Yale OpenHand Project

General Overview and Design Documentation
Last Updated: November 14, 2013

OVERVIEW

About Yale OpenHand Project

Fig 1. Selection of OpenHand designs, with the ARM-H prototype i-HY in the background

Commercially available robotic hands are often expensive, customized for specific platforms, and difficult to modify. It is typically impractical to experiment with alternate end effector designs. 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.

The **Yale OpenHand Project** is an initiative to advance the design and use of robotic hands designed and built through rapid-prototyping techniques in order to encourage more variation and innovation in mechanical hardware. This project intends to establish a series of open-source hand designs, and through the contributions of the open-source user community, result in a large number of useful design modifications and variations available to researchers.

While advances in rapid-prototyping and shape deposition manufacturing (SDM) have made it increasingly tractable to make custom parts expediently and on-demand, design choices must be made to make robotic hands suitable for repeated functional use, not just design prototyping. Hands developed through this project are designed to be minimalistic and rugged, especially appropriate for iterative design and operation in unstructured environments.

The released hand designs feature tendon-driven underactuated fingers. Underactuated hands 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. This design paradigm separates the actuation and finger elements, enabling a greater degree of customization.

The source CAD files allow for variable configurations, allowing users to quickly change functional parameters (ie. link lengths, transmission ratios) and manufacturing parameters (ie. shell thicknesses, hole dimensions) and have those changes propagate across all relevant parts.

About Model T

Fig 2. Four-fingered Model T

The Model T is the initial released design of the Yale OpenHand Initiative, based on the original SDM Hand. It consists of four underactuated fingers with compliant flexure joints, driven by a single actuator through a pulley tree differential. During grasp acquisition, each finger will continue to move until the links make contact with the object, reducing the need for sensors or feedback control.

Flexure joints are made through Dieless Deposition Manufacturing (DDM), utilizing Smooth-on polyurethane. Tendon-driven, flexure-based joints allow for adaptive behavior and robustness against collisions.

A minimal set of steel dowel pins and nylon pulleys (available through small parts distributors like McMaster) are required for the actuation differential, but all remaining parts are otherwise 3D-printed.

About Model T42

Fig 3. Model T42, more dexterous than the Model T, while maintaining benefits of adaptability through underactuated fingers

The Model T42 is a more dexterous and controllable extension of the Model T. It consists of two underactuated fingers with compliant flexure joints, each independently driven by a servo actuator. Although the fingers remain underactuated, there is no adaptive coupling between the fingers. However, this allows for more dexterous control, and the possibility of in-hand manipulation.

As with the Model T, the flexure joints are made through DDM, and the majority of hand components are 3D-printed. Due to the lack of an actuation differential, the overall profile of the hand is much shorter than the Model T, and the design also allows for much thicker fingers if desired.

Hand Comparisons

Hand	# Actuators	# Fingers	Base Height (mm)	Base Width (mm)	Weight (g)	Grip Force (N)
Barrett Hand	4	3	75.5	130	1200	15
Velo	1	2	~80	~45	?	10-20
Robotiq (2-finger)	1	2	90	140	890	30-100
Robotiq (3-finger)	2	3	~126	126	2300	15-60
Meka H2	5	4	63	96	800	?
Meka G2	1	2	63	96	400	80
Model T	1	4	75-90	100	400	~10
Model T42	2	2	55-80	100	350	?

References

T. Laliberte, C.M. Gosselin, G. Cote, “Practical Prototyping,” *Robotics and Automation Magazine, IEEE,* 8(3), 2001, pp. 43-52.

A.M. Dollar, R.D. Howe, “**The Highly Adaptive SDM Hand: Design and Performance Evaluation**,” *International Journal of Robotics Research,* 29(5), 2010, pp. 585-97.

R.R. Ma, L.U. Odhner, A.M. Dollar, “**A Modular, Open-Source 3D Printed Underactuated Hand**,” Proceedings of the 2013 IEEE International Conference on Robotics and Automation (ICRA), Karlsruhe, Germany, May 6-10, 2013.

