Grappler: Array of Bistable Elements For Pinching Net-Like Infrastructure to Low Gravity Bodies

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Near-Earth asteroids and comets are ubiquitous and are key destinations for studying the formation of our solar system. These bodies may also one day serve as resource restocking depots for longer duration missions. However, in-situ scientific analysis requires the development of microgravity-tolerant landers that are not subject to recoil on impact. Whereas prior art focuses primarily on anchoring and hopping mechanisms, this paper evaluates a novel mission architecture in which chains of bistable pinching elements called grapplers are used to land net-like infrastructure on low gravity bodies. Unlike single-point-of-contact landers, a net that is successfully adhered to an asteroid may serve broad and flexible use in the exploration of small bodies. For example, it may constitute infrastructure to enable locomotion of a swarm of distributed crawling sensors and actuators for high resolution study of the body's interior structure and surface properties. It may also serve as a foundation onto which larger scale sensing and communication structures can be built over time. Finally, it may serve as a series of hand holds used by astronauts to maneuver around the body. To adhere the net to a body, microgravity flight testing of a representative Grappler prototype demonstrates the tolerance of a bistable chain to variable impact conditions and terrain contours owing to the inherent adaptivity of the chain's pinching configuration- for a chain of n bistable elements, 2^n pinching configurations are possible. These pinching elements can be integrated sparsely or densely into net-like infrastructure. A computational model is also presented. Grapplers are compared to alternative net adhesion strategies ranging from passive wrapping to chemical rigidization.

I. Introduction

Asteroids and comets hold important clues regarding the origin of our solar system, as they are thought to carry chemical signatures from the epoch of planetary formation 4.6 billion years ago [1]. They also contain traces of the organic matter that may have seeded life on Earth, as well as valuable resources that can be useful for future production of water, fuel, and building materials. Small bodies are thus targets for both robotic and human exploration. However, our knowledge of the surface and substructure of these bodies remains limited; properties like surface strength, local topography, mass, and albedo require proximity operation for accurate characterization, and are known to vary widely - asteroid surfaces may range from loose regolith to rubble piles [1].

Despite challenges in predicting terrain remotely, suitable landers must be developed for analyses that require in situ probes. However, due to the weak gravitational field of low-mass bodies, any sort of landing system is at risk of rebounding off the surface. The landing process is thus one of the points of greatest risk to a mission's success. Historically, probes combat low gravity effects using an anchoring system, which may suffice for certain studies but inherently prohibits mobility. Alternatively, probes may rely on hopping mechanisms expressly designed for locomotion

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in low gravity environments, though precision positioning and control is inherently limited. Further, while today's missions are designed principally with scientific goals in mind, it may also one day be of considerable value to build large-scale infrastructure on low gravity bodies, and landers ought to be designed with such applications in mind as well.

II. Proposed Concept

To address both scientific and engineering objectives, alternative landing strategies can be studied. For example, in contrast to traditional single-point-of-contact landers, we propose using a tether or net to grapple to a near-Earth asteroid (see Figure 1). The net can be treated as foundational infrastructure onto which more complex systems are developed. For instance:

- The net can be used to enable locomotion of a swarm of distributed, reconfigurable sensor nodes for high resolution study of the body's interior structure and surface properties;
- The net can serve as a structural foundation for building solar panel arrays, fuel outposts, rest stops, large mirrors, or more imaginative structures on asteroids;
- The net may serve as a series of handholds used by astronauts to maneuver around the low gravity body.

In this way, a net-based lander can support both scientific and engineering goals.

There are various strategies that can be used to cinch a net to a low gravity body. This paper presents a potential class of solutions for mechanically adhering a net-like structure to a target object. A net is equipped with a series of bistable pinching elements called Grapplers which can grip to variable terrain contours and, importantly, can tolerate variable impact conditions. Each Grappler consists of one or multiple bistable elements. As the net drifts towards the asteroid, some bistable elements will actuate, one by one, when they come in contact with concave surface features, thereby cinching the net to the asteroid. The integration of pinching arrays into the net increases the net's adhesion strength and help to prevent recoil of the system. These pinchers may be sparsely or densely incorporated. End effectors with spikes may also dig into the surface in the case that there is a soft regolith layer. Finally the entire asteroid, or a large area of it, is covered by the net. A high level concept of operations is shown in Figure 1 and an example of the integration of a single bistable element into a net is shown in Figure 2.

Following initial mechanical adhesion to an asteroid, secondary fastening mechanisms can be actuated for permanently fixing the next, including ultraviolet curing resins for rigidization, electrically actuated polymers for tightening the net's grip, and web-weaving spider bots to expand the net's coverage over time. Crawling nodes can now transport sensors, actuators, and infrastructure to desirable locations.

The goal of this paper is to explore the use of bistable pinching elements (Grapplers) for gripping nets to bodies through the development of two prototypes that are tested in a microgravity environment. We seek to demonstrate primarily through experimental testing that multi-element Grapplers are able to tolerate variable impact conditions while successfully still cinching to a target because the set of actuated pinching elements can vary appropriately. Simulations in Section IV also provide a theoretical basis for the grappling mechanism.

For further consideration of mission architecture with a focus on net-crawling robots for distributed sensing applications, see our previous report[2].

