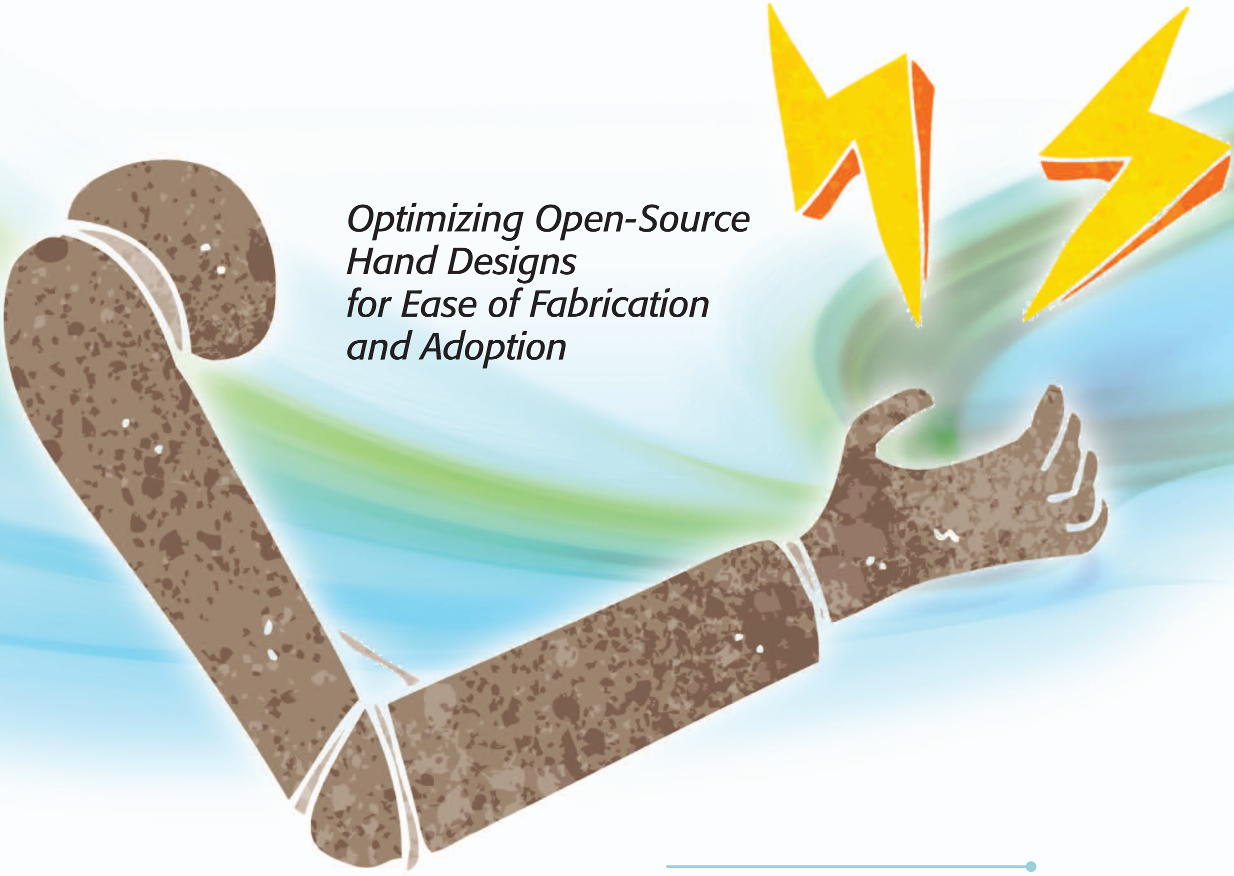
Yale OpenHand Project



Optimizing Open-Source Hand Designs for Ease of Fabrication and Adoption

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By Raymond R. Ma and Aaron M. Dollar

Although grasping and manipulation are key aspects of a robotic system's functionality, researchers often only have a limited selection of end effectors compatible with their manipulator base. This may either restrict the robotic system's full range of capabilities or force researchers to compensate for the end effector's intrinsic mechanical disadvantages through compensatory, nonoptimal control strategies. Advances in three-dimensional (3-D) printing have enabled researchers to quickly customize mechanisms for specific tasks, but the end product is usually not intended for extended use. It would be beneficial to identify strategies to augment the capabilities of additive manufacturing techniques to allow the easy and inexpensive construction of durable and functional hardware. To that end, this article details work on the Yale OpenHand Project, a library of low-cost, 3-D-printed, underactuated hand designs for researchers to freely implement and modify for their own use cases. The designs use cast flexural joints made via the hybrid deposition manufacturing (HDM) process to produce robust, impact-resistant subcomponents and help account for the structural shortcomings of fused deposition manufacturing (FDM). Several of these design examples are presented, evaluated, and compared with commercial alternatives. We hope that providing an accessible and extensible set of open-source hand designs will improve the iterative design process and produce many more options for researchers to utilize.

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The Initial HDM Process

Although numerous innovative grasping mechanisms have been presented in research literature [1], [2], end users of robot hands are either restricted to spending a substantial amount of time, effort, and money to fabricate custom hands or purchasing from a limited and expensive set of commercially available options [3]–[9]. Researchers may not have the resources or ability for the former, and in the latter case, they would be both unable to modify their designs and also dependent on the manufacturer for repairs and maintenance. Among other challenges, this situation prevents hardware and software research in manipulation from co-evolving.

