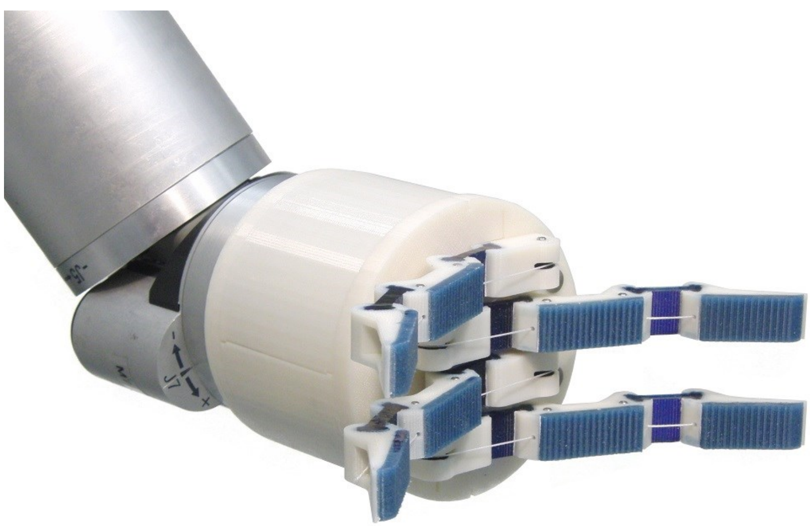
Yale OpenHand Initiative

Model T Documentation (Ver. 0.4)



OVERVIEW

About Yale OpenHand Initiative

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 Initiative is a project 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

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 Shape Deposition Manufacturing (SDM), 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.

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.

PARTS LIST (Model T)

Note: This part listing is for the default provided design of the Model T hand. User-made modifications to the design may necessitate alternative parts for a successful build.

Part Name	Quantity	Usage	Vendor
Robotis MX-64 Dynamixel	1	Actuator	Various – Robotis, TrossenRobotics, Crustcrawler
Ø1/8", L3/8" steel dowel pin (J1)	8	Support pin	McMaster [97395A435]
Ø1/8", L5/8" steel dowel pin (J2)	12	Support pin	McMaster [97395A445]
Ø3/8", Wd1/8" nylon pulley (P1)	12	Tendon route	McMaster [3434T31]
Ø1/4", L2-1/2" zinc-plated female standoff	4	Support	McMaster [92474A029]
a1.stl	1	Top Plate	3D Print
a2.stl	1	Top Plate Clamp	3D Print
a3.stl	1	Bottom Plate	3D Print
a4.stl	1	Bottom Plate Clamp	3D Print
b1.stl	2	Drive pulley block	3D Print
b2.stl	2	Routing block	3D Print
b3.stl	4	Differential block	3D Print
b4_a.stl	1	Servo block – A	3D Print
b4_b.stl	1	Servo block – B	3D Print
pulley.stl	1	Main drive pulley	3D Print
finger.stl	4	Finger shells	3D Print
shell.stl	2	Shell Covering	3D Print (optional)
M2.5, L7.5mm bolt	1	Fastener	Provided w/ Dynamixel
M2, L3mm bolt	2	Fastener	McMaster [91292A003]
2-56, L3/4" bolt	2	Fastener	McMaster [92196A084]

Cost Estimate:

Cost estimate is based on prices available through McMaster, TrossenRobotics, and Shapeways as of March 11, 2013. Costs decrease for parts bought in higher quantities in most cases. Part size is based on the default set of parameters and an approximate $2/cm^3 price point (courtesy of Shapeways). User-selected parameters will affect the estimated print volume to produce the 3D-printed parts.

Vendor	Details	**Cost** (USD)
TrossenRobotics	Actuator	299.90
McMaster	Fasteners, assembly components	54.61
Shapeways	3D Printing estimate (180 cm^3)	360.04
	Estimated Total:	714.55

OVERVIEW OF CAD DESIGN

Extensive use of linked variables and configurations were used in the creation of these files. There is an independent file called "*params.sldprt*" that contains 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.

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.

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 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.

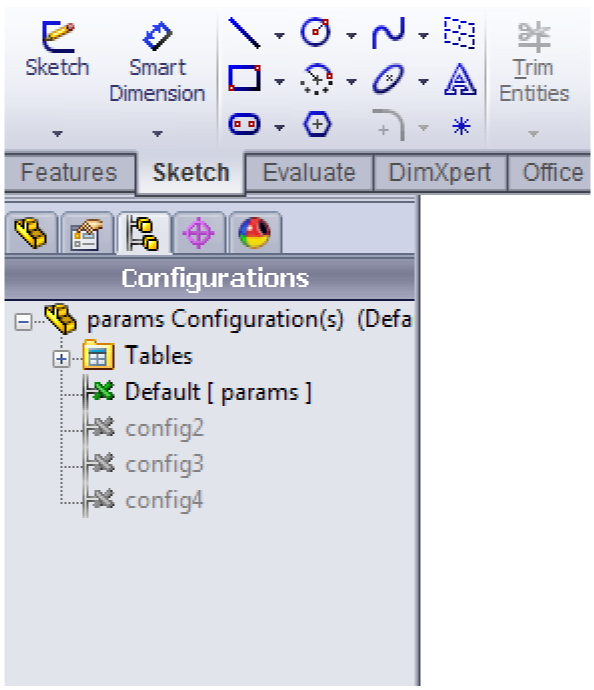


Fig. 1 – Configurations tab in Solidworks for editing and switching out sets of system parameters

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.

