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Design and Analysis of a Robust, Low-cost, Highly Articulated Manipulator Enabled by Jamming of Granular Media

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***Abstract*—Hyper-redundant manipulators can be fragile, expensive, and limited in their flexibility due to the distributed and bulky actuators that are typically used to achieve the precision and degrees of freedom (DOFs) required. Here, a manipulator is proposed that is robust, high-force, low-cost, and highly articulated without employing traditional actuators mounted at the manipulator joints. Rather, local tunable stiffness is coupled with off-board spooler motors and tension cables to achieve complex manipulator configurations. Tunable stiffness is achieved by reversible jamming of granular media, which—by applying a vacuum to enclosed grains—causes the grains to transition between solid-like states and liquid-like ones. Experimental studies were conducted to identify grains with high strength-to-weight performance. A prototype of the manipulator is presented with performance analysis, with emphasis on speed, strength, and articulation. This novel design for a manipulator—and use of jamming for robotic applications in general—could greatly benefit applications such as human-safe robotics and systems in which robots need to exhibit high flexibility to conform to their environments.**

I. Introduction

JAMMING—the mechanism by which granular media can reversibly transition between fluid-like and solid-like states [1]—has recently been demonstrated as a variable stiffness mechanism in robotic and industrial applications. Researchers have explored jamming as a means to create easily customizable architectural structures [2], provide variable force feedback in haptic interfaces [3], create a highly deformable mobile robot [4][5], to develop a universal gripper that can passively conform to and grasp a wide range of objects [6], and to create a variable stiffness endoscopic tube [7]. The combination of these projects highlights the primary benefits of utilizing jamming for robotics: it allows robots to be more human-safe, inexpensive, and robust compared to most technologies that have traditionally been used for such applications.

The goal of this paper is to further the use and understanding of jamming for engineering applications. Specifically, we present the design and analysis of a robotic manipulator composed of 1) serial modules that can transition between rigid and flexible states via jamming and 2) tension cables running along the length of the manipulator and whose lengths are controlled by spooler motors. We previously demonstrated this robotic architecture of coupling locally tunable stiffness with global actuation as a thrust toward soft robotics [8][9]. One of the main benefits of this type of system is that by eliminating the need for distributed—and often rigid and bulky—actuators throughout the robot, the system can be more robust and flexible, enabling it to conform to its environment better. In addition, the cost of the robot can be drastically reduced.

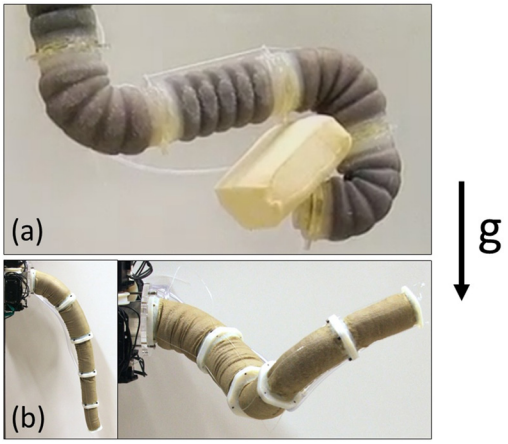


Fig. 1 (a) First prototype of jammable manipulator. (b) Second prototype of jammable manipulator: (left) in the unjammed state, and (right) jammed in a corkscrew configuration.

In this paper we also begin to explore how grain properties affect the performance of jammed systems. Specifically, we seek to maximize the strength-to-weight ratio of jammed systems. This is an important figure of merit for manipulators, where the robot must be able to support its own weight in addition to any payloads.

Because granular systems inherently lack mechanical structure in their unjammed states, their flexibility and high DOFs can be beneficial for hyper-redundant robotic systems such as a manipulator. Most approaches in hyper-redundant robotics have involved employing distributed and rigid pneumatic or electromagnetic actuators. Much of the effort in this area has been in developing snake robots, as they often require many controlled DOFs [10]. While these traditional snake robots have impressive capabilities and are useful in many applications such as search-and-rescue, they can be complex, fragile, and expensive. Often, these types of robots employ one traditional actuator, such as motor, per degree of freedom.

