM hand [1] and offer packaging advantages, but they can also present additional challenges in assembly. The possible slackening of the tendon cables in pulley differentials can be advantageous in unstructured operating environments where some of the fingers may inadvertently impact external obstacles, displacing the impacted finger without forcibly perturbing the other fingers. However, mechanical considerations also need to be made to ensure that the tendons do not slip off the actuating pulleys.

Given these tradeoffs, we have resorted to a hybrid pulley/whiffle-tree differential [15] in the presented design to allow for the required amount of differential travel with the smallest packaging size.

Within the finger, the two primary options for differential adaptability relate to a choice between a tendon-driven or

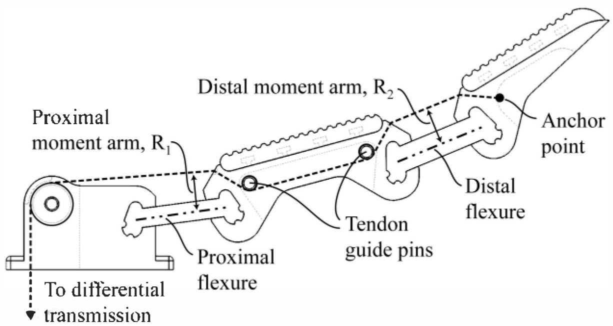

Figure 5. Diagram of the tendon routing path. Joint moment arms R are measured from the tendon routing holes to the flexure centerline.

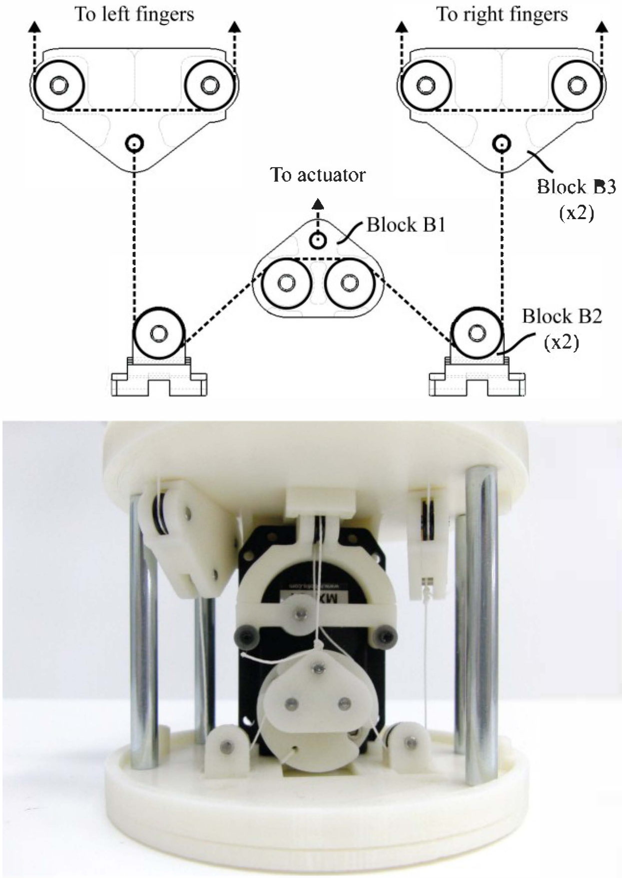

Figure 6. Diagram and implementation of the actuation differential used in this prototype design

linkage-driven transmission [1,5,10]. While both of these options are viable, we opt for a tendon-based design in order to minimize the size and number of parts required for assembly.

B. Finger Design

In order to be compatible with 3D printing technology, the finger designs should be converted to structures that have minimal number of small features and parts. While many finger designs include a large number of fasteners, we present designs that are nearly monolithic (Fig. 5) and require very few additional parts. The rigid parts of the fingers are a single part, while we print thin-walled molds to use for containing the flexure and fingerpad materials. These mold walls can be broken off after the materials have been poured and cured. In order to assist with the adhesion between the poured materials and the 3D printed base, we utilize series of small dove-tail joints distributed along the length of the fingerpad.

The basic set of finger system parameters commonly used in underactuated fingers [1] includes joint moment arms R, link lengths L, joint stiffnesses K, and initial joint resting angles. In this design, these parameters can be adjusted through modifying the geometry of the monolithic finger frame alone, simplifying the system selection and optimization process.