Finger/Hand Parameters

Parameter	Description	Default Value
K_1, K_2 (flexure stiffness)	Thickness (mm) of joint flexures in the hand	4.25, 5.77
Stiffness ratio	Distal to Proximal flexure stiffness ratio, approximately K_2^3/K_1^3	2.5
R_1, R_2 (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_2/R_1	1
Finger length	Total length (mm) of the finger, including both proximal/distal linkages	100
L_1, L_2	Lengths of the individual finger linkages	60, 40
Linkage ratio	Ratio of distal to proximal finger linkage length	0.67
T_1, T_2	Initial rest joint angle (degrees)	15, 15
L_B	Base linkage length (mm), separation between opposing finger bases.	29.57

Manufacturing Parameters

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	0.7
Width keep	Thickness (mm) of structural walls in the hand. Should have minimal flex.	3
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
Flexure anchor	Dimension (mm) of protrusions at the endpoints of the flexures that help anchor the flexures to the RP	3
Finger depth	Depth (mm), or side-to-side dimension of fingers. Needs to be a minimal of (*pulley thickness+2*width keep*)	15
Finger height	Height (mm) of finger bases. Determines the effective "palm" of this hand design. Needs to be large enough to fully encapsulate the joint flexures.	18
Finger pad thickness	Thickness (mm) of the finger pad cavities in the fingers	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

3D Printer Calibration

The default manufacturing system parameters listed in the previous section were tested on the *Stratasys uPrint* [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.

MOLD POURING

The flexures and finger pads for the OpenHand designs utilize two-part, off-the-shelf urethanes via Smooth-on Inc. The manufacturing process is a form of Shape Deposition Manufacturing (SDM), used extensively in the original Harvard SDM Hand. Unlike the traditional SDM process, where multiple pouring and material removal stages were necessary, SDM with 3D printing only requires a single pouring step, as the finger frame and mold cavities are created in a single step during printing.

Compound	**Usage**	**Demold time**	**A:B mix ratio**	**Shore A Hardness**
PMC-780	Joint flexure	48 hours	2:1	80
Vytaflex 30	Finger pad	16 hours	1:1	30
Vytaflex 20	Finger pad	16 hours	1:1	20

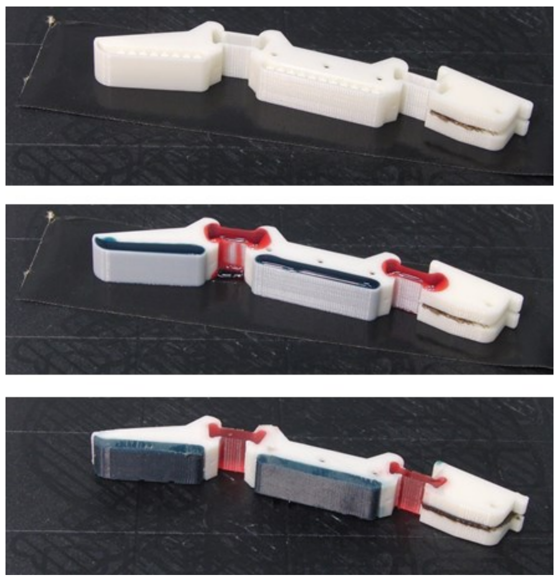


Fig. 2 – Overview of the SDM process for the OpenHand designs

Pre-pour preparation

Although the Stratasys 3D printers create a base of support material beneath the printed parts, they do not provide adequate sealing for the flexure joint material nor the finger pad material. The mold material will tend to leak through the support material, so it is recommended that all support material is removed prior to the mold pouring step. The authors recommend using adhesive to seal the bottom of the 3D printed frames. Heating duct tape has been shown to be particularly effective and easy-to-use due to its ability to hold shape.

Fig. 3 – 3D printed finger frame sealed on bottom face with adhesive

Urethane Degassing (Recommended, but Optional)

If a vacuum chamber is available, the urethane should be degassed to ensure a more homogeneous flexure mold. The urethane mixture will rise and fall, after which the urethane can be removed from the chamber. It is recommended that the urethane mixture not be left in the vacuum for more than 1-2 min.

Fig. 4 – Vacuum gas chamber for urethane degassing

Pouring

Urethane should be poured slowly to minimize bubble formation in the mold. Bubbles in the flexures, especiall in thin flexures, will result in undesirable stiffness and behavior. It is less of a problem for less viscous urethanes, such as those used for the finger pads, but special attention should be paid to the joint flexure material whenever possible. Enough urethane should be poured in each cavity such that a convex meniscus forms, if possible. Expect urethane to leak, and excess urethane after the molds cure can be removed in post-processing.

Fig. 5 – Enough mold material poured such that urethane just barely overflows

POST-PROCESSING

The authors created the OpenHand designs to minimize the amount of post-processing, but also acknowledge post-processing with the proper shop tools is always preferable. Reaming of attachment holes and filing of certain surfaces are strongly recommended for the best performance.