The increased accessibility of 3-D printing, in particular FDM thanks in part to open-source initiatives [10], has made it more tractable to expediently produce custom parts on demand [11]. However, these parts are generally nonmoving, nonload-bearing, and made of a single homogeneous material. To provide the community with the ability to 3-D print inexpensive, customizable, and easy-to-fabricate components that are load-bearing and articulated, modifications must be made to extend existing additive manufacturing processes. As a means to address some of those concerns, we had previously developed a fabrication technique called HDM, in which 3-D-printed parts are combined with additional, deposited resins to produce monolithic, multimaterials parts, integrating, for example, rubber flexure joints and soft fingerpads as well as components such as tactile sensors that are molded into the parts. A robotic finger produced using the HDM process is lightweight and robust and has a low part count, and its fabrication requires less than one hour of manual assembly.

Using the design guidelines established during the refinement of the HDM process, we have developed a library of extensible, open-source hand designs that are modifications of some of their previous underactuated hands [12] to enable effective dissemination via additive manufacturing techniques (Figure 1). These tendon-driven designs require only 3-D-printed components and readily available off-the-shelf parts. The designs utilize self-contained hobby servos for actuators, and the implementation of adaptive, underactuated mechanisms enables a high degree of capability with only open-loop control. The fingers utilize cast, flexural joints for increased robustness, and they can be easily swapped out due to their monolithic and modular design. The fabrication and assembly processes for each of the hands are extensively documented [13] with step-by-step instruction guides and videos to promote design improvements and adoption in various applications by end users in a variety of research domains.

Related Work

Functional Components via 3-D Printing

Parts created via FDM have primarily been either static fixtures or simple, nonload-bearing mechanisms, but the structural integrity of FDM parts can be enhanced through various postprocessing methods. Printed parts can be used as the limited-use mold components directly or the positive to create a more durable mold for injection molding. Fill-compositing [14] deposits epoxy or other resins within voids of printed parts and can improve the overall part strength by up to 45%. Articulated mechanisms can utilize cast flexures in place of revolute joints for increased durability [15] and compliance to minimize damage during collisions.

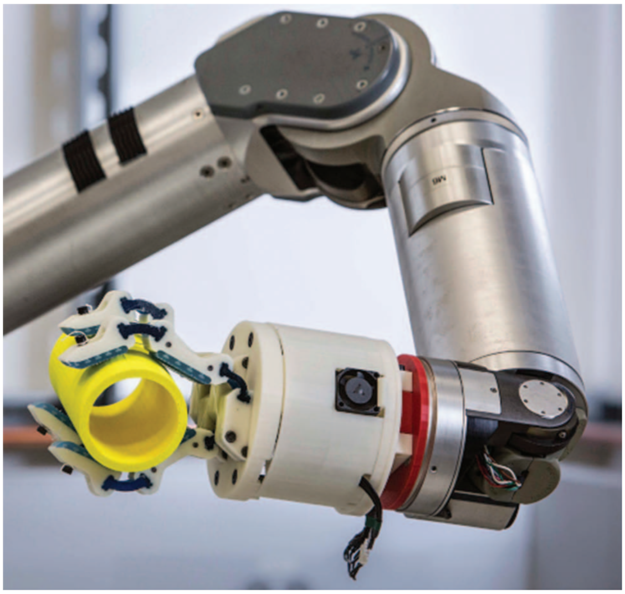

Figure 1. The underactuated, four-finger Model T hand mounted on a whole-arm manipulator (WAM). This was the initial hand design in the Yale OpenHand Project design library.

In robotics, relevant work has chiefly used FDM for body frame subcomponents in direct-drive systems such as miniature humanoids, modular robotics, and legged robots. Many of these systems are driven by hobby-grade servos and have little to no additional transmission elements. Researchers have also produced several proof-of-concept hand designs [16]–[18] using FDM and related low-cost, rapid-prototyping methods. However, to our knowledge, none have evaluated their designs' potential for long-term use or the structural limitations of the printed subcomponents. We will detail how the Yale OpenHand Project builds on these past initiatives in the section "Hand Design."

Underactuated Hand Design

The OpenHand Project implements many of the mechanical design strategies present in the shape deposition manufacturing (SDM) hand [12], an underactuated, tendon-driven, four-finger hand driven by a single actuator. Underactuated adaptability, via differential mechanisms within each finger as well as between the fingers, enable the hand to passively conform to various object geometries using only open-loop control. This hand was named for its fingers' fabrication process, SDM, where alternating material removal and deposition processes are combined to create multimaterial structures. The initial effort on the Yale OpenHand Project sought to recreate a more compact and simplified version of the SDM hand using 3-D printing and off-the-shelf components [19], as shown in Figure 1.

