Non-Cooperative Space Object Capture and Manipulation with Soft Robotics

Anthony Carambia
Clemson University
Dept. Electrical and Computer Engineering
Clemson, SC 29634
acaramb@clemson.edu

Chase G. Frazelle
Clemson University
Dept. Electrical and Computer Engineering
Clemson, SC 29634
cfrazel@clemson.edu

Apoorva D. Kapadia
Clemson University
Dept. Electrical and Computer Engineering
Clemson, SC 29634
akapadi@clemson.edu

Ian D. Walker
Clemson University
Dept. Electrical and Computer Engineering
Clemson, SC 29634
iwalker@clemson.edu

Abstract— **We describe and discuss the development of soft robotics for adaptive acquisition of non-cooperative Space targets. Specifically, we propose a novel soft robotic system featuring a compliant web, interconnected and manipulated by compliant continuum "fingers". We motivate and detail the underlying design concept, and then describe the results of experiments using a ground-based hardware prototype to dynamically capture and manipulate non-cooperative targets with varying sizes and trajectories.**

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1. INTRODUCTION

The stabilization, capture, and manipulation of non-cooperative Space objects and debris is currently the topic of significant interest. A largely unexplored but compelling alternative to established robotic Space capture concepts can be found in compliant continuous body, or continuum, robots. These soft robots are modeled after flexible appendages found in nature: elephant trunks, the arms and webs of octopuses, the tentacles of squids, and snakes. Their highly maneuverable structures provide capabilities beyond those of conventional rigid-link robots, notably nondestructive environmental interaction and compliant whole-arm grasping. We propose the application of such soft robotic structures to Space target capture and manipulation. The use of soft robotic elements as the physical interface between host and target bodies can result in more adaptive and safer operations than using traditional rigid-link robots, and more predictable and controllable behavior than using nets.

We are investigating a combination of soft robot arms and webs for capture and manipulation of non-cooperative Space objects. Soft robots offer specific operational advantages when compared with alternative mechanisms for Space object stabilization, capture, and manipulation. Traditional rigid-link robot arms, while generally more accurate than soft arms, require precise control to locate their end effectors, and their rigid link structures generate high contact and impact forces – clearly undesired in this application - in the presence of uncertainty in sensing or control. While the deployment of nets for the capture of Space craft and debris appears initially attractive due to the low mass and (folded) volume of nets, their application requires specialized mechanisms for deployment, and complex procedures to manage the nets. Soft robot webs offer both a significant reduction in control complexity and greater functionality over previously proposed approaches.

The paper is organized as follows. Section 2 discusses the motivation for soft robots in capture and manipulation of non-cooperative Space objects. In Section 3, we present a design concept for such robots. Development of, and experiments with, a prototype of the design are presented and discussed in Sections 4 and 5. Further discussion and and conclusions are provided in Sections 6 and 7.

2. BACKGROUND AND MOTIVATION

The Problem – The Earth is now surrounded by a vast number of human-made objects – tens of thousands of them with sizes larger than 10cm as of 2015 [1], with the number growing rapidly all the time. The vast majority of these objects (classified as Space debris) are inert, serving no useful purpose, and indeed pose a threat to those that are functional. Operational space systems are highly vulnerable to impacts with Space debris [2], occurrences of which are difficult to predict and compensate for [3],[4].

Each of the aforementioned space-based objects has been costly to launch into orbit, and yet virtually all payloads delivered into orbit are eventually destined to degrade into debris as their fuel expires, orbits decay, etc. Many satellites are capable of significantly longer functional life spans - providing a much greater return on investment - if they could be serviced in orbit. The potential benefits of active intervention, either to service/repair or to remove these various objects, are highly significant, in terms of both economics and safety. Given the vast number of objects, and the difficulties inherent in having a human presence in Space, robotic solutions for

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interception and handling are strongly motivated.

Established Robotic Technologies - Steady progress towards robotic in-Space servicing has been made through the years [5]. The potential of robotics for satellite servicing is by now well established, via the development of enabling technologies and Technology Demonstration missions. Notably, the 2007 Orbital Express mission [6] successfully demonstrated the feasibility of robotic satellite servicing. The mission demonstrated rendezvous with and robotic capture of a free-flying satellite, with transfer of fluids and multiple Orbital Replacement Units (ORU's) between the two spacecraft [7].

Orbital Express contributed to a series of prior and subsequent efforts in developing Space-capable robotic systems for satellite servicing [8],[9],[10],[10],[11],[12]. Recent comprehensive reviews of these efforts can be found in [13],[14],[15]. The common theme has been to deploy a servicing spacecraft vehicle equipped with one or more robot manipulators to perform the servicing tasks.

Successful intervention involves two phases: interception/capture and then stabilization/manipulation of the Space-based object by the intercepting craft. A key problem is that most target objects are non-cooperating, i.e. not directly controllable, and with motion trajectories that must be adapted to by the intercepting craft. Interception and capture of rotating/tumbling satellites is a hard problem which has been extensively investigated, e.g. [16],[17]. Ground-based technology demonstrations typically exploit air-bearing floors [18],[19],[20] to simulate in-orbit rendezvous and capture. However, it is not trivial to evaluate proposed solutions in hardware outside of actual space missions.