A class of hyper-redundant manipulators that seeks to maximize mechanical compliance is hydrostatic robotics, which often utilize hydraulics and pneumatics for actuation [11][12][13]. These types of robots are typically designed to mimic biological systems, as many applications can greatly

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benefit from robots that have the strength and dexterity of natural structures such as tongues, tentacles, and trunks [14]. Such systems are impressive, though they are not typically capable of both passively conforming to their environments and maintaining complex configurations.

Cable-driven systems can be controlled by traditional actuators such as motors, while also being highly dexterous [15]. These manipulator-type systems are often found in (but not limited to) surgical devices, which typically are too small to include on-board actuators [16] [17]. While many cable-driven robots are capable of being highly articulated, many of them lack the ability to lock arbitrary segments in place, thus complicating the control of the robot.

In this paper we describe a manipulator, shown in Fig. 1, with serial jammable segments composed of thin flexible membranes containing granular material. Jamming was achieved by applying a vacuum on the segments to create a differential jamming pressure. This approach enables manipulators that can be robust, low-cost, and highly articulated.

II. Granular Material Selection for Robotics

A. Background

Jamming is a useful variable stiffness mechanism for robotic applications due to its simplicity and combination of a relatively fast activation time (on the order of milliseconds) and the capability of transitioning between compliant states and rigid, load-bearing ones. Our goal is to understand how grain properties affect jamming, so that they can be optimized to fulfill a particular application's functional requirements.

The effective phase transition that occurs in jammed systems is analogous to what is observed in microscopic systems with attractive particle interactions [1][18][19]. Jamming, or when the effective solid phase is achieved, can occur only when the density of particles exceeds a threshold. As seen in many materials at the microscopic scale, systems can become unjammed, or achieve the effective liquid phase, when the temperature is raised (e.g., when the system is under vibration) to a critical value or when the material is sheared enough to cause the particles to move relative to each other. While significant work has been done in the physics community to understand how different grain parameters, such as shape and size distribution [20][21][22][23], affect the jamming transition, researchers have only recently begun to study jamming for robotic applications[4][6]. To transition between loose, flowing grains and rigid, interlocked ones presents an interesting problem. Because interparticle friction is primarily based on constant, physical grain parameters, grains that exhibit relatively low interparticle friction should flow well in the unjammed state and should also form a weaker solid in the jammed state than particles with higher interparticle friction, and vice versa.

For the manipulator application presented here, we identified and compared several materials.

B. Experimental Background

Compression tests were conducted on several lightweight granular materials that were hypothesized to exhibit high strength in the jammed state but still able to flow easily in the unjammed state. Grain characteristics of interest included: high porosity, large size distribution, and large shape distribution. The latter two are known to increase the density and interlocking ability of grains, thus increasing the overall strength of the jammed system. The materials tested were 1) coarsely ground coffee, 2) finely ground coffee, 3) sawdust, 4) diatomaceous earth, and 5) hollow glass spheres (10–50 microns diameter). Solid glass spheres (100–200 microns diameter) were also included as a comparison, as they are frequently used as a benchmark shape for granular studies. Microscopic images of each of these materials are shown in Fig. 2.

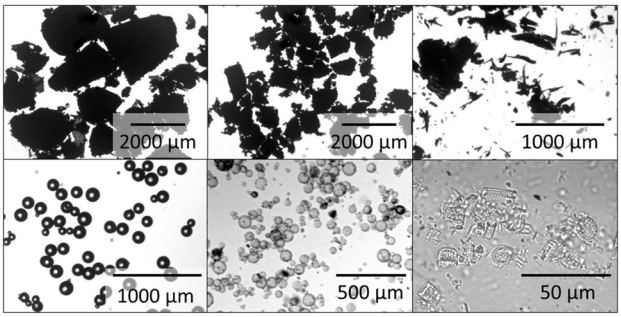


Fig. 2 Microscope images of the grains tested. Top row, left to right: coarsely ground coffee, finely ground coffee, sawdust; bottom row, left to right: solid glass spheres, hollow glass spheres, and diatomaceous earth.

Cylindrical test samples, with a diameter and height of 50 mm and 100 mm, respectively, were constructed by loosely packing grains into a thin (approximately 100 microns thick) latex membrane. Loose packing was achieved by dispensing the grains through a funnel and moving the funnel in a circular motion to achieve uniform piling. During this process, sample dimensions were controlled by applying vacuum pressure between the latex membrane and an outer rigid tube to maintain the cylindrical shape. Upon applying a vacuum to the inside of the membrane to jam the grains, the sawdust and diatomaceous earth samples tended to compact significantly, so exceptions were made for these materials in terms of initial packing density to ensure uniform sample dimensions. For all the compression tests, the differential jamming pressure was 75 kPa.