Underactuated fingers or transmissions can be found in several commercial hands [3]–[5]. Each two-link finger in the SDM hand and Yale OpenHand iterations is driven by a single tendon, and the final torque at each joint is determined by a combination of the actuating tendon force (f_a), the effective pulley radii

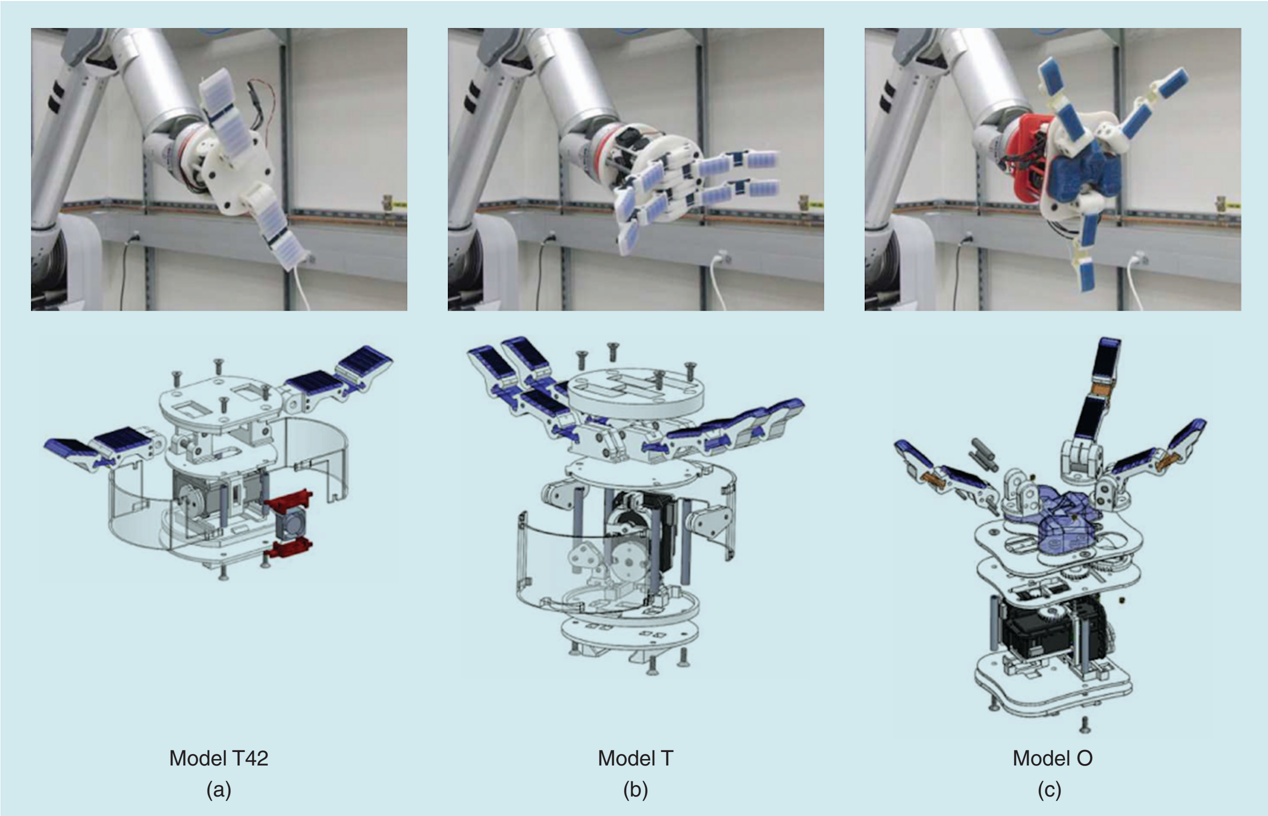

Figure 2. The various hand designs, all of which use a similar, minimalistic body design and underactuated fingers fabricated by the HDM process. (a) The Model T42 is intended for more dexterous tasks in addition to adaptive grasping. (b) The Model T, a direct derivative of the SDM hand, is intended purely for compliant power-grasping. (c) The Model O uses a topology similar to existing medium-complexity hands like the BarrettHand and i-HY, allowing it to transition between power-grasping and spherical-grasping modes.

$(R_{\text{Proximal}}, R_{\text{Distal}})$ at each joint, and the joints' stiffness (K_p, K_D) due to either additional passive elements or the material properties of the joint flexure. The effective pulley radii of flexural joints can be approximated as the shortest distance between the tendon and the centerline of the flexure. Past studies [12] have investigated the effects of these system design parameters on the joint behavior and functional hand performance. The default fingers evaluated in our past work use the following mechanical parameter values: $L_P = 62.75$ mm, $L_D = 37.25$ mm, $R_P = R_D = 9$ mm, and $K_D/K_P = 2.5$.

Open-Source Projects

The proliferation of affordable FDM machines has provided new opportunities for researchers to prototype their own custom equipment instead of relying on commercial distributors. FDM has been used by some researchers to create some ready-to-use mechanisms for medical research [20] and also significantly reduce costs for small-batch productions of select lab equipment [11].

Releasing source-files for printable designs online has expedited the adoption of new designs by not restricting production to traditional manufacturers. Encouraging participation by third-parties increases the rate of design iterations and provides additional insight that the original developers may lack. This philosophy was key to the development of the original RepRap project [10] and has spurred the progress of the e-NABLE community [21] in producing low-cost, printed prosthetics.

