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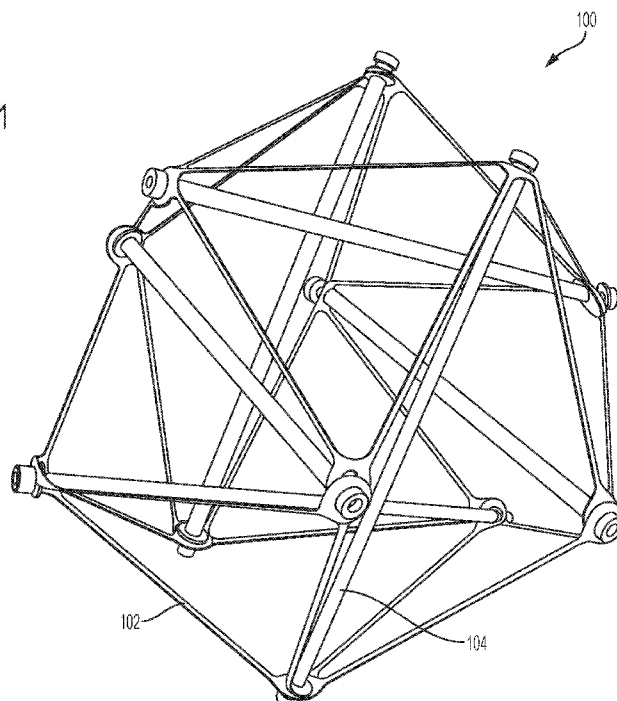
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FIG. 1



(57) Abstract: According to some embodiments of the invention, a tensegrity robot includes a plurality of compressive members; and a plurality of interconnecting tensile members connected to the plurality of compressive members to form a spatially defined structure without the plurality of compressive members forming direct load-transmitting connections with each other. The plurality of interconnecting tensile members forms a lattice, and the lattice comprises an elastic material.



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ELASTIC LATTICES FOR DESIGN OF TENSEGRITY STRUCTURES AND ROBOTS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. Provisional Application No. 62/466,913 filed March 3, 2017, the entire contents of which are hereby incorporated by reference.

STATEMENT OF GOVERNMENT SUPPORT

[0002] This invention was made with Government support under grant NNX15AD74G, awarded by the National Aeronautics and Space Administration (NASA). The Government has certain rights in the invention.

BACKGROUND

1. Technical Field

[0003] Embodiments of this invention relate to robots, and more particularly to tensegrity robots and methods of producing tensegrity robots.

2. Discussion of Related Art

[0004] Much prior work from the authors has demonstrated that tensile-integrity systems, called “tensegrity” systems, are useful for a wide range of applications, including space exploration in various ways [1-2, 5-8]. Spherical tensegrity structures can be actuated to roll along uneven ground [1-2, 5-7] and spine-like tensegrity structures can act as part of a larger robot that can walk [8]. These robots capitalize on the beneficial properties of tensegrity systems, such as low mass, variable stiffness, and redundancy to failure.

[0005] However, designing and prototyping a tensegrity robot is a time-intensive task. The robots’ cables require compliance for locomotion, which is usually achieved by a combination

of stiff braided cable and springs [5-8] or by elastic cord [2]. The designer generally has requirements for the system's compliance; commonly, a symmetric tension network is required. The nature of the distribution of forces in the elastic cables of the structure's tension network, as well as the precision required in adjusting the length of the cables to achieve the desired properties of compliance, create challenges for assembly and repeatability.

[0006] Assembly using either of the prior cable methods requires repetitive attachment, adjustment, and reattachment of the cables (generally done by tying and untying knots) to achieve symmetric cable lengths. The assembly process takes on the order of hours [6] or even weeks [7] to make a completed tensegrity, and it is prone to error in achieving symmetry. Using either of the prior cable methods also hinders repeatability, since the cables are manually adjusted for each robot and the resultant compliance is imprecise. In order to better design and evaluate different tensegrity systems, a more time-efficient, robust, and repeatable method is needed for tensegrity prototyping.

SUMMARY

[0007] According to some embodiments of the invention, a tensegrity robot includes a plurality of compressive members; and a plurality of interconnecting tensile members connected to the plurality of compressive members to form a spatially defined structure without the plurality of compressive members forming direct load-transmitting connections with each other. The plurality of interconnecting tensile members forms a lattice, and the lattice comprises an elastic material.

[0008] According to some embodiments of the invention, a tensegrity robot includes a plurality of compressive members; a plurality of first interconnecting tensile members connected to the plurality of compressive members to form a spatially defined structure without the plurality of compressive members forming direct load-transmitting connections with each other; a plurality of second tensile members connected to the plurality of compressive members, each of the plurality of second tensile members being in parallel to one of the plurality of first interconnecting tensile members; a plurality of actuators, each attached to one of the plurality of compressive members; and a controller in communication with the plurality of actuators. The plurality of first interconnecting tensile members forms a lattice, and the

lattice comprises an elastic material. Each actuator of the plurality of actuators is operatively connected to a corresponding one of the plurality of second tensile members so as to selectively change a tension on the corresponding one of the plurality of second tensile members in response to commands from the controller to thereby change a center of mass of the tensegrity robot to effect movement thereof.

[0009] According to some embodiments of the invention, a method of forming a tensegrity robot includes cutting a plurality of interconnecting tensile members from a sheet of elastic material; and connecting the plurality of interconnecting tensile members to a plurality of compressive members to form a spatially defined structure without the plurality of compressive members forming direct load-transmitting connections with each other. The plurality of interconnecting tensile members forms a lattice.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Figure 1 shows a tensegrity robot according to some embodiments of the invention.

[0011] Figure 2A shows passive tensegrity robot according to some embodiments of the invention.

[0012] Figure 2B show actuated tensegrity robots according to some embodiments of the invention.

[0013] Figure 3 shows the TT-4_{mini} robot, a tensegrity robot that uses the elastic lattice platform. This robot moves by adjusting the lengths of its cables with respect to its elastic lattice.

[0014] Figure 4 shows the tensegrity robot TT-3. All tensile members include cables and springs, each of which was individually tied together.

[0015] Figure 5 shows a modular elastic lattice according to some embodiments of the invention, made with 60A durometer rubber.

[0016] Figure 6 shows a single-piece elastic lattice for a 6-bar tensegrity structure according to some embodiments of the invention.

[0017] Figure 7 shows a step-by-step assembly sequence for a 6-bar tensegrity structure according to some embodiments of the invention.

[0018] Figure 8 shows three 12-bar tensegrity structures constructed using an elastic lattice. The structures are robust and quick to assemble, and they allow significant control over the systems' properties.

[0019] Figures 9A and 9B show two spine tensegrity structures constructed using prototyping methods described herein. Figure 9B shows the horizontal vs. saddle connectors: There are four horizontal strips of lattice material, compared to the many almost-vertical saddle connectors.

[0020] Figure 10 shows a step-by-step assembly sequence for forming a tensegrity spine structure according to some embodiments of the invention.

[0021] Figure 11 shows the TT-4_{mini} prototype performing punctuated uphill rolling on an inclined surface of 24°. The photo shows three steps by the robot.

[0022] Figure 12 shows visualization of the single-cable actuation policy. Each row corresponds to one cable, this policy can be repeated indefinitely.

[0023] Figure 13 shows simulation results of the TT-4_{mini}'s payload CoM trajectory while climbing a 16° incline using the single-cable actuation policy.

[0024] Figure 14 shows required percent of cable retraction to initiate forward rolling motion with single-cable policy. Increasingly negative percentages signify greater cable retraction.

[0025] Figure 15 shows visualizations of the two-cable actuation policies. Each row corresponds to one cable, and each policy can be repeated indefinitely.

[0026] Figure 16 shows a summary of Hardware Experiment results.

[0027] Figure 17 shows simulation results of the TT-4_{mini}'s payload CoM trajectory while climbing a 26° incline using the alternating two-cable actuation policy.

[0028] Figure 18 shows comparison of robot CoM height over time as a percent of neutral stance CoM height for single-cable and two-cable actuation policies. Maximum heights for each policy shown as dotted lines.

[0029] Figure 19 Shown in both simulation and hardware, the payload's CoM height at the robot's neutral state for single-cable actuation (left) is higher than that of the multi-cable actuation policy (right). The base polygon is highlighted in the lower figure.

[0030] Figure 20 shows comparison of projected CoM (circles) with supporting base polygons for single-cable (red) and two-cable actuation (blue) policies on a 10° incline. Direction of uphill travel is along the positive x axis. Distance from the uphill edge of the robot's base polygon (dotted lines) is less for multi-cable actuation than single-cable actuation. Similarly, distance from the downhill edge of the robot's base (dash-dotted lines) is greater for the multi-cable policy than the single-cable policy.

[0031] Figure 21 shows the TT-4_{mini} prototype climbing up a 24° incline surface with two-cable alternating actuation.

DETAILED DESCRIPTION

[0032] Some embodiments of the current invention are discussed in detail below. In describing embodiments, specific terminology is employed for the sake of clarity. However, the invention is not intended to be limited to the specific terminology so selected. A person skilled in the relevant art will recognize that other equivalent components can be employed and other methods developed without departing from the broad concepts of the current invention. All references cited anywhere in this specification, including the Background and Detailed Description sections, are incorporated by reference as if each had been individually incorporated.

[0033] According to some embodiments of the invention, a platform for prototyping tensegrity robots and structures is provided that significantly reduces the time required for manufacturing and assembly, as well as increases precision and repeatability of the tensioned robot. This platform simplifies tensegrity system design and allows for more scientific experiments to be performed in less time. According to some embodiments, the new platform

uses a rapidly manufactured modular elastic lattice as the tensile members in a tensegrity structures. The elastic lattice can be laser-cut out of a sheet of elastic material, then wrapped around the bars or other of a tensegrity structure, replacing the traditional cables and springs that are more commonly used. Production of the elastic lattice is efficient, as laser cutting is straightforward and fast. Wrapping the elastic lattice around the rods of a tensegrity system takes on the order of minutes, rather than on the order of hours that it takes to assemble a tensegrity using traditional methods. This prototyping platform has been used to create both type I and type II tensegrity systems using lattice designs either cut out of a single sheet or with individual smaller lattices. In particular, this prototyping platform has been used to make 6-bar spherical, 12-bar spherical, and spine-like tensegrity structures.

[0034] Embodiments of the invention address the challenges of rapidly prototyping and manufacturing tensegrity structures. According to some embodiments, a machine-cut lattice of elastic material is used in place of the spring/cable system in a tensegrity structure, automating the manufacturing of the tension elements and greatly simplifying the assembly processes, as well as creating consistent and repeatable prototypes. According to some embodiments, a design is made in 2D using computer-aided design software that is used to automatically laser-cut an elastic sheet. After the rigid elements of the system (rods, or other 3D structures) are manufactured separately, the laser-cut design can be attached to the rigid elements in a particular pattern, creating the tensegrity structure. This process is fast and efficient. Additionally, because the tensile members (the elastic lattice) are manufactured by a machine, e.g., a laser cutter, instead of created by hand, the final tensegrity system has a repeatable, consistent shape.

[0035] A tensegrity robot according to some embodiments of the invention is shown in Figure 1. According to some embodiments of the invention, a tensegrity robot 100 includes a plurality of compressive members 102; and a plurality of interconnecting tensile members 104 connected to said plurality of compressive members 102 to form a spatially defined structure without said plurality of compressive members 102 forming direct load-transmitting connections with each other. The plurality of interconnecting tensile members 104 form a lattice, and the lattice comprises an elastic material.

[0036] According to some embodiments, the plurality of interconnecting tensile members have an integral structure. Figure 6 shows an example of a plurality of interconnecting tensile members having an integral structure.

[0037] According to some embodiments, each of the plurality of interconnecting tensile members has a same length. For example, each side of the triangle lattice in Figure 5 has the same length. Each side of the triangle lattice in Figure 5 may be considered a tensile member. Accordingly, the embodiment shown in Figure 5 is a lattice comprises three tensile members, while the embodiment shown in Figure 6 comprises 24 tensile members.

[0038] According to some embodiments, each of the plurality of interconnecting tensile members connects one of the plurality of compressive members to another of the plurality of compressive members. The compressive members may be referred to herein as bars or rods. Figure 7 shows an example wherein each tensile member connects one compressive member to another compressive member.

[0039] According to some embodiments, each of the plurality of interconnecting tensile members has a length that is shorter than a length of each of the plurality of compressive members when no force is applied to the plurality of interconnecting tensile members. For example, in the top-left panel of Figure 7, the compressive members are longer than the tensile members when no forces, for example, stretching forces, are being applied to the tensile members.

[0040] According to some embodiments, the elastic material comprises silicone rubber. According to some embodiments, the plurality of interconnecting tensile members is cut from a flat sheet of the elastic material.

[0041] According to some embodiments, the tensegrity robot further comprising a plurality of junction members, wherein each of the plurality of junction members is configured to rigidly connect to one of the plurality of compressive members. According to some embodiments, the junction members have a shape that allows them to connect to the ends of the compressive members. The junction members may also have a shape that allows them to connect to the plurality of interconnecting tensile members.

[0042] For example, Figure 7 shows a tensegrity robot that includes a plurality of endcaps. Each endcap connects to an end of one of the compressive members. However, the embodiments of the invention are not limited to this structure. For example, the junction members may have a different shape, or may be integrated into the compressive members, such that the compressive members include a feature for connecting to the tensile members. For

example, the compressive members may be fabricated to have a knob or ridge that engages the tensile members.

[0043] According to some embodiments, the plurality of interconnecting tensile members includes a connection structure for connecting the plurality of interconnecting tensile members to one of the plurality of compressive members or to a junction member. According to some embodiments, the connection structure is a loop, wherein the loop is configured to encircle one of the plurality of junction members. For example, the tensile members may have loops or rings formed therebetween, as shown in Figure 6. The compressive member or the junction member may penetrate the ring, thereby becoming fixed to the tensile members. Alternatively, the connection structure may be a knob that engages a hollow compressive member. The connection member may be any structure that maintains a fixed relationship between an end of a compressive members and a corresponding position of the lattice.

[0044] According to some embodiments, the tensegrity robot includes six compressive members. According to some embodiments, each of the plurality of compressive members comprises a core rigidly fixed to a plurality of rods, each of the rods extending radially from the core. According to some embodiments, the plurality of compressive members are connected to the plurality of interconnecting tensile members such that the cores of the plurality of compressive members are linearly aligned. For example, in Figure 9B, the cores of a plurality of compressive members are linearly aligned to form a spine structure.

[0045] Figure 2B shows a tensegrity robot according to some embodiments of the invention. The tensegrity robot 202 includes a plurality of compressive members 212; a plurality of first interconnecting tensile members 206 connected to the plurality of compressive members 212 to form a spatially defined structure without the plurality of compressive members 212 forming direct load-transmitting connections with each other; a plurality of second tensile members 204 connected to the plurality of compressive members 212, each of the plurality of second tensile members 204 being in parallel to one of the plurality of first interconnecting tensile members 206; a plurality of actuators 208, each attached to one of the plurality of compressive members 212; and a controller 210 in communication with the plurality of actuators 208. The plurality of first interconnecting tensile members 206 forms a lattice, wherein the lattice comprises an elastic material. Each actuator of the plurality of actuators 208 is operatively connected to a corresponding one of the plurality of second tensile members 204 so as to selectively change a tension on the corresponding one of the plurality of

second tensile members 204 in response to commands from the controller 210 to thereby change a center of mass of the tensegrity robot 202 to effect movement thereof.

[0046] According to some embodiments, at least one of the plurality of actuators comprises a motor driven spool to wind up and release portions of a corresponding one of the plurality of second tensile members. According to some embodiments, the controller controls the plurality of actuators such that two of the plurality of actuators simultaneously change a tension on a corresponding two of the plurality of second tensile members to thereby change the center of mass of the tensegrity robot to effect movement thereof. According to some embodiments, the controller controls the plurality of actuators such that two of the plurality of actuators alternately change a tension on a corresponding two of the plurality of second tensile members to thereby change the center of mass of the tensegrity robot to effect movement thereof.