III. Related Work

A. Comparison to Previous Landing Technology

Anchors and hoppers are most commonly considered for landing and moving on low gravity bodies. For instance, the European Space Agency's 2014 Rosetta mission relied on a harpoon to anchor its Philae lander. This type of anchoring mechanism enables probes to drill into the terrain at the expense of mobility. Philae was deployed ballistically from the Rosetta launcher and used an internal flywheel for stabilization during descent. While contact with Philae was established, its harpoon anchor failed to fire, which added risk to the mission's success and ultimately prohibited any sort of subterranean drilling [3].

Likewise, robotic hoppers have a long history, beginning with the Soviet Phobos missions in the 1980's which failed due to computer malfunction [4]. More recently, in late 2018 the Hayabusa2 mission deployed a series of hoppers on asteroid Ryogu. Two tiny, solar-powered lander (MINVERVA-II1A and MINERVA-II1B) were deployed first, followed by a battery powered MASCOT lander. All three landers successfully maneuvered across the asteroid, though scientific

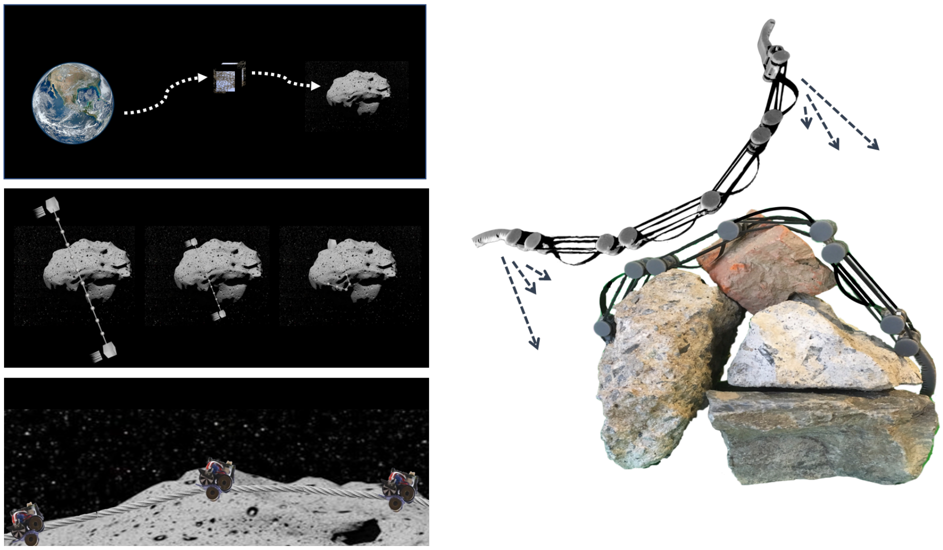

Fig. 1 Left: concept of operations for net-like lander. Structure is stowed in small satellite, launched at body of interest, and once adhering to structure can serve as foundational infrastructure for e.g. crawling robots. Right: Concept of operations for Grapplers: arrays of bistable pinching elements scattered sparsely or densely around the net are able to pinch to local features in the terrain.

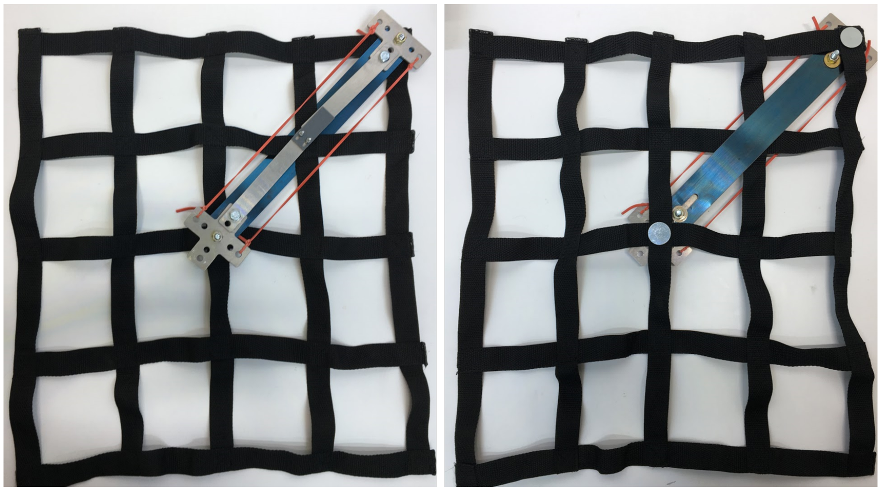

Fig. 2 Single grappler element incorporated in net. Left: Top view. Right: Bottom View. Pinching elements can be incorporated at any scale, including materials-level. They can be sparsely or densely distributed.

results are yet to be published. Various additional proposals exist for asteroid and comet rovers that hop and tumble, including Stanford's Hedgehog project in which three flywheels are used to control the lander's motion across a low gravity body [5].

Finally, some alternative landing approaches have recently been considered. For instance, a project at NASA JPL imagines using microspine grippers for robotic maneuvering, in which hundreds to thousands of sharp hooks integrated into a robotic foot latch onto small asperities on the surface of a rock [6]. A project at University of Colorado, Boulder explores large surface area soft robots that conform to surface structures and slither across asteroid surfaces, benefiting from large contact area for adhesion strength [7].

B. Mechanically Functional Materials

In robotic applications, control and actuation are typically considered as separate elements. However, as was discussed by McGeer [8], smart mechanical arrangements can create systems where the control is embedded in the actuation mechanism. This was demonstrated by example of the passive dynamic walker [8]. Searching for a similarly embedded solution for grappling to rocks, spring loaded camming devices (also known as friends or cams) provide a reference point for Earth-based applications [9]. These devices are used by climbers to scale non-secured walls. The camming devices are designed such that, if the climber should fall, the falling force is translated into proportionally stronger grip against the rock. Asteroid microspine gripping studied at JPL is an analog to this approach for microgravity environments [6].