Hand Design

Overview

A variety of hand topologies were implemented and tested as part of the Yale OpenHand Project. The Model T replicates the structure of the SDM Hand and has four interdigitating fingers driven by a single actuator via a floating pulley transmission [19] that equalizes the actuating tendon forces. The Model T42 has two independently driven, directly opposed, underactuated fingers, and the finger depth has been increased to minimize the flexures' out-of-plane twisting. Finally, the Model O [22] has three independent-driven fingers: a static thumb and two opposing fingers with a coupled abduction/adduction at their bases. This design can transition between multiple grasping configurations: a power-grasp form in which the thumb directly opposes the other two fingers and a spherical-grasp form in which all three fingers are directed toward the palm center.

Figure 2 shows the different hands mounted on the Barrett whole-arm manipulator (WAM), a manipulator commonly used in research applications, and their exploded views to highlight the relatively low number of parts. Wherever possible, the servo actuators' bodies provide additional support for the overall frame, which uses a series of sandwiched, interlocking pieces to minimize the fastener count. The use of a tendon-based instead of a linkage-based actuation system resulted in a more compact and modular design. The actuation bases can be modified independently of the fingers, and combinations of fingers in different spatial configurations can be quickly exchanged.

Actuator Selection

Robotis Dynamixel servos (Robotis) were selected as the actuators for the OpenHand designs due to their compact form factor, high torque output, and ease of control via transistor-transistor logic or RS-485. The details of the particular Dynamixel models used are listed in Table 1. The larger MX-64 servo is used in the Model T design, while the MX-28 and RX-28 are used in the Model T42 and Model O hands. The drive pulley attached to the servos typically have diameter of 9 mm, and the servos were run at 12 V, allowing the hands to be powered by commonly available ac/dc adapters.

The servos are back-drivable, but their geared transmissions provide considerable holding torque. Running the actuators in the default position-control mode, as opposed to the open-loop torque control as was used in the SDM Hand, takes advantage of the friction in the transmission due to the high gear ratio in the servo and the capstan effect in the tendon routing, allowing the hands to sustain a holding grasp force without needing to actively draw current and potentially overheat. This aspect is particularly important in developing a functional hand for repeated manipulation tasks.

Table 1. The dynamixel servo parameters.

Model	Dimensions (mm)	Mass (g)	Torque (Nm)
MX-64	40.2 × 61.1 × 41	126	7.3
MX-28	35.6 × 50.6 × 35.5	72	3.1
RX-28	35.6 × 50.6 × 35.5	72	3.7

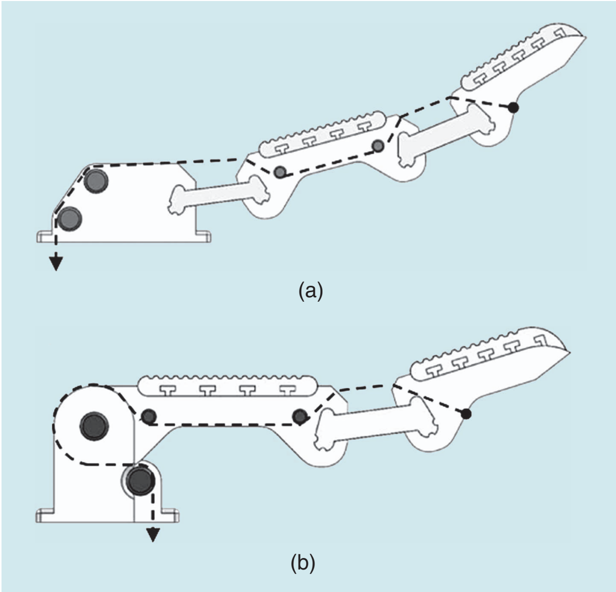

Figure 3. The tendon routing for both major types of finger designs, (a) flexure-base and (b) pivot-base, use steel dowel pins to redirect the actuating tendon, which helps avoid wear on the printed components and prolongs the operating lifetime of the finger.

Finger Designs

For all OpenHand models, we focused on two finger types: flexure-base and pivot-base. Their respective tendon-routings are detailed in Figure 3. The flexure-base model employs cast flexures for both the proximal and distal joints, adhering to the original SDM Hand design. When using flexures for both joints, the finger can be made as a monolithic component and exhibits a greater degree of adaptability and robustness to collisions due to the joints' out-of-plane compliance. The joint stiffness can be selected by adjusting the flexure thickness, and the effective pulley radius is determined by the positioning of the tendon routing ports around the flexure. The pivot-base introduces a more traditional revolute joint at the proximal to improve precision-grasp stability while maintaining the fingers' adaptability in the distal flexural joint. The joint stiffness for revolute joints can be set with torsion springs, elastic bands, or extensions springs, all of which are accommodated by the OpenHand designs.