OVERVIEW OF HAND DESIGN

Tendon-Based Actuation

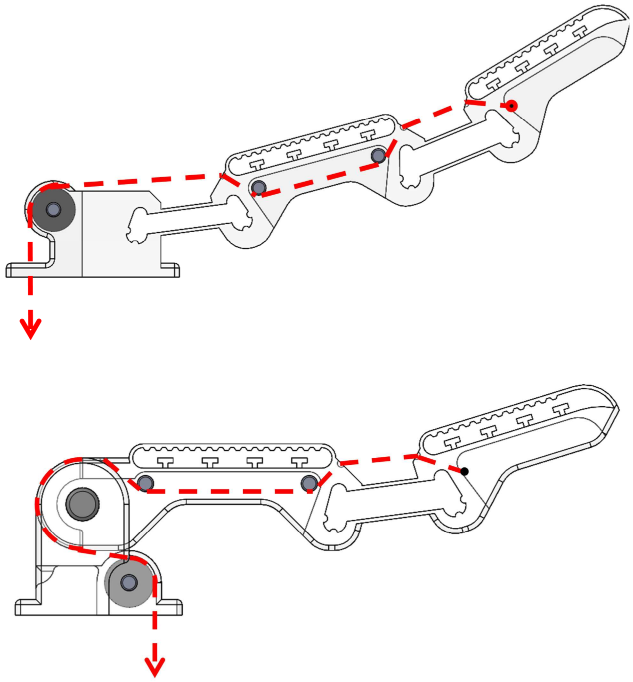


Fig 4. Tendon routing scheme for both supported types of fingers.

Fig 5. Example case of the passive adaptability made possibly by compliant flexure joints.

The actuation scheme for these designs are tendon-based, as opposed to linkage-based, in the interest of increased robustness, modularity, and design simplification. The use of tendons allows us to separate the more delicate actuation components from the parts of the hand that make contact with objects and the environment. This helps minimize damage that would be incurred by the hand's structural components in case of collisions or accidents in unstructured environments. This separation also simplifies the design such that different finger designs can be swapped out more easily.

Compliant, Flexure Joints

While pin joints are also supported and can be implemented in each design, the OpenHand designs were initially built around the use of compliant flexure joints made of polyurethane rubber. The use of flexure joints greatly simplifies the build process, increasing the allowable error tolerances during assembly. In design, these flexures are approximated as simple beams, and the effective joint stiffness ratios are approximated accordingly.

The flexure joints are made with common, off-the-shelf, rubber urethanes from Smooth-On. These urethanes are simple two-part mixtures that are primarily used for hobby mold-making and costumes. They do not require the use of additional laboratory equipment to mix and set, although the use of a vacuum chamber to de-gas the urethanes is highly encouraged. De-gassing creates a more consistent and homogeneous flexure, which increases its robustness and performance.

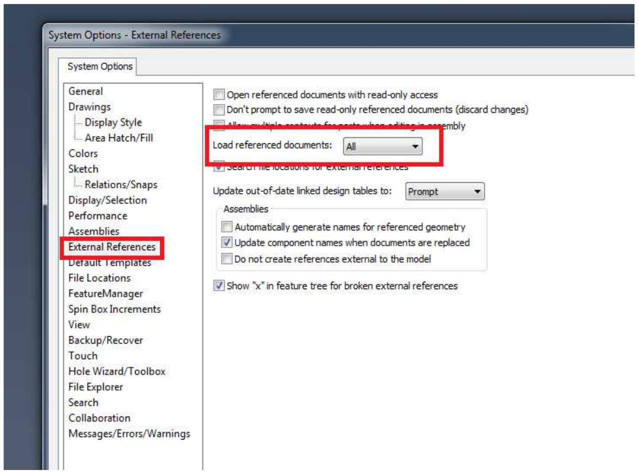
The use of flexures also increases out-of-plane compliance in these fingers, which is usually negligible in fingers with revolute joints. Out-of-plane compliance increases the adaptability of fingers, allowing them to more easily conform to the shape of objects. However, it also increases the twist-out behavior of these fingers when contact forces are sufficiently out-of-plane. This behavior is exacerbated in designs such as of the Model T, which have alternating, instead of opposing, finger arrangements. As a compromise, the alternative hand configurations consist of a pivot-base at the proximal joint and a compliant flexure at the distal joint. This helps leverage the robustness and compliance of the fingers during power-grasping while minimizing the problems with out-of-plane compliance, which is primarily affected by the lower stiffness at the proximal joint.

Underactuation

Underactuation, by definition, means that there are more degrees of freedom than controllable actuators. This means that even for designs where each finger has an independent actuator, external forces will determine the hand's final configuration. Underactuated mechanisms are the basis for adaptive finger designs and the notion of "mechanical intelligence," where the desired operational behaviors are built in to the fingers through careful selection of design parameters, as opposed to depending on control.

This design approach decreases the controllability of such hands and reduces the task workspace when compared to fully-actuated hand designs. However, when design parameters are properly selected, the hand can reliably operate in the desired workspace, albeit a smaller one, with simpler, open-loop control and fewer actuators. The default parameters used in the OpenHand designs reflect that of successful implementations which have been tested in our lab.

