Robotic Applications of Mechanical Metamaterials Produced Using SLA 3D Printing: Cthulhu-Morphic Grippers

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Solid Freeform Fabrication Symposium

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Introduction

In this paper we present a 3D printed flexible robotic gripper which has three individual independent tentacles, each with two sections, and a combined 12 DoF; produced through the creation of a mechanical metamaterial via SLA 3D printing. This gripper was built to improve upon existing soft robotic technologies by creating a highly versatile gripping device which can grasp a wide variety of items. This gripper is capable of the fine motor control necessary to hold a pen or a small screw, the gross motor strength to hold a sledge hammer, and the grip span to hold a shop-vac air filter. Grip strengths and failure modes for various gripping configurations are measured.

Illustration 1: various gripping modes available with a 3D SLA printed multi-tentacular (Cthulhu-morphic) gripper with each tentacle having two independently actuated 2-DoF sections (4 DoF per tentacle, 12 DoF total).

This technology has potential applications for warehouse or assembly line bin-picking and cobot operations, and would not require changing the end effector of the robot for each different item to be grasped.

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Purpose and Goals

In the near term future, robots will need to interact more often, and more safely with unprotected and untrained humans. We specifically chose to investigate soft robotic technologies because they are less likely to harm humans interacting with robots. Elastic material construction avoids pinch points, and provides resiliency and compliance, and 3D printing allowed rapid prototyping of multiple design alternatives. The goals of this work are to take advantage of 3D SLA methods to prototype soft robotic technologies to quantitatively evaluate multi-tentacular grippers with full independent actuation and a central controller, a.k.a. "Cthulhu-morphic" [Lovecraft 1926] grippers for range of grip styles, grip strength, and carrying capacity.

Background and Prior Work

The work upon which this research was built includes both natural evolution's inspiration and prior human research. Sea anemones, octopus, squid and elephants all possess flexible organs of manipulation, but with radically different control methodologies. Human-designed tentacle research include multiple drive methodologies (pneumatic, hydraulic, tension cable) but nearly all tentacle gripper research has been restricted to a single tentacle with a few actuators. Therefore, evaluating the increased usefulness of independently-actuated, centrally controlled multi-tentacular gripping is a goal of this research.

Naturally Evolved Tentacles

Naturally evolved tentacles generally operate on the principle of a *hydrostat* – a volume of liquid that nearly fills a flexible, columnar, semi-elastic pouch; the pouch can be distorted by external contracting muscles but the liquid contents within maintain a constant volume.

For a cylindrical hydrostat with muscular walls, symmetrical lengthwise contraction shortens the hydrostat (while increasing the hydrostat's circumference); asymmetrical contraction causes the hydrostat to bend, and contraction of circumferential muscle causes the diameter of the hydrostat to decrease, forcing the enclosed liquid to extrude lengthwise and extending the tentacle. Hydrostats can also be wrapped with a helical muscle to twist the hydrostat; at the critical helix angle of 54.733°, the force of lengthwise contraction and circumferential extension exactly balance and the idealized hydrostat twists without change in length [Keir, 1982].

Sea Anemones: Omitting the Hydra of phylum Cnidaria as it does not have differentiated muscle and connective tissue, as well as all other microscopic examples, the earliest evolved creatures capable of tentacular manipulation are probably sea anemones (order *Actiniaria,* identified in the fossil record back to the Middle Cambrian, ~500 MYA and their relatives of class Echinodermata such as crinoids, feather starfish, etc.).

The tentacles of anemones carry longitudinal and circular muscles around a central hydrostat. Tentacle control and feedback within Actiniaria is entirely distributed; there is no central "brain" and the neural network of any given tentacle communicates only to other nearby tentacles, "programmed" to sting food, and then push the food in the general direction of the central mouth.