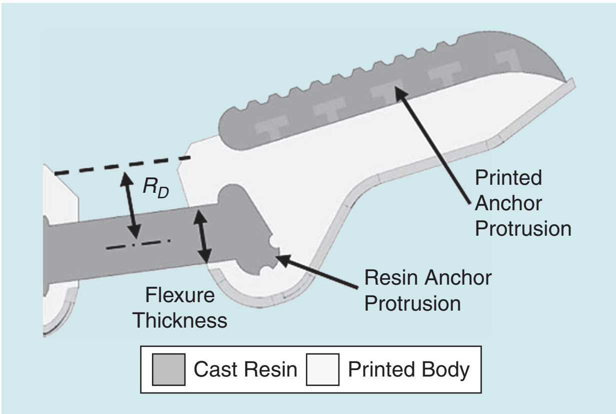

Figure 4. A closeup of the flexural joint and fingerpad interfaces with the printed body components.

HDM

The cast joint flexures and finger pads are integrated to the 3-D-printed bodies through a process called HDM [23], which extends the accessibility of SDM through 3-D printing. First, the full finger frame is printed as a single component. Voids allocated for the elastomers are connected to the main finger subbodies by thin walls of 0.7-mm thickness. These printed pieces have an open top to accommodate the deposition of mixed urethanes. Then, the two-part urethanes, PMC-780 for the flexures and Vytaflex 40 (Smooth-on) for the pads, are mixed and deposited within these temporary cavities. After the urethanes cure at room temperature, which takes 12–24 h, the thin walls are manually removed. The 3-D printing simplifies this fabrication process for nontechnical users.

Figure 4 illustrates a close-up view of the anchoring features used to more securely fix the elastomers to the printed

Table 2. A comparison of medium-complexity hands.

Hand	Number of Fingers	Number of Actuators	Base Height (mm)	Base Width (mm)	Weight (g)	Grip Force (N)
Barrett Hand [3]	3	4	75.5	130	1,200	15
2G Velo [29]	2	1	80	45		10–20
Robotiq (two-finger)	2	1	90	140	890	30–100
Robotiq (three-finger) [4]	3	2	126	126	2,300	15–60
Schunk SDH Hand [9]	3	7	98	122	1,950	
i-HY [22]	3	5	80	105	1,390	15
RightHand Reflex [5]	3	4			800	
Lacquey P102 [7]	3	1	76	113–203	1,250	15
Lacquey A101	3	1	52	127	1,000	15
Festo MultiChoiceGripper [8]	3	4	215	148	660	
OpenHand Model T	4	1	95	100	490	11.54 ± 1.20
OpenHand Model T42	2	2	55–80	90–105	400	9.60 ± 0.25
OpenHand Model O	3	4	90	100–125	752	12.33 ± 0.71

subbodies. Under the worst-case loading scenario, which typically would not occur at these interfaces as they are implemented in the OpenHand designs, both urethane materials can withstand up to 100 N of pulling force prior to fully disengaging from the printed bodies and failing [23].

Design for 3-D Printing

For this study, all printed parts were produced on a Stratasys Fortus 250 mc, a commercial desktop FDM printer. Circular clearances for revolute joints or press-fit components are printed with their axes of rotation parallel to the print direction to avoid shearing failure. Printed part geometries were kept as basic as possible, such that the preferred print direction could be easily identified.

Consistent with the guidelines for injection-molding, the printed part designs also avoid sudden changes in part thickness to avoid warping or peeling from the build platform. This is especially impactful for nonenclosed FDM machines, such as low-cost, do-it-yourself options [10]. Load-bearing features are always printed with solid infill and have a minimal dimension of least 3 mm in size, while sacrificial features, like temporary mold walls, are 0.7 mm in size.

Bearing surfaces, particularly for tendons, remain a challenge for 3-D-printed parts, and abrasions from repeated actuation cycles can wear through printed surfaces. A 100-lb test, 0.5-mm diameter Spectra line is used for tendon-routing in all of the hands. Consequently, the OpenHand designs include either steel dowel pins or small nylon pulleys to route the tendons, as shown in Figure 3. For useful adaptability and reconfiguration, friction along the routing path needs to be minimized.

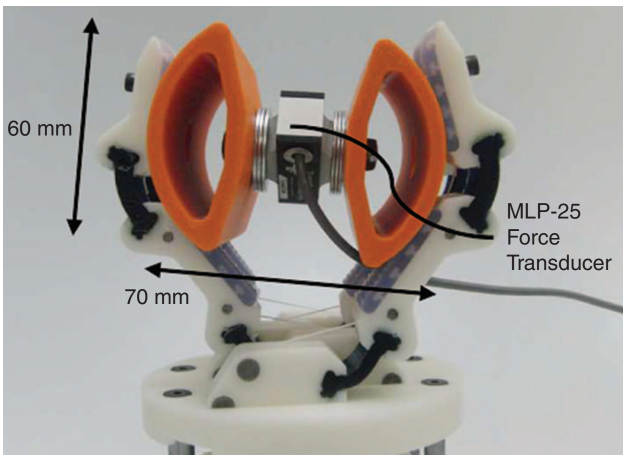

Figure 5. The load cell setup used to evaluate the maximum, sustainable grasp force for each hand. All evaluated hand designs have multilink fingers, so rounded contours were printed and attached to the load cell to maximize contact.

Performance

General Comparison

Table 2 compares the basic characteristics of the Yale OpenHand designs with that of available commercial hands. In terms of size and weight, the OpenHand options are comparable with commercial alternatives and can serve as a drop-in replacement on compatible manipulator platforms for basic grasping tasks. The low weight, due to the use of printed ABS, could make these designs particularly appealing for mobile manipulation applications.