Mechanisms where the control and actuation are equivalent can also be designed on a material level. Research has shown that the behavior of cellular solids can be programmed, allowing engineers to design materials with variable Poisson's ratio [10], tunable stress/strain curves [11], or even selective shape change under stress [12]. Ion et al. have demonstrated that by smartly combining such properties, fully functional mechanical devices can be designed out of a single material [13]. Furthermore, by adding bistable, springloaded cells, such mechanical devices can self actuate [14], as an impulse propagates changes in the bistable state of the cells through the material. We expand upon this body of work by exploring how a mesh or fabric constructed of such self actuated, functional materials might be used to grapple on to an asteroid. However, our current prototypes are on a macro-scale, compared to the work discussed in this section.

C. Use of Meshes, Nets, and Textiles for Aerospace Applications

Nets and meshes are familiar form factors to the aerospace community- they have been proposed and recently tested as a method for capturing hazardous debris in Low Earth Orbit [15] and they have been considered in various studies as infrastructure for deploying tethered arrays on orbit, included distributed antenna arrays and interferometers [16]. Meanwhile, there is substantial focus on developing deployable textile-based aeropsace structures with high packing efficiency.

However, nets have yet to be proposed as foundational infrastructure on low gravity bodies, which is a motivation for this study. More broadly speaking, textile structures have a multitude of applications in space missions ranging from solar sails to inflatables to protective outer layers for habitats and spacesuits. The materials are optimized for packing ratio, achievable surface area, controllability, and tolerance to the harsh space environment. One key challenge, however, relates to deployment strategy.

There exist detailed studies on the unfurling and launching of simple nets in low gravity environments (see e.g. [17, 18]) including two counts of in-space testing. However, the deployment of a net with integrated gripping mechanisms would eventually require further refinement of deployment models found in the literature.

When considered as a low-gravity foundational infrastructure, mesh landers are loosely inspired by the use of *geotextiles* on Earth - large-scale permeable fabrics woven into the ground to strengthen soil, armor sand dunes, or allow planting on steep slopes. They are integrated into the soil or root systems of vegetation in a textile-and-Earth combination, preserving existing fragile landforms and creating entirely new landscapes. It is now common practice for civil engineers to include geotextiles in city design, and the scale of these functional textiles is often enormous [19]. While geotextiles are designed with Earth's gravity-driven environmental effects in mind, the general principle of facilitating surface development using a textile-based structural support layer remains provocative.

The net itself can act as more than just the mechanical substrate of an asteroid landing system. Connecting lines might themselves sense the strain and deformation they are subject to [20] as might bistable grappling nodes [21]. At large scales this would require either distributed control for high resolution sensing [22] or interpolation of more sparse sensor data [23].

The present work applies the idea of self-actuating materials to large-scale net-like structures to study adhesion.

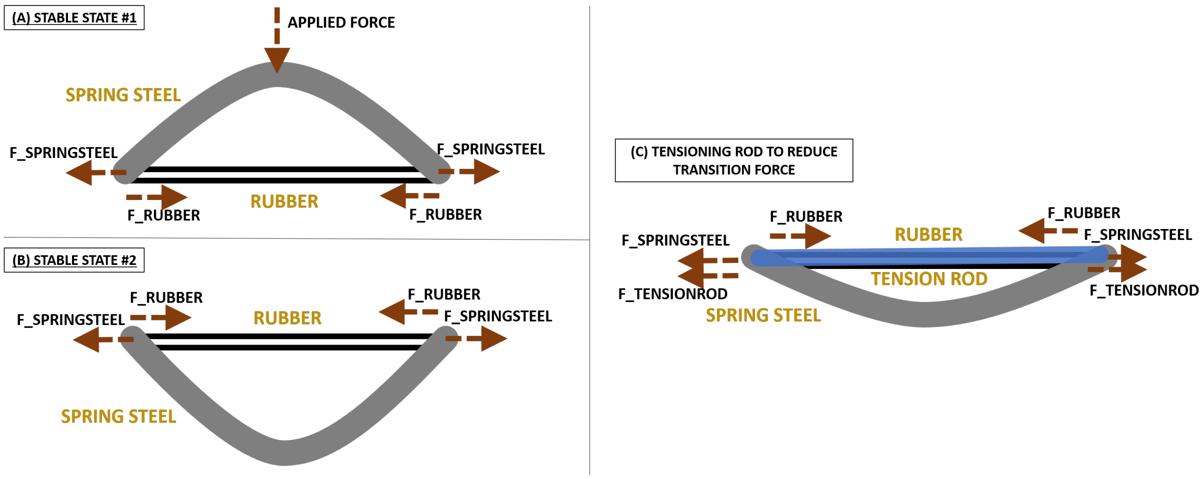

Fig. 3 (a) Simple diagram for bistable mechanism in stable state with direction of applied force indicated (b) simple diagram for second stable state after force is applied (c) tensioning rod holds the mechanism close to its transition point to reduce force required to transition the system between stable states

IV. Mechanism

A. Overview

Here we describe the conceptual, mathematical and physical principles leveraged in the design of Grapplers. The grappling mechanisms works as shown in Figure 3. It consists of a spring with two symmetric stable states.