C. Actuation

The Robotis MX-64 Dynamixel servo [16], which have been used in several previous hand and arm designs [17, 18], is self-contained and compact, has minimal weight (126 g), and can be purchased at a reasonable price (~250 USD). Additionally, the Robot Operation System (ROS) has to date maintained drivers for this family of actuators, making control and integration into existing ROS-based systems more straightforward than other solutions. This particular servo has a maximum torque output of 7.3 Nm, which has been more than sufficient for past designs, but Robotis also offers servos with higher torque and speed specifications. With a drive pulley diameter of 10 mm, the MX-64 can theoretically apply a maximum tendon force of 365N for each finger in this design.

D. Tendon Routing, Friction Minimization

While past work on the viability of rapid-prototyping in robotics applications [3,19] have produced basic joints and linkage systems, the authors are not aware of any prior work on the durability or extended use of such mechanisms. [19] details some considerations that should made with respect to printing orientation to maximize part stiffness in the desired loading directions, and the presented design takes those suggestions into account.

100-lb test Spectra fishing line were used as tendons in this hand. Under significant load, these tendons can wear and cut through the rapid-prototype material. To prevent this, 3.18 mm steel tendon guide pins were press-fit into the fingers, as shown in Fig. 5, providing a harder sliding contact with substantially lower frictional forces.

Limiting friction in tendon transmissions is of paramount importance when designing a robot hand. The design of this open-source hand minimizes the contact between tendons and the rapid-prototype material. Wherever possible, the tendon runs across free-spinning pulleys to maximize actuator efficiency. Fig. 6 details the differential routing.

IV. Hand Fabrication

This section provides an overview of the manufacturing techniques used to construct the hand, focusing primarily on the fingers. As in the authors' previous work on fingers produced using shape deposition manufacturing (SDM), the fingers are hard-soft composite structures that integrate links, hinges and pads into a single piece. Unlike previous designs, however, the fingers on this hand require no extensive machining of molds. This makes the fingers much

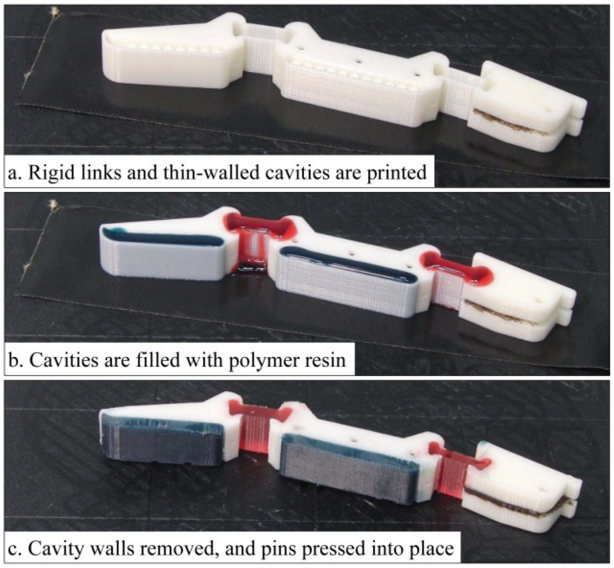

Fig. 7. Finger molding process: (a) 3D printed finger has cavity with 0.7mm thick shell. (b) Liquid rubber mold is poured into the cavities and cures within the 3D printed framework for 16-48 hours. (c) Cavity shell is removed, and additional pins are added for the final result.

easier to manufacture with limited equipment, while retaining the most attractive features of SDM.

A. Rapid Prototyping Equipment Used

Printed components were produced from solid models by a Stratasys uPrint SE [20]. This low-cost 3D printer supports a single ABS material, and a soluble support material that can be dissolved from the printed parts. However, to simplify fabrication, the printed parts for the gripper were designed so that the support material could be removed manually without the use of a lye bath or cleaning solution. This printer model has a layer resolution of 0.254mm (0.010 in). The smallest feature in this grasper design has a critical dimension of 3mm. The relative softness of the ABS made it ideal to pursue press-fit assembly with dowel pins instead of other fasteners where possible. Some features require some simple post-processing (e.g. reaming) to accommodate this design decision.