[0047] According to some embodiments, the plurality of first interconnecting tensile members have an integral structure.

[0048] According to some embodiments of the invention, a method of forming a tensegrity robot, includes cutting a plurality of interconnecting tensile members from a sheet of elastic material; and connecting the plurality of interconnecting tensile members to a plurality of compressive members to form a spatially defined structure without the plurality of compressive members forming direct load-transmitting connections with each other, wherein the plurality of interconnecting tensile members forms a lattice.

[0049] According to some embodiments, the method further comprises connecting a plurality of second tensile members to the plurality of compressive members, each of the plurality of second tensile members being in parallel with one of the plurality of interconnecting tensile members; and connecting a plurality of actuators to the plurality of compressive members, each one of the plurality of actuators being operatively connected to a corresponding one of the plurality of second tensile members so as to selectively change a tension on the corresponding one of the plurality of second tensile members to thereby change a center of mass of the tensegrity robot to effect movement thereof.

[0050] The prototyping platform according to some embodiments is much faster than prior approaches. Prior approaches take hours, days, or even weeks, while this approach takes just minutes to assemble a structure.

[0051] Embodiments of the invention can result in consistent prototypes. This means that the tensegrity structures are symmetric (which is difficult to achieve by hand) and that multiple mostly-identical structures can be manufactured very quickly.

[0052] The elastic lattice used in this approach has different mechanical properties in comparison to a traditional spring. The elastomer can experience plastic deformation more easily, which has a currently unknown effect on the use of these structures under cyclical use conditions.

[0053] Some embodiments of the prototyping platform use an elastomer that is compatible with the laser-cutting process. This means that the elastic lattice must be made of a material that does not release toxic chemicals when burned or ablated away. Additionally, this elastomer should be tested and calibrated for its mechanical properties when in the lattice structure, in order to make good predictions of its cyclic loading behavior and plastic deformation limits. Additionally, we currently only use thin elastomer material, cut into straight lines. Our current embodiment uses attachment points for the lattice, with the lattice sandwiched between them, held tight by a nut and bolt assembly. According to some embodiments, two washers are used as the attachment points for the lattice. This makes the lattice remain in place during movement. However, the embodiments of the invention are not limited to this design.

[0054] Possible variations on this platform include the use of different types of material, different sizes and thicknesses of material, and different patterns of material. This could include curved members of the lattice instead of straight lines, as well as more complicated patterns that optimize a 3D shape when assembled. Additionally, many different types of attachments between the lattice and the rigid tensegrity elements could be used, including different levels of compression, rotation, or 3D movement.

[0055] There are many successful implementations of this rapid prototyping platform, including 6-bar spherical tensegrity structures, cubic 12-bar tensegrity structures, octahedral 12-bar tensegrity structures, double six 12-bar spherical tensegrity structures and both type I and type II spine-like tensegrity structures. Examples are shown in the Examples section. Additional structures can be formed using the lattice and methods described herein.

[0056] Finally, since this lattice is designed for use with tensegrity robots, it may be designed to be retracted by a motor to adjust its length or tension in different locations, or be paired with an additional actuator in some way to similarly change its shape.

[0057] Although a static model is used to demonstrate the basic concept of a tensegrity structure according to some embodiments, the addition of actuators is required to gain scientific insight into the tensegrity robot's capabilities. To do so, a 6-bar tensegrity robot with six actuators was constructed, which is referred to as the TT-4_{mini}, the 4th generation spherical tensegrity robot of miniature size. Figure 2A shows the robot 200 prior to actuation. Figure 2B shows the fully-actuated robot 202. The robot 202 makes use of small components and the modular elastic lattice to allow for rapid hardware iterations and performance testing. The robot 202 has cables 204 in parallel with the elastic lattice 206. The cables 204 are connected to actuators 208 that can adjust the length of the cables 204. A controller 210 can be in communication with the actuators 208 to control the actuators 208 to adjust the lengths of the cables 204.

[0058] The robot moves by adjusting the lengths of its cables with respect to its elastic lattice, thereby shifting the base of the robot with respect to its center of gravity, and causing the robot to roll forward. With the new tensegrity prototyping platform, we were able to quickly manufacture and assemble a passive 6-bar tensegrity structure as the basis of an actuated tensegrity robot. Previously, it required days to assemble a new version of a tensegrity robot. With the new technique, we were able to assemble a new functional six-bar tensegrity robot under an hour. This platform drastically increased the rate of prototype development, which allowed us to investigate new concepts quickly.

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[0068] The following examples describe some further concepts of the invention with reference to particular examples. The general concepts of the current invention are not limited to the particular examples.

[0069] EXAMPLES

[0070] Example 1 – Modular Elastic Lattice Platform for Rapid Prototyping of Tensegrity Robots

[0071] Challenging environments for robot locomotion, such as those in space applications, have motivated recent research into tensegrity (tension-integrity) robots [1, 2, 3, 4, 5]. These robots include rigid elements held together in a network of cables in tension. As designed for use in space, tensegrity robots can be made as spheres that roll on a variety of terrains [6, 7, 8, 9, 10, 11], snake-like robots which crawl along the ground [12, 13, 14], or as

part of walking four-legged robots [15, 16, 17]. All of these robots are designed to exploit the various beneficial properties of tensegrity structures: low mass, variable stiffness [1], redundancy to failure [18], among other benefits.

[0072] Although tensegrity robots have the potential for robust locomotion, practical prototyping of each of the above robots has presented challenges. Manually attaching the springs and cables of each robot introduces human error, and takes a long time for assembly. These difficulties provide the motivation for this work.

[0073] Tensegrity structures were first introduced in the mid-1960s in architecture and art [19, 20, 21]. The structures' passive combination of cables-in-tension and bars-in-compression became a significant design feature in several architectural and sculptural structures [22, 23].

[0074] In contrast, tensegrity robots change their shape by adjusting the lengths of their cables. Many different types of tensegrity robots have been created, including robot designs that use pneumatic actuators [6], shape-memory alloy actuators [24], linear motors to pull on cables [25], direct actuation via servomotors [26], as well as motors attached to spools [27]. Regardless of the actuation method used, a tensegrity structure must have all tensile elements in tension to maintain a stable structure.

[0075] The University of California's Berkeley Emergent Space Tensegrities (BEST) Laboratory has been collaborating with the National Aeronautics and Space Administration's (NASA) Ames Research Center on using tensegrity structures as the basis for the next generation of space exploration robots [15, 7, 5]. These structures have been used as spherical robots, designed to land and roll along different terrain, and robot spines designed to help a four-legged robot walk.

[0076] In particular, a spherical tensegrity robot has the potential to be used as both a lander and a rover since it has the ability to passively distribute forces across the entire structure. The tension network provides shock protection from the impact of landing without requiring complex parachute systems while also serving as a mobility platform for exploring unpredictable environments.

[0077] Five different actuated spherical tensegrity robots have been developed within this collaboration: the SUPERball at NASA Ames [15], the TT-1 and TT-2 robots at UC Berkeley [7, 8], the TT-3 robot at UC Berkeley [5] (Figure 4), and the TT-4_{mini} (Figures 2B and 3). Each

of the four “TT” robots from UC Berkeley have improvements on design, actuation, and control. The TT-4_{mini} contributes a major step in manufacturing and assembly for these robots.

[0078] The UCB-NASA collaboration is extending the research of spherical tensegrity robots to 12-bar tensegrity structures, which represents the next largest symmetric form. We are simulating and creating rapid prototypes of two geometric forms of 12-bar structures in order to learn more about their mobility, impact, and payload characteristics. We anticipate that the 12-bar structure will increase the capabilities of tensegrity robots for planetary surface exploration. We present herein the first designs of these 12-bar robots.

[0079] Finally, tensegrity spine robots have been developed to assist the walking of four-legged (quadruped) robots over uneven terrain. The Underactuated Lightweight Tensegrity Robotic Assistive Spine (ULTRA Spine) is a tensegrity robot with five independent vertebrae that can bend and twist, emulating a backbone’s motions [15]. Though simulations and controllers have been developed for the ULTRA Spine, the development of hardware prototypes has been hampered by the challenges of manually assembling the robot, and the difficulty in creating symmetric tension on both sides of the spine. This invention addresses both of those challenges, among others.

[0080] Tensegrity structures are notoriously difficult to assemble because the members are not in balanced compression and tension until the structure is fully assembled. In the intermediary steps of assembly, forces are unevenly distributed and the structure is difficult to constrain. It is easy to make mistakes in assembly, such as connecting the wrong tension and compression members to one another. To illustrate the complexity of assembly, a low-fidelity prototype of a 6-bar tensegrity structure made with wooden dowels and springs can take as long as an hour for a team of five people to assemble.

[0081] Additionally, it is challenging to maintain symmetric tensions in the elastic members in order to create a symmetric tensegrity structure. For example, using a cable in series with an extension spring for the elastic member, as is done on TT-3, requires that the cables be of equal length to achieve equal tensions. This means that the system needs to be carefully manufactured or calibrated; if not, the system is susceptible to undesired deformation and will not perform shape-shifting maneuvers as expected. Other methods for the elastic members, such as using bungee cords or other elastic materials, have the same difficulties.

[0082] The inventors examined an assembled 6-bar tensegrity structure and conceptualizing how the tension members (cables in series with springs) could be deconstructed from a 3D structure to the 2D plane. The external geometry of a 6-bar robot is that of an icosahedron with the tension members forming a portion of the vertices. The triangular faces of the solid could thus be mapped onto a flat sheet of material. A new elastic medium, silicone rubber, was selected to replace the traditional cables and springs. The new configuration was first tested using a plastic sheet, which was cut to trace the tension members of an assembled 6-bar tensegrity robot. The production of this low fidelity prototype made it evident that eight triangular units, such as the one in Figure 3, were needed to form the 6-bar tensegrity structure.

[0083] The first elastic prototypes of the lattice for a 6-bar spherical tensegrity were created using 0.02 in. thick, 20A durometer silicone rubber and cut with a single-beam Universal Systems laser cutter. The lightness of the silicone rubber caused challenges during the laser cutting process. Because it was so light, the venting system of the laser cutter caused the rubber to lift up and flap as it was being cut, risking the correct profile of the cut. This risk was averted by putting masking tape on both sides of the rubber sheet, thus making the sheet heavier so it did not lift up and flap. This ensured that the proper design could be created without impeding the cutting ability of the laser.

[0084] After we made a number of prototypes with this silicone lattice, it became clear that the 0.02 in. thick, 20A durometer silicone rubber did not have the correct material properties for the 6-bar tensegrity; the hardness and thickness of the silicone rubber did not provide enough tension to the system, even with different width profiles.

[0085] The prototypes in the next iteration were made with 0.0625 in. thick, 60A durometer silicone rubber. By experimenting with various widths of the rubber elastic lattice, the desired tension in the system was achieved using this material. These prototypes were produced using a double-beam Universal Systems laser cutter. The heavier silicone rubber did not face the same manufacturing issues as the 20A durometer silicone rubber but presented new difficulties in the laser cutting process. Initially the laser cutter only etched the silicone rubber instead of cutting it. The optimal laser cutting setting was achieved on the cutter by using only the top laser beam instead of both laser beams.

[0086] The elastic prototypes made with 60A durometer silicone rubber (Figure 5) were much stiffer than the previous versions and could withstand higher tension. Thus, these prototypes better demonstrated the unique characteristics of tensegrity structures.

[0087] The benefits of the modular elastic lattice address many of the challenges of tensegrity prototyping. As the laser cut profile of the lattice can be very quickly customized, these benefits are applicable to any tensegrity structure.

[0088] First, the lattice enables rapid manufacture and assembly. Laser cutting is simple and fast, so the lattice is quickly produced. Assembly of the structure with the lattice is on the order of minutes, as exemplified by the cases of the 6-bar, 12-bar, and spine tensegrity structures. Previous methods required an hour or more. Additionally, the modularity of the lattice allows experimentation with the number of lattice pieces to optimize assembly time for a given tensegrity system.

[0089] Second, the lattice gives significant control over the system's tensions. The precision and consistency of the laser cutter results in identical elastic members, making achieving symmetric tensions in a system much simpler. Additionally, the spring constant of the elastic member can be changed by adjusting the profile of the laser-cut elastic member, and thereby the system's tensions can be designed.

[0090] We conducted tension tests with the 60A durometer rubber to estimate how changing the width of the elastic members alters the corresponding spring constant. The laser cutter was used to produce equal length strips of the lattice material of six different widths. The experimental setup included securing one side of the strip and pulling on the opposite side with five different forces and recording the respective displacement. Nine repetitions of this process were conducted on each of the widths; the resulting data is seen in Table 1. This data is used when designing new lattices to estimate the width that will result in the desired spring constant and therefore the desired tension.

TABLE 1: SPRING CONSTANT TO WIDTH COMPARISON.

Width (mm)	Spring Constant (N/m)	$\pm$ Error (N/m)
6.35	986	24.52
7.94	1472	35.56
9.53	2104	55.96

11.11	2364	56.50
12.70	2812	67.75
14.29	2973	68.22

[0091] In order to demonstrate the advantages of the elastic lattice prototyping method, we describe herein the use of the lattice on the 6-bar, 12-bar, and spine tensegrity structures.

[0092] The elastic lattice enabled rapid prototyping of 6-bar tensegrity structures. We experimented heavily with the modularity of the elastic lattice for this structure. We found that combining the eight triangles into a single piece made assembly quicker and simpler. The single-piece lattice is shown in Figure 6. This lattice structure is then used in the demonstration assembly shown in Figure 7.

[0093] Figure 7 illustrates the step-by-step sequence required to assemble a 6-bar tensegrity structure using this newly developed prototyping method. Since the main two elements of a tensegrity structure are tension and compression, we decided to use thin-walled aluminum rods as the compression elements in our static tensegrity prototype. Endcaps were used as the connection between the modular elastic lattice and the aluminum rods. According to some embodiments, the endcaps are manufactured by 3D printing, though other production techniques may also be used. A fully assembled 6-bar tensegrity structure according to some embodiments requires one of the one-piece lattices (eight connected rubber elastic triangle lattices), twelve of the 3D printed endcaps, and six of the aluminum rods.

[0094] The result is a tensegrity structure that can be built in a few minutes by a single person, whereas previous 6-bar structures required 1-2 hours and two or more people. We conducted a test in which we gave ten subjects clear instructions and asked them to assemble a 6-bar tensegrity structure with the elastic lattices. It took the subjects an average of 77 seconds with a standard deviation of 24 seconds.

[0095] Although a static model is used to demonstrate the basic concept of a tensegrity structure, the addition of actuators are required to gain scientific insight into the tensegrity robot's capabilities. To do so, a 6-bar tensegrity robot with six actuators was constructed, which is referred to as the TT-4_{mini}, the 4th generation spherical tensegrity robot of miniature size (Figures 2B and 3). The TT-4_{mini} makes use of small components and the modular elastic lattice to allow for rapid hardware iterations and performance testing.

[0096] With the new tensegrity prototyping platform, we were able to quickly manufacture and assemble a passive 6-bar tensegrity structure as the basis of an actuated tensegrity robot. Previously, it required days to assemble a new version of a tensegrity robot. With the new technique, we were able to assemble a new functional six-bar tensegrity robot under a hour. This platform drastically increased the rate of prototype development, which allowed us to experiment on new concepts quickly.

[0097] In addition to 6-bar tensegrity robots, the BEST Lab is investigating 12-bar tensegrity structures as a new platform for tensegrity robots for planetary surface exploration. There are several variations of symmetric 12-bar tensegrity structures. Our lab is conducting a design study of two 12-bar tensegrity structures to select one that will best serve the design objectives of the robot. These structures are the cube and the octahedron, so named for the shapes from which the pattern of rods of the structures evolve.

[0098] We created structural prototypes with the goal to gain preliminary design insights into their deformation and impact characteristics with physical testing. Prototyping these structures presented significant challenges. Each of the 12-bar structures has 36 cables and a complex geometric form. They are also higher tension systems than the 6-bar structure. These factors can make them difficult to assemble and, important to the design study, make it difficult to achieve symmetric tensions in the elastic members.

