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

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## Abstract

Presented in this paper is a 3D printed flexible robotic gripper which has three individual independently actuated tentacles, each with two sections, and a combined 12 degrees of freedom (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 hold 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. With an axial lift capacity well in excess of 100N, this gripper is strong enough to be useful in industrial applications. Potential industrial uses include warehouse or assembly line bin-picking and cobot operations.

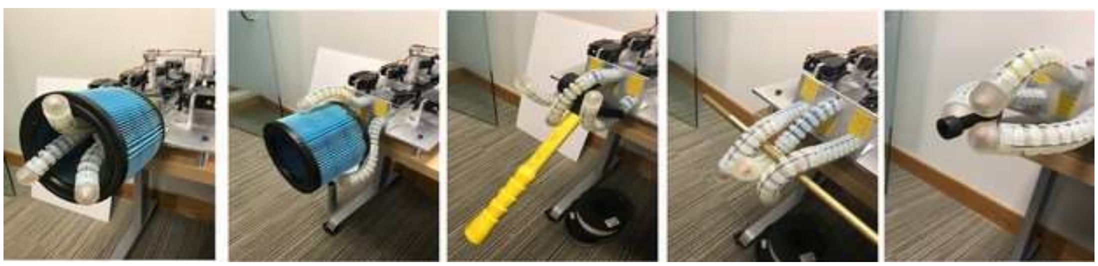

*Illustration 1: various gripping modes available with a 3D SLA printed multi-tentacular (Cthulhu-morphic) gripper.*

## 1. Introduction

The inception of this project was to design a soft robotic end effector which was versatile enough to pick up a wide variety of objects. Elastic material construction avoids pinch points, and provides resiliency and compliance, and 3D printing allows for rapid prototyping of multiple design alternatives. The goal of this work was 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"[1] grippers for range of grip styles, grip strength, and carrying capacity.

## 2. Background and Prior Work

The work upon which this research was built includes both natural evolution's inspiration and prior human research. Sea anemones, octopuses, squid, and elephants all possess flexible organs of manipulation; but with radically different control methodologies. Human-designed tentacle research includes multiple drive methodologies (pneumatic, hydraulic, tension cable) but nearly all tentacle gripper research has been restricted to a single tentacle with a few

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actuators. Therefore, evaluating the increased usefulness of independently-actuated, centrally controlled multi-tentacular gripping is a goal of this research.

## 2.1 Naturally Evolved Tentacles

Naturally evolved tentacles generally operate on the principle of a *hydrostat* – either a skeletal hydrostat; a volume of liquid that nearly fills a flexible, columnar, semi-elastic pouch, which can be distorted by external contracting muscles while the liquid contents within maintain a constant volume,[2] or a muscular hydrostat; which functions in the same manor, without a volume of liquid.[3]

For a cylindrical hydrostat with muscular walls, symmetrical lengthwise contraction shortens the hydrostat and increases the hydrostat's diameter; asymmetrical contraction causes the hydrostat to bend, and contraction of circumferential muscle decreases the diameter and increases length of the hydrostat. 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.[4] Relevant to research work, from this tentacle in nature, is the method for bending the tentacle. Asymmetrical muscle contraction can be simulated with asymmetrical loading of the 3D printed tentacle.

*Sea Anemones:* One of the earliest evolved creatures capable of tentacular manipulation are sea anemones. The tentacles of anemones carry longitudinal and circular muscles around a central hydrostat. Tentacle control and feedback 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.[5] Unlike Sea Anemones, the gripper described here requires coordinated movement. Centralized control is crucial for effectively grasping objects.