ABS Frame Removal

Either the bandsaw or a small file can be used to cut away the flexure joint and finger pad cavity frames. The compliance of the cured urethane allows for the walls to be partially cut and then physically snapped apart, helping ensure that the joints are not damaged during post-processing. Excess urethane from the pouring process can be removed via belt sander, file, or a sharp blade.

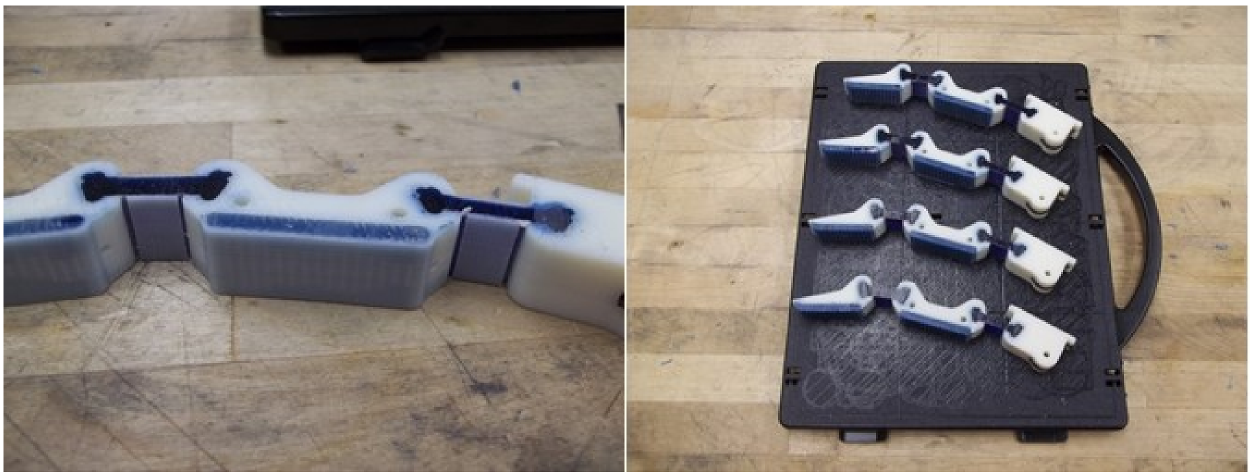


Fig. 6 – Minimal cuts required to remove the mold cavity walls

Finger Tendon Routing Holes

Proper tendon routing holes are necessary to minimize friction in finger actuation. While 3D printed ABS is sufficient for structural purposes, it is less than adequate as a bearing surface. Rope tendon will tend to cut in to the ABS over extended use. Previous design iterations used tubing as sleeves to prevent wear and tear in the ABS. For simplicity, the OpenHand designs use offset steel dowel pins in positions such that contact between the actuation tendons and the ABS is minimized.

The finger surfaces are designed such that the tendon enters the finger orthogonal to the hole surface. The steel dowel pins are positioned such that the tendons run tangent to the pin surface on the inside of the finger. The tendon routing hole diameter should be minimized (~1mm) such that the tendon has just enough clearance to slide freely.

Due to printer limitations, it's generally not possible to print the tendon routing holes directly. Even with support material, the small hole size makes it difficult to completely clear the hole without damaging the surrounding ABS. The authors caution against trying to drill out support material. Because it is harder than the ABS, the support material often deflects the drill bit into the surrounding ABS, especially for small diameters. Instead, the available designs have starter divot holes to help guide drilling in the right direction.

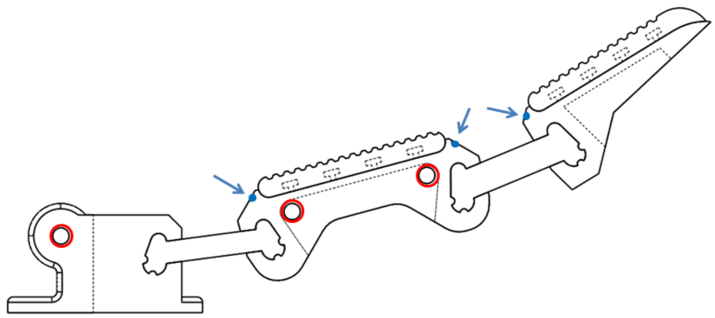


Fig. 7 – Through holes that need to be drilled/reamed

A mini-jig has been included in the source files to help with tendon routing hole alignment.

Press-fit Pin Holes

The authors recommend the use of a reamer to ensure a proper press-fit for the steel dowel pins. Pins are used for securing pulleys and acting as a bearing surface for rerouting tendons. For pulleys, it is important to size the holes and insert the pins such that the pulley still spins freely after assembly. Due to the use of ABS, the walls may deflect effectively pinch the pulley as the pin is inserted. In the authors' experience, it is helpful to either slightly oversize the pin holes or to use a block of material serving as a shim to prevent the ABS walls from bending during pin insertion.

ASSEMBLY

Final assembly of the OpenHand designs can be divided into 3 main segments: top/fingers, actuator block, and bottom base. The main assembly components are kept as independent as possible such that those parts can be modified and replaced as expediently as possible. At the same time, the authors have tried to minimize the number of fasteners to create a simpler assembly.