A compounding issue, both for on-ground hardware evaluations and in-orbit deployment, is that conventional robot structures are inherently poorly suited for capture/stabilization of non-cooperative targets, particularly for the critical initial contact phase. The core robotic technology proposed, developed, and evaluated in-orbit thus far has been the conventional rigid-link manipulator. Rigid-link manipulators are ideally suited for operation in predictable, pre-engineered environments (e.g. factories), where their rigid structures provide high precision and repeatability. However, the very rigidity of their structural elements providing these advantages in highly predictable situations make them poor tools for contacting and stabilizing non-cooperative objects. The rigid link structure requires a grappling point, and provides a mechanically stiff interface, typically generating high impact forces in collision with rigid objects [21], with the magnitude of the impact forces further amplified by relative motion between the end effector and contacted object. These forces can result in damage to the contacted object – a significant concern when approaching a highly valuable satellite for servicing, the robot, or both, and/or failure of the intended grasp.

Attempts to compensate for the limitations of rigid-link robot structures to achieve safe and stable Space object capture/stabilization have been made [22]. The most obvious, and most effective, approach is to maneuver the capturing vehicle such that there is no, or almost no, relative motion between it (and thus the base of the robot) and the target before the robot is deployed. However, this requires highly accurate sensing and real-time control on the part of the capturing vehicle, and in practice there will always be some residual relative motion between the bodies. Enhancements to the robot include the use of direct or implicit force sensing, to make the system "algorithmically compliant" [22]. However, these solutions require additional hardware and/or increased algorithmic complexity, require case-by-case fine tuning of parameters, and are not guaranteed to succeed in practice.

Some alternative technologies to robot manipulators for object capture/stabilization have been proposed, for example the use of magnets [23] or dry adhesion [24]. But in these cases, detailed knowledge of, or prior access to, the target object's structure would be needed, and the intercepting vehicle would still need fairly accurate relative positioning to apply the proposed methods.

In addition to spacecraft servicing, the use of robot manipulators has been proposed for the capture and manipulation of Space debris [22],[25]. However, these strategies inherit the same issues as noted previously at the capture interface. There is, therefore, strong motivation for mechanically soft or compliant interfaces, across the spectrum of capturing non-cooperative Space objects.

Previously Proposed Soft and Compliant Interfaces – Recognizing the above difficulties, researchers have proposed several solutions based on physically compliant interfaces for interception, capture, and manipulation of non-cooperative Space objects. The concept of composite-based flexible "tentacles" has been proposed [1], to provide a compliant interface. The use of a flexible "brush" to stabilize the target has been suggested [26]. The authors note however that it would be difficult to ensure long term contact, due to the problem of controlling the friction. In each of these proposed approaches, bouncing remains a potential problem, and fairly accurate relative positioning between the capturing craft and Space object would be required.

The deployment of tethers for debris acquisition has been analyzed [27]. Tethers are difficult to test on the ground and require a method of adhesion to the target. The use of harpoons [28],[29] offers one way to achieve this. However, there is a risk of the harpoon impact generating more debris, and the tether line connection makes it difficult to predict the relative motion between the bodies [1].

An intriguing alternate strategy is the use of nets [30], [31], [32]. Nets, which can provide multidimensional restraint, require lower accuracy in deployment than any of the approaches discussed thus far, offering greater stability and reliability than tethers/harpoons, with the ability to passively stabilize the target by surrounding it with compliant lines. However, nets are non-trivial to control, requiring complex deployment/control mechanisms, and having the potential of tangling and generation of critical oscillations [1]. Nets are also inherently unable to capture objects smaller than the size of the holes within the net structure.

Proposed Alternative Solution - In this paper, we introduce a new approach to non-cooperative Space object capture and manipulation, one that features the adaptability of nets, along with the active controllability of robot structures. Specifically, we propose a soft smooth web structure, with the web shape controlled by compliant continuum robots interconnecting the soft web elements. The soft web can be viewed as "filling in the holes" of a net, and key strands of the net viewed as being replaced by compliant, controllable continuum robot elements.

Continuum robots, in contrast to robots based on rigid links, have smooth compliant backbones [33], similar to elephant

Figure 1. Vampire squid. Image credit: MBARI

trunks and octopus arms [34]. These compliant backbones give continuum robots the ability to navigate congested spaces well beyond those of conventional rigid-link robots [35]. Continuum robots have accordingly been extensively applied in medical procedures [36]. They can be deployed as "active hoses", for example in robotic refueling applications [37]. In addition, and most relevant here, continuum robots can actively wrap their structures around objects to generate adaptive and robust grasps [38].

Continuum robots have been proposed previously for Space operations. The first long thin tendril continuum robot for in-Space inspection operations was developed at NASA/Johnson Space Center in 2006 [39]. The authors recently developed refined versions of the tendril, aimed at inspection operations inside and in between the equipment racks on the International Space Station (ISS) [40].

Continuum robot "tongues" for grasping and manipulation of partially known and/or non-cooperative space objects has been proposed in [41],[42]. The key innovation herein is in the incorporation of continuum robot elements into a soft web, in an enclosed structure. The approach, detailed in the following section, offers several key advantages: (1) the soft web structure can adaptively envelop objects with significantly reduced demands on precision from the capturing vehicle (similar to nets); (2) the compliant structure reduces impact forces, in comparison to making contact with rigid-link robot structures; (3) the embedding of continuum robot elements in the web allows direct controllability of the structure, unlike with nets; and (4) the full-surface structure can catch small objects which would slip through nets.

We note that compliant surfaces (1-meter square thin membranes) have also been suggested for orbital debris removal in the highly innovative Brane Craft Program [43]. The approach introduced herein is inherently more scalable, and thus applicable to the acquisition and manipulation of a much wider range of potential Space-based objects, as discussed further in the following section.