Bistable mechanisms like this are familiar to many in the context of consumer snap bracelets or Venus flytraps. In this case the two stable states are symmetric. However, a tensioning rod is used to hold the structure very close to its transition point. In this configuration, a small impact force from an asteroid surface feature triggers a state transition in the system and allows the grappler to cinch itself onto a structure.

B. Mathematical Treatment: Toy Model

Most compliant bistable mechanism configurations achieve their bistability through the snap through behavior of buckled beams. In such mechanisms, the flexible segment undergoes combined compression and bending loads during state transition. The Euler-Bernouilli equation models the relationship between an applied force and a beam's deflection and is given as:

$$\frac{d^2}{dx^2}(EI\frac{d^2w}{dx^2}) = q \tag{1}$$

where E is the elastic modulus, I is the second moment of inertia perpendicular to the applied load, q is force per unit length, and z(x) is the deflection in the z direction at position x along the beam's length. The spring steel used in Grappler behaves as a buckled beam.

More simply, the following bistable switch toy model is developed using Simulink and supporting libraries [24, 25]. A pair of two rigid beams of length L are connected on one end by a revolute joint with spring constant k_1 and at the other end by a linear spring with spring constant k_2. A rotational hard stop applied to the revolute joint is used to simulate the rigid tensioning rod. When a force F_a is applied to the revolute joint along the y axis, the spring will experience an extension force equal to $F_a\cos(\theta)$.

The spring has initial length x_0. The tensioning rod extends the initial length of the spring to $x_0 + \Delta x_1$. Impact with a surface applies an impulse to the beam pair equal to $\int F dt$. The energy applied to the spring is then equal to:

$$E_a = \frac{\int F_a \cos(\theta) dt}{2m} = 1/2k(\Delta x_2)^2 \tag{2}$$

If $x_0 + \Delta x_1 + \Delta x_2 > 2L$, the restorative spring force will pull the bistable mechanism to its second equilibrium state.

Meanwhile, the y component of the impulse will cause a recoil acceleration of the system equal to $\frac{F_a \sin(\theta)}{m}$. The gripper end effector length sets a limit on how far from the target object the system can travel due to recoil while still gripping successfully.

The tensioning rod serves two roles - it reduces the total activation energy required to flip a bistable element to its second equilibrium point, and it reduces the initial value of θ such that a greater percentage of the impact force is dedicated to extending the spring ($F_a \cos\theta$) rather than accelerating the object away from the body ($F_a \sin\theta$).

The target object is modeled as a sphere and is connected to the model using a planar joint which allows for one rotational and two translational degrees of freedom. Contact forces between the Grappler and target object are modeled using a linear force law with contact stiffness and contact damping configured, as well as a stick-slip continuous friction law with coefficients of kinetic friction and static friction configured. Rigid end effectors - rigid wings with greater friction coefficients - are applied in certain simulations to each end of the bistable joint. Representative simulations for failed and successful grapples for a single element Grappler are shown in Figure 4 (in which rigid end effectors are omitted), and Figure 5 (in which rigid end effectors are incorporated).

The model is then extended to a three-element Grappler with end effectors interfaced using weld joints. A grappling example for a preliminary model is shown in Figure 6, in which the impact is off center. In the pictured grapple example, all 3 joints are actuated in the impact. These models support the notion that pinchers can adhere to representative spherical targets. A natural extension to the presented modeling work is to study variable terrain contours and geometries, which will necessitate complex friction models.

C. Extension to Large n

While models and prototypes are developed for n=1 and n=3 cases, the number of pinching nodes dictates the structure's configuration space. A generalized grappler with n pinching nodes will have 2^n configurations and may more closely adhere the net to the target's terrain contours. Node size and spacing must be considered as well - stars, grids, and other alternative configurations may prove effective.

V. Prototype Manufacturing

Two prototype Grapplers were fabricated which explore different aspects of a proposed mesh landing system and are physical realizations of the models described in the previous section. The first prototype is a 3-node Grappler and was designed to explore how multiple pinching nodes might help conform to surface structures and tolerate variable impact conditions. The second prototype is a single node Grappler and is used as a point of reference. It also demonstrates a simple proof of concept of a collision-position and state sensing spring. These prototypes are depicted in Figure 7.

Nodes in both prototypes are fabricated using spring steel and rubber. Rubber bands are used to create a spring force, and end effector wings are fabricated using laser cut sheet metal and 3D printed flexible spikes. The tensioning rod is fabricated using laser cut acrylic. In the 3-node Grappler, mating joints between neighboring nodes are 3D printed in plastic.

The single node Grappler is mechanically simpler, as it only has one bistable node. However the bistable spring is instrumented so as to sense if and where a collision occurred, as well as sensing its own bending state.

A layer of piezoresistive fabric (by Eeonyx, non-woven, 20kOhm per square) was placed between two layers of spring steel. When bent, the force exerted on the fabric increases which can be used to infer bending angle. In addition, seven pressure sensitive switches were constructed from thinner spring steel and mounted along the bistable element. When touching an object these switches are compressed. Pressure sensitivity is created by a sheet of velostat between the switches and the main spring. Velostat was chosen for its high sensitivity, the Eeonyx fabric was chosen for its higher dynamic range. All sensors were sampled using the Teensy3.6 prototyping platform.

VI. Evaluation in Microgravity Environment

A. Experimental Setup

For evaluation of the prototype in microgravity conditions, a representative target object is fabricated out of milled polystyrene foam core coated in a thin layer of mortar and topped with SIKA Corporation 187782 Concentrate Bond Adhesive to minimize flaking. Two contours were manufactured - one in the shape of a near Earth asteroid Apophis 99942 and one in a neutral, symmetric cubic shape with rough topological features. The target object is mounted to an 80/20 frame.