C. Experimental Results and Discussion

Fig. 3 presents representative stress vs. strain curves, and Table 1 includes density and effective compression modulus data for each of the materials tested. Note that the density values are for the materials prior to each test with an applied 75 kPa differential jamming pressure. Analysis of the stress-strain curves provides valuable insight about the materials that is not necessarily captured in individual parameters such as a material's compression modulus or yield stress. For example, while the solid glass beads have the largest effective modulus, their yield stress is barely one fourth of that of the coarsely ground coffee, which had a relatively

large effective modulus, making the latter a potentially better option for many applications.

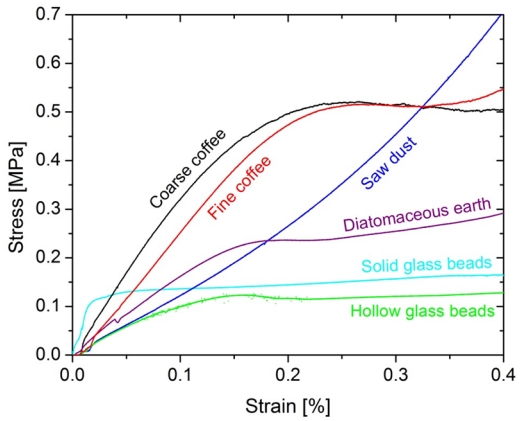


Fig. 3 Compressive stress vs. strain data for the grains tested.

Table 1. Density and Effective Compression Modulus of Grains

Grain material	Jammed density [kg/m^3]	Effective compression modulus/Density [kN-m/kg]
Hollow glass beads	83	12.8
Coarse coffee	445	6.8
Solid glass beads	1445	5.9
Fine coffee	505	5.4
Sawdust	400	4.2
Diatomaceous earth	485	3.1

The convex shape of the stress-strain curves for sawdust is typical of that of certain materials such as a flexible foam, which locally collapses before densifying to become a solid mass. This suggests that materials like sawdust can be very soft if not packed densely, which would also eliminate the porous (low density) characteristic of the sawdust that made it a desirable candidate to begin with. Sawdust from other types of wood could possibly yield more favorable results. Even though ground coffee is a porous and organic material like sawdust, it exhibited more of a typical material response—which includes an effective elastic regime followed by a plateau regmine—under compression, suggesting that the particles are much stiffer than those of sawdust, allowing the ground coffee to maintain its porosity under load.

Of the materials tested, ground coffee produced the most favorable combination of having a high strength-to-weight ratio in addition to large absolute strength. Hypotheses for why coffee performs so well include that the ground coffee has both significant surface roughness and irregular, jagged features that increase interparticle friction. At the same time, releasing the vacuum pressure causes ground coffee to unjam relatively easily and flow well compared to many materials that have been tested qualitatively. Future work involves quantifying and understanding how grain properties affect both the strength of a jammed system and the ease at which grains jam/unjam. The difference in the strength between the coarse and fine coffee grind can possibly be attributed to the coarse coffee having a larger size distribution of particles, as shown in Fig. 2. When there is a larger range of particle sizes, smaller particles tend to fill the voids of larger ones to maximize the solid volume fraction, thereby minimizing the degrees of freedom of the particles to induce jamming.

Another notable difference between ground coffee and the other materials tested is that it inherently contains some moisture (oil), which might contribute to the bulk strength due to attractive capillary forces between particles.

III. Design of Jammable Manipulator Prototypes

Two prototypes of a jammable manipulator have been developed to-date. Both prototypes were composed of five serial jammable segments. Each segment utilized: coarsely ground coffee as the granular media, a low-stiffness compression spring along its length, and an outer flexible membrane. The primary purpose of the spring was to help constrain the bending motion of each segment to improve its precision while still being soft enough to maintain the overall flexibility of the manipulator. The springs also served as force-restoring elements to help return segments to a neutral position when unjammed.