Octopus: The octopus (along with squid, cuttlefish, and nautilus, all of order *Octopoda*, identified in the fossil record as far back as the Carboniferous, ~296 MYA) demonstrate the next level of improvement in tentacle evolution. Besides the longitudinal and circumferential muscles enclosing the hydrostat, Octopoda have a third paired muscle set wrapped helically around the central core, allowing a twisting action in the tentacle and bringing the array of suckers on the ventral side to bear on the target [Kier 2016]. The central hydrostat of the arm contains nerves, arteries, and sets of interlaced horizontal and vertical traverse muscle fibers (the veins run external to the hydrostat). These traverse fibers allow the cross section of the hydrostat and tentacle to be altered from a relaxed nominally cylindrical shape to a flattened ovoid or vertical ovoid, and produce six DoF per lengthwise unit of tentacle.

Though the Octopoda tentacle control system is far more advanced that the anemone's, the central octopus brain is not directly involved in octopus grasping; the octopus' neural cord within the hydrostat is the primary arm control processor. It has been demonstrated that octopuses do not possess tactile stereognosis (the production of a 3D mental model of an object being held), nor proprioception (the octopus central brain does not know exactly where the arms are nor what the arms are doing; an octopus attempting fine motor tasks must use visual servoing).

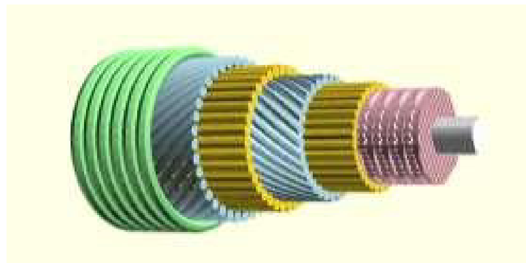


Illustration 2: Simplified CAD model of an octopus tentacle anatomy showing circumferential extension muscles (green), oblique helical torqueing muscles (blue), inner and outer longitudinal shortening and bending muscles (yellow), the central hydrostat containing traverse aspect-ratio muscles (pink) and the central neural cord and artery (gray). Drawing based on Kier 2016.

Snakes: the snakes (order *Serpentes*) evolved from the lizards perhaps as long ago as the early Jurassic, 167 MYA, and might be considered to be "all tentacle". However, as snakes have lungs and use a diaphragm muscle to breathe, as well as having intestinal peristaltic muscles to transport and digest food. Neither of these processes is amenable to being treated as an incompressible constant volume, so the snake body is not a hydrostat. Instead, the snake's "hydrostat" is confined to the 400~800 sections of bony (hence incompressible) spinal column, with longitudinal and helical muscles actuating bending and twisting locomotion. Like the elephant, the snake uses centralized control in the brain to coordinate ~2000 degrees of freedom.

Elephants: The elephant (and its relatives, order *Proboscidea*, evolving about 60 MYA) possess trunks providing an excellent example of convergent evolution as compared to the octopus' tentacle, despite evolving entirely independently of the octopus. The trunk anatomy originates from the elephant's lip and nose structures with longitudinal, circumferential, and helical muscle fibers surrounding a cartilaginous central hydrostat containing radial traverse muscles, nerves, and the nasal passages. Control of the trunk is in the elephant's mammalian brain; the trunk contains roughly 40,000 separately controllable muscles (and thus the trunk is highly overactuated with 40,000 degrees of freedom).

Human-Engineered Tentacles

Most teams that built soft robotic grippers used either hydraulic or pneumatic actuation [Galloway 2016] [Marchese 2015] [Suzumori 1991]. Due to the high material strain of these actuation methods, material selection was of the utmost concern for these teams. Manti et al. built a cable actuated gripper which used a single cable to control all three fingers; simplifying control but limiting the type of grasps the robot could produce [Manti 2015 a,b]. The approach here expands and improves cable actuated soft robots into the fully-actuated domain.

Hannan's PhD work used tension springs and a constant-length clevis-joint robot arm with four independent 2 DoF sections to achieve a kinematically predictable and controllable robot arm including a wrap-grasping ability similar to an elephant's trunk [Hannan 2002].

Bizdoaca et al. considered the control problems of using shape-memory alloy soft-robotic servos instead of electromagnetic motors [Bizdoaca 2009]. Devalla et al, Homberg et al, and Morales et al. extended the concept of automatic soft-robotic and biomimetic grasping to grasp based object recognition, but the actual gripping element is a 1-DoF robotic pincer or a 1-DoF pneumatic soft finger, not a high-DoF tentacle [Morales 2006], [Devalla 2012], [Homberg 2015].