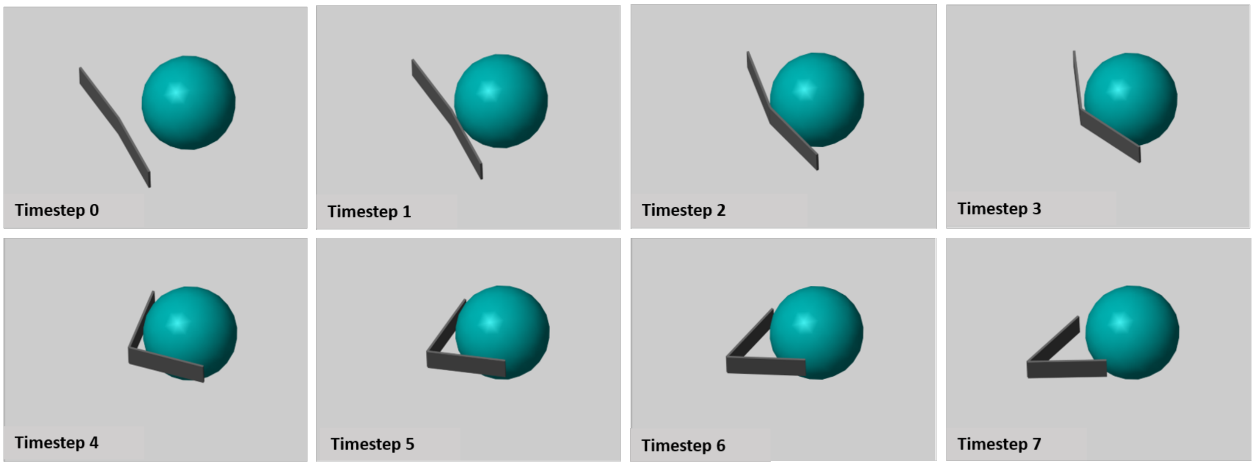

Fig. 4 One pinching element, no end effectors (failed grip)

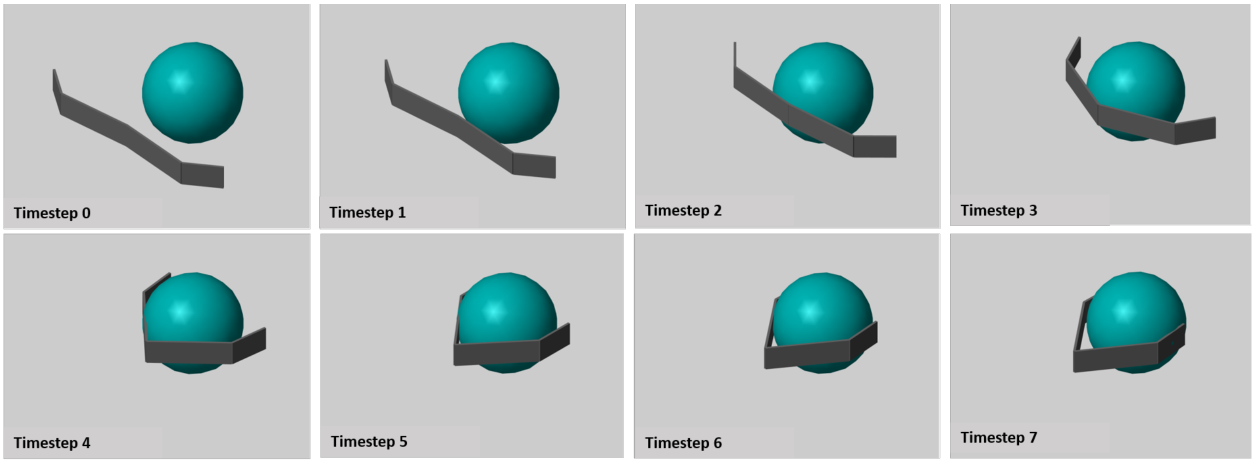

Fig. 5 One pinching element, end effectors (successful grip)

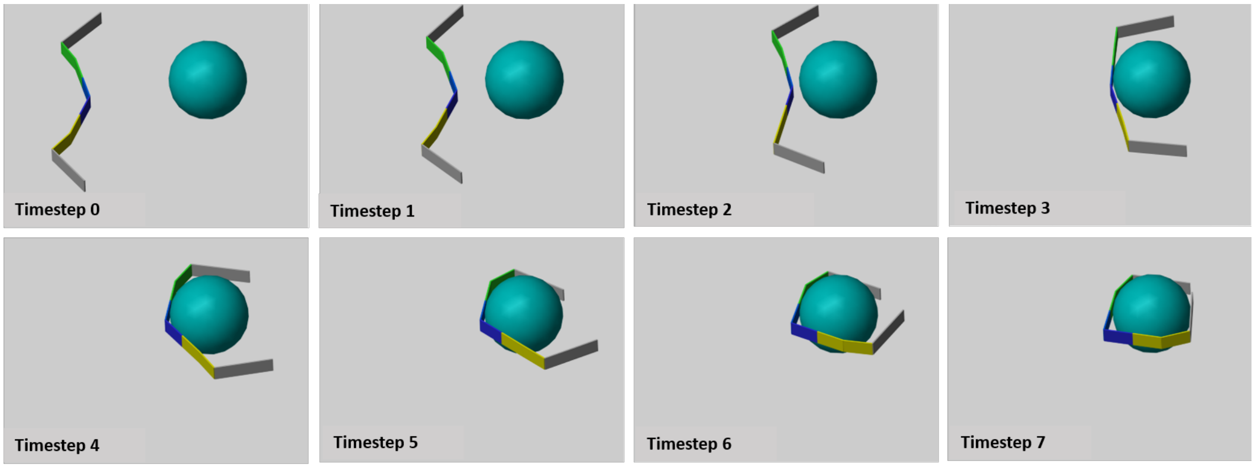

Fig. 6 Three pinching elements, end effectors (note that an asymmetric impact point causes grappler element responses that are asymmetric in time)