3. Soft Robot Concept

The use of a soft web manipulated by compliant muscular elements has precedents in the natural world. A variety of animals such as the vampire squid (Figure 1) feature such structures.

The combination of robotic continuum elements and soft webs was suggested by the authors in [44], and expanded on in [45]. Additionally, in [46], webs were demonstrated to aid a robot octopus in swimming. Soft web-based continuum structures have not previously been proposed for object capture or manipulation, or for Space operations, to the best of our knowledge.

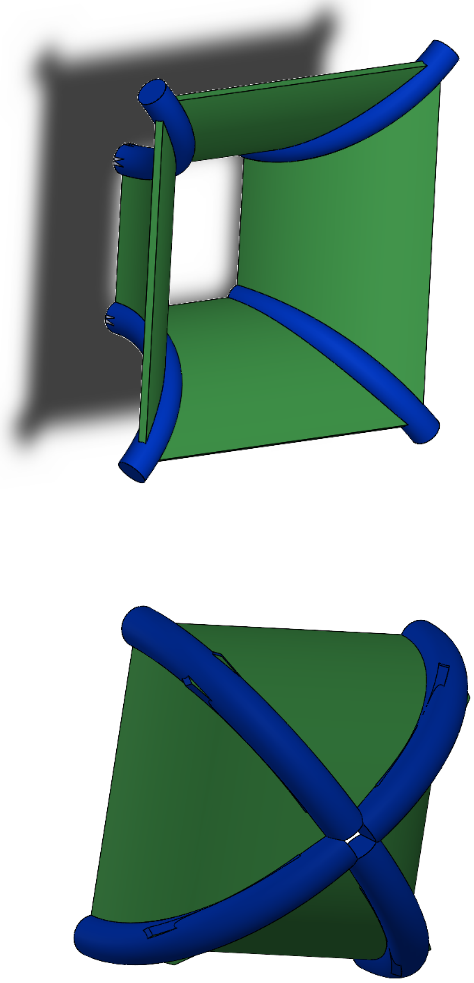

Figure 2. Soft robot design concept and operation: (Top Image) continuum elements in the open configuration; (Bottom Image) continuum elements shape and close soft web to safely envelope, capture, and stabilize target

The design concept proposed in this paper for capturing and manipulating non-cooperative Space objects, is illustrated in Figure 2. Several actively controlled continuum robot elements are interconnected by a passive soft surface web. The continuum elements could be constructed of single or multiple sections (a section is an independently controllable length of backbone, featuring two degrees of bending freedom), depending on the projected class of space objects to be handled. Remote actuation of the continuum elements could be achieved in one or a combination of several ways: via tendons bending a compliant backbone (the point(s) along the backbone at which groups of tendons are terminated defines the section endpoints), via fluidic actuation of artificial muscles comprising the backbone, or by direct remote actuation

Ref	Type	Contact Force	Relative Rate Uncertainty	Relative Attitude Uncertainty
[21]	Dual rigid-link arms	$\leq$ 12N	0	10^o/s
[23]	Magnetic	2.4N	0	0
[24]	Dry adhesion	$\leq$ 9N	0	6^o/s
[25]	Rigid-link Arm	0.23 N	2.5 cm/s	$\leq 4^o$/s
[26]	Flexible brush	$\leq$ 45N	0	10^o/s
This paper	Soft Web	2.67N	$\leq$ 5.25 cm/s	$\geq 90^o$

Table 1. Table I: Comparison of Proposed Grasping Technologies

of compliant concentric tube structures. Each of these design strategies has proved effective for continuum robots in 1-g applications, but fluidics is typically not a preferred option in Space, thus tendons and/or remote tube actuation are the preferential modalities.

Functionally, the design concept directly exploits the ability of the continuum "fingers" to use their inherent compliance to safely adapt to relative motions between the capturing craft and the target, guiding the soft web to create a "whole body grasp" to gently wrap around the target, maintaining the non-destructive grasp in the presence of relative rotational motion between the capturing vehicle and the target.

Operationally, one key advantage of the design is that all the actuators are located at the base of the robot, and they can thus be housed entirely within the capturing vehicle. This reduces the complexity of the portion of the robot which would be directly exposed to the Space environment. If the configuration (shape) sensing of the continuum elements was also located at the base of the structure (via, for example, the use of string encoders as implemented in [34]) the entire externally deployed structure could be made electrically inert. The web structure could be folded (rather like an umbrella, or some types of solar arrays) and retracted when not in use.

Programmatic and economic advantages of the design concept, compared to previously proposed approaches, are numerous. Continuum robot designs are highly scalable, over lengths ranging from several centimeters to tens of meters [38]. The design is correspondingly applicable to potential missions across the range of scales of existing Space objects. Versions of the design could be tailored to "filtering" very small particles to non-destructive stabilization of large satellites. Continuum robots are also low-mass and low cost, in comparison with traditional robot manipulators.

In the following Section, we describe a hardware realization of the design concept, in a simple ground-based prototype. Illustrative experiments with the prototype are reported and discussed in sections 5 and 6. A comparison of the properties of the prototype with those of previously proposed technologies is given in Table I.

4. PROTOTYPE

In an early design realization of the webbed gripper [47], a prototype was actuated via pressurized air. This choice was made since pneumatic actuators were readily available in our laboratory. In applications involving Space deployment, it is probable that remote actuation of tendons using electric motors would be a preferred modality. Tendon-based actuation also inherently generates stronger forces than pneumatics.