Assembly – Finger (4x)

Components: finger.stl (1x), pin P2 (3x), pulley J1 (1x)

Friction between the base pulley and the ABS sides is the primary source of inefficiency in the actuation system for the OpenHand. It is important to ensure that all support material has been removed, and that the pulley is free-spinning after assembly. Filing down the sides of the ABS can be helpful.

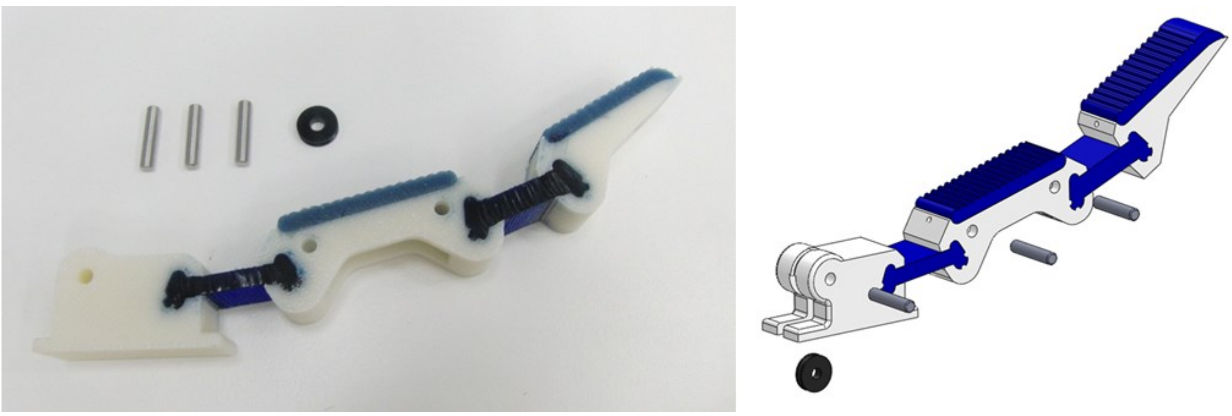


Fig. 8 – Components and quick assembly for finger

Assembly – Drive Block (1x)

Components: b1.stl (1x), pin P2 (3x), pulley J1 (2x)

Because two separate parts are used to clamp the pulleys, spacing is less of an issue as compared to other pulley blocks, but be aware that the pulleys should be free-spinning after assembly.

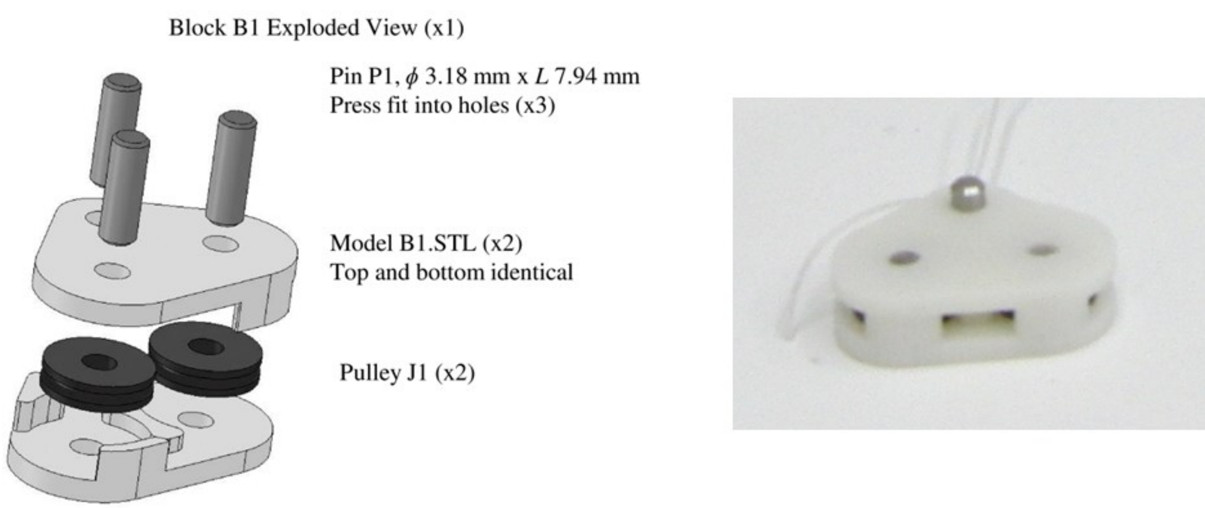


Fig. 9 – Components and assembly for floating drive block

Assembly – Base pulley block (2x)

Components: b2.stl (1x), pin P2 (1x), pulley J1 (1x)

Reroutes the actuation tendon at the base of the hand. Due to the thin walls (~5mm), this part is the most susceptible to inadvertent deflections during press-fit of the pin. Please take extra precaution (either with a physical shim or hole sizing) to ensure that the pulley is still free-spinning after assembly.