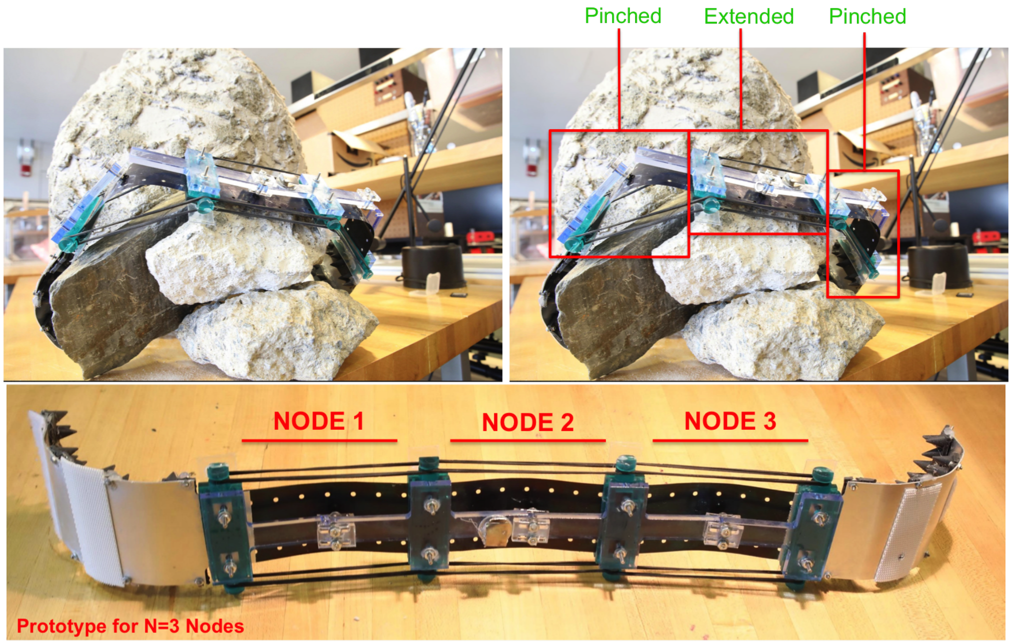

Fig. 7 The 3-node Grappler with n=3 bistable elements and curved end effectors

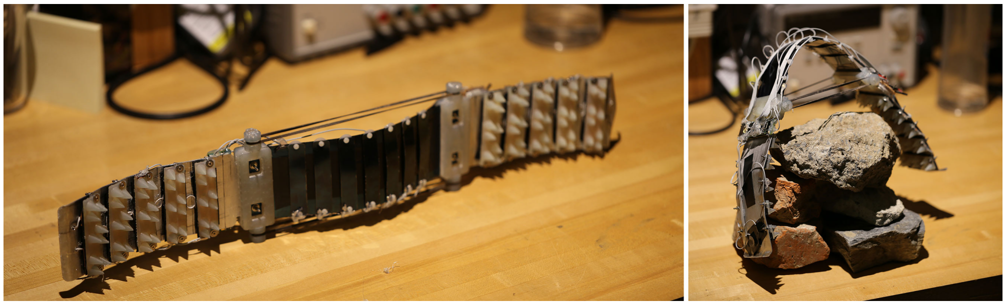

Fig. 8 Single node Grappler with a n=1 bistable elements and flat end effectors

Fig. 9 Preparing to manually launch sample (left). Successful grapple moments after manual launch (right).

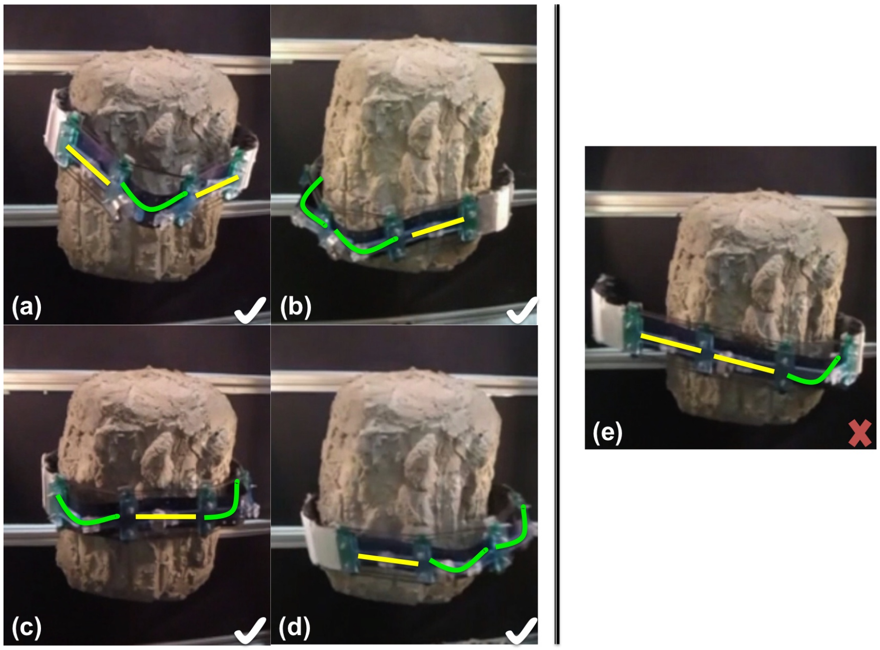

Fig. 10 Results from five grappling trials conductive in micro-gravity conditions. Green overlay is used to indicate pinched nodes, and yellow overlay is used to demarcate flat notes. (a)-(d) constitute successful grappling configurations whereas (e) constitutes failed grappling