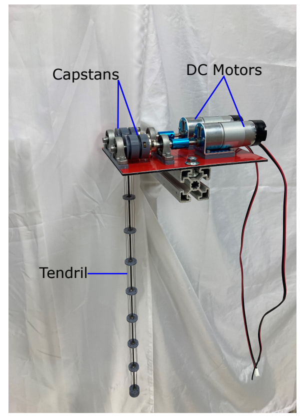

Figure 3. Single Tendril System

Therefore, we developed a second prototype, reported on herein, based on tendon-actuated "tendril" digits.

Prototype Development

The tendon-actuated, webbed gripper was designed with four individual tendril subsystems [48]. An individual tendril subsystem, pictured in Fig. 3, was assembled using a carbon fiber backbone (45cm in length), to provide the "continuum" nature of the digit, and a series of tendons that were used to bend the backbone and alter the direction and magnitude of said bend. The actuator package of each tendril subsystem consists of two DC motors, in conjunction with two capstans, that were connected to the tendons, along with the appropriate hardware to connect the capstans to the shafts of the DC motors. One of the DC motors in each tendril subsystem was individually responsible for bending the tendril inward (i.e. closing direction), while the other motor pulled the tendons responsible for bending the tendril outward (opening direction). In order to provide increased torsional rigidity to the tendril, each motor was connected to two tendons that ran in parallel along the backbone, for a total of four tendons per backbone. The two tendons on each motor were spooled on the same capstan and at the same rate during motion, while also providing additional stiffness in the plane perpendicular to the plane of bending. Each individual actuator package measured 22cm$\times$15cm$\times$5cm.

To promote reconfigurability and to save space, the four tendril subsystems were initially arranged as depicted in Fig. 4. The top- and bottom-most actuation packages were aligned so the related tendrils would bend in the same plane, as are the left- and right-most actuation packages. The intersection of the two bending planes occurred at the center of the gripper. In this initial arrangement, the center-to-center distance between neighboring tendrils was 30cm, chosen such that the

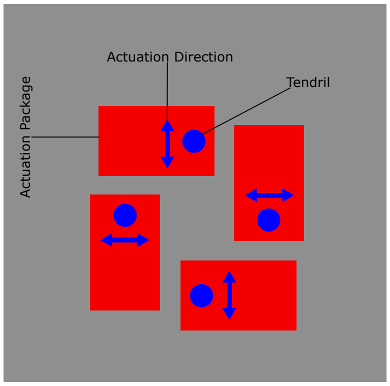

Figure 4. Tendril actuation package arrangement (from above).

Figure 5. Tendril Arrangement With No Web Attached (from side).

tendril end-effectors at the maximum rate of bending meet in the center point underneath the gripper. The arrangement of the physical tendrils in this configuration (without the web) is depicted in Fig. 5.

The concept for the web was to create 4 tubes out of a knit fabric (composed of 96% polyester and 4% spandex) to individually encompass each tendril and then connect the tendril covers with flat panels composed the same fabric. In realizing this concept, we were instead able to create the web from one continuous piece of fabric, arranging the tendril covers into the same strip of fabric that constitutes the interconnecting panels. The idea was that this would be easier to manufacture and would lead to more uniform connections between the tendrils. The fully constructed web after placement over the tendril digits can be seen in Fig. 6. The dimensions of the web elements were 30cm (base to base) by 40cm (base to tip) when unstretched.

An Arduino Due was used to handle the control of the 4 tendrils. In total, 8 motor drivers (MD10C R3) were used to control the 8 individual tendon motors (Andymark NeveRest Classic 60 Gearmotors), powered by a series of 12V DC power supplies. The resulting gripper could be moved from fully open to fully closed, and vice versa, within 2 seconds.

Stiffness Control

Continuum robots, and more specifically tendrils, are very susceptible to external forces. Prior to construction of the gripper it was predicted, and subsequently confirmed after construction, that the presence of the web would hinder the range of motion of the tendrils. In order to counter this, a stiffness control [49],[50] algorithm was implemented to allow for each tendril to compensate for the external spring-

Figure 6. Fully Constructed Web

like force of the web.

The intent of the stiffness controller was to counter the implicit stiffness of the fabric web. As in [49], we modeled this stiffness as a virtual spring which then enacts a restricting force on the end-effector of the form:

$$\mathbf{F} = [K]\Delta\mathbf{x} \tag{1}$$

$$\Delta\mathbf{x} = \mathbf{x} - \mathbf{x^d} \tag{2}$$

where K $\in \mathbb{R}^{n\times n}$ is the stiffness matrix of the material, $\Delta\mathbf{x} \in \mathbb{R}^{n\times 1}$ is the change in effector position with respect to an arbitrary position, and $\mathbf{F} \in \mathbb{R}^{n\times 1}$ is the force vector experienced at the end-effector. In practice for rigid-link robots, after calculating the predicted forces at the end-effector, one can use the robot Jacobian to calculate the effective torques needed to exert force $\mathbf{F}$ at the end-effector. In our case, we relate the force to a virtual torque represented by continuum robot kinematics, but calculated using the familiar equation:

$$\tau = [J]^T F \tag{3}$$

where the Jacobian matrix J relates end-effector forces to (virtual) joint torques.