Takeuchi and Watanabe developed a mechanism for changing the stiffness of the "skin" on their gripper in order to improve dexterity by means of a Peltier device to chill and warm an agar gel under the rubber top layer [Takeuchi 2016]. Material conformability and friction property considerations like those discussed there are highly relevant to the gripper described here.

Stoll et al. of FESTO AG & Co. KG constructed a biomimetic air-driven tentacle robot arm of three 2-DoF sections, terminated with a 1 DoF gripping tentacle, with two rows of vacuum suckers to prove enhanced grab given the single tentacle. [Stoll 2017].

Mason et al. analyzed and tested multi-fingered single-link rod-fingered gripper designs that, while highly underactuated, prevented inter-finger slack or tension interchange by placing separate per-finger compliance elements in parallel (rather than the more common series arrangement), thereby preventing inter-finger crosstalk and making a more stable grip. [Mason 2012]

Although poorly documented in the English language, Yamamoto et al. and Skyentific AG independently researched a series of cable-driven continuum tentacle robot arms with coil compression spring cores (pseudo-hydrostats) yielding 3 DoF – that is, bend in two directions, plus change in length [Yamamoto 2018], [Skyintific 2017].

Definition and Justification of the term "Cthulhu-Morphic"

The reader may note from the above that in both natural evolution and human engineering, single-tentacle centralized control grippers exist, and multi-tentacled distributed-control grippers exist, but the category of multiple independently actuated tentacle grippers with centralized control is essentially vacant. Our research is an exploration of the pros and cons of this particular taxon of gripper, which by inspired coincidence bears a slight resemblance to the fictional minor deity "Cthulhu" of H.P. Lovecraft. Thus, we define a gripping device with multiple tentacles, a high DoF, near-full or full actuation, and a centralized, coordinating control processor to be a *Cthulhu-morphic* gripper.

Materials and Design Iteration

The grip strength of pneumatically and hydraulically driven devices is limited by the material properties of the elastomer (usually cast silicone) used to create the gripper. We chose to build a cable actuated gripper in an attempt to increase the speed, grip strength and carrying capacity of the device versus hydraulic or pneumatic tentacles. To allow a full 12 DoF, a cylindrical shape was selected as it would allow for symmetrical movement in all directions.

A Formlabs Form2 SLA printer was chosen as the primary fabrication tool for the soft gripper due to the short fabrication time and cost as compared with form casting; wide range of materials available for prototyping through the Formlabs materials library; and the expanded possibilities for component architecture produced via 3D additive manufacturing as compared with more traditional manufacturing methodologies.

The first design iterations were printed with the Formlabs Elastic resin (~ Shore 50A). Version 1 was a cylindrical tube with a center hole to pass cables controlling other sections and two holes toward the outer edges of the cylinder through which the steel cables would pass to actuate that section. Versions 2-4 added exterior trapezoidal grooving to decrease the bending cross-section and increase flexibility. Versions 2, 3 and 4 had groove wall angles of 0°, 15°, and 20° angles respectively.