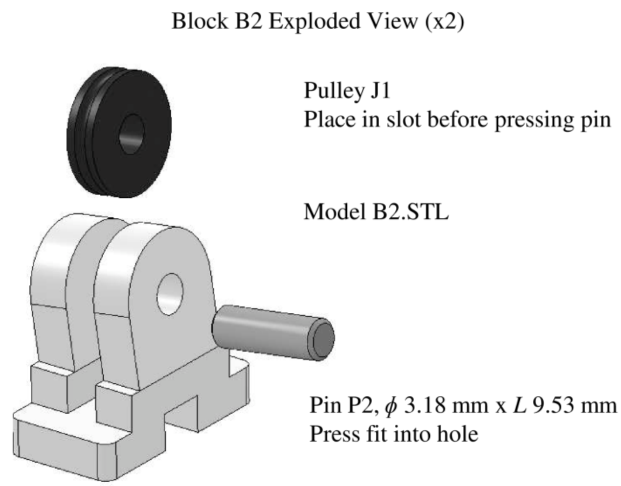


Fig. 10 – Components and assembly for base pulley block

Assembly – Differential block (2x)

Components: b3.stl (2x), pin P2 (3x), pulley J1 (2x)

Assembly is identical to that of the main floating drive pulley.

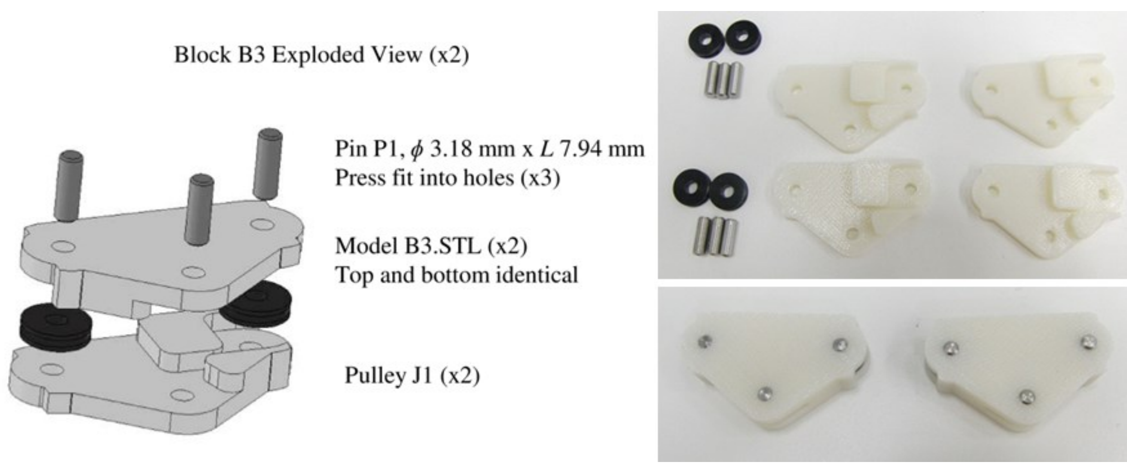


Fig. 11 – Components and assembly of floating differential pulley blocks

Assembly – Actuator block (1x)

Components: MX-64 Dynamixel (1x), b4a.stl (1x), b4b.stl (1x), pin P1 (2x), pulley J1 (2x), pulley.stl (1x)

Note that top pulley should be spinning freely after assembly. As susceptible to deflecting ABS as the bottom base pulley blocks.