Microgravity conditions are induced for ~20 second time periods on board an airplane flying parabolic arcs. During these periods, Grapplers are manually launched at the target object to induce variable impact conditions for each trial. Experimental procedure is depicted in Figure 9. Several GoPro Hero Session cameras are used to film the experiment. Seven trials using a 3-element bistable chain are completed, and for comparison, 8 trials using a 1-element bistable sample are completed.

B. Results

1. Flight Video Annotated With Sensor Data

A video compilation of trials (including sensor data overlay) is available at [26]. The sensor data associated with Grappler A was primarily used as a method for annotating this video to better communicate the mechanism at work to broad audiences, as shown in 11.

2. Analysis of Grappler Prototype Pinching Configurations

In this section, the notation (XXX) is used to describe pinched states for the 3-node Grappler, where 1 corresponds to pinched, and 0 corresponds to extended. A 3-node Grappler has seven possible pinching configurations when its initial state (000) is omitted. During only seven experimental trials, the Grappler snaps from its initial (000) configuration to five out of seven possible pinched states, demonstrating the sensitivity of the pinched configuration to the nature of impact. These results are summarized in Table VI.B.2 and the achieved pinching configurations are pictured in Figure 10. Successful trials are biased towards configurations in which two nodes out of three are pinched, which is a function of the size and radius of curvature of the target object as compared to the pinching element sizes.

Of the remaining two configurations that were not seen during microgravity testing, one constitutes the chain's fully pinched condition ((111), too tight a pinching radius for this target object), and one constitutes the state (100), symmetric to (e) in Figure 10 and an unviable grappling configuration. Further, the Grappler successfully grips to the target object during 6 out of 7 trials, failing only in configuration (001) depicted in Figure 10e.

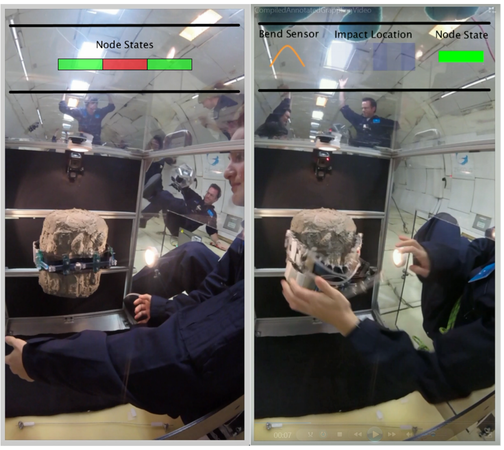

Fig. 11 Excerpts from video with data overlay. Pinching state is overlaid for the 3-node Grappler. Bend, pressure, and pinching state are overlaid for the 1-node Grappler.

Table 1 Pinching Configurations Recorded For 3-Element Bistable Chain Under Microgravity Conditions

Pinching Configuration	Count	Grapple?
(001)	1	N
(010)	1	Y
(011)	1	Y
(100)	0	N/A
(101)	2	Y
(110)	2	Y
(111)	0	N/A

For comparison, the single node Grappler successfully grapples only 2 out of 8 times. This may be due to a confounding factor - the radius of curvature of the end effectors in this design was reduced, which may have affected the sample's ability to grapple relative to its 3-element counterpart. However, a contributing factor to this discrepancy may also be the reduced configuration space of a single bistable element as compared to a 3-element Grappler. Because the 3-element Grappler has these additional degrees of freedom, its cinched state more closely follows the contour of the target object.

Bistable grippers operate reasonably under normal gravity conditions as well, but are particularly well suited to microgravity conditions since there is no gravitational force to operating counter to the pinching strength of the nodes.

C. Comparison Between Flight Sensor Data and Model For One Node Grappler

Figure 12 shows a juxtaposition of simulated and experimental data for one trial using a single node Grappler, as well as bend sensor data captured during experimental testing. Qualitatively, the behavior is similar in each case - the bistable element recoils off the target object but the end effectors grip with enough speed and force to secure the Grappler in place. Bend sensor data suggests some oscillatory behavior during the transition which cannot be explained from model or visual data, but may suggest some amount of flexing during impact. Pressure sensor data was deemed either erroneous or noisy for formal analysis but is included as a video overlay.