B. Polymer Overmolding

In order to obtain reliable contact with a grasped object and reduce slip, 5mm thick polymer pads were molded directly into the hard finger links by printing the fingers with a thin (0.7 mm) shell tracing the outline of each pad. Fig. 7a depicts a partially-made finger as it looks when it is removed from the Stratasys rapid prototyping machine. When the links were removed from the tray of the rapid prototyping machine, the bottom edges of the shells were sealed with tape, so that mold cavities were formed. A urethane elastomer (Vytaflex 30, manufactured by Smooth-On, Inc.) was poured into the finger pad cavities, as shown in Fig. 7b. After the urethane was cured, a small saw was used to cut away the mold shell, leaving the exposed finger pads. Adhesion of the finger pads to the links was improved by the addition of small crenellations on the surface of the printed links. These trap the soft urethane so that peeling is less likely.

The flexure hinges on the fingers were formed in a fashion similar to the finger pads. Flexure molds were formed by connecting each rigid link with thin walls. The interior void in the link at each end of the flexure was used to trap the molded elastomer, so that the flexure cannot pop out of the links. A much stiffer polymer, Smooth-On PMC-780, was used for the flexure joints. The thickness of each flexure was varied to provide the appropriate stiffness ratio between joints.

C. Wrist Chassis

Fig. 6 shows the chassis, assembled from several pieces of printed ABS and a set of metal stand-offs running the length of the hand. These stand-offs and the Dynamixel MX-64 servo provide a firm structural support for the wrist. Within the wrist chassis, the differential transmission connecting the single actuator to the four fingers of the hand is run over a series of pulley blocks. The pulley system is arranged symmetrically about the chassis profile and was designed to minimize the number of unique parts. To achieve the smallest possible wrist package size, the two stages of the differential were rerouted and run in opposite directions, minimizing the necessary height of the hand base.

D. Palm

Fingers are clamped onto the top surface of the wrist. The palm top plate can be modified to accommodate a variety of finger base lengths, as long as the tendon routing hole is kept constant. Details of this arrangement can be found in the Appendix. The finger joints can be widely spaced or spaced in a single line down the center of the palm. This is intended to give researchers maximum flexibility depending on the desired manipulation task, such that the range of allowable test objects is not restricted by the initial finger operation parameters.

V. PERFORMANCE COMPARISON BETWEEN FINGER DESIGNS

Although flexure joints were used in both the proximal and distal joints in this initial design, there are a few major performance considerations relating to the choice of finger type. In general, the flexure-based designs provide the largest amount of adaptability to out-of-plane contact, but have the lowest torsional stiffness. Conversely, the compliant pin-joint designs have the highest torsional stiffness but the lowest adaptability to out-of-plane contacts. As a middle-ground, we suggest a finger design that includes a compliant pin-joint proximally and a flexure joint distally, to give a balance between the two [21].

A. Flexure Joints

Flexure joints have been shown to be particular desirable in unstructured environments [1], where the hand may inadvertently collide with undetected obstacles or parts of the environment. The hard-stops in revolute designs can potentially lead to damage in the joints. Elastomer joints also allow the fingers to deflect out of plane, improving the ability of flexure-based fingers to conform and adapt to irregular object surfaces.