In lieu of the traditional rigid-link robot kinematics needed for stiffness control, we utilize the constant-curvature kinematic model presented in [51], reproducing the equations relevant to a planar, fixed length continuum robot below:

$$u = \frac{l_2 - l_3}{d\sqrt{3}} \tag{4}$$

$$v = \frac{s - l_1}{d} \tag{5}$$

$$s = [l_1 + l_2 + l_3]/3 \tag{6}$$

where u and v are rotation values that relate direction and magnitude of bending and s is the length of the continuum backbone. The values l_1, l_2, and l_3 relate absolute tendon lengths for a 3 tendon configuration and d measures the radial distance between the backbone and the tendons. In the case of the tendril digits used in the gripper, s is a constant value.

Using the model above, and considering the values u and v as virtual joint values, we relate the virtual torques about u and

v to the tensions in the tendons l_1, l_2, and l_3 using eqs. (4),(5) to derive the Jacobian:

$$J_{uv} = \begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{\sqrt{3}d} & -\frac{1}{\sqrt{3}d} \\ -\frac{1}{d} & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{l_1} \\ \dot{l_2} \\ \dot{l_3} \end{bmatrix} \tag{7}$$

where $\dot{u}$ and $\dot{v}$ are the derivatives of u, v, respectively, with respect to time. Likewise, $\dot{l_1}$, $\dot{l_2}$, and $\dot{l_3}$ are the rates of change for each tendon length over time. In the case of a planar continuum robot, we only need to use u or v to describe the motion of the robot. Given the simplicity of v, we select this value to define the remainder of the model, simplifying the Jacobian to:

$$J_v = -1/d \tag{8}$$

The remainder of the method is as follows: the displacement of the robot end-effector is measured according to the forward kinematics in [51] and multiplied with the measured material stiffness of the web (k). The Jacobian J_v converts the external force to tendon tension (T). Tension is converted to torque exerted on the tendon capstan of radius r_c and the compensating torque is combined with the torque output of a standard PD controller τ_{PD}:

$$F_b = k * \sqrt{\Delta x^2 + \Delta z^2} \tag{9}$$

$$T = J_v^T F_b \tag{10}$$

$$\tau_{stiff} = T * r_c \tag{11}$$

$$\tau_{out} = \tau_{stiff} + \tau_{PD} \tag{12}$$

The tendency of the fabric to stall a torque limited PD controller was measured by incrementally increasing the maximum torque available to the PD controller and then recording how much tendon the motor could retract. The relevant stall data, seen in Fig. 7, was collected by dynamically attempting to reach a desired tendon length while constrained by the fabric and then recording the actual amount of tendon that could be retracted. As an example, when the PD controller was limited to a maximum of 0.4 Nm of torque, it was only able to retract 10mm of tendon. This method was repeated until the maximum bending position was reached.

Also depicted in Fig. 7 is the output of the stiffness controller, based on tendon retraction and ideal kinematics. As can be seen, the stiffness controller output trends well with the observed minimum torque needed to reach various tendon lengths (as related by the stall data). The addition of a bounded PD controller (i.e. the PD controller is limited to a maximum torque magnitude) clearly enables the combined controller to exert more than enough torque to reliably reach any position in the desired range of motion, providing valuable insight into the viability of stiffness controller. In the remainder of this work, the PD controller has been limited to a maximum torque corresponding to a 13.7% duty cycle (35 PWM) to the tendon motors. For clarification, the selected motors were capable of bending the tendrils (including fabric stiffness) when there was no duty cycle limitation, but this resulted in a snapping motion that was not desirable for gentle, controlled grasping.

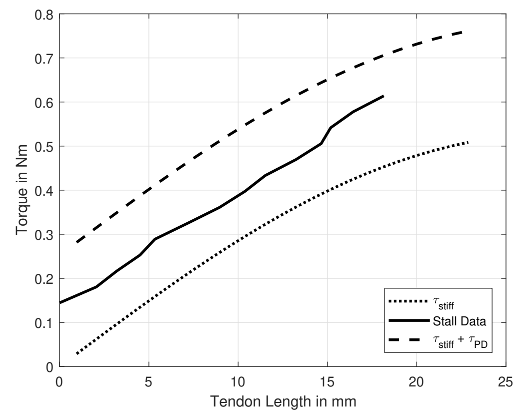

Figure 7. Comparing the tendency of tendon motor stall under load with the developed stiffness controller.

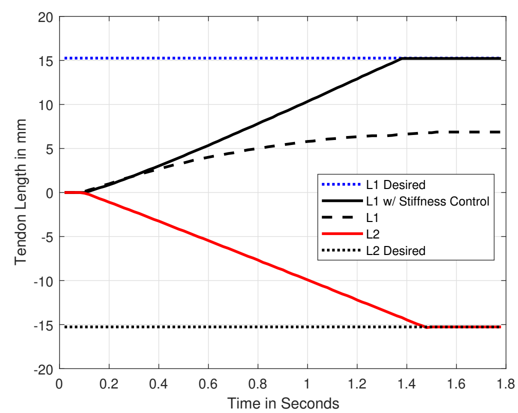

Figure 8. Stiffness Control Evaluation

We illustrate the combined controller executing a desirable motion while constrained by the web, testing both with and without the stiffness control active. As seen in Fig. 8, the system attempts to retract 15 mm of tendon. We can see from the plot of L_1 without the stiffness controller that the bounded PD controller is not able to reach the desired position (it retracts approximately only 6.87 mm of tendon). In contrast, tendon L_2, which is not under tension, is able to smoothly release the desired 15mm. With the stiffness controller active, the L_1 motor is able to match the rate of the L_2 motor, despite the building tension and resistance of the fabric.