The holding grasp force for OpenHand was measured by an MLP-25 load cell, shown in Figure 5. Printed attachments to the load cell were used to guarantee that all finger links made contact during the force measurement. All hands were run at 12 V, with the servos' maximum torque limited at 40% of their specified stall torque, as recommended by the manufacturer. The hands are capable of a much higher grasp force than the values listed in Table 2, but the recorded values

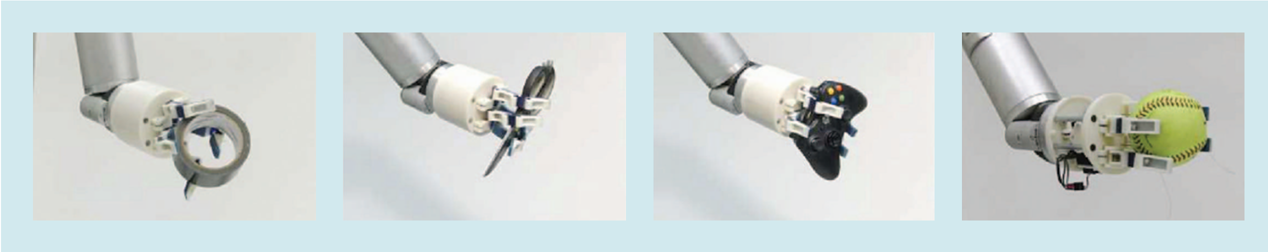

Figure 6. The four fingers of the Model T can passively adapt to the object geometry with a single open-loop control input in the absence of sensing.

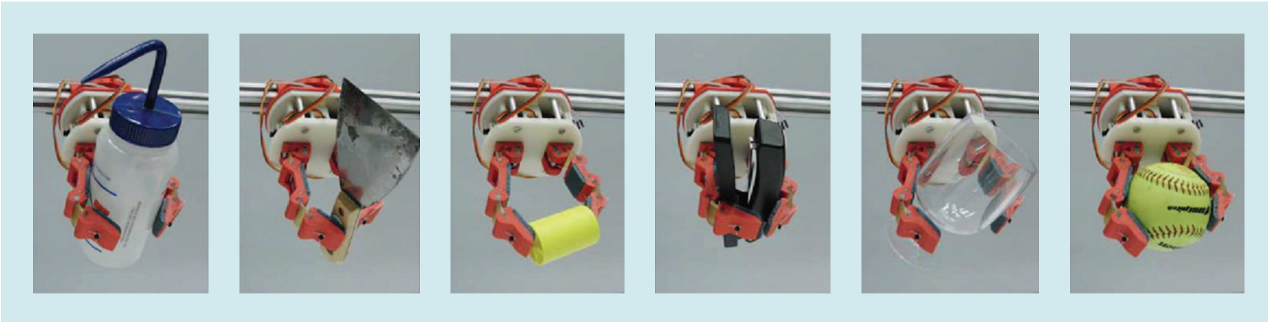

Figure 7. The Model T42 has two, directly opposing, underactuated fingers that can passively conform to different geometries through power-grasps or perform precision-grasps on smaller objects.