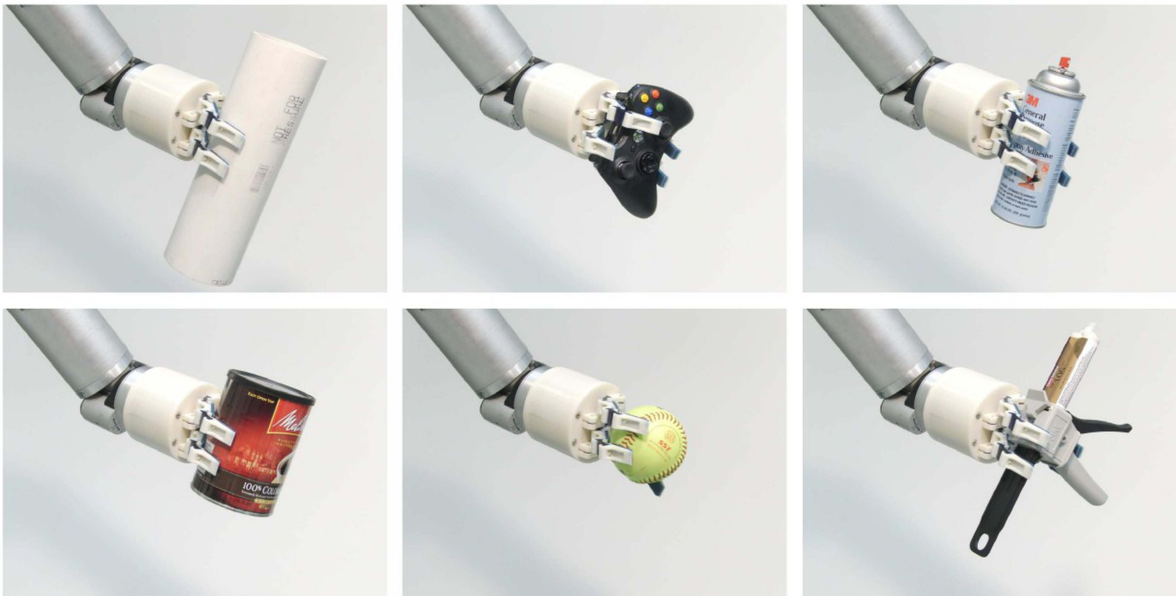

Fig. 8.Example grasps with the prototype hand. Fingers are driven with constant torque control and are capable of conforming to a wide variety of object geometries.

TABLE I. GRASPER COMPARISON

Hand	**# Fingers**	**# Actuators**	**Base Height (mm)**	**Base Width (mm)**	**Weight (g)**	**Grip Force (N)**
Barrett Hand	3	4	75.5	130	1200	15
2G Velo	2	1	80	45	?	10-20
Robotiq (2-finger)	2	1	90	140	890	30-100
Robotiq (3-finger)	3	2	126	126	2300	15-60
Meka H2	4	5	63	96	800	?
Schunk SDH Hand	3	7	98	122	1950	?
Open-source Design	4	1	75-90	100	400	10

B. *Revolute Compliant Joints*

The use of revolute joints, on the other hand, provide more consistent and reliable behavior, and the authors have shown that they are particular useful in more complicated, dexterous manipulation tasks [17]. However, out-of-plane adaptability in power-grasping is lost due to the increased rigidity, and the fingers are more susceptible to damage in collision cases.

VI. GRASPER PERFORMANCE

Table I compares the open-source hand design to existing, commercially available robotic hands. In terms of weight and hand base footprint, the hand presented in this paper compares favorably with the alternative options. The maximal grip force of 10N was measured with a load cell clamped between plates spaced 28mm apart, with finger parameters L_1=69mm, L_2=46mm, R_1=9mm, R_2=9mm, K_2/K_1=2.5. This grip force will vary with respect to the selected finger parameters, and the non-backdriveability of the actuator allows the fingers to resist much larger forces than they can actively exert.

Fig. 8 shows the underactuated hand grasping a selection of objects with varying geometries. The same grasping control was applied to all objects: the servo was driven at a constant torque until all finger links made contact with the object or all fingers were driven to their limits, at which point the tendon position was locked.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we present a low-cost design for an underactuated hand with compliant joints made through 3D printing and SDM. Rapid iteration of design and testing is crucial to the development and validation of new designs, and we aim for this prototype to be the basis for a mechanical design platform that other labs can practically customize and extend to further explore the application of underactuated hands with compliant joints.

The creation of an easily accessible and extendable design intends to eliminate the constraint of the rigid, closed designs of existing robotic hands, which often come bundled with certain manipulation platforms. By presenting a minimalistic design released open-source for public use, the authors hope to motivate and quicken the innovation of robotic hands, in both research and educational settings.

The overarching goal of this project is to create an open-source hand design that researchers can reproduce and customize on their own. We aim to minimize the barrier of entry to new and novel hand designs. This design and future modifications will be released online at (www.eng.yale.edu/grablab/openhand), and eventually also available as a ROS repository, giving other labs the opportunity and mechanism to simultaneously progress software and hardware simultaneously. By encouraging widespread adoption, novel designs can be more thoroughly validated by different groups with differing areas of manipulation research.

To better promote the open-source goal of this project, future revisions will further simplify the manufacturing and assembly requirements. Detailed guides for assembly and rigs for any necessary finishing procedures will be provided.