[0099] Initial attempts at creating structural prototypes without the elastic lattice were slow and necessitated the building of jigs. It took several days to make simple prototypes from wooden dowels and elastic bands. Regular tension and structural robustness was very difficult to achieve in these early prototypes. Consequently, hand tests of deformation and impact characteristics yielded low scientific return.

[0100] The rubber lattice prototyping method allowed us to build these two tensegrity structures much more quickly and with significantly more control over the systems' tensions. Following a similar methodology as was used for the 6-bar tensegrity structure, we created a lattice for each of the 12-bar structures by observing geometric patterns and designing modular pieces. We estimated the appropriate profile of the pieces to achieve desired tensions in our system using the data from Table 1. We then connected the pieces to create lattice shells. Next, we attached bars to the interior of each lattice shell to erect the tensegrity structures. The final structural prototypes are shown in Figure 8. The top structure is the octahedron, and the middle

structure is the cube. Once the lattices are designed, assembling each structure takes between 5 and 10 minutes.

[0101] We have used these elastic lattices effectively in our design study, and because of the ease of assembly, robustness, and control over system properties that they allow, these prototypes will serve as the basis for actuated 12-bar robots.

[0102] Although most tensegrity research has involved rolling spherical structures, many other tensegrity shapes have robotic applications, including spine-like tensegrity robots. One tensegrity spine currently under development is the ULTRA Spine [15], which is used as the body of a quadruped robot. The ULTRA Spine experiences the same prototyping challenges as the two spherical designs described above, and has benefitted from the elastic lattice prototyping platform in its most recent iteration.

[0103] As part of a walking quadruped robot, the ULTRA Spine is designed to assist the placement of the robot's feet using only lightweight mechanisms. The robot includes vertebrae that are attached to each other using a network of tensioned connectors, like other tensegrity structures. Current models of the robot bend the spine by shortening the length of the horizontal connectors [15], visible in the Figure 9B. In addition, the passive tensegrity network in the spine also gives benefits related to quadruped walking, such as passive force distribution through the body, and adjustable stiffness between different legs.

[0104] The first prototype of the spine was manufactured and assembled using cables and springs, as shown in Figure 9A. The cables in the tension network were made of braided Dyneema, purchased off-the-shelf. Each braided cable is then tied to an extension spring, and its length is adjust such that the robot remains evenly tensioned. The springs and cables are fastened to the thin-walled aluminum rods using unique 3D printed endcaps with screws and washers. The specific components described herein are listed as examples, and a person of ordinary skill in the art would recognize that the embodiments of the invention are not limited to components comprising the materials, sizes, or spring constants listed here.

[0105] The assembly process for the cable tension network is not only time consuming, but is also very prone to error. Even with detailed instructions, the process takes over three hours with at least two people measuring, cutting, and placing each of the thirty two cables. Different assembly jigs must be used at specific times during the assembly. During assembly, the cables are first loosely attached to each vertebrae, then the saddle cables are hand tuned to maintain

rotational stability. After that, the horizontal cables are tightened until the robot is able to stand. However, due to the relationship between each tensioned component, this process can be very tedious and inaccurate. When one saddle or horizontal cable is not the correct length, the vertebrae are unevenly spaced, yielding an uneven distribution of weight across the robot. These inconsistencies result in low scientific returns when cables are actuated during tests.

[0106] The lattice prototype can included the same five vertebrae, but the tensile network is maintained by the elastomer lattice jacket that wraps around the vertebrae (Figure 9B). The rubber replaces cables and springs of the original prototype, eliminating many of the assembly and manufacturing challenges. Figure 10 illustrates the sequence required to assemble the spine tensegrity structure using one full lattice and five vertebrae. The same thin-walled aluminum rods are used and a bolt and screw act as endcaps that clamp onto the lattice and fit into the rods. A fully assembled spine tensegrity structure utilizes one lattice, twenty bolt endcaps, and twenty of the aluminum rods.

[0107] With the new prototyping platform, the total assembly time for the spinal tensegrity structure was reduced from around three hours to seven minutes, even with a single person. A simple and easily visualized pattern reduces the complexity of the system and allows for the assembly process to be quickly learned with limited direction. The lattice creates a consistent and repeatable tension network that can be used when evaluating the spine's design. After applying a force to create the bending or torsional moment, the lattice allows the robot to return to its original shape through its control of the shape or profile of the robot and the tension network established by the elastomer.

[0108] Elastic lattice designs for all three types of tensegrity robots were assembled multiple times to quantify improvements in their use. Table 2 shows the results of these trials and compares them with the general assembly times for previous robot designs, performed by members of the BEST Lab who had experience assembling traditional cable-and-spring robots. The elastic lattices significantly reduced assembly times by as much as an order of magnitude for the 6-bar and spine robots.

TABLE 2: ROBOT ASSEMBLY TIME COMPARISON

Robot	Old Method	Elastic Lattice
6-Bar Sphere	1-2 hrs	77 s $\pm$ 24 s (N = 10)
12-Bar Sphere	1-2 hrs	5-10 min
Spine	3-5 hrs	6 min 14 s $\pm$ 97 s (N = 8)

[0109] The newly developed rapid prototyping method using modular elastic lattices has simplified the traditional methods of building tensegrity structures. As such, we were able to shorten the time for assembly of a static structure from one hour to within a few minutes. In addition, we were able to modify the static structure into an actuated robot by attaching actuators and a controller; the total assembly time of an actuated robot using this prototyping platform is less than an hour. In addition, the examples described herein illustrate the extensibility of the platform for related applications, such as the rapid prototyping of 12-bar and spine tensegrity structures. For researchers, this rapid prototyping platform can significantly reduce the complexity of constructing tensegrity structures.

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[0138] Example 2 – Inclined Surface Locomotion Strategies for Spherical Tensegrity Robots

[0139] According to some embodiments of the invention, a teleoperated spherical tensegrity robot is capable of performing locomotion on steep inclined surfaces. With a novel control scheme centered around the simultaneous actuation of multiple cables, the robot demonstrates robust climbing on inclined surfaces in hardware experiments and speeds significantly faster than previous spherical tensegrity models. This robot is an improvement over other iterations in the TT-series and the first tensegrity to achieve reliable locomotion on inclined surfaces of up to 24°. We analyze locomotion in simulation and hardware under single and multi-cable actuation, and introduce two novel multi-cable actuation policies, suited for steep incline climbing and speed, respectively. We propose compelling justifications for the increased dynamic ability of the robot and motivate development of optimization algorithms able to take advantage of the robot’s increased control authority.

[0140] A tensegrity structure according to some embodiments includes rods suspended in a network of cables, where the rods and cables experience only compression and tension, respectively, while in equilibrium. Because there are no bending moments, tensegrity systems are inherently resistant to failure [1]. Additionally, the structures are naturally compliant, exhibiting the ability to distribute external forces throughout the tension network. This mechanical property provides shock protection from impact and makes the structure a robust robotic platform for mobility in an unpredictable environment. Thus, tensegrity robots are a

promising candidate for exploration tasks, especially in the realm of space exploration, because the properties of tensegrity systems allow these robots to fulfill both lander and rover functionality during a mission.

[0141] Analysis of tensegrity robotic locomotion on inclined terrain is critical in informing path-planning and trajectory tracking decisions in mission settings. Despite the crucial role of uphill climbing in planetary exploration, the TT-4mini robot is the first untethered spherical tensegrity robot to achieve reliable inclined surface climbing.

[0142] The TT-4_{mini} robot was rapidly constructed using a novel modular elastic lattice tensegrity prototyping platform [2], which allows for rapid hardware iterations and experiments.

[0143] This work presents the simulation results of inclined uphill locomotion for a six-bar spherical tensegrity robot as well as the prototyping and hardware experiments performed to validate these results. We show that the TT-4_{mini} robot can achieve robust locomotion on surface inclines up to 24° using a two-cable actuation scheme in hardware, as shown in Figure 11.

[0144] Herein, we first describe the topology and design of the TT-4_{mini}, which uses a novel rapid tensegrity prototyping method. Next, we analyze incline locomotion performance in simulation under a single-cable actuation policy. This policy is tested on hardware to establish a performance benchmark against which two-cable actuation policies can be evaluated. Two variants of multi-cable policies are found in simulation, one suited for steep inclines and the other suited for speed. We demonstrate significant performance improvements in both tasks over the single-cable benchmark and discuss the primary factors that lead to improved performance.

[0145] Tensegrity robots have become a recent subject of interest due to their applications in space exploration [3]. The natural compliance and reduced failure modes of tensegrity structures have motivated the development of multiple tensegrity robot forms [1]. Some examples include spherical robots designed for locomotion on rugged terrain [4], [5], [6], snake-like robots that crawl along the ground [7], and assistive elements in walking quadrupedal robots [8], [9], [10].

[0146] Tensegrity locomotion schemes have been studied in both the context of single-cable actuation [11], and (rarely) in the context of multi-cable actuation [12]. However, much of this exploration into tensegrity multi-cable actuation policies has been in the context of vibrational, rather than rolling motion.

[0147] While there exists extensive prior work in incline robotic locomotion, the literature does not directly address tensegrities. For example, Stanford's spacecraft/rover hybrid robot has demonstrated through simulation and hardware tests the potential for uphill locomotion. Rather than a tensegrity mechanism, however, Stanford's hybrid robot uses a flywheel-based hopping mobility mechanism designed for traversing small micro-gravity bodies [13].

[0148] Movement on rough or uphill terrain is a frequent occurrence in space exploration, and has proven to be a necessary challenge for traditional wheeled rovers. For instance, Opportunity has ascended, with much difficulty, a number of surfaces up to 32° above horizontal [14]. On the other hand, NASA's SUPERball, which is also a 6-bar tensegrity robot, has demonstrated successful navigation of an 11.3° (20% grade) incline in simulation [15]. However, as will be discussed later, the TT-4_{mini} is the first tensegrity robot to successfully demonstrate significant inclined surface locomotion, not only in simulation, but also in hardware testing.

[0149] In order to greatly simplify and expedite the process of assembly we developed a modular elastic prototyping platform for tensegrity robots [2]. The TT-4_{mini}, a six-bar spherical tensegrity robot, was the first tensegrity robot assembled using this new prototyping platform and can be rapidly assembled in less than an hour by a single person. To construct the robot, a regular icosahedron structure is first rapidly assembled using the modular elastic lattice platform and six aluminum rods of 25 cm each, creating the passive structure of the tensegrity robot. A total of six actuators and a central controller are then attached to the structure, resulting in a dynamic, underactuated tensegrity robot, as shown in Figure 2B.

[0150] A spherical tensegrity robot can perform rudimentary punctuated rolling locomotion by contracting and releasing each of its cables in sequence, deforming its base and shifting its center of mass (CoM) forward of the front edge of its supporting base polygon. This contraction places the robot in a transient, unstable state, from which it naturally rolls onto the following stable base polygon. After the roll, the robot releases the contracted cable and returns to its neutral stance before initiating the next step in the sequence. Herein, the neutral stance of

the robot refers to the stance in which no cables are contracted and the only tension in the system is due to gravity.

[0151] While other robots have successfully achieved punctuated rolling on flat ground using this technique [16], [15], we show that the TT-4_{mini} is not only capable of the same, but can also do so on an inclined surface.

[0152] As there had been very little previous work on uphill climbing with spherical tensegrity robots, we first validated the actuation policy in simulation. Using the NASA Tensegrity Robotics Toolkit (NTRT) simulation framework, we simulated the single-cable TT-4_{mini} actuation scheme (Figure 12) for uphill climbing on surfaces of varying inclines. Results showed that the robot could successfully climb an incline of 16° in simulation using a single-cable actuation policy.

[0153] Simulation results at this incline are shown in Figure 13. Beyond 16°, we found that the robot could no longer reliably perform locomotion, for the following two reasons: (1) The robot was unable to move the projected CoM sufficiently forward to initiate an uphill roll, and (2) Deformation of the base polygon shifted the CoM behind the back (downhill) edge of the polygon, initiating a downhill roll.

[0154] To analyze the limitations of single-cable actuation policies, we studied the relationship between actuation efficiency and incline angle using simulated sensor data. At each angle of inclination, we recorded the cable actuation required to initiate rolling, as a fraction of initial cable length. As expected, we found that initiating tipping of the robot at greater angles of inclination requires greater cable contraction (Figure 14). Interestingly, the extent to which the angle of inclination affects the required cable contraction is dependent on which particular cable is being actuated. Due to the inherent symmetry of the 6-bar spherical structure, the TT-4_{mini}'s repeating six-step gait can be separated into two repeated three step sub-sequences, which arise from the uneven, yet symmetric, distribution of tensions in the springs suspending the central payload (in this case, the central controller).

[0155] Our results imply that climbing steeper hills requires greater power consumption and more careful motion, motivating the development of more efficient actuation policies for uphill locomotion. This analysis highlights the mechanical limits of single-cable actuation policies, thus encouraging exploration of alternative actuation policies.

[0156] In order to validate the results from software simulations, we constructed an adjustable testing platform which allowed for incremental adjustments of the surface incline angle. Using this setup, we considered as successful those trials in which the TT-4_{mini} was able to reliably travel 91.4 cm (3 ft) along the inclined plane. We considered as failure those trials in which the TT-4_{mini} failed to reach the 91.4 cm mark.

[0157] We found that the robot was able to successfully perform uphill climbing up to 13° in hardware with a single-cable actuation policy. Beyond 13°, relaxing a member after its successful contraction consistently shifted the CoM beyond the robot's backward tipping point, causing the structure to roll down the incline. The coefficient of static friction between the robot and the surface, measured for all 8 stable robot poses, ranged from 0.42 to 0.57 with a mean of 0.49. This corresponds to maximum inclines before slipping ranging from 23° to 29°, with a mean of 26°. We believe the reason for this range is due to the lack of material homogeneity at contact points between the robot and the ground, which can include some combination of the rubber lattice and metal end-cap. In addition, as the distribution of weight on the end of the rods changes with the robot's orientation, it is likely that the frictional forces for each face are not uniform.

[0158] Based on these results, we did not expect, nor did we observe any failure due to sliding in the single cable actuation tests. However, as will be discussed in later sections, this does become a limiting factor in the robot's performance at much steeper inclines. These results are consistent with failure modes observed in simulation.

[0159] As a baseline for comparison in later sections, the robot's average velocity was recorded when travelling 91.4 cm along a 10° incline. Across 10 trials under these conditions, the TT-4_{mini} achieved an overall average velocity of 1.96 cm/s. For reference the robot has a rod length of 25 cm. These results serve as the first demonstration of a tensegrity robot reliably climbing an inclined surface.

[0160] Having reached the limits of inclined locomotion for the single-cable actuation policy, the following actuation policies were explored.

- Simultaneous actuation policy: Similar to single-cable actuation, except the next cable contracts as the current releases, allowing for more steps to be made in less time. See Figure 15, upper plot.

- Alternating actuation policy: To preserve a low center of mass during uphill rolling, the next cable is fully contracted before the current is released. See Figure 15, lower plot.

[0161] We found that multi-cable actuation policies allow the robot to climb steeper inclines and travel at significantly faster speeds than the single-cable actuation policy. The following sections present the performance results of two-cable actuation policies in simulation, and their validation through hardware experiments, summarized in the table in Figure 16.

[0162] The two-cable actuation policies, as described above, were implemented and tested in NTRT as open-loop controllers using the same robot model and inclined surfaces as the aforementioned single-cable simulations. These simulations demonstrated vast improvements in incline locomotion stability as well as average speed, with the robot able to navigate inclines up to 26° using alternating two-cable actuation (Figure 17) and 24° using simultaneous two-cable actuation.