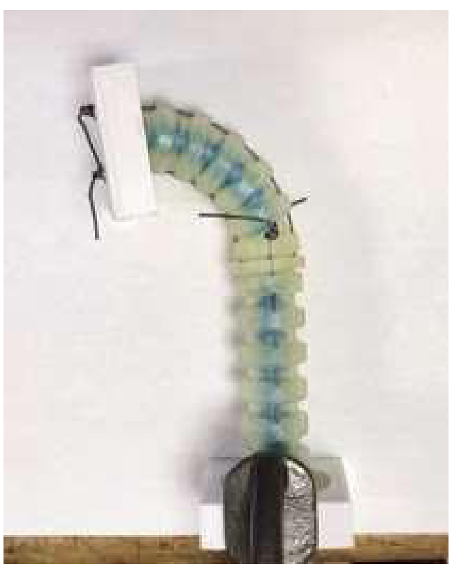


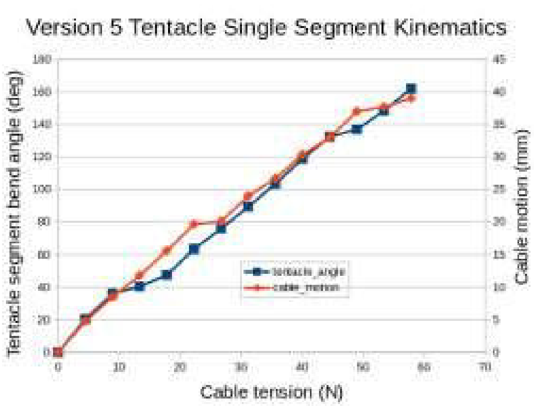
Illustration 3: Testing range of motion with a desktop jig on a two-section tentacle of design version 5.

The maximum range of motion of these versions was tested using a simple benchtop system. Two end plates were 3D FDM printed out of PLA. The bottom test plate was clamped to the bench and the cables were loaded with increasing force to bend the section and the corresponding bend angle recorded. Versions 1 and 2 would not print with the necessary holes for the actuation cables, likely due to capillary forces of the resin, therefore; those designs were discarded and versions 3 and 4 were compared. Version 3 reached a maximum of 132° of bending with 36 N of force while version 4 reached a maximum of 134.5° of bending with 31 N of force.

The maximum cable force these versions could withstand was limited because the cables ripped through the Elastic material; their experimental lifetime was only a few dozen cycles. Other 3D printing materials of greater strength exist, in both SLA and FDM polymers. SLA Durable was selected because it has a low coefficient of friction, which will allow the cables to move more freely. While we recognized the necessity of having Durable material in contact with the cables, we wanted to maintain the high range of motion achieved with the Elastic sections. Several further designs were considered for making modular sections which would be part Elastic, for range of motion; and part Durable, for cable actuation.

Illustration 4: Samples of each part type for the final version 5 design – a fairlead and a 25mm OD guide ring (translucent white, Formlabs Durable), a friction cap and an 80mm x 19mm OD / 13mm ID core tube (fluorescent yellow, Formlabs Elastic) and two spacer / cable guide 12.3mm x 5mm ellipsoids (blue, Formlabs Tough). All prints made at 0.1mm resolution.

Version 5 employed an 80mm long core tube and ring system for interfacing the flexible and rigid parts of the design; one Elastic core tube has seven ridges around outside of the tube, one ridge for each Durable ring. The rings maintained the exterior trapezoidal cross section, but also had notches in the center, into which the ridges on the core would seat. Based on the results from test 1, the rings had 20 degree groove angles. Version 6 had eight smaller Elastic sections which were connected by these same Durable rings. In an attempt to concatenate multiple sections, each Elastic section had a quarter dome at either end; producing a complete ridge which would seat inside the ring when two sections were put together. Version 7 also used the rings to connect the sections; the sections were designed such that a reduced-diameter top end of one section would insert inside the bottom end of the next section. A guide ring slid over the overlapping ends and locked everything together.



Plot 1, showing the linearity of an 80mm tentacle section with respect to cable tension, cable motion, and bend angle.

These designs were tested using the same methodology from the first round of testing. During testing, the sections in versions 6 and 7 pulled apart from each other, disabling the gripper. Version 6 reached a maximum of 107° of bending with 31 N of force; however, it was unable to relax past 50.5° when returned to 0 N force. Version 7 reached 123.5° of bending with 31 N of force, but only relaxed to 45.5° when returned to 0 N of force.

Version 5 performed nicely (see Plot 1); the Elastic core produced a smooth curve; while the Durable rings ensured that the steel cables did not rip through the guide holes. Version 5 was able to reach 162° of bending with 58 N of force and then return to its original shape. Based on these results, version 5 was selected as the mechanical architecture for the final design of the tentacular gripper, with further work done to concatenate the sections.

Each tentacle is comprised of two sections, stacked end to end. In order to actuate each section separately, and produce four bending DoFs from one tentacle, a fairlead connector concatenates multiple tentacle sections together.