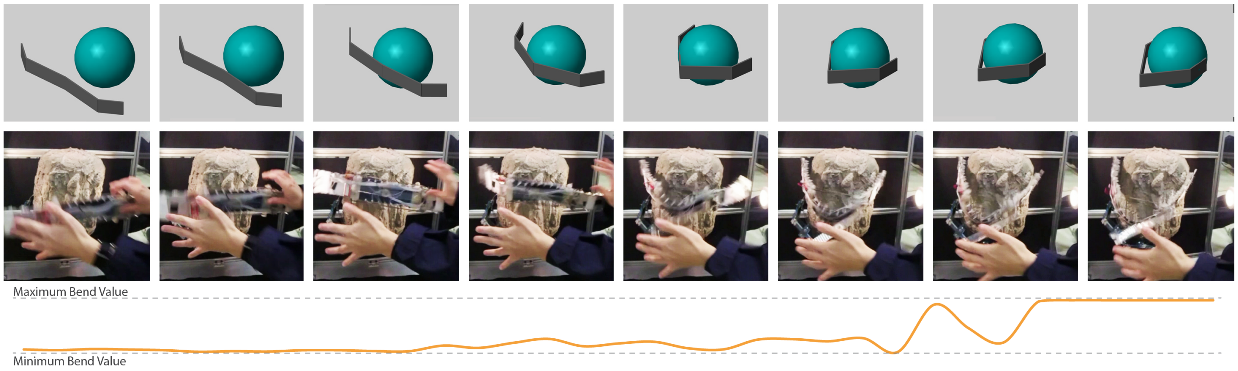

Fig. 12 Comparison of modeled grapple, experimental grapple, and bend-sensor data

VII. Conclusion and Future Work: Deep Integration of Bistable Elements Into Net

A. Summary

We have shown experimental evidence that multi-element Grapplers are robust to variable impact conditions and terrain contours when used for adhering to a low gravity body. Grapplers are a candidate method for adhering a net to a low gravity body. We have also shown computational models for single element and three element Grappers that can adhere to simple targets. This work lays a foundation for future consideration of bistable pinching elements as a method for landing foundational net-like infrastructure on a low gravity body. To conclude, we summarize benefits of net-like landers as compared to hoppers, anchors, and soft robots -

1) **Large Surface Area**: As compared to anchors and hoppers, the initial landing process benefits from the grappling and adhesion afforded by a single large net, or a suite of many small nets. In contrast, we know that single point-of-contact anchors used in prior low-gravity lander missions are susceptible to failure due to rebounding risk.
2) **Finely Controlled Locomotion** It is difficult to deduce ahead of time which regions will prove most worthy of further study. Control algorithms for rope-crawling bots will be inherently more reliable than ballistic hopper control algorithms, particularly in erratic and unpredictable terrain. For instance, if a crater is found to have exposed useful subterranean data, a collection of spectrometer nodes may congregate in the area and carefully scan the wall of a crater at centimeter-scale precision or better.
3) **Net Polymer Can Be Functional**: As an example, the membrane itself can act as a power routing, collecting, or sensing element [20] from e.g. a flexible solar panel hub embedded on the net.
4) **Infrastructure for Longterm Use**: In the longer term, more elaborate infrastructure (solar arrays, deep space interferometers, fuel depots) can be built on an asteroid using the net as a foundation. Further, it may be possible for the crawlers to weave additional polymer into the net in order to grow the size and functionality of the structure over time.
5) **Grappling to Variable Terrain**: A chain of bistable elements provides additional gripping force relative to a simple net structure, while tolerating variable terrain and variable impact conditions.

B. Extensions to Mechanism

In future prototypes, the bistable spring can also be used to sense its own state. To achieve this the spring can be coated with a piezoresistive layer. When in a stable state, the 'outside' convex side expands relative to the 'inside' concave side of the spring. This leads to a differential in resistance which can be used to measure the springs state. The voltage measured between these two variable resistances corresponds monotonically to the degree that the spring is bent - the artificial resting position close to the transition point therefore has a known voltage. Grappling success can be inferred from spring state, with a successful grapple indicated by the spring coming to rest before it reaches resting state 2 (see Figure 13).

Tristable [27] or multi-stable [28] nodes may be capable of conforming more precisely to both concavities and convexities in terrain, and is also worthy of exploration.

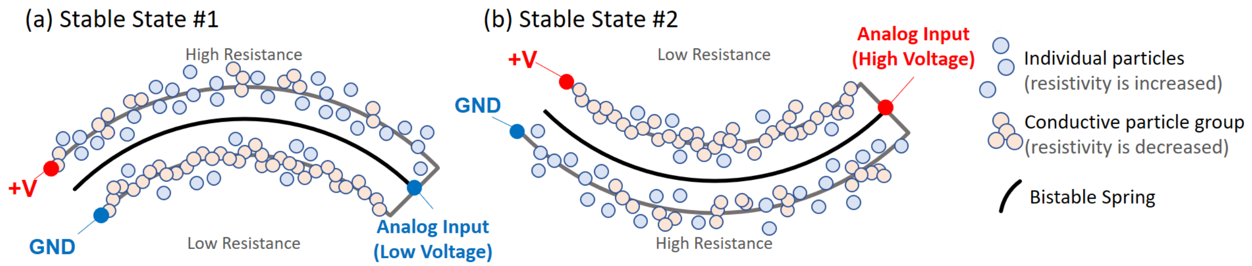

Fig. 13 Simplified model of spring coated with piezoresistive material. The resistivity of the top and bottom of the spring changes based on its state.

Actuating elements may one day be integrated at microscale, in which case the bistable pinching becomes a property of a new, fibrous MEMS structure with the capacity to both conform and grip to surfaces.

VIII. Acknowledgements

We wish to thank the MIT Media Lab Space Exploration Initiative for the opportunity to test the Grappler project under microgravity conditions. This work was supported by the European Research Council, grant no. 648785. Thank you to MIT undergraduate student Veronica C. LaBelle for preparing the prototype in which a grappler is incorporated into a net (Figure 2).

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