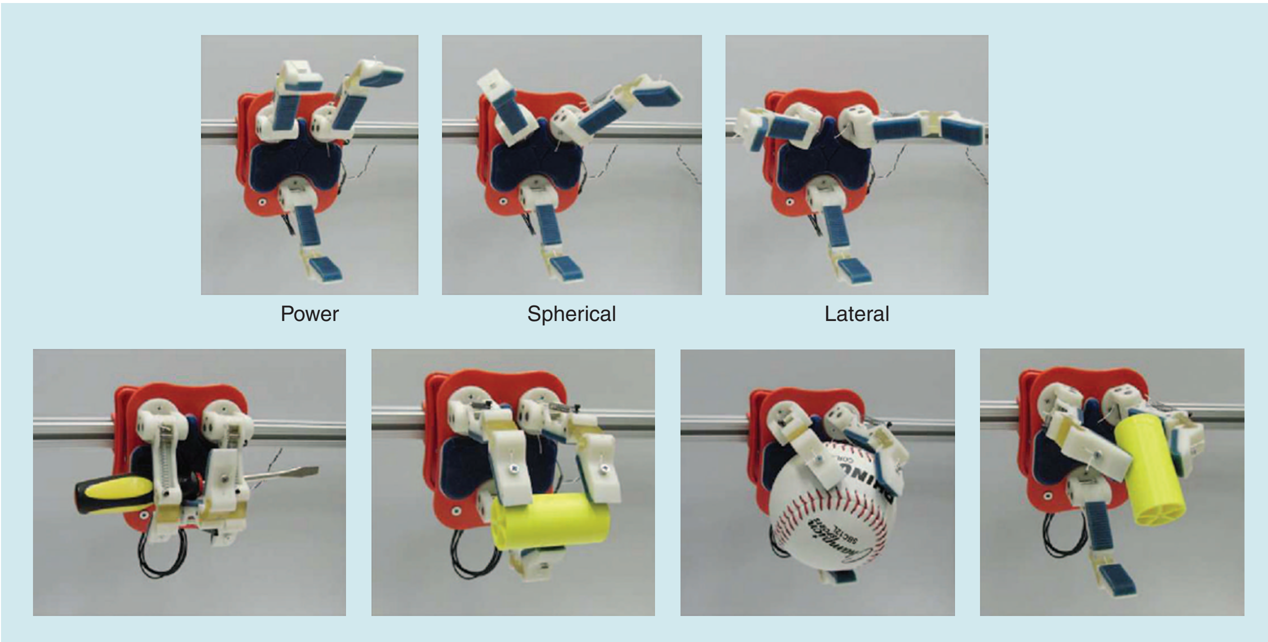

Figure 8. An actuator in the hand base of the Model O transitions it between power-grasping, spherical-grasping, and lateral-grasping modes. The hand topology is common to several existing commercial hands.

reflect the hand's sustainable grip force over extended periods of time, not its peak output. To our knowledge, there is not a standardized procedure in place to test the grip force of robotic hands, and the methodologies used to obtain the results for the commercial hands in Table 2 have not been made publicly available.

Hand Functionality

Figures 6–8 further detail the particular grasping and manipulation capabilities of each of the three hand designs discussed in this article. The Model T has been optimized for power-grasps where the fingers wrap around and immobilize the object. Due to the actuation transmission, the four fingers

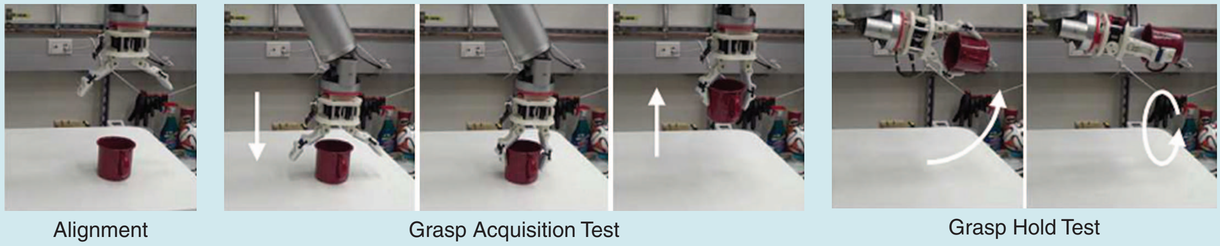

Figure 9. A summary of the open-loop grasp evaluation test. The grasp acquisition tests whether or not the hand can successfully pick an object off the table with open-loop control. The grasp hold test determines whether the object remains within the grasp in different orientations.

continue to move until either all phalanxes have made contact or a joint limit is reached. This results in a high degree of passive adaptability, as shown in Figure 6. In contrast, the Model T42's two independently actuated fingers allow for stable precision grasping but still retain a high degree of adaptability (Figure 7). The Model O can switch between multiple base configurations, shown in Figure 8, facilitating the grasp of a wider range of object geometries.

Dexterous manipulation primitives have also been demonstrated with these underactuated designs. The passive reconfiguration in underactuated fingers can enable robust surface-constrained precision grasping. This same reconfiguration, in combination with the joint elasticity in the fingers, also enables in-hand manipulation, assuming the hand operates in the subset of actuation space that maintains no-slip contact conditions.

Open-Loop Grasping Evaluation

Optimal grasp planning is beyond the scope of this article, but a rudimentary, open-loop grasping test was performed to help elucidate the grasping capabilities of these underactuated hand designs. Similar to tests run in [18] and [24], the hands were directed to perform surface-constrained grasping. In each trial, the hand was initialized with its palm directed downward at the table and oriented such that it was aligned with the object's principal axis. The hand was then lowered toward the object until either the palm touched the object or the fingers would otherwise be obstructed by the table during grasping closure. Regardless of the object geometry, the same open-loop command was given to the hand to close and then attempt to lift the object. After lifting, if the object remained in the grasp, the hand was reoriented by $\pi/2$ radians such that its palm axis vector now pointed outwards. The hand was then rotated about its palm axis by π radians and then back to help determine the grasp quality and its ability to maintain a hold on the object under the influence of gravity in different orientations. Figure 9 summarizes the procedure in these grasping tests. The tests were performed for all three OpenHand designs and both types of fingers for the Model T and T42. For the Model O, the fingers were oriented such that the static finger directly opposed the other two in a power-grasping configuration.

Table 3 details the results for a selection of household objects with different geometries. Grasp acquisition by itself was quite

Table 3. The results of open-loop grasp testing.