*Octopus:* The octopuses 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.[6] The central hydrostat of the arm contains nerves, arteries, and sets of interlaced horizontal and vertical traverse muscle fibers. 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. The octopus is able to change the tentacle cross section at will, however; a 3D printed tentacle will not have that level of control. If the tentacle cross section deforms, it will be a result of Euler Buckling. This would negatively impact the performance

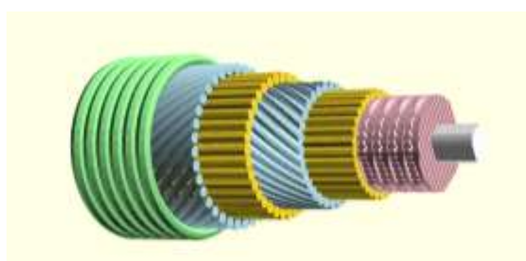


*Illustration 2: Simplified CAD model of an octopus tentacle anatomy showing circumferential extension muscles (green), oblique helical torqueing muscles (blue), inner and outer longitudinal shortening and bending muscles (yellow), the central hydrostat containing traverse aspect-ratio muscles (pink)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

of the tentacle by reducing behavior predictability, which is crucial for accurate location control.

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 nor proprioception.[7]

*Snakes:* the snakes (order *Serpentes*) evolved from the lizards perhaps as long ago as the late Cretaceous, 110 MYA,[8] and might be considered to be "all tentacle". However, snakes have lungs and intestinal peristaltic muscles to transport and digest food.[9] These organs cannot be 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 vertebra, with longitudinal and helical muscles actuating bending and twisting locomotion. A similar stack of rigid, incompressible, convex plates was eventually incorporated into the gripper described here.

*Elephants:* The elephant (and its relatives, order *Proboscidea*, evolving about 60 MYA) possess a trunk, 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.[10] The cartilage is sufficiently stiff to maintain the opening of the nasal passages even when the trunk is highly curved; a similar system will be used in the design of this gripper to provide a low friction passageway for steel actuation cables to pass through the tentacle segments.

### 2.2 Human-Engineered Tentacles

Most teams that built soft robotic grippers used either hydraulic or pneumatic actuation.[11, 12, 13] 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.[14, 15] The work presented in this paper 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.[16] 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.[17, 18] Springs do not drive the tentacle segment effectively into a single minimum energy configuration because Hooke's law is linear; flexing one spring while relaxing another isn't structurally "stiff." Additionally, the servo drivers in systems with springs have to work against the force of the spring to reach the desired position, reducing the carrying capacity of the gripper. For these reasons, springs will not be used in the tentacle described in this paper.

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.[19] Material conformability and friction property considerations like those discussed there are highly relevant to the gripper described here. The portion of the gripper in contact with the object to be grasped must have a high enough coefficient of friction to prevent slipping or dropped objects.

Stoll et al. of FESTO AG & Co. KG addressed the issue of maintain control over the grasp item by constructing 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.[20] The use of a vacuum to maintain grip strength compensates for the single tentacle design, however; the goal of the work described here is to construct a multi-tentacular gripper, so vacuums will not be used.

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 producing a more stable grip.[21] Avoiding crosstalk is relevant to the design of the gripper described in this paper, with regard to the spatial organization of actuator cables within the tentacle. Series arrangement was also used here, to maintain order.

## 3. 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. This 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.[1] Thus, a Cthulhu-morphic gripper is defined here as a device with multiple tentacles, a high DoF, near-full or full actuation, and a centralized, coordinating control processor.

## 4. Design

### 4.1 Actuation

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. A cable actuated gripper was chosen for this project to increase the speed, grip strength and carrying capacity of the device versus hydraulic or pneumatic tentacles.[11, 12, 13, 14, 15] To provide a full 12 DoF, a cylindrical tentacle shape was selected as it allows for symmetrical movement in all directions.

### 4.2 Material Selection

A Formlabs Form2 SLA printer was chosen as the primary fabrication tool for the soft gripper due to the short fabrication time and low 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.[22]

The first design iterations were printed with the Formlabs Elastic resin (RS-F2-ELCL-01) of Shore hardness 50A. This resin was selected because it is described in the Formlabs material library as "suitable for prototyping parts normally produced with silicone … [and] for parts that will bend, stretch, compress, and hold up to repeated cycles without tearing, and spring back quickly to their original shape."[23] As discussed in Section 4.4, parts printed from this material successfully produced a wide range of motion. However, this resin is not designed for friction wear and is prone to tearing at points of contact. Therefore, it was reserved for the joint section of the tentacles which would produce bending motion. The parts of the tentacle which interfaced with actuation cables required a different material.