[0163] The significant performance improvements achieved with the two-cable policies are primarily due to the increased stability of the robot and its subsequent ability to avoid rolling downhill during actuation. We believe that this is due to a combination of two primary factors, namely CoM height and number of contact points between the robot and the ground. From the simulation results in Figure 18 it was observed that the average CoM was consistently lower throughout the actuation sequence of the robot, especially at the critical moments approaching the tipping point. On a flat surface, it was found that the maximum CoM heights were 93.1% and 79.8% of the neutral stance CoM height for simultaneous, and alternating actuation, respectively.

[0164] In addition to the lower CoM, both two-cable policies maintain at least one cable in contraction at all times. In contrast to the three contact points in single-cable actuation, the contracted cable keeps the robot in a perpetually forward-leaning stance with four points of contact with the ground, resulting in a larger supporting base polygon (the convex hull of the four contact points), as illustrated by Figure 20.

[0165] Moreover, the stance of robot places the projected CoM uphill of the centroid of the base polygon and farther away from the downhill edge, as opposed to behind it as in the single cable case. This leads to a drastic improvement in incline stability, as the robot is less likely to

roll backwards due to external disturbances. Conversely, this also means that it is easier for the robot to roll forwards, as the distance to move the projected CoM outside the supporting polygon in the desired direction is smaller and therefore easier to achieve. This is especially apparent in Figure 20, where the CoM is 51.4% closer to the uphill edge when compared to the single-cable case. The stances of single-cable and two-cable actuation are shown in Figure 19.

[0166] As the robot no longer returns to a neutral state before initiating the next roll sequence, the simultaneous policy saw a notable increase in average speed. However, it did not appear that the increased speed has much effect on the robot's ability to navigate an incline, as the punctuated manner in which actuation is performed means that little if any momentum is preserved from one roll to the next.

[0167] In accordance with simulation results, the ability of the robot to actuate multiple cables simultaneously and in alternating order resulted in significant improvements in its ability to navigate steep inclines and achieve high speeds.

[0168] The TT-4_{mini} was able to leverage alternating two-cable actuation to reliably climb a 24° (44.5% grade) incline, far outperforming the robot's previous best of 13° (23.1% grade) set via single-cable actuation. Such a significant improvement establishes this performance as the steepest incline successfully navigated by a spherical tensegrity robot to date. Indeed, the primary cause for failure of two-cable alternating actuation at and beyond 24° was not falling backwards, but rather slipping down the slope due to insufficient friction, in accordance with our measurements mapping the robot's mean coefficient of friction to a theoretical max incline of 26°. This suggests that further improvements may be made to the robot's incline rolling ability given careful consideration of material choices in the next design iteration.

[0169] Not only did the robot's incline climbing performance improve, but its locomotion speed did as well. As mentioned previously, on an incline of 10°, the traditional, single-cable actuation policy traveled a distance of 91.4 cm with an average velocity of 1.96 cm/s. However, when performing simultaneous two-cable actuation, the robot was able to travel the same distance with a 10-trial average velocity of 4.22 cm/s, achieving an increase of over 115% beyond the single-cable baseline. We anticipate that this improvement can be increased by further overlapping the contractions and relaxations of more cables in the simultaneous actuation policy. As the number of cables being simultaneously actuated increases, the rolling pattern increasingly resembles a fluid, spherical roll. However, more complex actuation

patterns also require an increasingly skilled robot teleoperator. We recognized that an increase in operator skill leads to an increase in performance, but this also indicates the great potential for intelligent policy optimization and automation. This has the potential to far outperform human operators and achieve ever faster locomotion and the conquering of steeper inclines.

[0170] We have demonstrated, through both simulation and hardware results, the ability of a spherical tensegrity robot to perform consistent uphill locomotion on steep inclines. This was made possible through the development of a novel multi-cable actuation scheme, which allowed the TT-4_{mini} to reliably perform forward locomotion on much steeper inclines and at greater speeds than what was previously possible using only single-cable actuation.

[0171] Due to the inherent coupled, nonlinear dynamics of the robot, multi-cable actuation policies render robotic control a challenging intellectual task, providing a launch point for future work. Artificial intelligence (particularly evolutionary algorithms and deep reinforcement learning architectures) may be integrated in this robotic platform to optimize locomotive gaits on varied inclines, and even generate optimal tensegrity topologies, areas which have proven promising in prior work [17], [18]. Learning algorithms may be leveraged to achieve more fluid and efficient locomotion using a robust and fully autonomous control policy.

[0172] References – Example 2

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- [0191] The embodiments illustrated and discussed in this specification are intended only to teach those skilled in the art how to make and use the invention. In describing embodiments of the invention, specific terminology is employed for the sake of clarity. However, the invention is not intended to be limited to the specific terminology so selected. The above-described embodiments of the invention may be modified or varied, without departing from the invention, as appreciated by those skilled in the art in light of the above teachings. It is

therefore to be understood that, within the scope of the claims and their equivalents, the invention may be practiced otherwise than as specifically described.

WE CLAIM:

1. A tensegrity robot, comprising:

a plurality of compressive members; and

a plurality of interconnecting tensile members connected to said plurality of compressive members to form a spatially defined structure without said plurality of compressive members forming direct load-transmitting connections with each other,

wherein said plurality of interconnecting tensile members forms a lattice, and

wherein said lattice comprises an elastic material.
2. The tensegrity robot according to claim 1, wherein said plurality of interconnecting tensile members have an integral structure.
3. The tensegrity robot according to claim 1 or 2, wherein each of said plurality of interconnecting tensile members has a same length.
4. The tensegrity robot according to one of claims 1-3, wherein each of said plurality of interconnecting tensile members connects one of said plurality of compressive members to another of said plurality of compressive members.
5. The tensegrity robot according to one of claims 1-4, wherein each of said plurality of interconnecting tensile members has a length that is shorter than a length of each of said plurality of compressive members when no force is applied to said plurality of interconnecting tensile members.
6. The tensegrity robot according to one of claims 1-5, wherein said elastic material comprises silicone rubber.

7. The tensegrity robot according to one of claims 1-6, wherein said plurality of interconnecting tensile members is cut from a flat sheet of said elastic material.
8. The tensegrity robot according to one of claims 1-7, further comprising a plurality of junction members, wherein each of said plurality of junction members is configured to rigidly connect to one of said plurality of compressive members.
9. The tensegrity robot according to one of claims 1-8, wherein said plurality of interconnecting tensile members includes a connection structure for connecting said plurality of interconnecting tensile members to one of said plurality of compressive members or to a junction member.
10. The tensegrity robot according to claim 9, wherein said connection structure is a loop, wherein said loop is configured to encircle one of said plurality of junction members.
11. The tensegrity robot according to one of claims 1-10, wherein said tensegrity robot includes six compressive members.
12. The tensegrity robot according to one of claims 1-9, wherein each of said plurality of compressive members comprises a core rigidly fixed to a plurality of rods, each of said rods extending radially from said core.
13. The tensegrity robot according to claim 12, wherein said plurality of compressive members are connected to said plurality of interconnecting tensile members such that said cores of said plurality of compressive members are linearly aligned.

14. A tensegrity robot, comprising:

a plurality of compressive members;

a plurality of first interconnecting tensile members connected to said plurality of compressive members to form a spatially defined structure without said plurality of compressive members forming direct load-transmitting connections with each other;

a plurality of second tensile members connected to said plurality of compressive members, each of said plurality of second tensile members being in parallel to one of said plurality of first interconnecting tensile members;

a plurality of actuators, each attached to one of said plurality of compressive members; and

a controller in communication with said plurality of actuators,

wherein said plurality of first interconnecting tensile members forms a lattice,

wherein said lattice comprises an elastic material, and

wherein each actuator of said plurality of actuators is operatively connected to a corresponding one of said plurality of second tensile members so as to selectively change a tension on said corresponding one of said plurality of second tensile members in response to commands from said controller to thereby change a center of mass of said tensegrity robot to effect movement thereof.

15. The tensegrity robot of claim 14, wherein at least one of said plurality of actuators comprises a motor driven spool to wind up and release portions of a corresponding one of said plurality of second tensile members.

16. The tensegrity robot of one of claims 14 and 15, wherein said controller controls said plurality of actuators such that two of said plurality of actuators simultaneously change a tension on a corresponding two of said plurality of second tensile members to thereby change said center of mass of said tensegrity robot to effect movement thereof.

17. The tensegrity robot of one of claims 14 and 15, wherein said controller controls said plurality of actuators such that two of said plurality of actuators alternately change a tension on a corresponding two of said plurality of second tensile members to thereby change said center of mass of said tensegrity robot to effect movement thereof.

18. The tensegrity robot according one of claims 14-17, wherein said plurality of first interconnecting tensile members have an integral structure.

19. A method of forming a tensegrity robot, comprising:

cutting a plurality of interconnecting tensile members from a sheet of elastic material;
and

connecting said plurality of interconnecting tensile members to a plurality of compressive members to form a spatially defined structure without said plurality of compressive members forming direct load-transmitting connections with each other,

wherein said plurality of interconnecting tensile members forms a lattice.

20. The method forming a tensegrity robot according to claim 19, further comprising:

connecting a plurality of second tensile members to said plurality of compressive members, each of said plurality of second tensile members being in parallel with one of said plurality of interconnecting tensile members; and

connecting a plurality of actuators to said plurality of compressive members, each one of said plurality of actuators being operatively connected to a corresponding one of said plurality of second tensile members so as to selectively change a tension on said corresponding one of said plurality of second tensile members to thereby change a center of mass of said tensegrity robot to effect movement thereof.