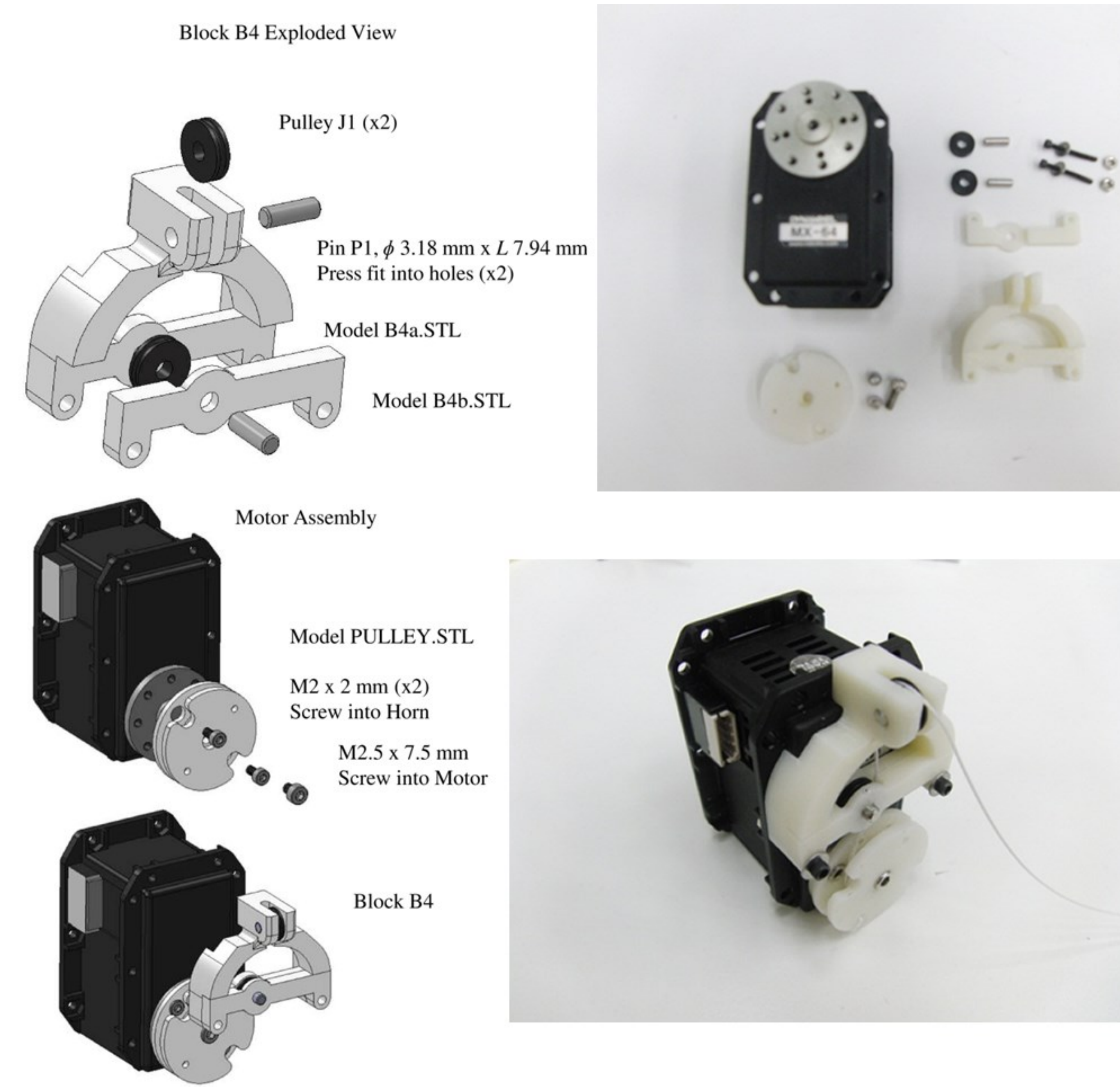


Fig. 12 – Components and assembly of the motor block

Assembly – Top/Fingers (1x)

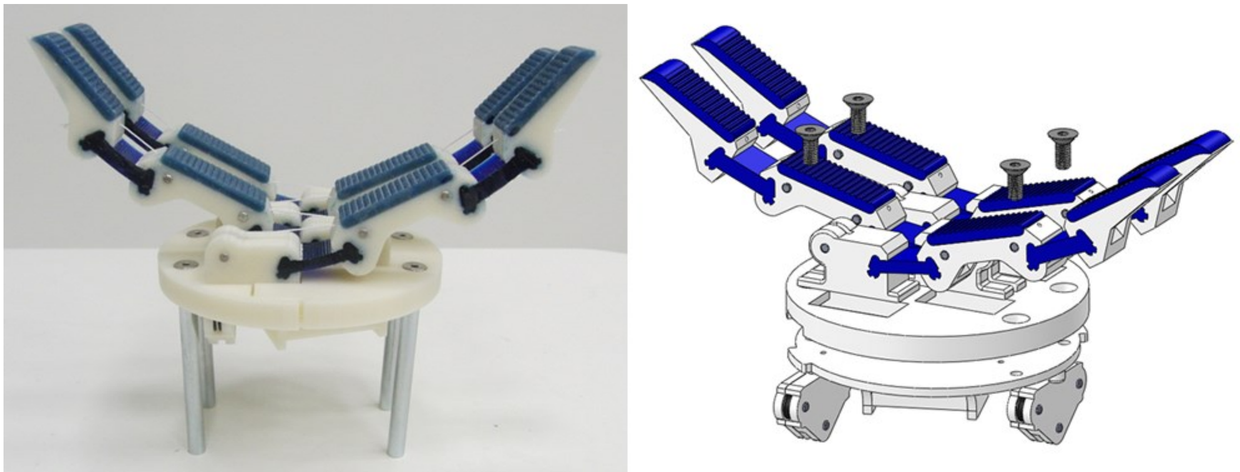


Fig. 13 – Components and assembly of the top frame sub-assembly. Note the lack of fasteners. Plate a2.stl is used to clamp the fingers in place. Fingers should be inserted from the top of part a2.stl

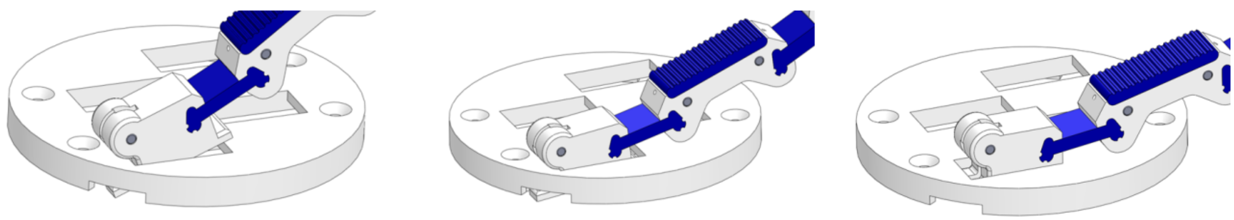


Fig. 14 – Finger insertion from top of plate a2.stl. Finger base should fit snugly into the top plate

Assembly – Bottom base

Currently, the bottom plates a3.stl and a4.stl have attachment holes for the WAM. Attachment to other manipulator platforms will necessitate edits in those part files. Aside from the bolts connecting to the standoff supports, everything else fits together by press-fit. The bottom plates clamp the bottom pulley blocks much like how the top plates clamp and secure the finger bases.