Each segment also included rigid end caps for connecting one fluid line per segment and for guiding the tension cables, which ran along the length of the entire manipulator. All the fluid lines were connected to a single, off-board air vacuum pump; each segment's fluid line was also connected to an off-board solenoid valve to enable isolated jamming control of each segment. This allowed the manipulator to effectively achieve $n \times m$ DOFs, where n is the number of segments and m is the number of DOFs per segment. Position control was performed by selectively jamming/unjamming individual segments and controlling the length of the tension cables.

A. Prototype 1

As shown in Fig. 1, the first prototype of the manipulator was composed of five identical segments. One of the main challenges of designing the manipulator segments to resist loads in bending was to prevent grains from squeezing out of the mid-length portion of the segments, or where the segments tended to bend the most, as this was where the most strength would be needed to support loads in the jammed state. A smooth-ridged, bellows-like outer membrane (1.5 mm thick) was cast out of silicone to prevent the membranes from buckling during bending and to help maintain uniform distribution of the grains. The total length of the manipulator was 355 mm. The length of each segment was 50 mm, and the narrowest and widest inner diameters of each segment (due to the ridge shape) was 20 mm and 30 mm, respectively. An 8 mm diameter spring with stiffness 600 N/m was implemented in each segment.

This prototype demonstrated that jamming is very effective as a rapidly activatable tunable stiffness mechanism and that ground coffee provides adequate changes in stiffness to easily decouple unjammed segments from jammed ones, as shown in Fig. 1. While this prototype exhibited high flexibility and could hold itself in complex shapes, it was barely strong enough to support its own

weight when the entire manipulator was jammed in a horizontal position. The total mass of the manipulator was 190 grams. The mass percentage breakdown was: 23% end caps and springs, 36% silicone membranes, and 41% ground coffee. The mass of the tubes and tension cables was negligible.

B. Prototype 2

1) Design of Jammable Segments

The primary goal of the second prototype was to improve the strength-to-weight performance and payload capacity of the manipulator. To achieve this, design modifications were made to decrease unnecessary mass in the system. The following changes were made: thin (150-microns thick) latex sheets—that were wrapped around and sealed—replaced the cast silicone membranes; the manipulator became tapered along its length; and the springs had outer diameters equal to those of the segments they were contained in. Commercially available springs were selected based on their relative dimensions (to maintain aspect ratios of individual segments and to create an overall tapered shape) and minimal stiffness. Because the membranes no longer had a confining structure built into them as the silicone membranes had, the larger-diameter springs served an additional purpose of maintaining the cross sectional area of each segment during bending. A schematic of the manipulator is shown in Fig. 4.

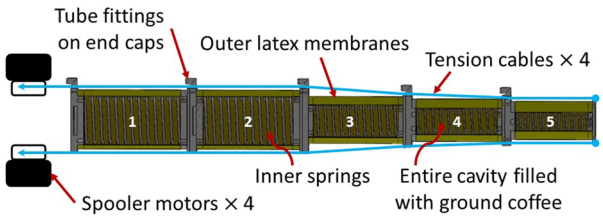


Fig. 4 CAD drawing showing a cross sectional view of the manipulator.

The total length of the manipulator was 380 mm. Each segment was designed to have a 2:1 length-to-diameter ratio. The segments were also designed to scale linearly to create the overall tapered shape, though the final prototype was limited by commercial availability, and the largest two segments ended up being the same size. The stiffness of the springs was approximately 180 N/m. The total mass of the manipulator was 345 grams (sans electromechanical components). The mass percentage breakdown of the second prototype of the manipulator was: 43% end caps and springs, 7% latex membranes, and 50% ground coffee. By decreasing the unnecessary mass of the membranes, the relative mass of the ground coffee was increased, thereby increasing the robot's strength-to-weight ratio. However, the relative mass of the end caps and springs increased not only because larger springs were used, but also because end cap design improved at the cost of becoming larger to enable a more modular design than in the first prototype.

The second prototype could easily support its own weight when jammed in a horizontal position.

2) System Components

The system for the second prototype of the manipulator was complete with motors (Dynamixel MX-28) for controlling the length of the cables, and solenoid valves (SMC NVKF334V) for controlling the air flow at each segment. While a manipulator composed of any number of segments requires only three sets of motors and cables, spaced 120° apart, to control three DOFs (including compression/extension) of every segment—and therefore create any arbitrary overall shape for the manipulator—four motors were employed, spaced 90° apart, to simplify the control.