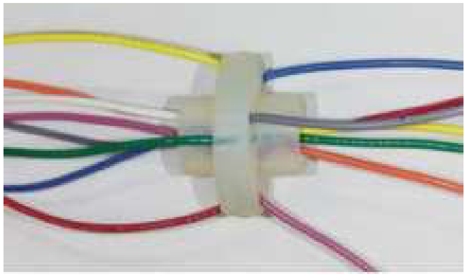


Illustration 5: Fairlead used to connect the distal and proximal tentacle sections; colored wire is used here to facilitate understanding of the cable routing that provides separate actuation of the tentacle sections.

Four cables are used to actuate each section. The cables which actuate the distal section run through the hollow center of the proximal section and are kept near the tentacle centerline by blue plastic ellipsoidal spacers (printed in blue Formlabs “Tough” resin) to minimize inter-section cable tension crosstalk, while the cables which actuate the proximal section run through the Durable rings on the outside of the section.

Illustration 6: Fine Grasp (0.0 mm radius) fingertip mounted on a fairlead, printed in Formlabs Elastic material.

The fairlead connecting the proximal and distal sections has eight individual S-shaped channels which route the four exterior cables to the inside and the four interior cables to the outside. The ellipsoidal shape of the blue spacers allows the spacer stack to bend freely while maintaining cable centering and keeping the entire stack from compressing lengthwise when under cable tension. This maintains the independent actuation of the two sections, while enclosing all cables within the tentacle. A final fairlead connector is used to connect the fingertip to the distal end of the distal tentacle section. This fairlead has a small ridge onto which a groove in the fingertip seats. The cables actuating the distal tentacle section terminate and are housed inside the hollow center of the fingertip. Several different fingertip shapes were 3D printed and tested on the gripper.

Servos and Controls

The gripper is actuated using 12 hobbyist grade servo motors (Hitec HS-805BB) which have a 180° range of motion. The actual layout is shown in figure 7. Each of the 12 PWM servo control lines are connected to a separate digital I/O pin on an Arduino Mega, so the position of each servo can be independently set to any value between 0° and 180°. Each servo carries two flexible nylon-covered stainless steel cables 0.92mm diameter (McMaster p/n #34235T28) attached to opposite ends of a bellcrank. Each servo cable pair flexes the same tentacle section in opposite directions; an angle of 90° on the servo is nominally “zero curvature” for that degree of freedom on that tentacle; rotating the servo shaft toward 0° flexes that tentacle section in one direction and rotating the shaft toward 180° flexes that same tentacle section in the opposite direction.

The Cthulhu-morphic gripper is fully actuated, with independent motion in every degree of freedom and realizing over +/- 120° of bend per tentacle section for the +/- 90° of servo motor shaft motion (the 120° motion limit versus the 162° tentacle section limit is due to limited bellcrank arm length lessening the available cable motion, not lack of servo torque). The minimum interior radius at maximum (120°) curvature is about 30mm.

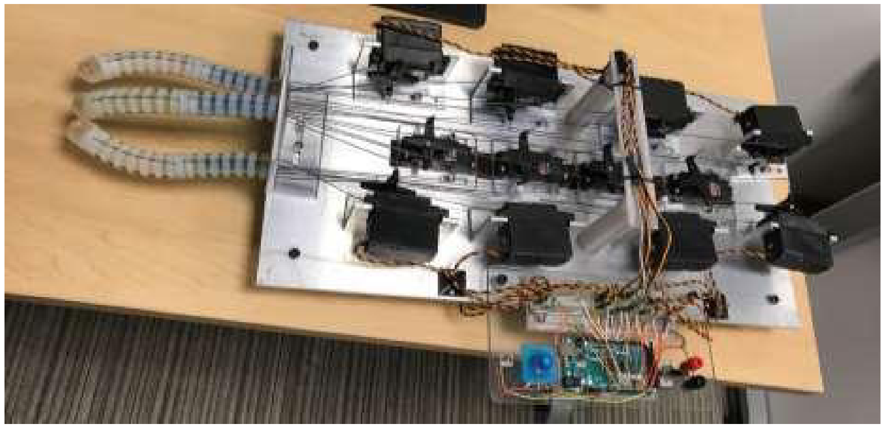


Illustration 7: Complete gripper and control panel assembly. Three sets of four servos, one for each DoF, actuate tentacle movement.