The parts which come into direct contact with the coated steel cable used to actuate the tentacles must be able to withstand the friction from repeated motion of the cables across the printed part without wearing. Additionally, the friction from this interaction must be minimized in order to prevent inefficiency. Formlabs Durable resin (RS-F2-DUCL-02) was selected to interface with actuator cables because it is designed for "low friction assemblies and non-degrading surfaces."[24]

Much like knuckles on a finger, range of motion and motion control are increased by concatenating multiple sections of tentacle, end to end. In order to independently actuate each of the sections, a method for passing actuation cables for the distal section of the tentacle through the proximal section was required. This method and the architecture used to achieve it will be discussed in further detail in Section 4.3. Relevant here is the materials used to produce these two parts of the tentacle assembly.

One somewhat concealed, but critical part of the design, is the interior spacer and cable guide. This part sits inside the hollow center of the tubular section and allows the cables to move freely without contacting the Elastic part, and keeps the cables close to the tentacle centerline; thereby minimizing intersegment crosstalk. These interior guides act as a mechanical metamaterial realization of the tentacle's hydrostat; like the cartilaginous rings in an elephant's trunk keep the nasal passages open, the guides must maintain their shape to prevent the surrounding elastic tube from collapsing in during loading, and they must also not degrade under the transverse motion of the cables. Tough resin, a now defunct legacy product of Tough 2000, was used for this part. At the time of production, Tough was the strongest and stiffest Formlabs material available; Tough 2000 is even tougher and stiffer. "Tough 2000 Resin [is designed] for prototyping strong and sturdy parts that should not bend easily."[25]

*Illustration 3: Samples of each part type for the final version 4 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 parts printed at 0.1mm resolution.*

The second part of the concatenation system sits between the two sections. The cables actuating a given section are located on the outside of the section – as far as possible from the center axis to provide the maximum lever arm, and therefore the maximum bending torque. As previously stated, the cables which actuate the distal section run through the hollow core of the proximal section. Therefore, a device is needed to switch the distal actuation cables from the inside of the proximal section to the outside of the distal section, and vice versa. This part will contact every single actuation cable of the tentacle. It therefore must produce as little friction as possible. For this reason, Durable resin was also selected for this part.

The final piece of the tentacle is the fingertip. Fingertips were printed out of Elastic resin, because this type of resin has a higher coefficient of friction than either Durable or Tough resin. It was hypothesized that this would prevent objects from slipping out of the grasp of the tentacles. A selection of parts used in the final design are shown in Illustration 3.

### 4.3 Physical Architecture

The process of selecting the optimal physical architecture for the tentacle was iterative. The final version was selected after several rounds of designing, testing and redesigning. The test criteria, process, and results will be detailed in Section 4.4. This section documents each version of the design and how test results informed the next round of design changes. Table 1 lists a description each version and the feedback which informed the next iteration. CAD screenshots of each version are in Appendix A.

*Table 1: Tentacle Section Design Versions.*

| Version | Description | Result/Feedback for Next Version |
|---|---|---|
| 1 | Hollow cylindrical tube with a center hole to pass cables controlling other sections. Two holes through outer rim edges of the cylinder for actuation cables. | Did not print successfully – cable holes closed, likely due to capillary action. Solid cylinder body requires a lot of force for small bend angle with hand test. |
| 2 | Cut ridges with rectangular cross section along the length of the tube to allow cable actuation holes to print. | Did not print successfully – cable holes closed, likely due to capillary action. Ridges provide higher bend angle with less force required during hand testing. |
| 3a | Changed groove cross section from rectangle to trapezoid to increase range of motion and improve print – 15° cut. | Actuation holes printed successfully. Trapezoidal ridges increased range of motion - 20° version bent slightly further. With increased load to bend section further, cables ripped through Elastic material. |
| 3b | Changed groove cross section from rectangle to trapezoid to increase range of motion and improve print – 20° cut. | |

| | | |
|---|---|---|
| 4 | Printed trapezoidal ridges as separate rings out of Durable resin. Notches in ring interior seat onto round ridges spaced along full length Elastic resin core. | Bent into smooth curve during loading and completely relaxed to original position after unloading. |
| 5 | Used same ring system as in version 4, instead of seating along the length of one long core, rings are used to connect multiple abutting short cores. | Rings pulled off sections during loading, unable to return to original position. |
| 6 | Used same ring system as in version 4, rings are used to connect multiple overlapping short cores. | Overlapping sections separated under load, unable to return to original position. |

Version 4 was selected as the final design because it performed best during testing. However, a single section has only two degrees of freedom – it can bend along the x or y axis. To create a tentacle which is capable of grasping a wide variety of items with potentially complex geometry, more degrees of freedom were desired. By stacking two sections, end to end, each tentacle could have four degrees of freedom. A concatenation system was designed to achieve this goal.