Future modifications will improve the modularity of this design. This will create allowances for the addition and/or substitution of other actuators, differential mechanisms, and a wider range of customized fingers.

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APPENDIX: ASSEMBLY OF HAND TRANSMISSION

This appendix contains diagrams showing how to assemble the chassis of the hand. The layout of the tendon transmission is documented in Fig. 6, but the individual pulley blocks labeled in the figure are made up of several pieces each. Fig. 9-12 show the construction of each block. Each is held together with press-fit pins, and also act as arbors on which the pulleys rotate.

For assembly, first assemble the pulley blocks B1, B2, B3, and B4, as shown in Fig. 9-12. The pins must be pressed into the printed parts, either with an arbor press or with a pair of pliers. Due to compliance in ABS, it is suggested that the pins are only pressed with pulleys and shims in place to avoid accidentally clamping the pulleys such that they cannot spin. Second, attach the drive pulley onto the servo horn. Once this is fastened, affix block B4 onto the motor. This block re-directs the drive tendon (initially exiting at the top of the drive pulley) downward, where the tendon attaches to block B1 as shown in Fig. 6. At this point, insert blocks B2 into the base plate (BASE.STL) as illustrated in Fig. 13. Then, screw the 8-32 standoffs into the base. Seat the motor assembly in the top plate of the wrist (TOP.STL), and mate the top and bottom halves by slotting the flanges on the bottom of the motor into the base. Fasten the standoffs to the top plate.

Now that the transmission is assembled, the final tendons can be threaded into the pulley blocks, as described in Fig. 6. The length of the tendon should be chosen so that at the limit of the servo travel, block B1 is nearly in contact with the base, and the B3 blocks are nearly in contact with the top plate.

Block B1 Exploded View (x1)