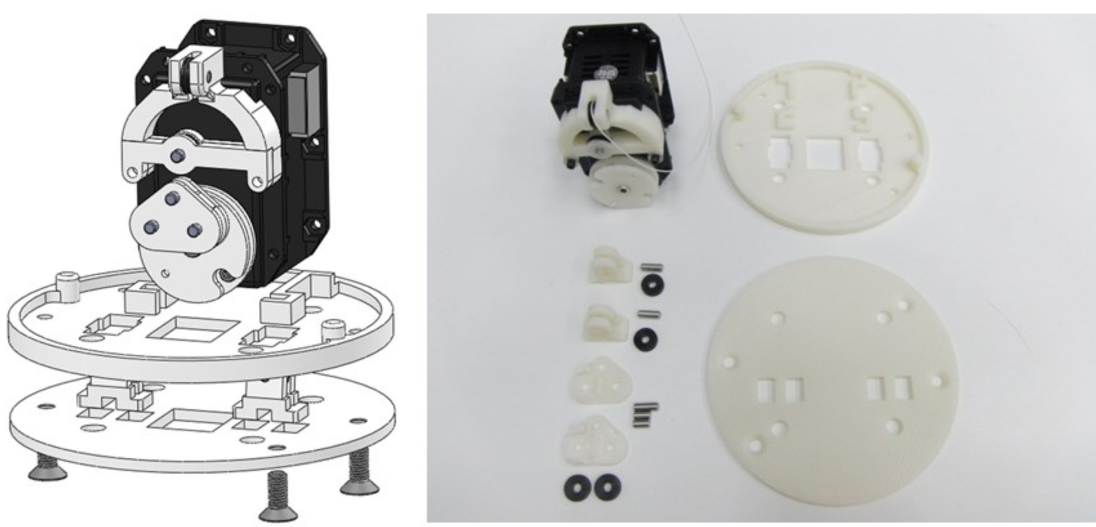


Fig. 15 – Components and assembly of bottom base block, with the actuator block

Tendon-routing – Top Assembly

For each pair of fingers, the top tendon terminates at the distal finger link. The tendon can be affixed in any method. The authors suggest tying a knot on a small machine nut to serve as a stop. Note that the tendon travels through the fingers, both top plates, and the floating differential block. The tied tendon length should be set such that it is taught with the fingers in the rest position. The fingers can be deflected to provide more clearance for tying the knots at the right point if necessary.

The tendons may experience significant load during operation, so try to ensure that the tendon will not slip or change length. Some users have suggested "pre-stretching" the tendon with a heavy weight overnight prior to use in assemblies.

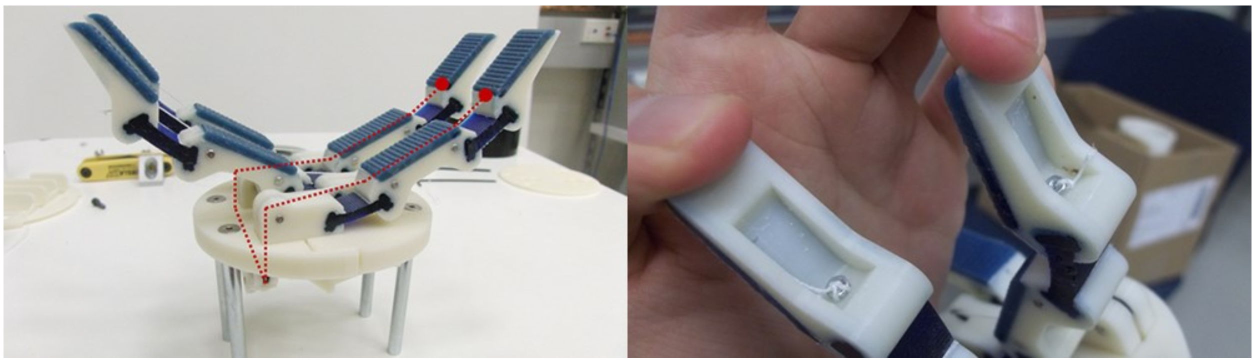


Fig. 16 – Tendon routing path for the top sub-assembly.

Tendon-routing – Main Assembly

The main assembly tendon runs between the two floating differential blocks and through the bottom pulley blocks and main drive pulley block. The tendon between the main drive pulley block and the servo horn can be left during this assembly step. The tendon between the differential blocks needs to be tied as short as possible. It is preferential to have the main pulley block flush against the bottom plate after this tendon is properly affixed. To generate more slack in the tendon, the fingers can be manually deflected if necessary.