Four cables are used to actuate each section. The cables which actuate the distal section run through the hollow center of the proximal section. To prevent inter-section cable crosstalk, and contact with the soft Elastic resin core, a spacer system was designed. These spacers are printed in Tough resin. Initially, a two-part system was designed, in which convex ellipsoid spacers and concave cylindrical spacers were alternated. Each has four small holes, arrayed in a circle around the centerline z-axis, one for each actuation cable. CAD screenshots of these spacers are shown in Appendix B. The convex spacers nested into the concave spacers to create a stable stack. However, load testing data showed that this spacer system limited the range of bending motion of the tentacle section. Based on this data, the concave spacers were removed from the design, leaving just the convex ellipsoid spacers. Due to their ellipsoid shape, a stack of these spacers can wrap around into a circle. Thus, they are able to conform to the curved shape of the Elastic core without collapsing along the z-centerline axis. This keeps all of the actuation cables in line and provides structural stability to the tentacle, without sacrificing range of bending motion.

The second part of the concatenation system is the piece which routes the actuation cables for the distal section from the inside out, and the cables for the proximal section from the outside in. This pieces, hereafter referred to as the fairlead or fairlead connector, has eight individual S-shaped channels which route the four exterior cables to the inside and the four interior cables to the outside, shown in Illustration 4. This connector has a reverse hourglass profile, each end inserts into one end of a tentacle section, while the center has the same outer diameter as the Durable rings, which interface with the actuation cables.

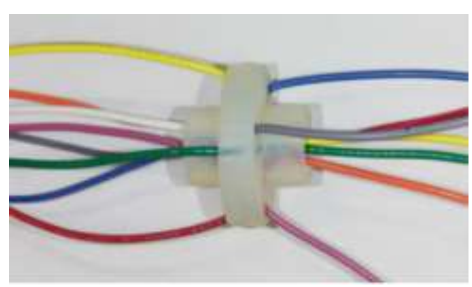


*Illustration 4: Fairlead used to connect the distal and proximal tentacle sections; colored wire is used here to facilitate understanding of the cable routing that provides separate actuation of the tentacle sections.*

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 at one end, 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. CAD screenshots of both fairleads and fingertips are included in Appendix B.

Wedge, triangular pyramid, and dome shapes fingertips were printed out of Elastic resin. An example is shown in Illustration 5. These shapes were chosen as examples, but this is not an exhaustively tested or extensive list. The shape of the fingertip used for a particular job depends on the type of objects the gripper will be used to pick up. The dome shape tip is the most versatile shape, able grasp both small items, like screws, and larger items, like a hammer. The wedge tip would be useful in sliding motions to lift paper or other thin materials. The grasp of the triangular pyramid fingertips may be unstable and/or unpredictable for a control algorithm because it is possible for only edges, only flat faces, or some combination thereof to converge at the grasp point depending on the angle of attack for each tentacle.

*Illustration 5: Fine Grasp Wedge (0.0 mm radius) fingertip printed in Formlabs Elastic material, mounted on a fairlead. Photographed fairlead printed in blue Tough resin for optical contrast in image.*

**4.4 Physical Architecture Performance Testing**

The maximum range of motion of each version of the tentacle section was tested using a simple benchtop system. Two end plates were FDM 3D 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. Benchtop system shown in Illustration 6, test results in Table 2. Two angles were measured for each version, the maximum bend angle achieved under loading, and the minimum return angle when unloaded. In addition to a high range of motion, the section must also return to a 0° angle when unloaded.