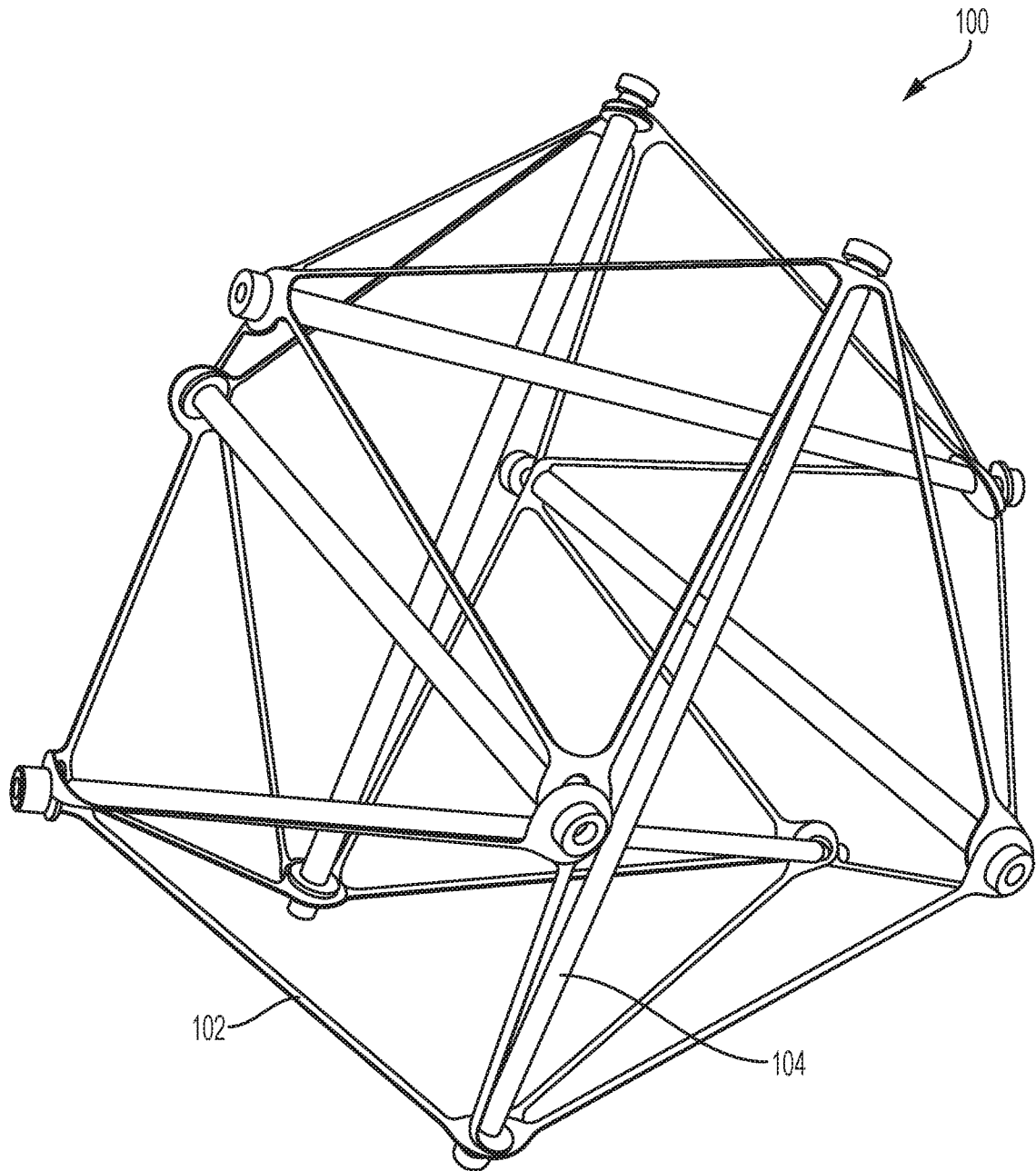


FIG. 1

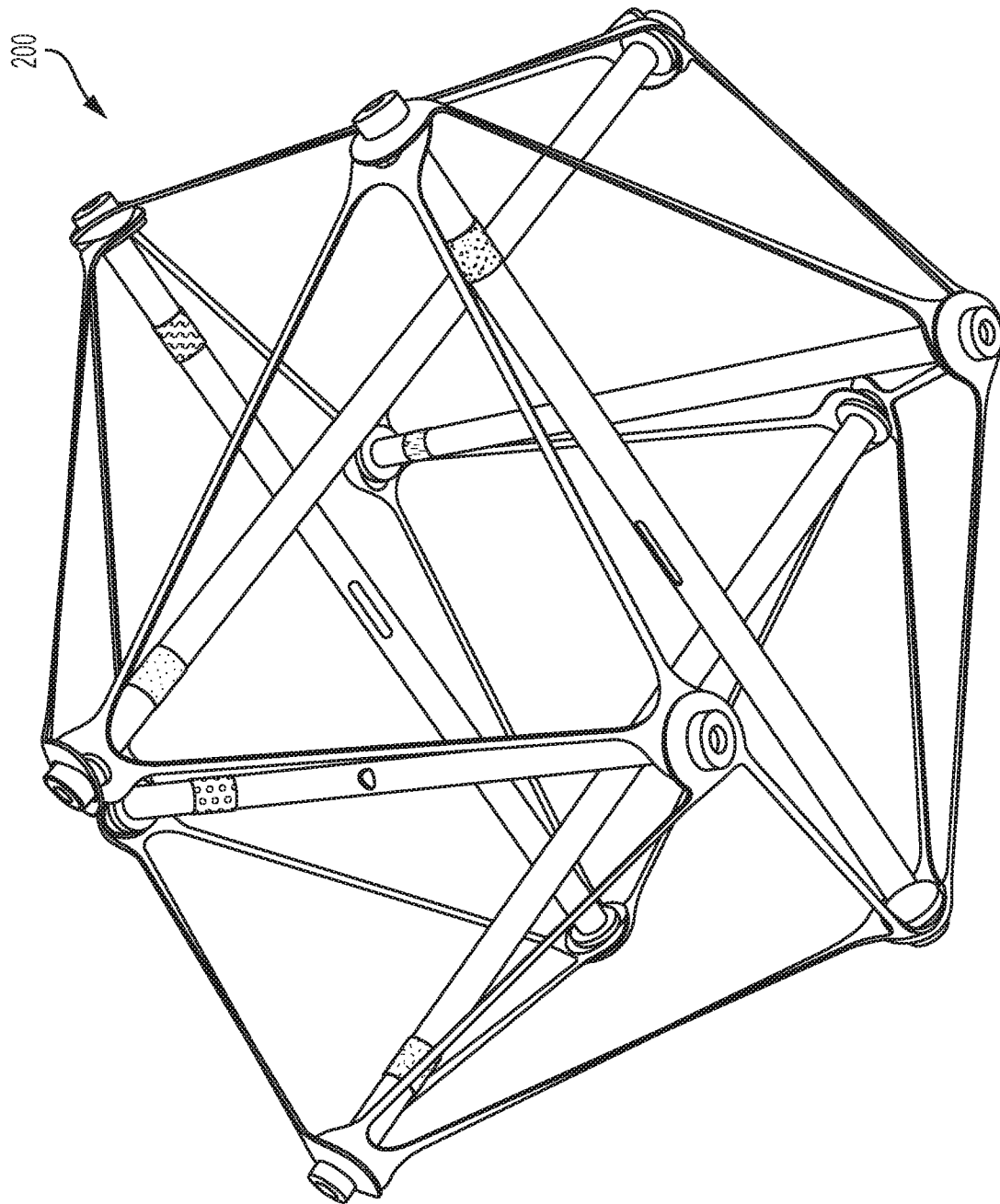


FIG. 2A

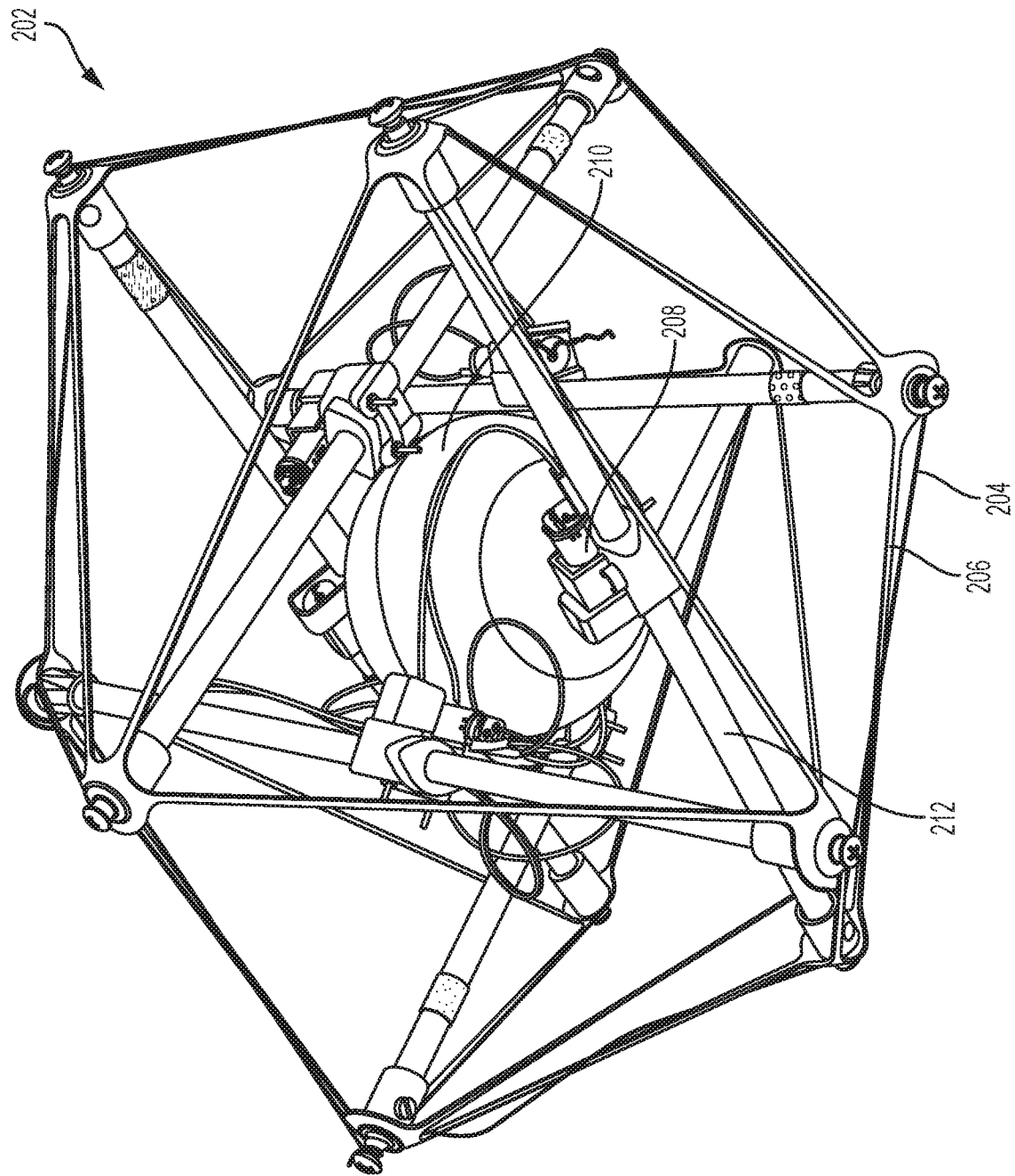


FIG. 2B

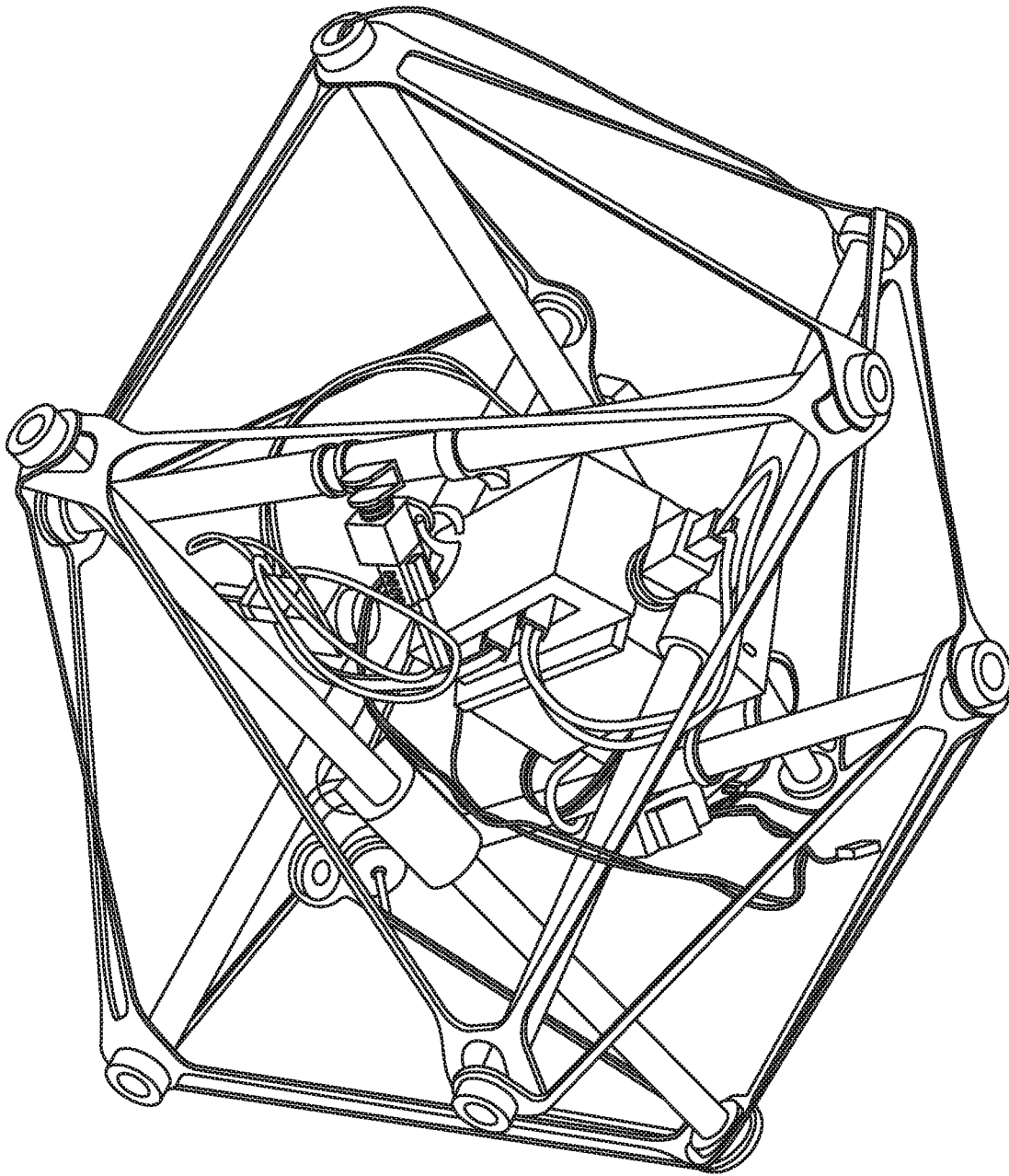


FIG. 3

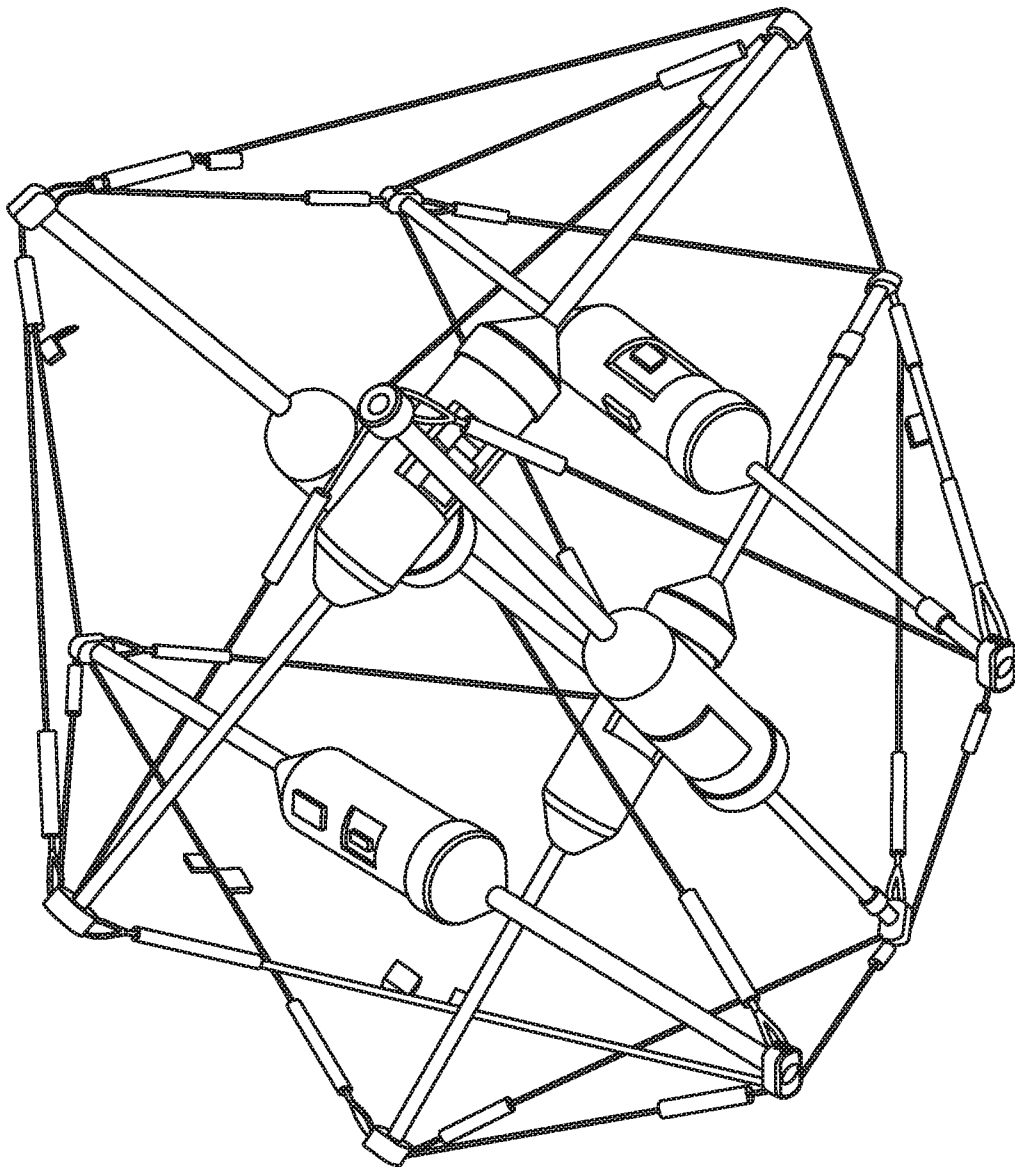


FIG. 4

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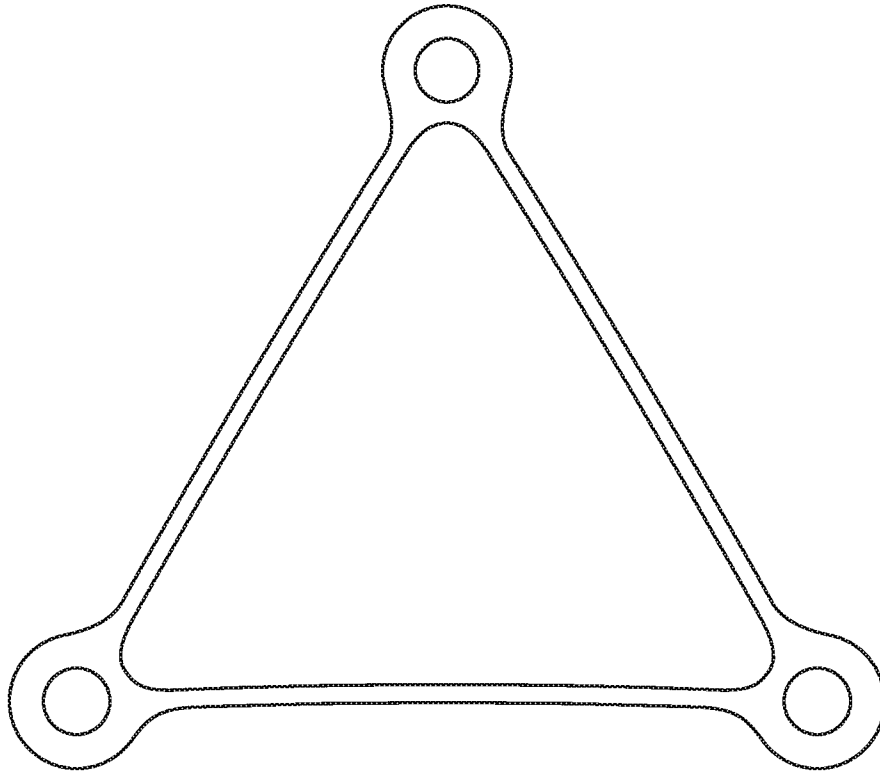