5. Experiments with Prototype

Following the implementation of the stiffness controller, we conducted a variety of experiments to validate the gripper's potential. The goal of the experiments was to show that the gripper could grasp a range of objects without precise knowledge of its location with respect to, and to not damage, the target.

Qualitative Experiments

For initial testing, experiments involved grasping a series of spherical objects with a wide variation in object diameter. The first object we highlight was a red foam ball (diameter of 18 cm), seen in Fig. 9 as a time lapse of the grasping motion. Initially the gripper was unactuated and once the ball was in frame the gripper was opened to provide a larger area for the ball to pass through into graspable range of gripper. Once the ball was within the volume of the web, the gripper could begin to actuate into the closed position, securing the object as seen from inside the gripper in the bottom right image in Fig. 9. Similar results were obtained with a 30cm diameter target sphere.

Further experiments focused on the capture of a significantly smaller, 6.5cm diameter sphere. The test was conducted similarly to the 18cm ball experiment above, and so we only report on the ability to retain the smaller object. As seen in the left image of Fig. 10, the presence of the web allowed the gripper to retain the small object, which settled partially underneath one of the tendrils. Without the web, this object would be able to fall through the gaps between the digits. We also performed the same task without the presence of the stiffness controller. The result, seen in the right image of the figure, was the inability to bend the digits of the gripper enough to fully close the web and thus allowed the small object to fall through.

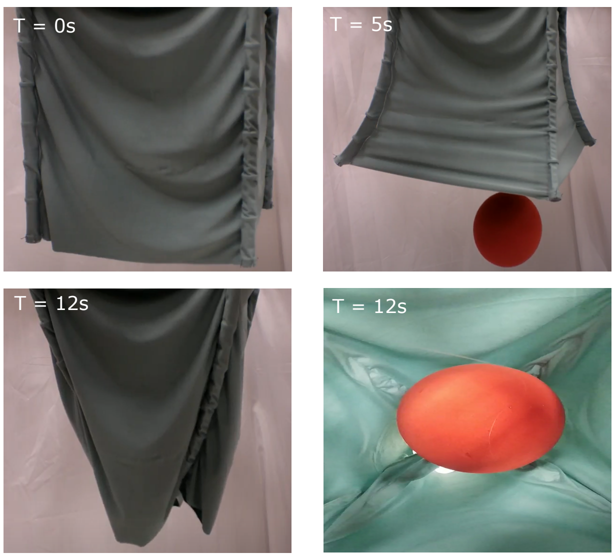

Figure 9. Time Lapse for Grasping 30cm ball

After completing tests demonstrating the gripper handling a range of different sized objects, experiments were conducted to depict that the gripper can handle non-uniform shapes. For example, in one test, the target was a box measuring 39cm$\times$31cm$\times$18.5cm. It is worth noting that the size of this box was also larger than previously tested spheres. As with

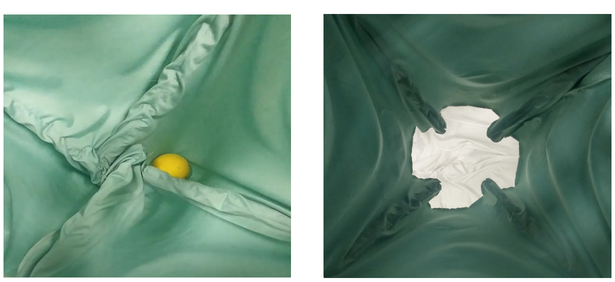

Figure 10. Grasping of small object (6.5cm diameter sphere). The web retains the object despite size (left). An absence of stiffness control prevents the gripper from fully closing to capture small objects (right).

Figure 11. Capturing of large, non-uniform object.

the previous tests, the box was brought to the range of the gripper and then the gripper was allowed to close once the box was mostly in the gripper's enclosing volume. As seen in Fig. 11, the gripper was still able to secure and stabilize the box, utilizing both the tendrils for supporting the mass and the webbed material for security.

A subsequent series of tests with the gripper, aimed at examining the ability of the gripper to function in grasping objects with relative attitude as well as rate uncertainty, were conducted with balloons. Balloons of diameter 30cm were launched towards the gripper. In ten such tests, all resulting in successful grasps, the gripper base was fixed, and a variety of spins imparted to the balloons. Figure 12 shows a time lapse of a representative test, over the course of 8 seconds. The spinning balloon was gently caught in the web and secured by the closing of the gripper, which provided sufficient force to restrain the balloons without damage. The average relative attitude change in the balloon experiments was over 90^o.

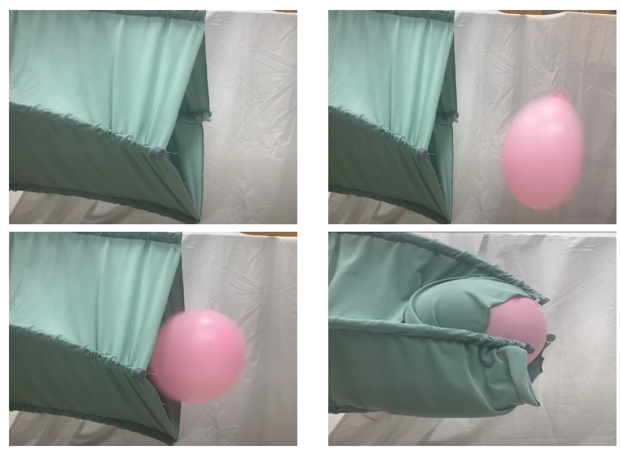

Figure 12. Capture of balloon.