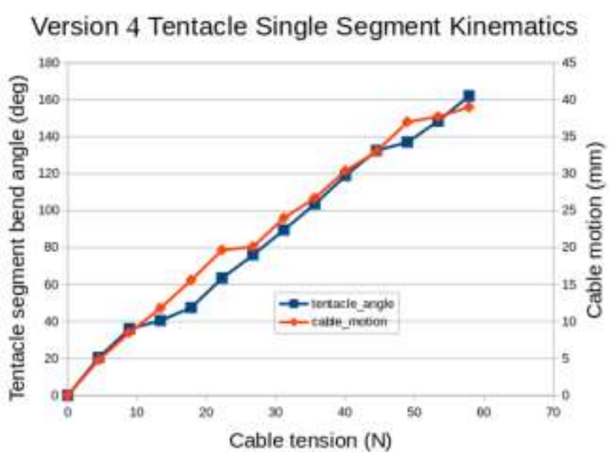
*Illustration 6: Testing range of motion with a desktop jig on a two-section tentacle of design version 5.*

Versions 1 and 2 did not print successfully, and were therefore not tested. Versions 3a and 3b did print and were tested, however; the maximum load listed in Table 2 was the maximum load before the cables ripped through the Elastic material. Therefore, the unloaded return angle could not be recorded. Versions 4-6 all survived testing and the complete results of the loading and unloading test are included in the table.

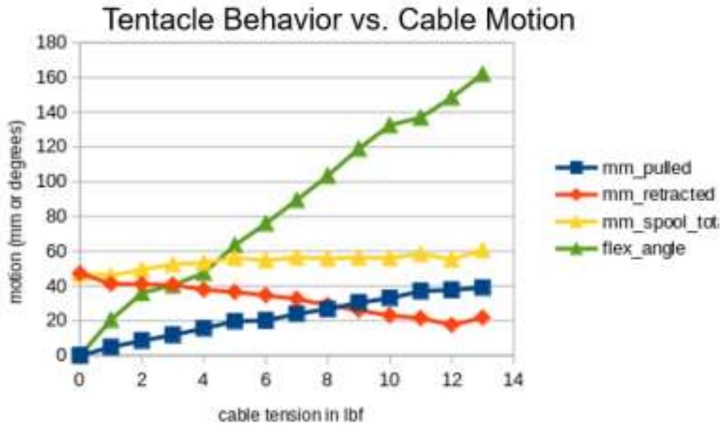
*Table 2: Load Testing Results.*

| Version | Maximum Load (N) | Maximum Bend Angle (°) | Minimum Return Angle (°) |
|---|---|---|---|
| 1 | 0 | - | - |
| 2 | 0 | - | - |
| 3a | 36 | 132 | - |
| 3b | 31 | 134.5 | - |
| 4 | 58 | 162 | 0 |
| 5 | 31 | 107 | 50.5 |
| 6 | 31 | 123.5 | 45.5 |

Version 4 was the only version which successfully returned to the 0° start angle after unloading and it also reached the largest bend angle: 162°. Further testing on this version was done to determine the linearity of the bending; that is whether each additional angle of bending was produced from a consistent additional reduction in actuation cable length. The results of this test are graphed in Plots 1 and 2. The results show that each addition angle of bending is produced from a consistent reduction in cable length, which means that the location of the tentacle can be predicted from the length of the cable. This will allow for consistent and accurate control of the tentacle using a control algorithm. Based on these results, version 4 was selected as the mechanical architecture for the final design of the tentacular gripper, with further work done to concatenate the sections.




*Plot 1. Linearity of tentacle section deflection with respect to cable tension, cable motion, and bend angle.*




*Plot 2. Comparison of tentacle flex angle (green) with measures of actuator cable displacement.*

### 4.5 Servos and Controls

Three tentacles were arranged in a triangular array and used as a gripper. The gripper is actuated using 12 hobbyist grade servo motors (Hitec HS-805BB) which have a 180° range of motion. The layout is shown in Illustration 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 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 the 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