FIG. 5

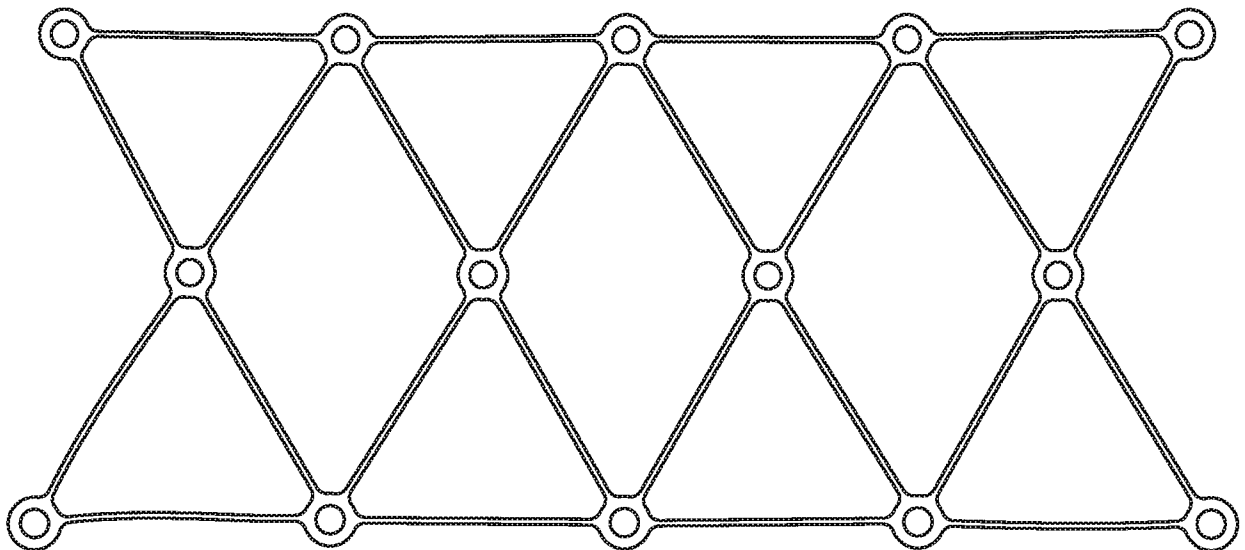


FIG. 6

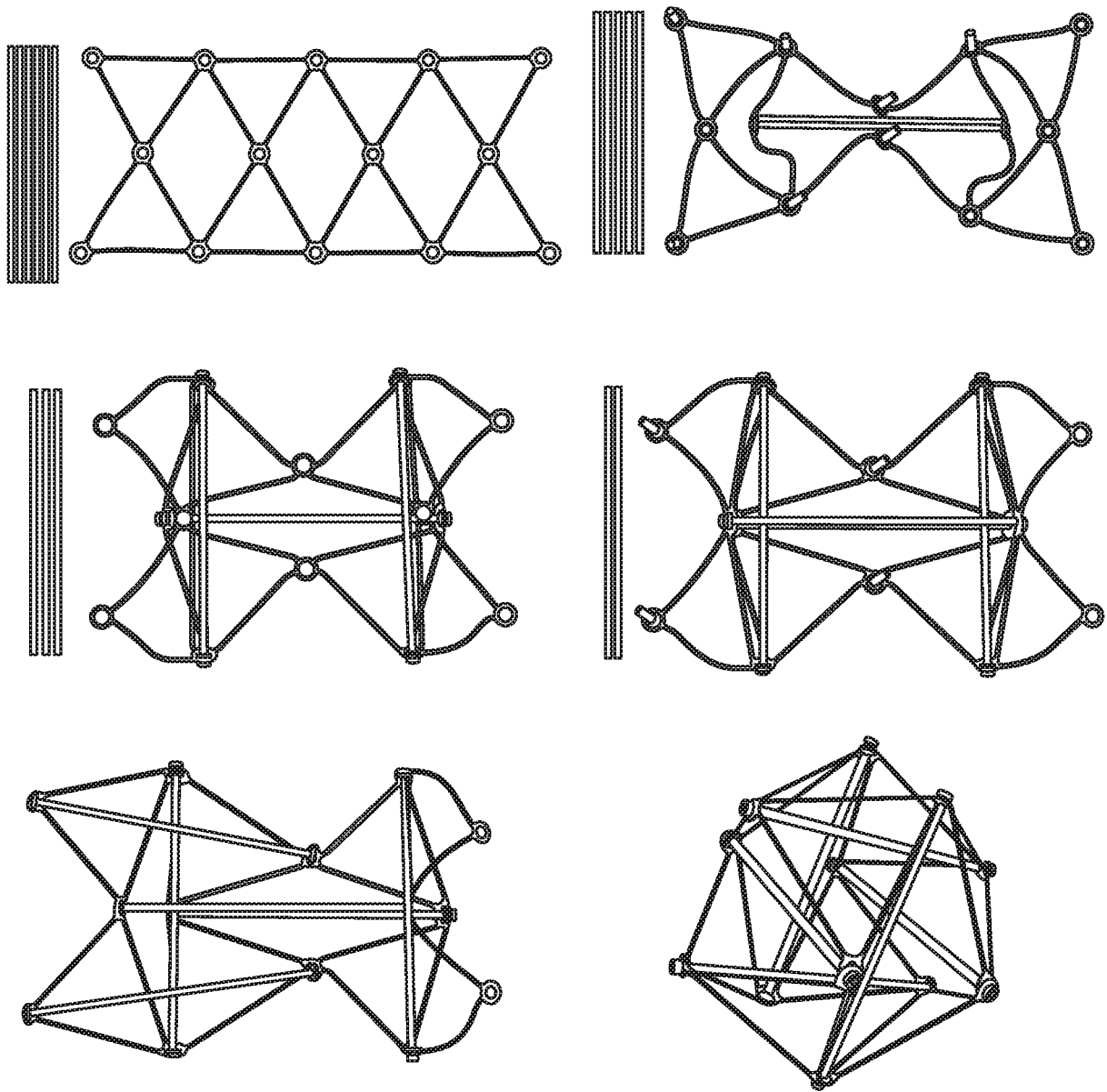


FIG. 7

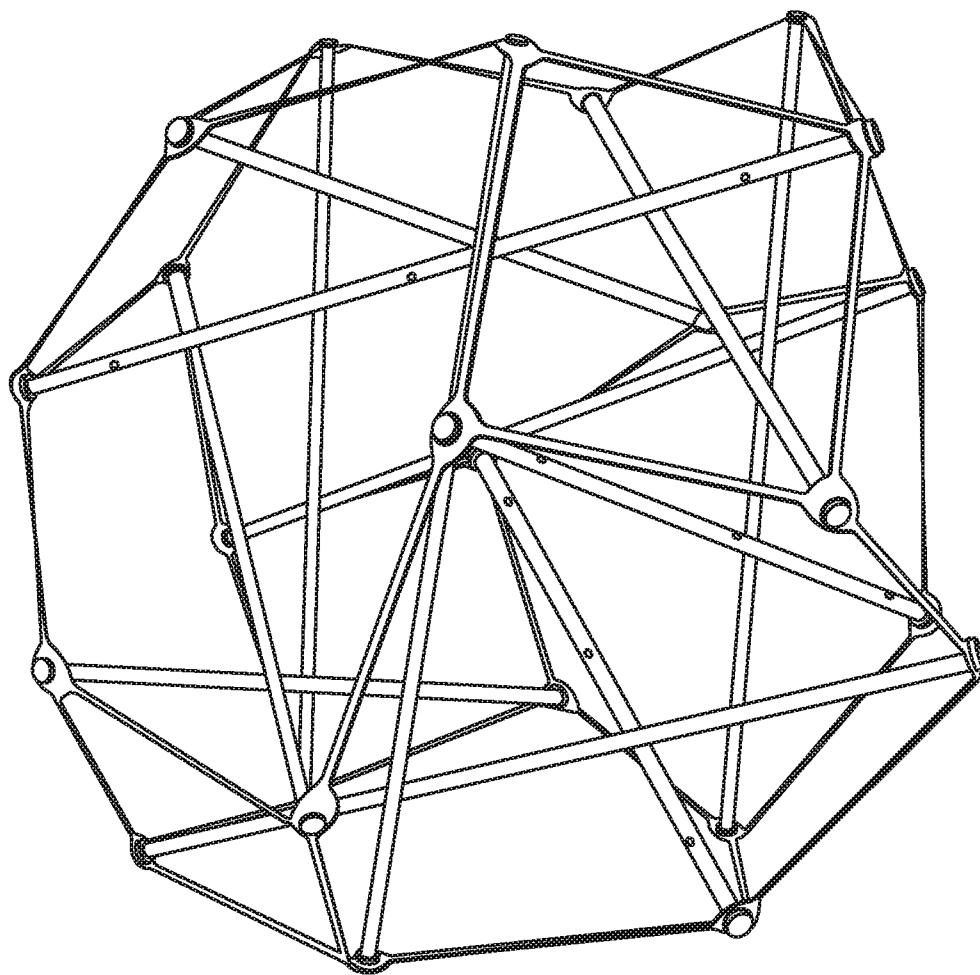


FIG. 8

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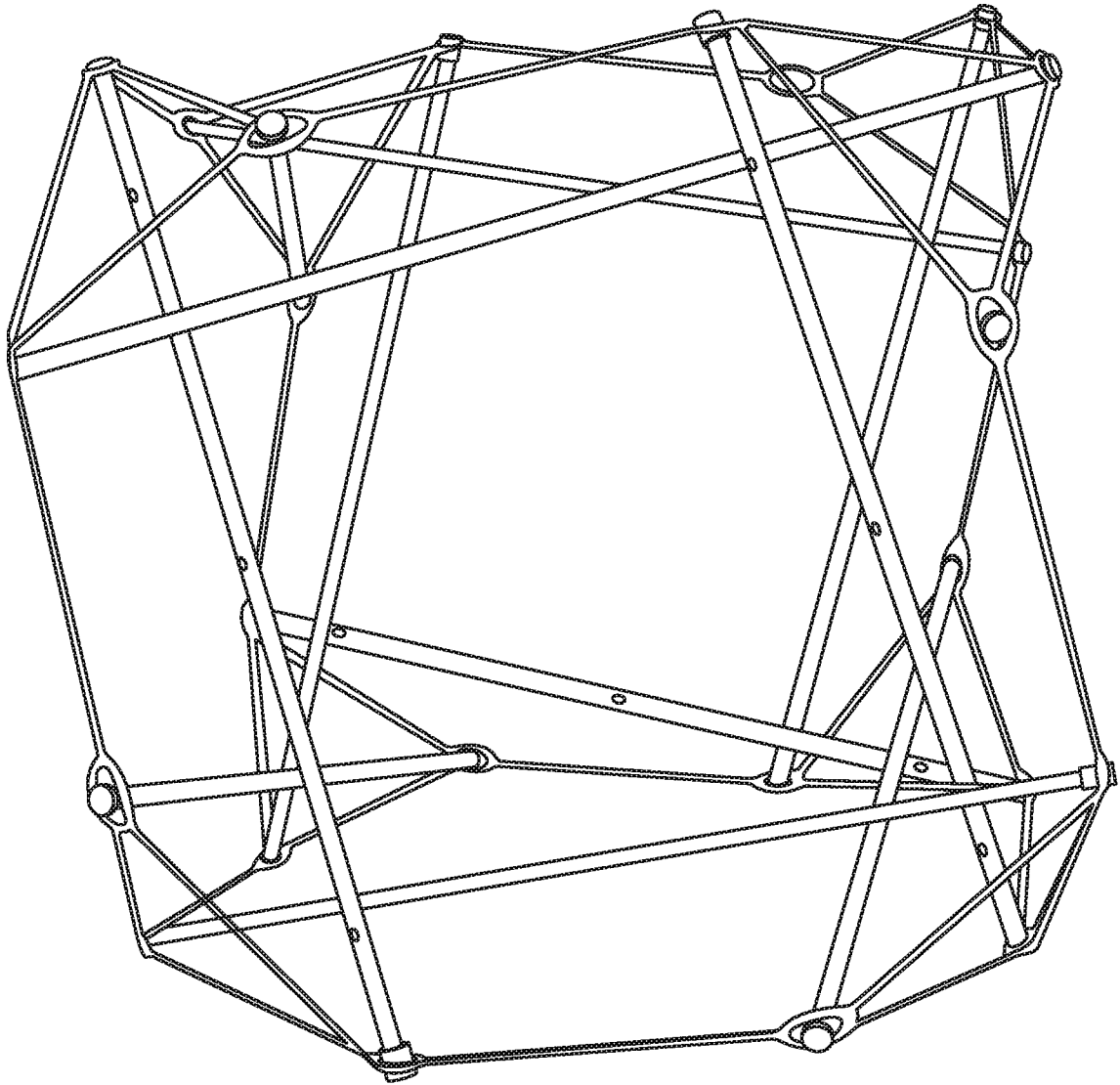


FIG. 8
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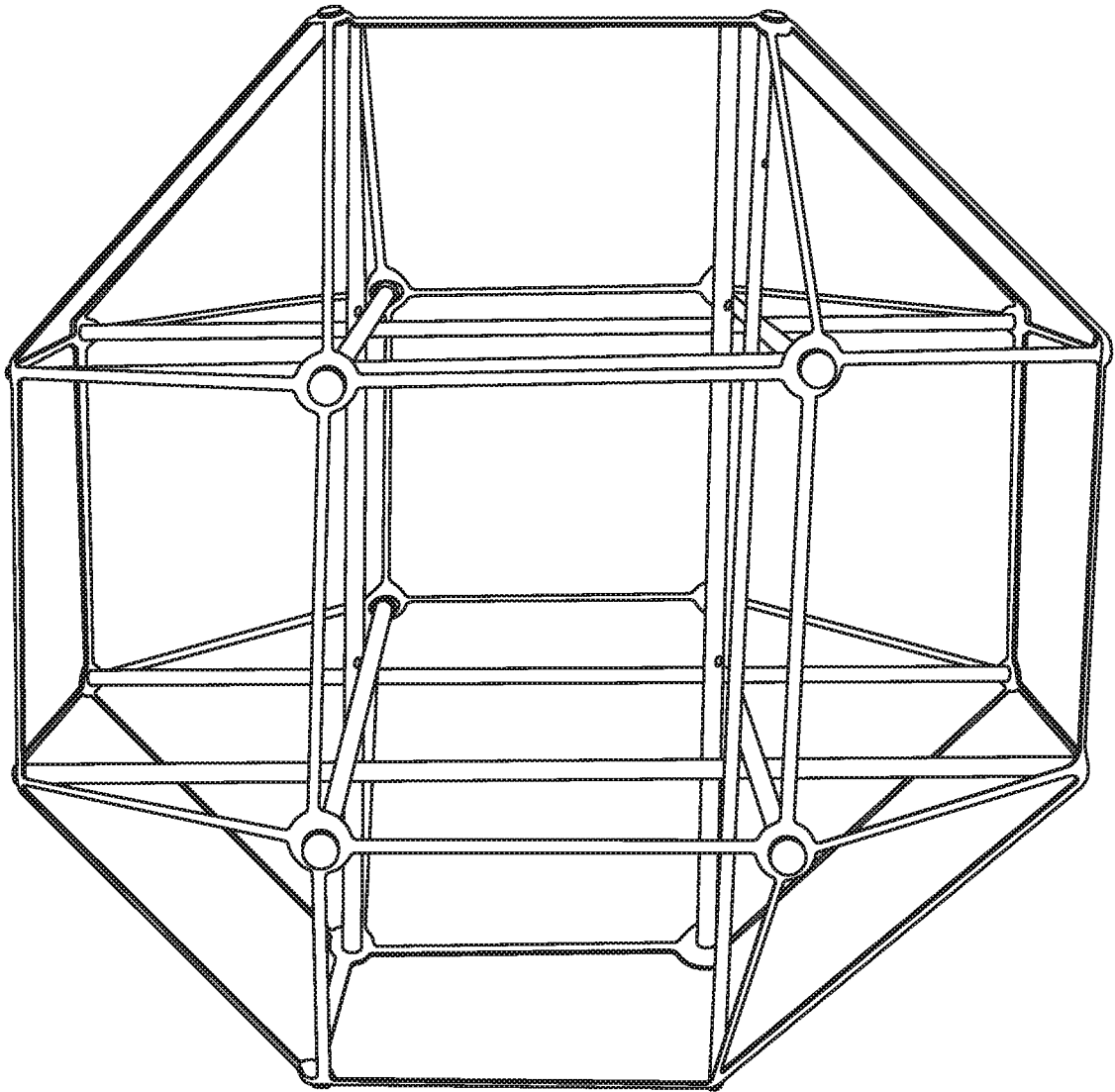