The next set of experiments examined the capture of a drone. The drone had a length of 14 cm, a width of 14 cm, and a height of 4.5 cm. In these tests, there was non-trivial and unmodeled relative motion between the gripper and object (drone) to be captured. Ten tests were conducted, all resulting in successful grasps. Figure 13 depicts a representative case, with a time lapse of 10 seconds. In this experiment the drone was flown in an unpredictable and uncooperative manner, while the gripper captured it successfully. Once the drone was in range, the gripper closed around it. The system again benefited from the web material by retaining the drone between the digits, despite the drone's small size.

In the above experiments, for the capture of smaller objects relative to the web size, such as the drone and balls, as well as

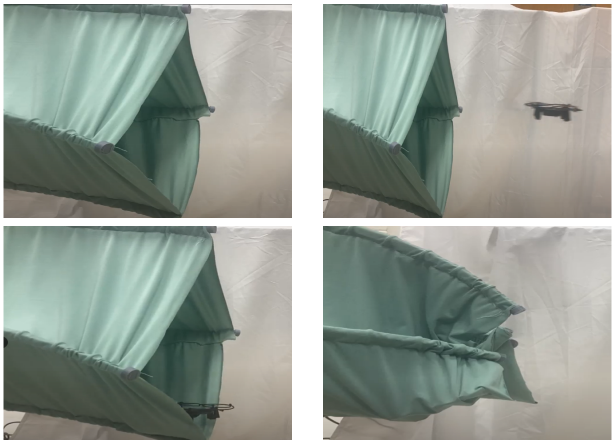

Figure 13. Drone Grasping

Figure 14. Capture of ball.

in experiments reported in the next section, in numerous cases the objects initially bounced off the web surface. However, in all cases, the web closed sufficiently quickly to safely constrain and grasp the object, demonstrating the adaptability of the design and its ability to robustly and safely capture objects even in the presence of significant uncertainty of their initial grasp location with respect to the gripper.

Quantitative Experiments

We next conducted a series of quantitative experiments. All of the subsequent experiments were conducted with the gripper initially positioned above the target. The various targets were then moved into the gripper's range of motion in a variety of ways.

A winch was used to pull three objects into the range of the gripper. The objects were a foam ball of diameter 6cm, a cardboard box of dimensions (17cm by 11.5cm by 6cm), and the 29cm diameter spherical component (comprised of styrofoam) of a "Sputnik craft". Collectively, these objects represented a range of scales, relative to the gripper size, from small (ball) to large ("Sputnik"). Their surface properties ranged from smooth with relatively low friction (box) to relatively rough and high friction ("Sputnik").

One end of a thin cable was connected to each of the objects, with the other end wound around a spool at the winch, located above the center of the gripper. When raised toward the gripper, the winch speed was used to vary the relative rate between the gripper and target. The suspended objects presented a range of attitude differences, with the ball maintaining its attitude relative to the gripper, but the irregular shape of the box and the off-set center of mass of the"Sputnik" resulted in variation of relative attitudes between target and gripper in those cases.

The ability of the gripper to grasp each object was tested 5 times at each of three winch speeds: 1.12 cm/s, 3.43 cm/s,

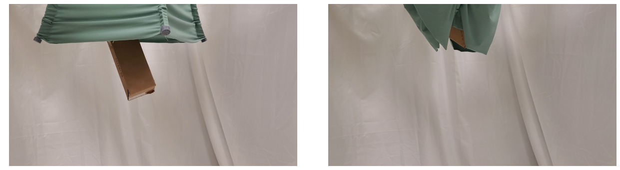

Figure 15. Capture of box.

and 5.25 cm/s, for a total of 45 tests. The three speeds were empirically selected through the use of a potentiometer as the input for the winch, and the resulting speed was measured by examining video footage of a square grid placed behind the gripper workspace with the grid plane orthogonal to the axis of a fixed camera. In each experiment, the gripper was manually closed as the target entered its range. See Figures 14, 15, and 16. The results of the tests are summarized in Table II. Overall, 44 of the 45 grasps were successful. The exception case was for a trial of the box at the highest winch speed, when the operator closed the gripper too soon, and the closed gripper failed to envelop the box, which subsequently slipped out of the grasp.

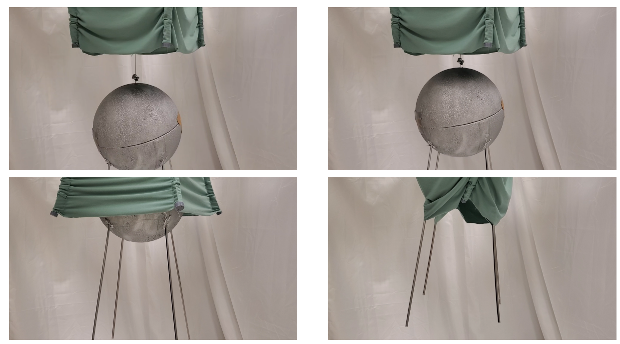

Figure 16. Capture of "Sputnik".

In order to evaluate gripper grasp forces, we instrumented a target (an extruded aluminium bar) with two Sensata 1724-1065-ND linear potentiometers. The linear potentiometers were calibrated over a range of 58 to 200 grams, and attached on two sides of the target, which was subsequently grasped by the gripper in a series of ten experiments.

We conducted ten grasp tests using the instrumented target. The average recorded grasp force was 2.67 N.