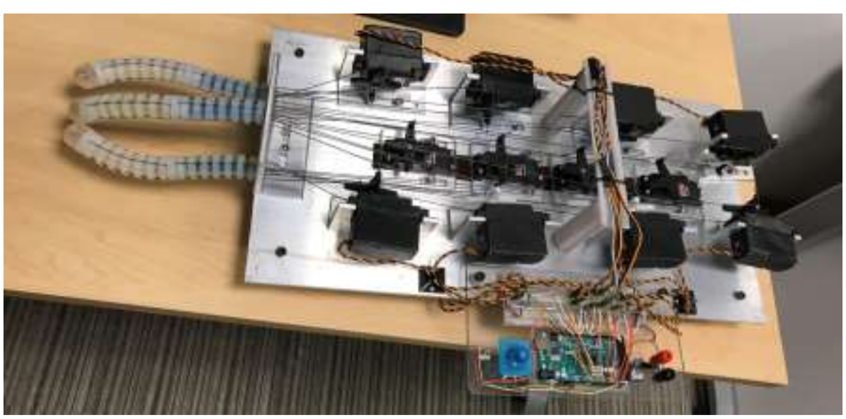


*Illustration 7: Complete gripper and control panel assembly. Three sets of four servos, one for each DoF, actuate tentacle movement.*

limited bellcrank arm length, which reduces the available cable motion, not lack of servo torque. The minimum interior radius at maximum (120°) curvature is about 30mm.

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.

## 5. Gripper Evaluation

The grasp load capacity, initial and maximum current draws, and failure mode was determined for several grasps and are tabulated in Table 3. 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 36 to 160 N. For comparison the researchers constructed a "classic" parallelogram-grip robot gripper with friction-rubber jaws, actuated with two of the same type HS-805BB servos. This classic gripper achieved only ~15% to 25% of the grip strength of the Cthulhu-morphic gripper, that is, 1 - 3 kg lift, 10 - 30 N axial pull-out strength on similar test objects.

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

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 instances in which a local configuration optimum grip is not the global optimum grip and centralized (rather than distributed) control is a requirement.

Some grasp modes which one might 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. Therefore, the grasp strengths listed should be considered as lower bounds.

*Table 3: 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 |

## 6. 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.

## 7. Conclusions

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.

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.

## 8. Discussion and Future Work

This Cthulhu-morphic gripper is 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. With integrated sensors for object identification, this gripper would be highly useful in many factory and warehouse settings for moving or sorting objects.

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. The applications of tapered or sensortipped tentacles have not yet been considered, 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, 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 this test gripper had only three tentacles with relatively wide base spacing, this mechanical interlocking was not used 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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## 10. Appendix A