A vacuum pump with maximum 101.3 kPa (1 atm) vacuum pressure was utilized to jam the segments. A vacuum storage tank was added in line with the pump to increase the short-term volumetric flow rate of air.

IV. Prototype Performance and Analysis

In this section we highlight the unique capabilities of the presented manipulator architecture. The results presented here were from tests performed with the second prototype of the manipulator.

A. Speed

The speed parameter of interest is the time it takes for the manipulator to transition between jammed and unjammed states, since this influences the manipulator bandwidth and its ability to respond to its environment.

Tests for determining the jamming speed of the manipulator were conducted by dropping the manipulator (with one fixed end) from an unjammed, straight, horizontal position and recording the time between when the solenoid valves were activated and when the manipulator jammed and reached a completely rigid and still position. Because the transition time was rapid, this was done by recording a video of the test and determining the speed by parsing individual video frames. The time required to jam the manipulator was 0.2 seconds. Note that this time can vary for a given system depending on the volumetric flow rate of the air. Similar tests were conducted to determine the unjamming speed, which was 0.1 seconds.

B. Strength

Many manipulator applications require the system to pick up and transport payloads, thus requiring adequate strength from the jammable segments. As previously discussed, there is potential to further understand how grain properties affect jamming to enable designers and engineers to specify grain properties to fulfill functional requirements for a given application. In general, even jammed granular media that that can support high compression loads have minimal tensile strength; for a vacuumed system, the tensile strength is expected to be dictated by the applied vacuum pressure because grains typically do not interlock to resist tensile loads. Therefore, the bending strength of jammed systems is expected to be limited by the differential jamming pressure.

An important advantage of the manipulator system presented here is that the cables can provide significant tensile force. Fig. 5 presents data that was used to determine the stiffness and strength of the jammed manipulator with and without the use of tension cables. In these tests, the manipulator was cantilevered in the jammed configuration

and weights were hung from its free end, and the displacement of the tip was recorded. Both cases appeared to have both an effective linear elastic regime and a yield point. Without tension cables, the yield load was 80 grams; with tension cables, the yield load was 740 grams. This latter result indicates that the manipulator was able to support a payload equal to more than 200% of its own weight (sans electromechanical components); in contrast, many industrial manipulators can support payloads that are only a fraction of their own weight [24].

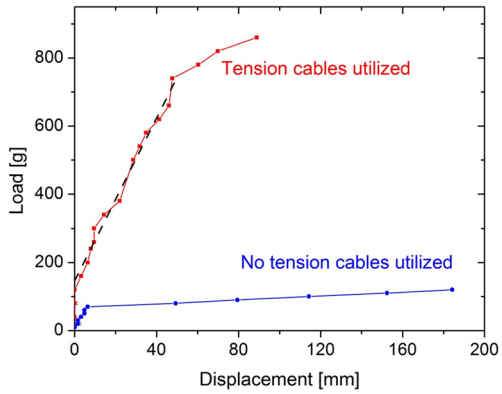


Fig. 5 Load vs. displacement curves for the cantilevered, jammed manipulator. One test was conducted with tension cables to provide tensile force and the other was tested without them. The dotted line represents the linear fit for the apparent elastic regime for the former case.

When the tension cables were not utilized, the failure mode that was observed—when adding payload to the free end of the jammed, horizontal manipulator—was the jammed grains separating from the smooth, rigid end caps. This effect can be mitigated by roughening or adding protruding features to the end plates.

C. Dexterity and Articulation with Simple Control

Probably the most impressive advantage that the jammable manipulator has over traditional systems is its flexibility and ability to conform to its environment with simple control. For example, the manipulator can easily wrap around an obstacle because the unjammed segments can passively conform to other objects. This contrasts with a more traditional system in which high local precision (usually via motors) is required for complex maneuvering. In addition, because of the high DOFs of the system, the manipulator can reach the same end effector position with many configurations. An example of this is illustrated in Fig. 6.

Fig. 6 also demonstrates how the manipulator was able to fold on itself and maintain highly articulated configurations via jamming. The reachable workspace boundary of the manipulator is nearly a sphere with a radius equal to the manipulator length. Of course the flexibility of the manipulator also depends on details such as the stiffness of the spring and membrane; the first prototype was more compliant than the second one due to their different components. A highly articulated and adaptable manipulator such as the one presented would also benefit human-safe robots, as such robots can be more responsive and accommodating to their environments.