OVERVIEW OF CAD



☐ Open referenced documents with read-only access
☐ Don't prompt to save read-only referenced documents (discard changes)
☐ Allow multiple contexts for parts when editing in assembly
Load referenced documents: All
☑ Search file locations for external references
Update out-of-date linked design tables to: Prompt
☐ Automatically generate names for referenced geometry
☑ Update component names when documents are replaced
☐ Do not create references external to the model
☑ Show "x" in feature tree for broken external references

Fig 6 – Solidworks setting that will automatically load the externally-referenced parameter files

Extensive use of linked variables and configurations were used in the creation of these files. The intent of this approach is to provide a standardized and consistent approach to shared mechanical design, and to simplify the process of making basic changes to the overall hand structure. Users with limited experience with CAD can modify the hand design parameters by changing configuration values instead of having to edit each CAD file individually.

There are two independent files called *params_print.sldprt* and *params_finger.sldprt* that each contain a sketch with basic system parameters linked to an internal configuration. This was used in lieu of text-based global variable files in the interest of speed. This file must be open while modifying the other part files for the relations to properly resolve.

As of SW2012, there is still considerable lag in rebuilding if utilizing external global variable files. To the authors' knowledge, this has been a persistent software bug with no available solution. Unfortunately, use of a reference part for system parameters means that this part file should be open in order to resolve the equations in other part files. The authors hope this minor inconvenience does not hinder development or use. This can be set automatically by going to **Options>>System Options>>External References** and setting the "*Load referenced documents*" drop-down menu to "*All*". If this causes problems or system crashes, please try having both *params_print.sldprt* and *params_finger.sldprt* open before trying to open other dependent parts or assemblies.

Parameter-Based Design

The primary system parameters cover the basic system parameters for underactuated fingers as described in various literature, as well as basic manufacturing parameters. Limitations in terms of printing or machining capability may necessitate changing these default settings. System parameters may be changed directly in the default configuration or children configurations (under *configurations tab* in SW). Please consult online SW documentation for more details.

Steps were taken to ensure that all components were fully defined in the SW context. Each feature is named appropriately and divided such that there were as few confusing or redundant features as possible. Arbitrary dimensional values were avoided as much as possible. Each dimensioned value should be tied to a system parameter and/or a pre-existing part feature wherever possible.

While arbitrary configurations may be added/selected, the authors cannot guarantee that the mechanism can be built (both physically and virtually in CAD) with your desired system parameters. If a significant use case arises which cannot be fulfilled by the current CAD framework, please contact the authors with as much detail and specification as possible, and we will do our best to make appropriate modifications before the next release.

Making Parameter Modifications

Quick modifications can be made by changing the dimensional values defined in the values sketch of the parts *params_print.sldprt* and *params_finger.sldprt*. After making these desired changes, a rebuild (ctrl+B) of the part/assembly will implement the necessary updates in the parts. As this project progresses and more iterations have been assembled, we will include the tested configurations in the parameters files. For certain desired configurations, the part files may need further editing and error-correction, but the authors hope that this approach will minimize the additional work that other users will have to do in order to make more customized and task-specific designs.

Parameters – Design (*params_finger.sldprt*)

These parameters are related to the overall behavior and performance of the underactuated fingers. They were chosen based on prior research/work on underactuated hands.

Parameter	**Description**	**Default Value**
K_P, K_D (flexure stiffness)	Thickness (mm) of proximal (P) and distal (D) joint flexures in the hand	4.25, 5.77
Stiffness ratio	Distal to Proximal flexure stiffness ratio, approximately K_D^3/K_P^3. You normally want the distal joint to be stiffer than the proximal such that the finger doesn't cage prematurely.	2.5
K_P length, K_D length	Length (mm) of the joint flexures.	
R_P, R_D (transmission radii)	Effective radius (mm) of transmission at each joint. Approximately the orthogonal distance from tendon routing port to center of flexure.	9, 9
Transmission ratio	Ratio of distal to proximal transmission radii, R_D/R_P	1
Finger length	Total length (mm) of the finger, including both proximal/distal linkages (L_P+L_D)	100
L_P, L_D	Lengths of the individual finger linkages	60, 40
Linkage ratio	Ratio of distal to proximal finger linkage length	0.67
T_P, T_D	Initial rest joint angle (degrees)	15, 15
L_B, L_B pivot	Base linkage length (mm), separation between opposing finger bases. This value will differ between the pivot-base and flexure-base configurations. It doesn't necessarily reflect the exact distance between the effective rotational centers of the proximal joint.	29.57, 22.75
Height	Distance (mm) from the back of the finger to the midplane of the fingerpad	18
Depth	Side to side dimension (mm) of each finger. For this design, this value is determined by the selection of tendon routing pins	16
Pad thickness	Thickness (mm) of the finger pad cavity	4.5

Parameters – Printing (*params_print.sldprt*)

The following parameters are related to the printing tolerances and small parts selection of the hand components. These need to be modified according to the selection of 3D printer and its printing performance. The printing parameters listed here were used in successful prints on the *Stratasys uPrint* and *Stratasys Fortus 250mc*.