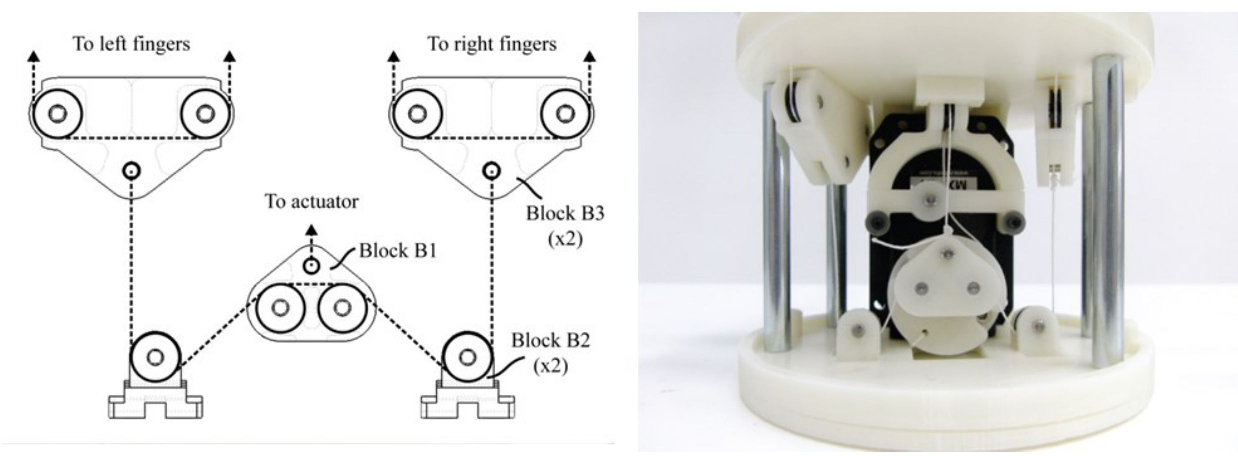


Fig. 17 – Main assembly tendon routing

Assembly – Final Frame Assembly

Top and bottom sub-assemblies are held together through the four female standoff components. The top features of the actuator block interface with the bottom features of the top sub-assembly. The final tendon routing between the differential blocks can be done before or after the final frame assembly.

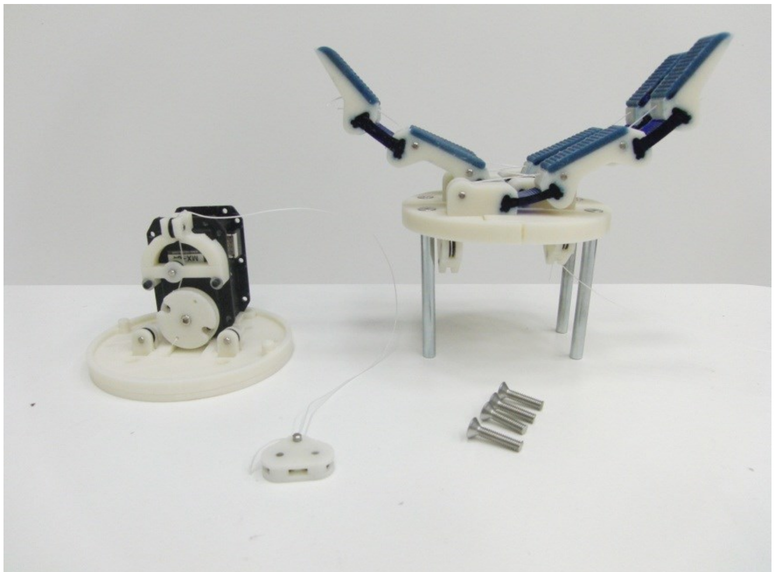


Fig. 18 – Major sub-assemblies prior to assembly

Assembly – Drive tendon zero-ing

The final assembly step involves properly zero-ing the drive tendon between the servo horn and the pulley. The bolts on the servo pulley can be loosed such that the pulley is free-spinning. Drive the servo to its zero position and manually turn the pulley until the drive tendon is taut. At this point, re-affix the pulley to the servo horn. This step is unnecessary if the hand will only be driven in torque mode (see [**SUGGESTED CONTROL**]).

SUGGESTED CONTROL

Robotis Dynamixel servos were selected for the OpenHand designs due to their self-contained design and high level of support. Details for the MX-64 servo can be found here. Older iterations of the hand utilized the smaller RX-28 for actuation, but the authors worry that a less powerful servo would not be as robust to potential assembly and manufacturing inconsistencies. With the MX-64 servo, a grip force of up to 10N can be consistently generated, making the OpenHand designs on par with currently available commercial products.

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.

OPTIONAL FAN ASSEMBLY

Overheating can be an issue with Robotis Dynamixel servos. These series of servos have fairly conservative built-in safety features that may interfere with desired performance. In past iterations of the hand, a small Sunon fan was used to circulate air across the servo motor, lowering the operational temperature (according to the onboard sensor) by 10°C. The current design accommodates a 25mmx25mm footprint for the fan. Getting a larger 12V fan, with depth of 10mm, enables the user to power the fan directly off the MX-64 servo, which also runs at 12V. Using a smaller fan, such as the 5mm deep, 5V fan, will require a step-down circuit, commonly available at vendors like Pololu.

CONTACT

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

Please direct questions and suggestions to raymond.ma@yale.edu