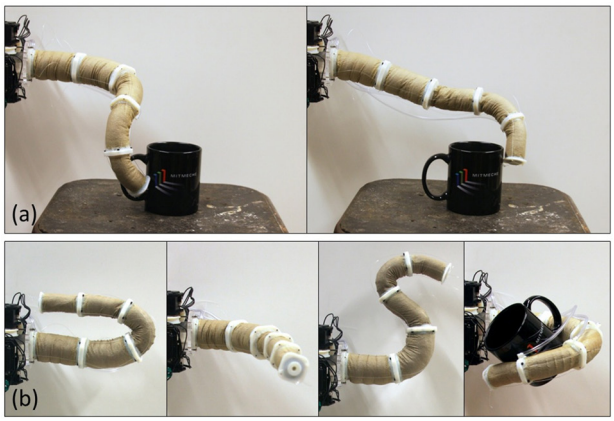


Fig. 6 The manipulator demonstrating its ability to: (a) reach an end effector target with multiple configurations, and (b) achieve many complex and highly articulated shapes. Note that the manipulator is jammed to rigidly hold its shape in all these images.

V. Future Work

A. Optimizing Grain Properties

Ongoing work is being conducted to understand how grain properties affect jamming so that grains can be optimized to achieve engineering functional requirements. We are interested in studying parameters such as grain shape, surface roughness, size distribution, and shape distribution. For applications in which the grains need to transition between rigid, load-bearing states and flexible, compliant ones, we need to identify grains that can both achieve high strength—preferably tensile in addition to compressive—in the jammed state and also flow relatively easily when unjammed.

B. Manipulator Design

As previously discussed, the strength of the manipulator can be further improved by making simple adjustments to components such as the end caps. The goal in future prototypes include removing the relatively large, rigid end caps altogether and integrating the plumbing more seamlessly into the manipulator, such as by running the tubes through the center of the structure.

One limitation of using vacuum pressure as the jamming mechanism is that the maximum differential jamming pressure is atmospheric pressure. Therefore, utilizing positive pressure could significantly increase the strength of jammed granular systems. However, it is not clear how positive pressure can be utilized in systems in which grains need to "freeze" in arbitrary shapes, as in the case of the manipulator, because a positive-pressure system tends to take the shape of the membrane it is contained in.

To simplify the manipulation capabilities of the manipulator, a rotational degree of freedom could be added to the robot (e.g., by adding another motor at the base of the manipulator) to rotate the entire structure.

C. Feedback and Control

This new type of manipulator architecture in which binary local control is coupled with global actuation creates new and interesting problems for motion and path planning of manipulators. Important cost objectives are introduced, such as the number of operations that are required to reach an end effector position. Additionally, the mechanical compliance of granular systems adds to the complexity of the problem. We initially plan to use visual tracking systems, such as through infrared cameras, to provide closed-loop feedback for controlling manipulator position. We can also draw inspiration from what researchers have learned about manipulator-like systems in nature, such as trunks and tentacles. For example, octopi create pseudo discrete joints along their flexible tentacles to efficiently grasp nearby food [25].

Future work would also involve integrating sensors along the manipulator to not only determine the shape and position of the manipulator but to also sense its environment.

D. Potential applications

It is obvious that jammable systems can greatly benefit human-safe robotics, as they can very quickly transition between high-strength, rigid states and very compliant ones. In addition, robots such as a jammable manipulator can be extremely dexterous and articulated, such that they can easily adapt to their environments, potentially increasing the capabilities of traditional manipulators.

As discussed, the strength of current systems that utilize vacuum pressure to achieve jamming is limited by atmospheric pressure. An area that could exploit this fact is underwater robotics, where the operating environments can generate extremely high jamming pressures and therefore very strong structures.

VI. Conclusion

We have presented the design and analysis of a novel robotic manipulator that utilizes jamming of granular media to achieve local stiffness control while tension cables control the shape and position of the robot. Performance analysis has demonstrated that this type of system can be high-force and highly articulated compared to more traditional manipulators. Early results in identifying grains with high strength-to-weight performance were also presented.

Acknowledgment

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