Parameter	**Description**	**Default Value**
Width destroy	Thickness (mm) of shell wall that will be removed in post-processing. Usually used in walls for flexure and finger pad cavities. This value is usually the smallest consistent wall width that the printer can produce as a free-standing structure. Most FDM printers are limited by a 0.35mm nozzle at best.	0.7
Width keep	Thickness (mm) of structural walls in the hand. Should have minimal flex.	3
Width Tab	Length (mm) of finger base tab used to constrain the fingers to the top base plates.	4
Pulley diameter	Diameter (mm) of nylon pulleys used in tendon rerouting	9.5
Pulley thickness	Thickness (mm) of nylon pulleys used in tendon rerouting. Should be large enough to allow pulleys to spin freely, but small enough such that the tendons will not get caught between the pulleys and the adjacent walls	2.4
Base diameter	Diameter (mm) of the hand base	100
Pin diameter	Diameter (mm) for steel dowel pin holes. The authors recommend that all such holes are machined/reamed in post-processing to ensure the best press-fit, but many 3D printers have the necessary resolution to produce acceptable dimensionality	3.175
Print Free	Extra tolerance (mm) added to clearances within with other printed or small parts components need to fit and spin freely. For example, pulley clearances or finger base clearances.	0.35
Print Fit	Extra tolerance (mm) added to clearances to allow for a press-fit without further post-processing. This value is taken from the printing tolerances suggested by Shapeways.	0.1

3D Printer Calibration

Fig 7 – example calibration piece that may help with setting the appropriate printing parameters

The default manufacturing system parameters listed in the previous section were tested on the *Stratasys uPrint* [link] and Stratasys Fortus 250mc [link]. In terms of resolution specifications, most non-hobby 3D printers are capable of the lowest resolution needed for the OpenHand design iterations, but structural and aesthetic quality may differ. The authors recommend that users print out calibration parts (included in source files) to determine the most appropriate manufacturing parameters.

Critical dimensions

Width destroy specifies the width of the ABS walls that will be cut away in post-processing after pouring the molds. This should be as thin as possible to make removal easy, but also thick enough to resist handling during support material removal before pouring. The authors have noticed that many 3D printers may specify a resolution of *x*, but in fact can only print walls of thickness at least *2x*, because it needs to print at least 2 layers at minimum. It is suggested that *width destroy* be set to the minimal sized wall that the printer can extrude accurately. If these walls are to be used for finger pad features, such as the grip surface present in certain models, this value may need to be adjusted.

Width keep is the minimal dimension used for structural walls in the OpenHand designs. By trial and error, the authors have found that 3mm is an adequate thickness on the Stratasys uPrint, but this value may differ for other printers.

Pulley thickness/diameter specify the proper spacing for the tendon pulleys. The most significant source of friction and inefficiency in this hand design will be due to pulleys that are not free-spinning. 3D printed parts do not necessarily produce smooth surfaces, depending on the direction in which they are printed. To help ensure minimal friction, these surfaces can be filed down, or the pulley parameters can be changed in the CAD files to provide extra spacing.

Pin diameter should be dimensioned to provide a secure but not necessarily tight press-fit for the steel dowel pins. Only radial loads are expected on these dowel pins. As long as these pins are not loose, the assemblies should perform as expected. Also note that if the diameter dimension is particularly tight, press-fitting the dowel pins may deflect and deform the ABS walls and potentially pinching the pulleys into a non-spinning configuration.

SUGGESTED CONTROL

Robotis Dynamixel servos were selected for the OpenHand designs due to their self-contained design and high level of support.

Using the USB2Dynamixel is the most straightforward way to interface with the Dynamixel servos. However, any standard USB to RS485 convertor, such as ones provided by Sparkfun, should work. Robotis provides software libraries for both C and Matlab, 3rd party groups have created libraries in Python, and Robot Operating System (ROS) has an active dynamixel node repository.

It is suggested that users avoid using position mode during grasp acquisition whenever possible, as that makes the servo particularly susceptible to overload faults when the fingers become fully constrained. The MX-64 has a torque control mode that should be used for grasp acquisition. Lower-tier models, such as the RX-28, do not have explicit torque modes, but can emulate that behavior by switching to wheel mode, as described here. Changing the wheel speed effectively controls the output torque in that instance.

However, maintaining torque or wheel mode after a grasp has been acquired can also put excessive load on the servo. The authors recommend switching back to position mode after the grasp has been acquired in order to minimize the current load on the servo. The non-back-drivability of the servo helps ensure that maintaining position draws far less current than maintaining torque post grasp.

CONTACT

More details and the latest updates can be found at www.eng.yale.edu/grablab/openhand

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