6. Discussion of Results and Future Work

Tests with the both balloons and drone were highly successful. The gripper was able to successfully and gently capture the drone and balloons (evidenced in part by the ability to grasp and release a balloon without the balloon bursting). This occurred despite the fact that each time the gripper interacted with the balloons or drone the trajectory of the moving object was different. In no case was damage caused to the captured object. This demonstrates that a web-based gripper can gently grasp uncooperative objects, moving in three dimensions, of a variety of shapes, sizes, and trajectories, even though both the underlying hardware and control strategy are very simple.

The quantitative results reflect and record the capabilities of the specific prototype constructed and evaluated herein.

Object	Slow (1.12 cm/s)	Medium (3.43 cm/s)	High (5.25 cm/s)	Overall
Ball	5/5	5/5	5/5	15/15
Box	5/5	5/5	4/5	14/15
“Sputnik”	5/5	5/5	5/5	15/15

Table 2. Table II: Success Rates Grasping Different Objects at Three Relative Capture Rates

Note that variations of the design, using alternative materials and actuators, would result in properties (grasp force, gripper adaptability, etc.) significantly different to those of the prototype reported in this paper. Operational variants of the design would almost certainly feature more powerful actuators (hence stronger grasp force) as well as embedded sensors to enable more automated grasping modes. Suitable materials for the web (for example to prevent tearing from sharp objects) need to be identified.

One longer-term challenge in moving the design forward towards operations is pre-flight testing. The inherent compliance of the gripper would render underwater testing impractical, since fluid dynamics disturbances, not present in the Space application, would have significant impact on gripper behavior. The use of air-bearing tables or traditional robotic contact dynamics emulators also appears problematic. Innovative concepts for testing such soft grippers, and soft robots in general, are called for.

Overall, the results show that the proposed gripper design has the ability to capture a wide range of objects without knowing the target’s precise location. It also has the ability to capture objects that would be damaged by a traditional gripper. The implementation of stiffness control allowed for the tendrils to better resist the external forces of the fabric. This allowed for a wide range of objects to be grasped.

Modifications to the current design could be made to capture small objects. Smaller targets tended to escape direct contact with the tendrils, falling into the folds of the fabric. In some of these cases, the fabric would not completely enfold the object, thus the gripper enveloped but failed to stabilize it. Potential solutions for this include more or more complex continuum sections, or to embed magnets in the web material so that when the gripper closes, the magnets will attract to each other and seal to smaller regions within the web. A higher density of continuum sections would improve performance all around, allowing for the backbones to make direct contact with the smaller objects and potentially enable fine manipulation of very small objects. However, this would be at the cost of higher physical complexity. Alternatively, the system could remain open and the capturing craft could “trawl” in a region of interest, allowing the web to passively “fish” for smaller objects along its trajectory.

In our ongoing work, we are refining the design and prototypes. We plan to explore the improvements gained from increasing the number of continuum fingers from four backbones to eight. This will more directly represent the morphology of biological analogs such as of the vampire squid, and our insight from the experiments reported here is that this is likely to improve the performance of the gripper.

7. Summary and Conclusions

We have presented a novel concept for non-cooperative Space object capture and manipulation. The approach is based on a compliant robot system featuring a soft web structure. The approach offers several key advantages: (1) the soft web structure can adaptively envelop objects with significantly reduced demands on precision from the capturing vehicle (similar to nets); (2) the compliant structure reduces impact forces, in comparison to making contact with rigid-link robot structures; (3) the embedding of continuum robot elements in the web allows for direct controllability of the structure, in contrast to nets; and (4) the full-surface structure can catch small objects which would slip through nets. The design is inherently scalable and low-cost relative to solutions based on using traditional rigid-link robot manipulators. The discussion is supported by illustrative experiments using a simple ground-based hardware prototype.

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BIOGRAPHY

***Anthony Carambia** received the B.S. Degree and M.S Degree in Electrical Engineering from Clemson University, Clemson, SC, in 2020 and 2022, respectively. He is currently working as an embedded systems engineer for battery powered power tools. His current research interests are in the applications of continuum robotics in space. Other research interest include embedded systems and there application in robotics, space travel, and space debris clean up.*

***Chase Frazelle** received his B.Sc. M.S., and Ph.D. degrees in electrical engineering from Clemson University, Clemson, SC, in 2015, 2017, and 2021, respectively. His research focused on the control and modeling of extensible continuum robots with the aim to improve the reliability and automation of such manipulators for space exploration and investigation. Other research interests include human-robot interfacing, embedded systems, and interaction with distributed systems.*

***Apoorva Kapadia** received a B.E. in Instrumentation Engineering from Mumbai University, India in 2002. He further earned M.S and Ph.D. degrees in Electrical Engineering from Clemson University in 2004 and 2013 respectively. He is currently a Visiting Assistant Professor in the Electrical & Computer Engineering department at Clemson University and spends his spare time looking into continuum robot design and application paradigms along with novel uses of embedded systems.*

***Ian D. Walker** received the B.Sc. Degree in Mathematics from the University of Hull, England, in 1983 and the M.S. and Ph.D. Degrees in Electrical and Computer Engineering from the University of Texas at Austin in 1985 and 1989, respectively. He is currently a Professor in the Department of Electrical and Computer Engineering at Clemson University. Professor Walker's research centers on robotics, particularly novel manipulators and manipulation. His group conducts basic research in the construction, modeling, and application of biologically inspired "trunk, tentacle, and worm" robots.*