FIG. 8
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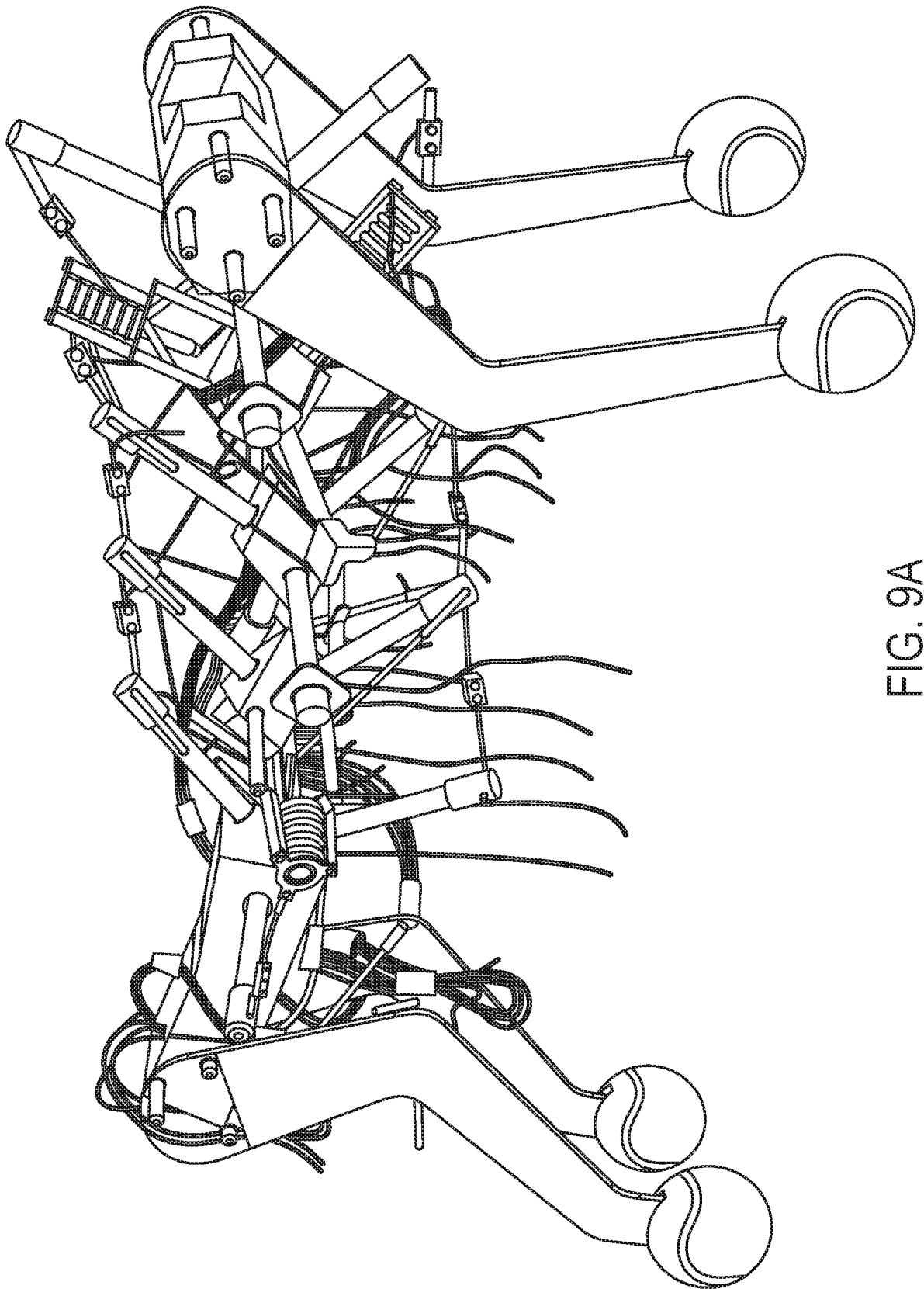


FIG. 9A

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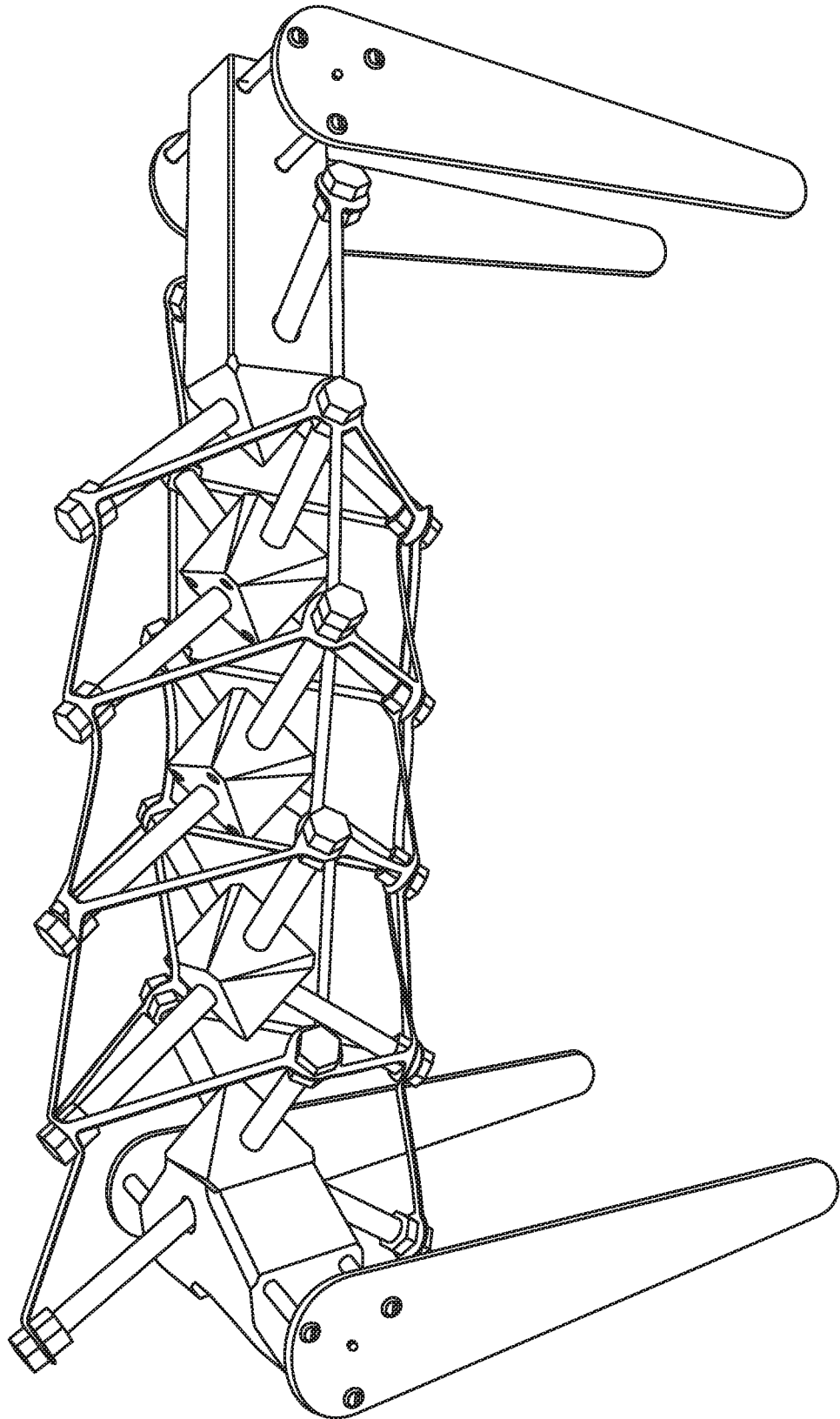


FIG. 9B

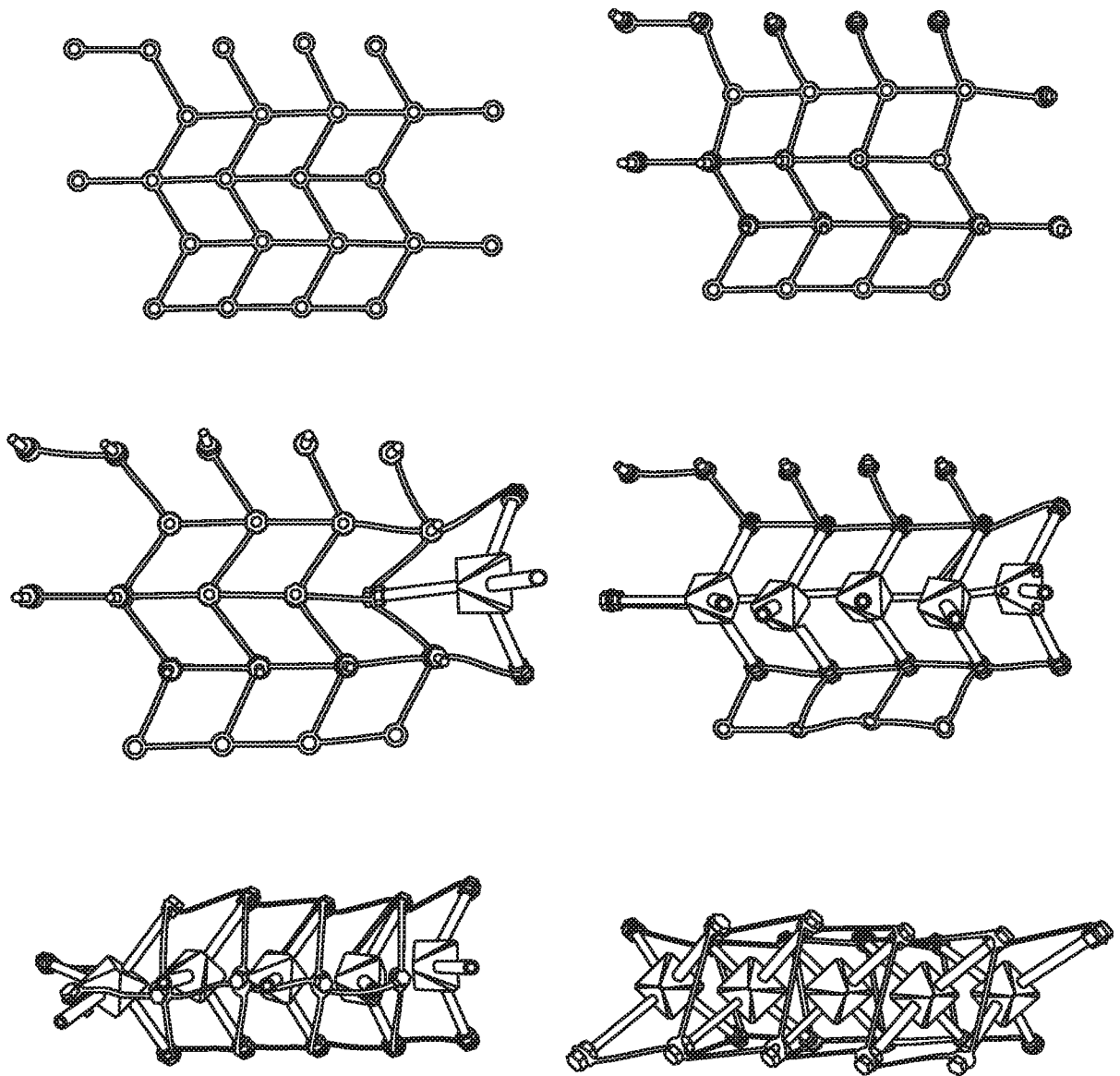


FIG. 10

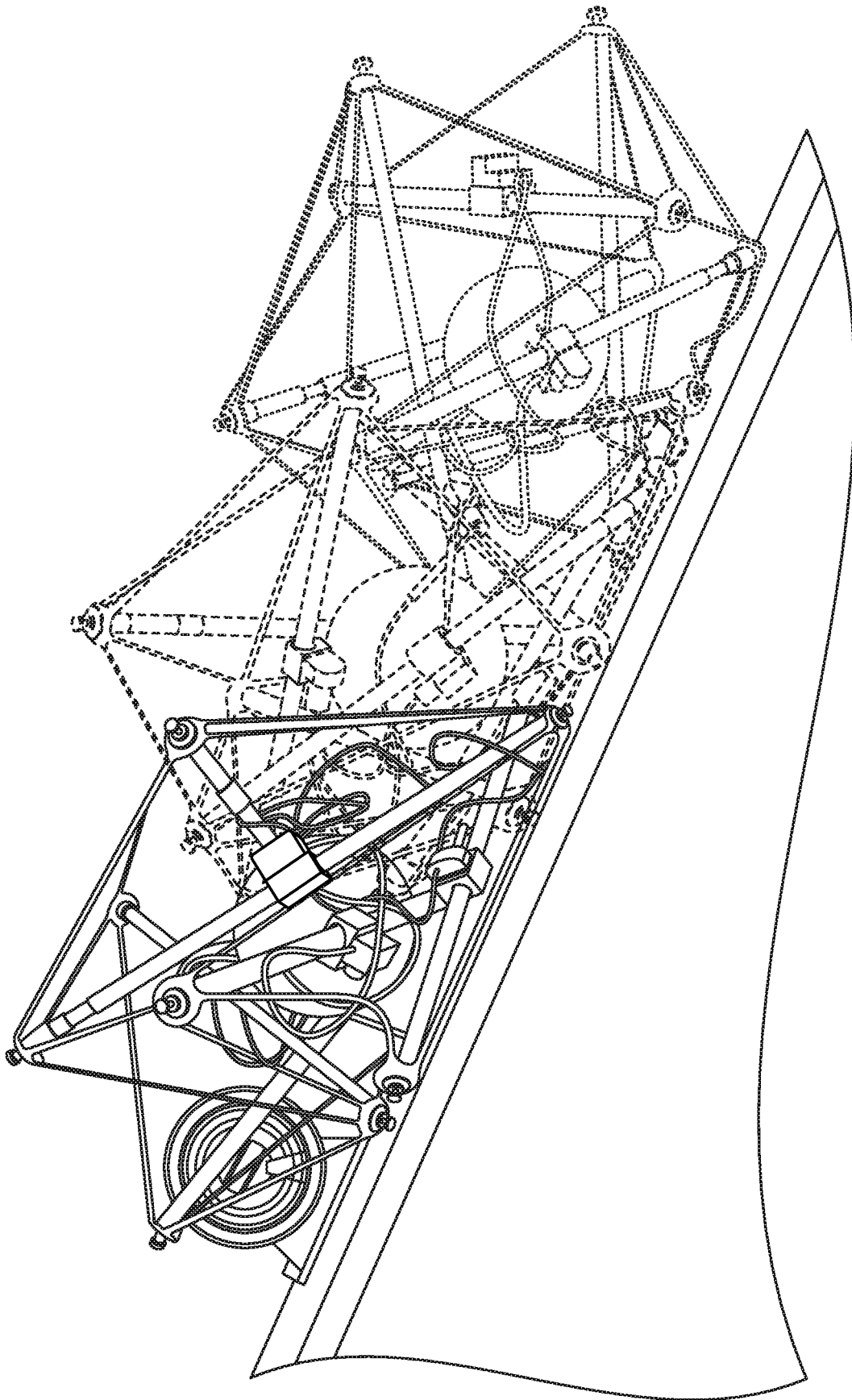


FIG. 11

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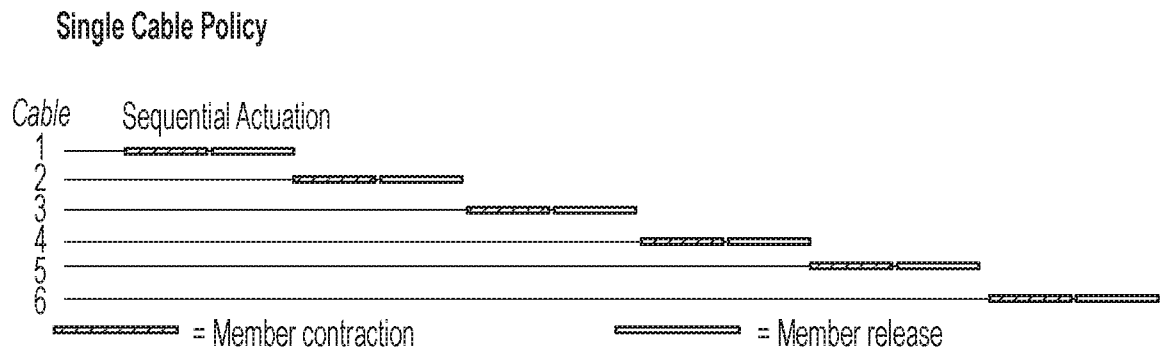