				
Object	Coffee Cup	Mustard Bottle (Full)	Spatula	Cheez-It Box (Full)
Weight (g)	118	432	104	453
Size (mm)	89 × 89 × 83	38 × 76 × 178	38 × 102 × 356	64 × 161 × 229
Grasp Acquisition Test (Hold Test)				
T (Pivot)	5/5 (5/5)	5/5 (4/5)	5/5 (5/5)	5/5 (3/5)
T (Flexure)	5/5 (1/5)	5/5 (5/5)	5/5 (5/5)	4/5 (0/5)
T42 (Pivot)	5/5 (5/5)	5/5 (4/5)	4/5 (3/5)	5/5 (0/5)
T42 (Flexure)	5/5 (4/5)	5/5 (2/5)	3/5 (2/5)	5/5 (0/5)
O	5/5 (5/5)	5/5 (2/5)	5/5 (5/5)	5/5 (2/5)

repeatable regardless of the object. The Model T42 had the most difficulty acquiring a stable grasp on the spatula, due to its fingers' inability to interdigitate. One finger has to wrap over the opposing finger to generate the proper contact conditions. This kinematic limitation was more apparent during the holding test, where the spatula could jostle loose during reorientation even if the initial grasp was successful. All hands had difficulty sustaining a hold on the box due to its weight and size. In particular, flexure-base fingers tended to sag and twist under the load of heavier objects. A pivot-base provided more stability and less reconfiguration during the grasp hold tests.

Open-Source Dissemination and Development

Project Release and Adoption

The Yale OpenHand Project was initially released to the academic community during 2013 IEEE International Conference on Robotics and Automation [19], through an interactive, hands-on tutorial that guided participants through the HDM fabrication process. For each hand design, short descriptions, Solidworks source files, exported stereolithography and standard for the exchange of product data files, full bill of materials, and step-by-step written and video assembly guides were made available via open-access, online repositories [13]. To produce some basic grasping and manipulation primitives, simple Python control scripts to control the Dynamixel servos were also provided. The online repository contains a set of mechanical coupling adapters to attach these hand designs to some of the more common manipulator arm systems, including Baxter, Universal Robotics arms, and Barrett WAM. Our primary goal is to provide an extensive and complete set of documentation such that interested researchers and users can build their own hands independently.

The Solidworks source files are annotated and labeled to make it easier for other developers to tweak the existing design. Also, common, adjustable, global parameter values referenced by all part files are used to make minor dimensional adjustments. For example, dimensional parameters related to FDM printer constraints, such as a minimal wall thickness (0.7 mm) or a structural wall thickness (3 mm), can be changed in a single master parameter file before it propagates to and updates all dependent files. In this way, the source files operate a lot like script-based, computer-aided design packages such as OpenSCAD [25].

To date, the full hand archive files have been downloaded over 1,000 times from the project website, the videos related to OpenHand have been viewed over 20,000 times on Youtube, and we have verified 27 cases where one or more of the OpenHand designs have been included in existing research projects. In particular, fingers from the Model T42 have been modified to extend the capabilities of the standard Baxter gripper [26], and the developers of that project have likewise released online documentation and source files for their modifications. Another study more recently integrated optical feedback sensors into an OpenHand design to investigate tactile manipulation [27]. A few teams also evaluated the designs for the 2015 Amazon Picking Challenge [28]. An alternative project [17], citing the OpenHand Project as a source of inspiration, has worked to replace cast flexures and pads with cut strips of rubber and other compliant material, for the goal of producing low-cost prosthetic devices.

Challenges and Lessons

A number of lessons were learned as a result of this effort. Despite attempts to simplify the HDM process as much as possible, casting with multipart urethanes is not a widely practiced process, even with options as readily available as Smooth-on. More traditional design alternatives, which replace all flexure joints with standard revolute joints that do not require casting, were then released to help accommodate these needs. The cost of the Dynamixel servos was also a barrier to adoption, especially for smaller labs and hobbyists, so a design modification was made to the T42 actuator base to accommodate cheaper hobby servos as well.

We have verified 27 cases where one or more of the OpenHand designs have been included in existing research projects.

Based on feedback from early adopters, the T42 was the most commonly evaluated design, due to its relatively low part count, more compact form factor, and similarity to existing parallel jaw grippers. Mechanical design simplicity minimizes the necessary initial investment. For hardware, it seems that it is advantageous to offer several design options of varying complexity.

The majority of adopters built the hand designs in their default configurations, without making any additional modifications or adjusting the mechanical design parameters. Optimizing manipulation capability by adjusting the system design parameters is a key tenet of the research methodology behind the OpenHand Project, but doing so would require physical testing, not something that the average adopter prioritizes. A thorough experimental evaluation of different parameters' effect on hand performance will be needed to better guide users in selecting the appropriate design parameters for their particular applications. It remains to be seen if users will further customize and extend the OpenHand design library or merely use it as is.

Conclusions and Future Work

In this article, we presented work toward an open-source library of 3-D-printed hands that can be used in manipulation research and mobile robotics applications. The designs leverage the use of tendon-based actuation, flexures, and the HDM process to maximize system robustness. Experimental work showed that the OpenHand designs performed favorably when compared to commercial alternatives. An open-source hand that researchers can fabricate and upgrade independently of manufacturers makes repairs and component modification more efficient and, hopefully, will also promote the coevolution of hardware with software and control in the field of robotic manipulation.

However, we feel that simply releasing and validating the designs in the open-source robotic hands library is not enough. A major focus for future work is to identify willing end users who will put their own design modifications online, thereby allowing progress in the research community to move even faster.

Acknowledgments

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Raymond R. Ma, Department of Mechanical Engineering, Yale University, New Haven, Connecticut. E-mail: ray.r.ma@gmail.com.

Aaron M. Dollar, Department of Mechanical Engineering, Yale University, New Haven, Connecticut. E-mail: aaron.dollar@yale.edu.