Eight predetermined grasps are programmed into the Arduino Electrically Erasable Programmable Read Only Memory (EEPROM). These grasps include several types of pinch and wrap grips. Using a potentiometer, the user can select among these saved grasps, and a serial-over-USB command line interface allows for the fully independent control of individual servos by human or control software. The position of each servo is saved in an array; should the user want to create another pre-programmed grasp; they simply save the current array under a unique name. Using the Arduino EEPROM, all saved arrays can be recalled, edited, and resaved at any time. Total current draw and voltage delivered to the gripper (nominally at a constant 6.2 volts) is monitored at the power supply.

Grasp Strength Test Results

The grasp load capacity, initial and maximum current draws, and failure mode was determined for several grasps are tabulated in Table 1. Testing was done by closing the tentacles around a test object in each type of grasp and then pulling the test object either straight out (axial) or straight down (radial) from the gripper via a calibrated force scale.

With the exception of distal pinches, pullout strength varied from 4 to 18 kg, 36 to 160 N (8 to 36 lbs). For comparison, a “classic” parallelogram-grip robot gripper with friction-rubber jaws, actuated with two of the same type HS-805BB servos achieves only ~15% to 25% of this grip strength, that is, 1 - 3 kg lift, 10 - 30 N (2 - 6 lb) axial pull-out strength on similar test objects.

Note that some high-performing grasps such as the proximal hug wrap, the reverse distal wrap and the internal counter-expanding wrap require coordinated central control and “unconventional” positioning of the tentacles. Essentially some tentacles take a weaker grasp in order to obtain a stronger grip for the tentacle array, including bracing one tentacle against another. These cases exemplify where a local configuration optimum grip is not the global optimum grip and centralized (rather than distributed) control is a requirement.

We should note that some grasp modes we would expect to be very strong (such as "boa constrictor" full wraps) are not possible with only two sections of tentacle with +/- 120° bend and 30mm minimum radius per section (such as wrapping a 10.3mm diameter test object); therefore, the grasp strengths listed should be considered as lower bounds.

The Tentacle as a Mechanical Metamaterial

The combination of the rigid cable-guide outer rings, the core tube of elastomer, the stack of ellipsoidal spacers, and the steel cabling produces a highly anisotropic mechanical metamaterial. In tension, it is highly inelastic due to the steel cables; in compression it behaves unconventionally - it neither compresses axially nor will it undergo tall-column Euler buckling (which typically creates a single sharp crease or kink) but instead bends in an essentially circular arc with complete recovery even when bent 180 degrees. In shear, and without cable tension, a tentacle deflects noticeably under its own weight, but the tentacle sections themselves are resistant to second and higher order curvatures ("S" curves and other curves with more inflection points.)

Viewed another way, the Cthulhu-morphic gripper is an analog computer finding the minimum elastomer energy configuration given the boundary conditions of the servo cable settings and the object being grasped. This view could lead directly to improved control algorithms for the gripper.

Conclusions

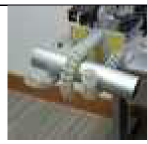
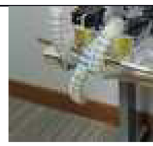
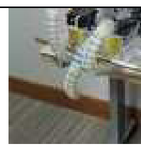
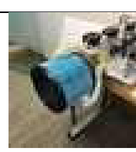
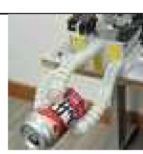
Illustration 8: The Cthulhu-Morphic Gripper grasping common tools and laboratory supplies.

The use of 3D printing was essential to prototype the gripper efficiently through so many design iterations. Some parts would have required multipart molds to produce, others such as the fairleads cannot be efficiently made in one piece with any other technology. Additionally, the possibility of future improvements on control algorithms stems directly from the mechanical metamaterial produced by the use of multiple SLA resins with vastly different material properties.