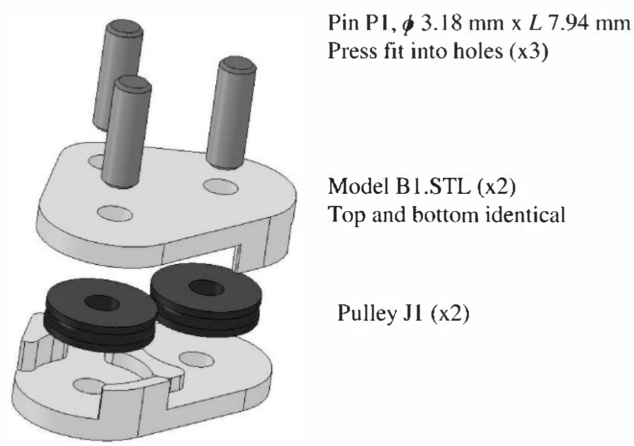

Fig. 9

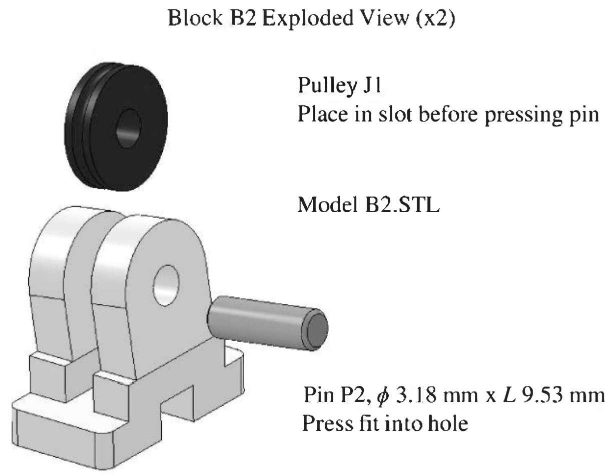

Fig. 10

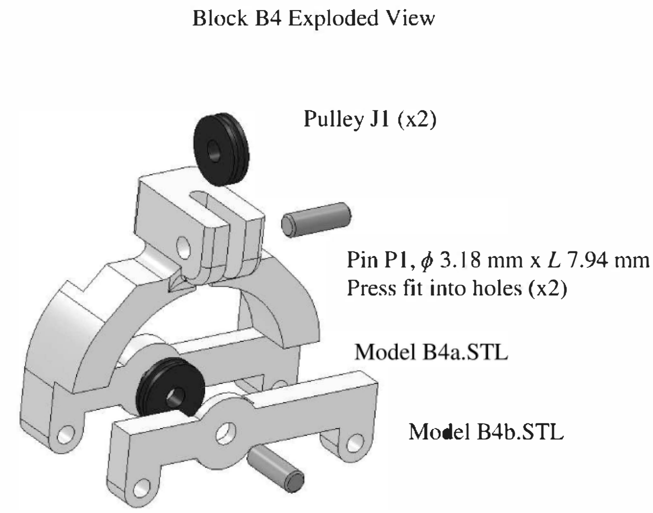

Fig. 12

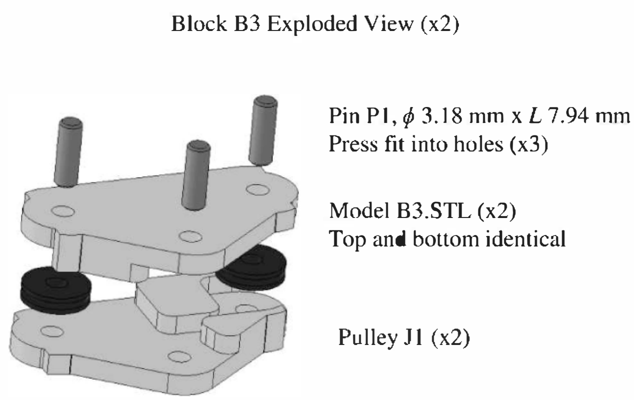

Fig. 11

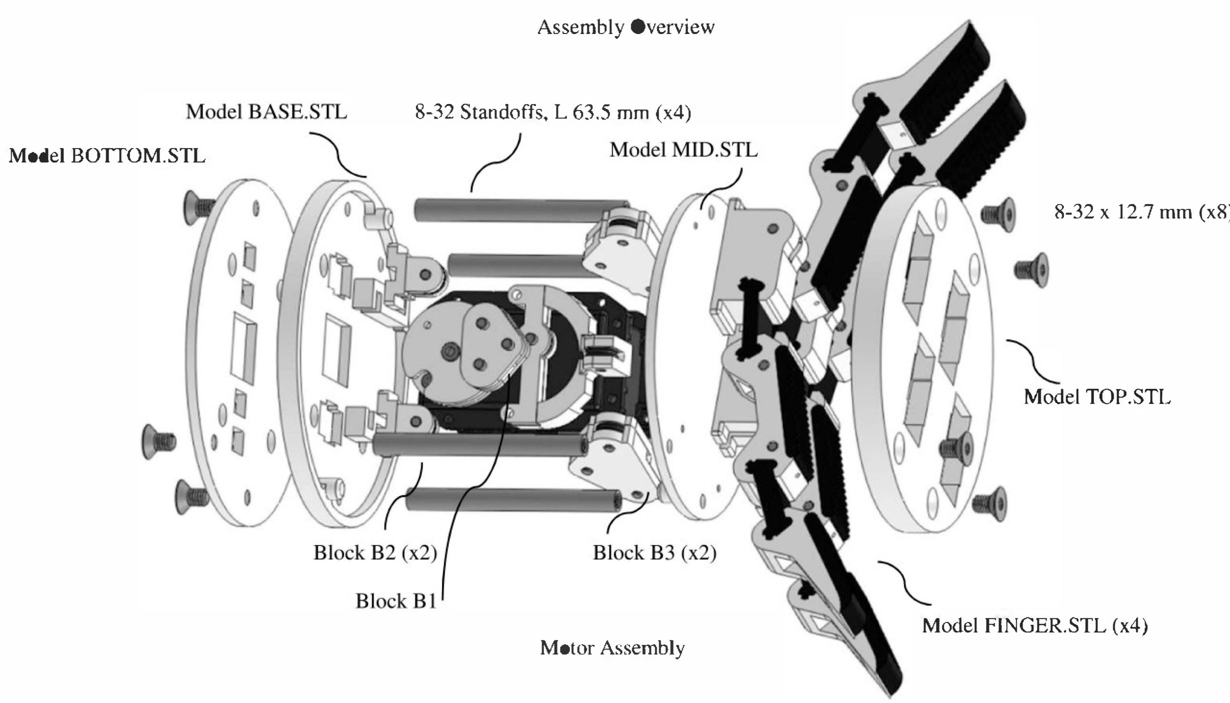

Fig. 13