*Illustration A1: Tentacle section version 1.*

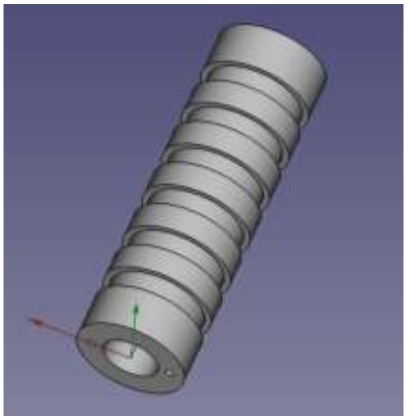

*Illustration A2: Tentacle section version 2.*

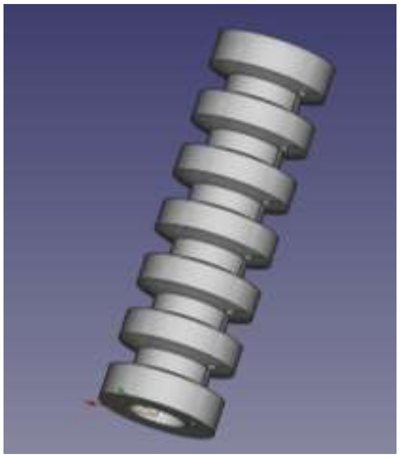

*Illustration A3: Tentacle section version 3a.*

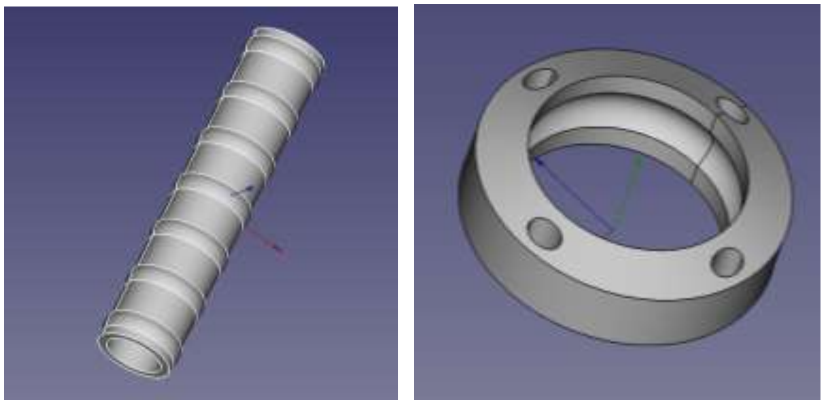

*Illustration A4: Tentacle section version 4 Elastic core and Durable Ring.*

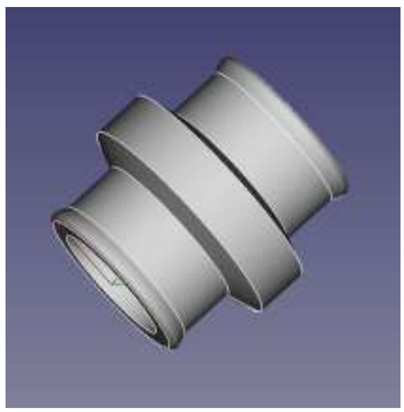

*Illustration A5: Tentacle section version 5.*

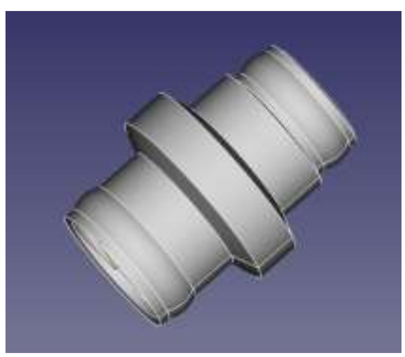

*Illustration A6: Tentacle section version 6.*