We believe that this Cthulhu-morphic gripper's superior grip strength and adaptability are a result of coordinated central control and the use of a mechanical metamaterial which provides high tensile and compressive strength while remaining supple in the lateral directions. Using a central controller enables high strength ensemble grasps, considerably stronger than conventional parallel grippers even with traction-rubber grip jaws, and enables grasping objects far smaller than the minimum tentacle bend radius.

In the short term, we see the Cthulhu-morphic gripper as most useful for warehouse bin-pick and place operations. The gripper is agile enough to pick up many different objects, with a size range from zero (with appropriate fingertips) to larger than 150 mm without modification. Integrating sensors for object identification, this gripper would be highly useful in many factory and warehouse settings for moving or sorting objects.

Table 1: Grasp Strength Testing Results – Version 5 design, three tentacles, two sections/tentacle, fully actuated (12 DoF), +/- 120° flex per tentacle section, 30mm minimum interior flex radius.

Grasp Mode	**Example Grasp**	**Max Pull at Grasp Failure**	**Object**	**Pull vector**	**No-load Current Draw (A)**	**Max Current Draw (A)**	**Failure Mode**
Distal Wrap		36 N (8 lb)	10.3 mm tube	Axial	3.8	4.8	Fingertips pulled off
Proximal Hug Wrap		67 N (15 lb)	10.3 mm tube	Axial	4.5	7.9	Cable ripped from servo
Proximal Hug Wrap		36 N (8 lb)	10.3 mm tube	Radial	4.8	6.6	Tube Slipped out of grasp
Reverse Distal Wrap		49 N (11 lb)	10.3 mm tube	Axial	2.3	2.7	Fingertips pulled off
Internal Counter Expanding Wrap		160 N (36 lb)	104 mm inside diameter tube	Axial	4.4	5.6	Fingertips pulled off
Internal Expanding Distal Pinch		31 N (7 lb)	104 mm inside diameter tube	Axial	2.1	3.0	Fingertips pulled off
Large External Pinch		18 N (4 lb)	147 mm outside diameter tube	Axial	3.1	3.7	Fingertips pulled off
Extreme Distal Pinch		0.1 N (0.02 lb)	66 mm tube	Radial	2.3	2.3	Object slipped from grasp

Improvements and Enhancements

There is room for improvement in this gripper in several key areas. Firstly, the fingertips currently attach to the gripper using a simple friction fit. This makes it easy to change tips without disassembling the entire gripper; however, it does mean that the fingertips can peel off the gripper in a high-force situation.

The choice of servos and their planar arrangement on a single 300 x 600mm plate of 1/4" (6.35mm thick) aluminum was made on the basis of expediency and expense. Optimizing the servo layout into 3D and using a higher-performance robotics-grade servo such as Dynamixels would simultaneously provide force sense, improve speed, and shrink the required servo volume and gripper mass by 75% (from ~4 kg down to ~1 kg). Better proximal fairlead design to route the cables smoothly from the servos into the tentacle would minimize corner-turning friction and reduce slack. We have not yet considered the applications of tapered or sensor-tipped tentacles, although they are certainly useful, especially for stereognosis.

It would be possible to further improve the grasp strength by coating the outside rim of the low friction rings in the grasp area with a high-friction elastomer, either as a painted-on coating or as a high-friction snap-on cover.

A useful side effect of the ring-and-groove tentacle is that if the ring and groove dimensions are properly chosen, then one tentacle's ring and groove surface can mesh like gear teeth into the grooves and rings of another identical tentacle, providing a high strength "lock", very similar to humans interlacing the finger knuckles on left and right hands. Because our test gripper had only three tentacles with relatively wide base spacing, we did not use this mechanical interlocking in any of the grasp strength tests, but it should be considered in the future.

The present system does not provide any torque feedback; adding feedback would allow for more precise control of the gripper and make the device more dexterous. Integrating sensors would provide additional information which could further enhance the performance of the gripper and potentially allow for object identification and independent grasp selection. Increasing the number of tentacles in the system would also make the system more dexterous and allow for more advanced object manipulation, object identification, and stereognosis.

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