## 11. Appendix B

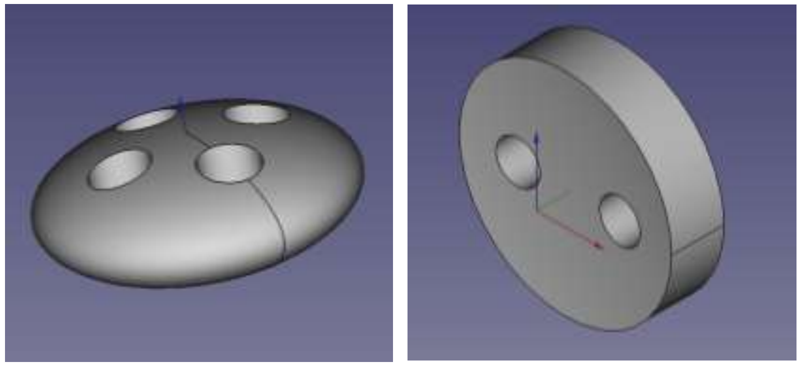

*Illustration B1: Convex ellipsoid and concave inverse ellipsoid spacers.*

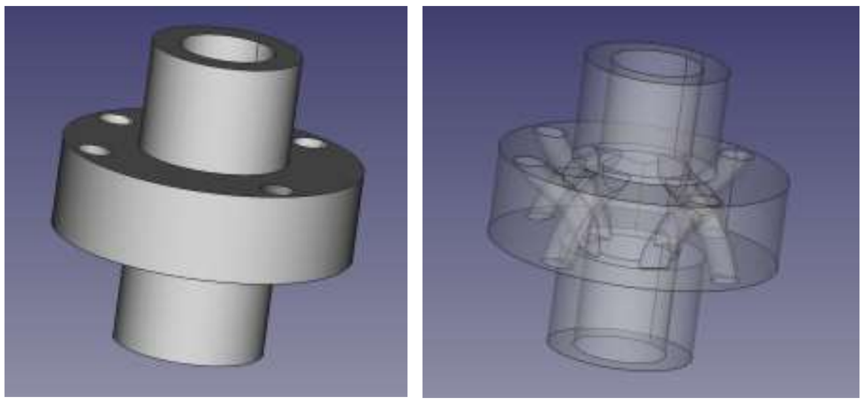

*Illustration B2: Section-section fairlead connector.*

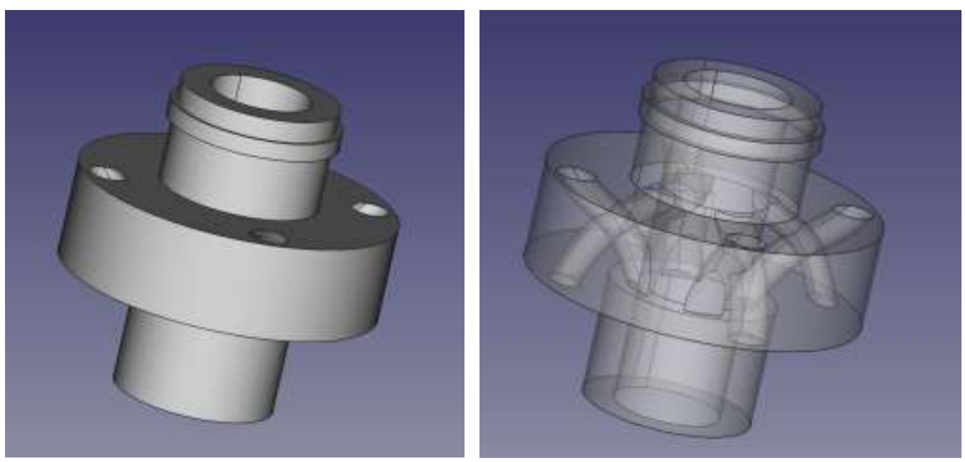

*Illustration B3: Section-fingertip fairlead connector.*

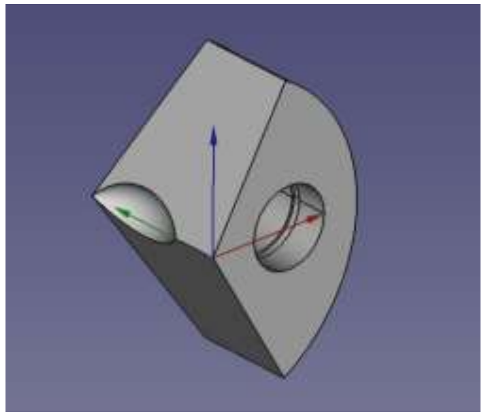

*Illustration B4: Wedge fingertip.*

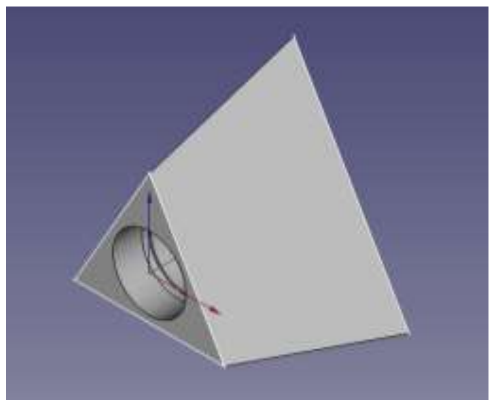

*Illustration B5: Triangular pyramid fingertip.*

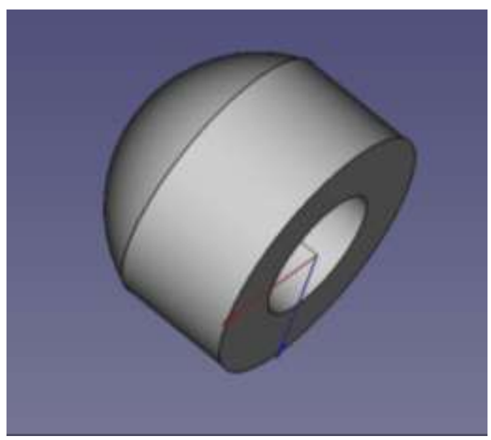

*Illustration B6: Dome fingertip.*