FIG. 12

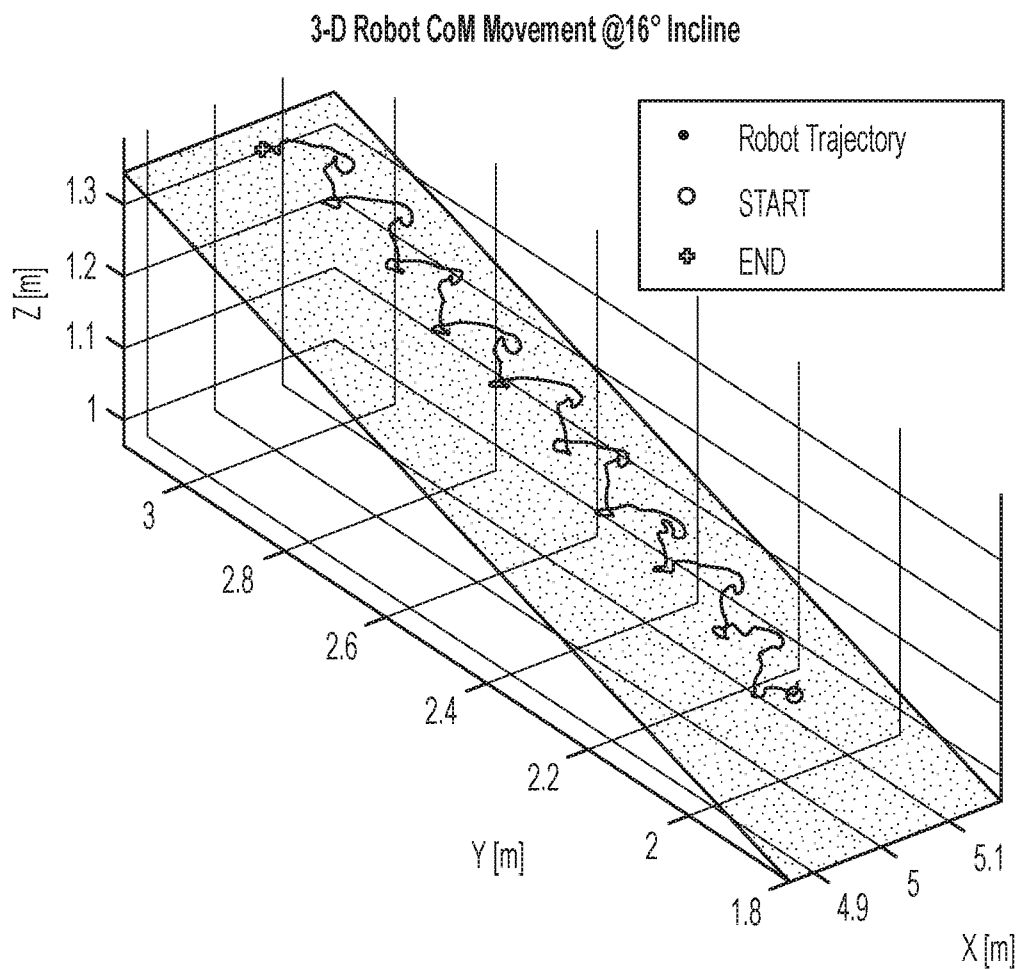


FIG. 13

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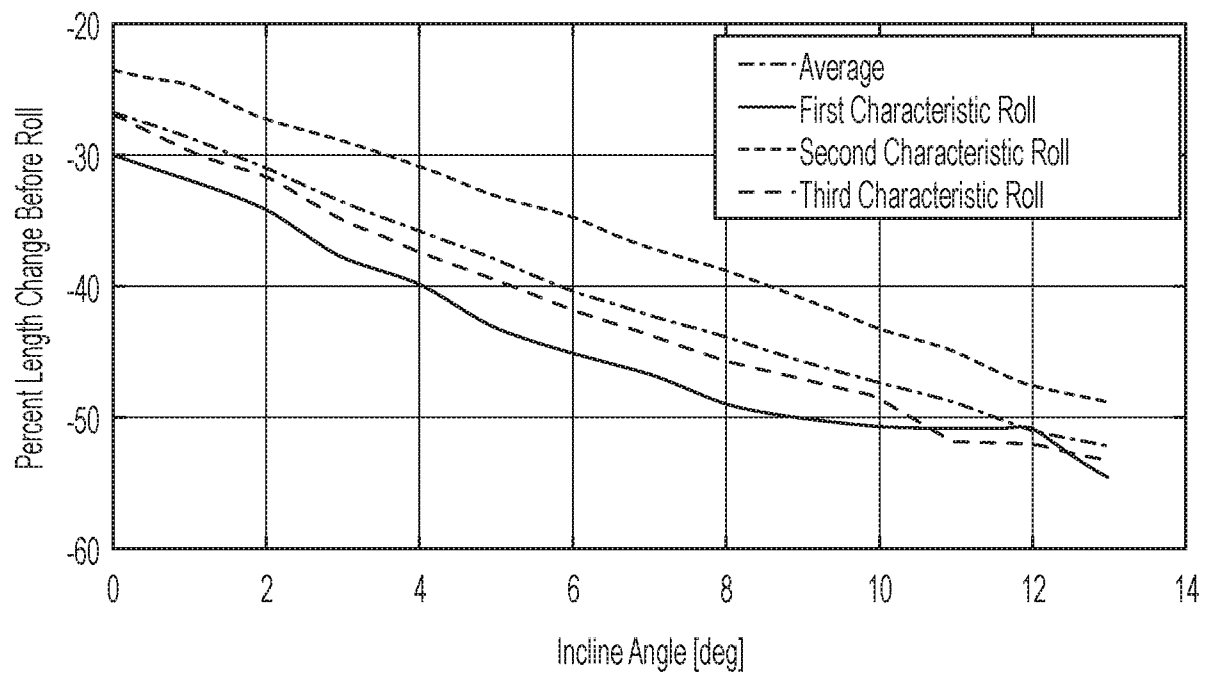


FIG. 14

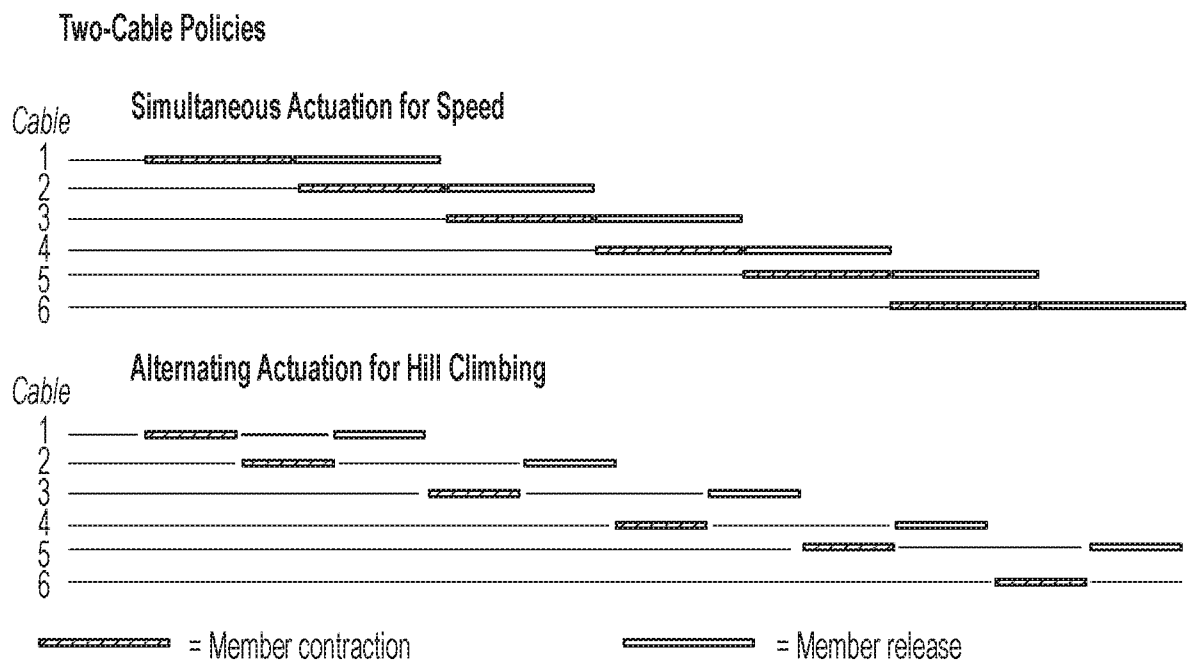


FIG. 15

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Summary of Hardware Experiment Results

Strategy	Avg. Speed @ 0° [cm/s]	Avg. Speed @ 10° [cm/s]	Max Incline [°]
Single	3.19	1.96	13
Simultaneous	6.32	4.22	22
Alternating	3.02	2.12	24

FIG. 16

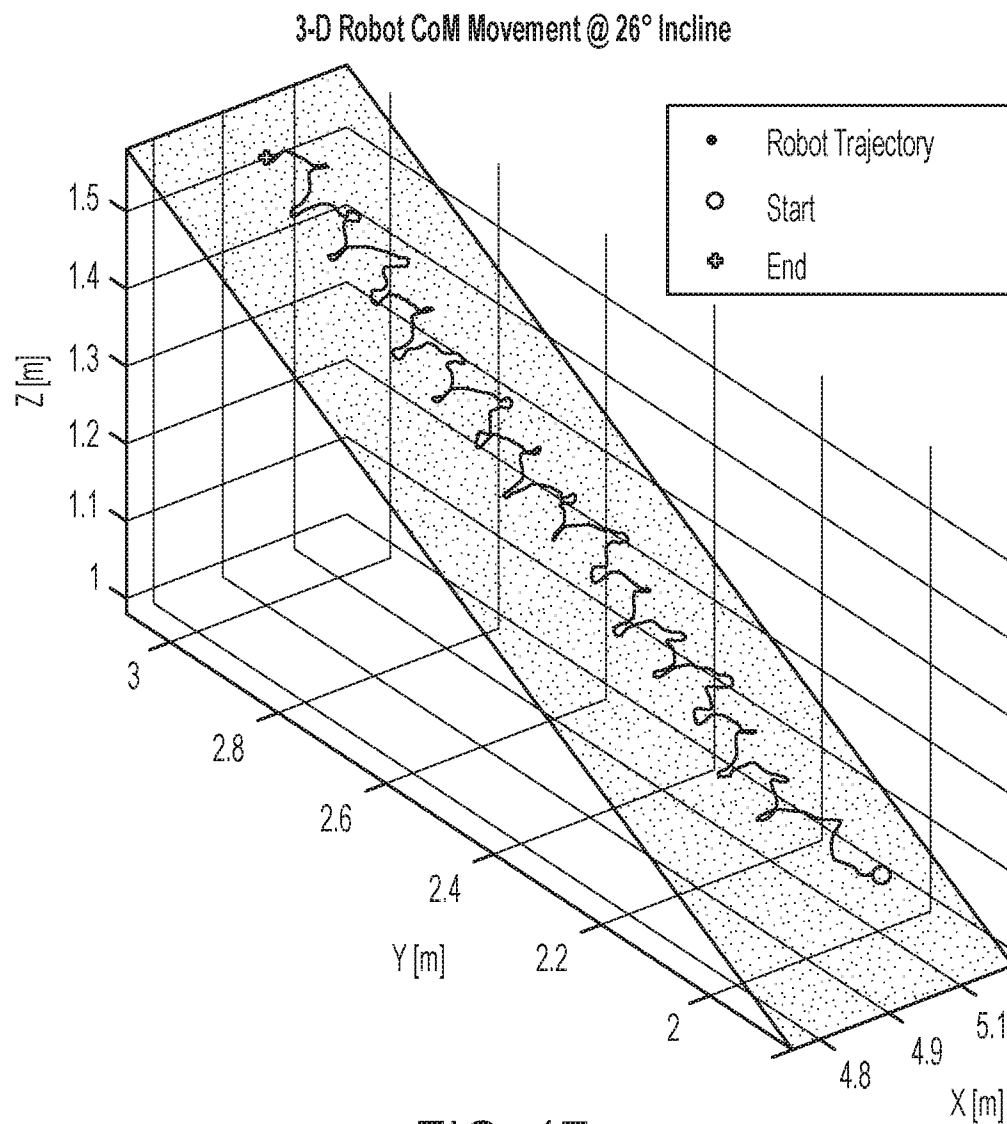


FIG. 17

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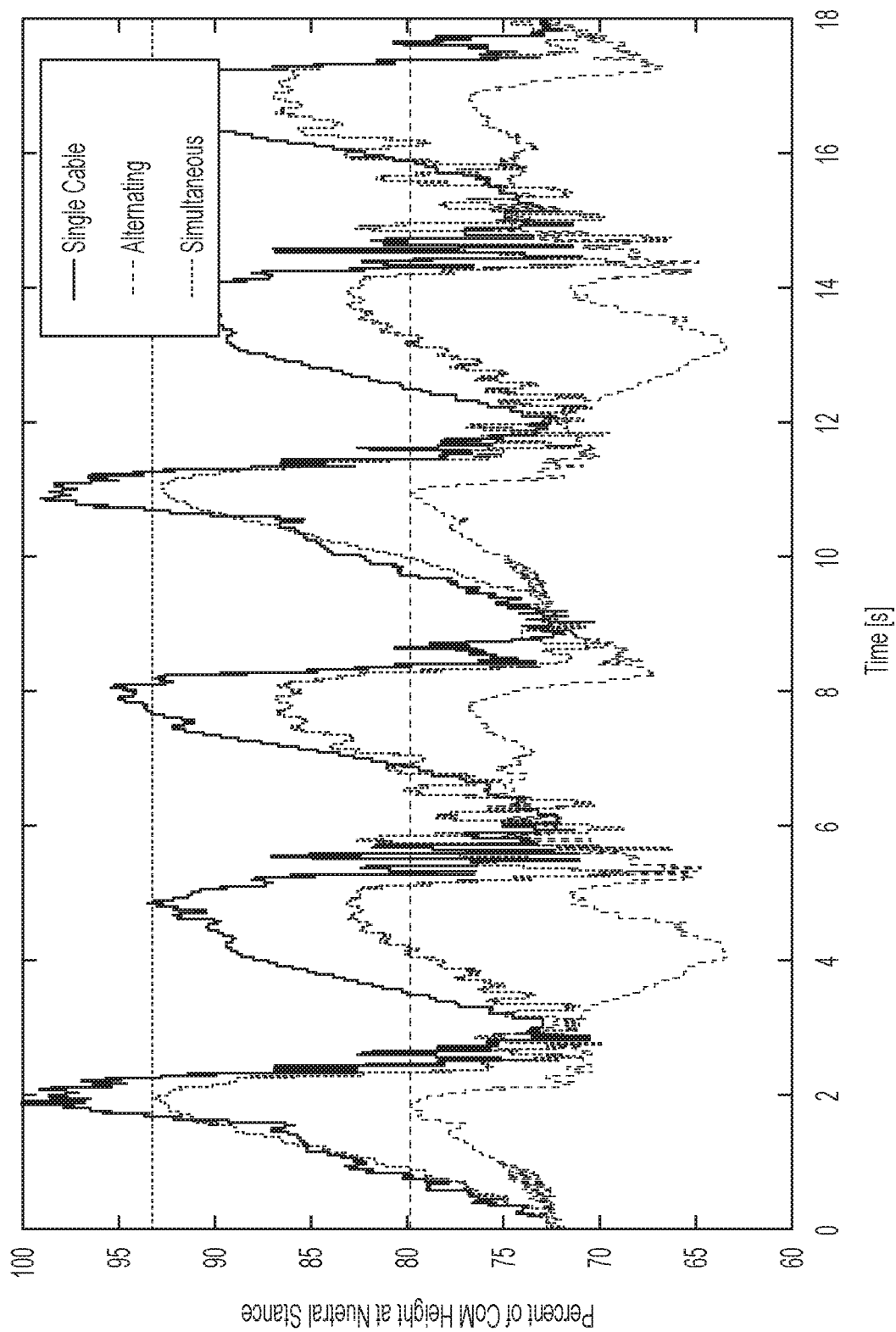


FIG. 18

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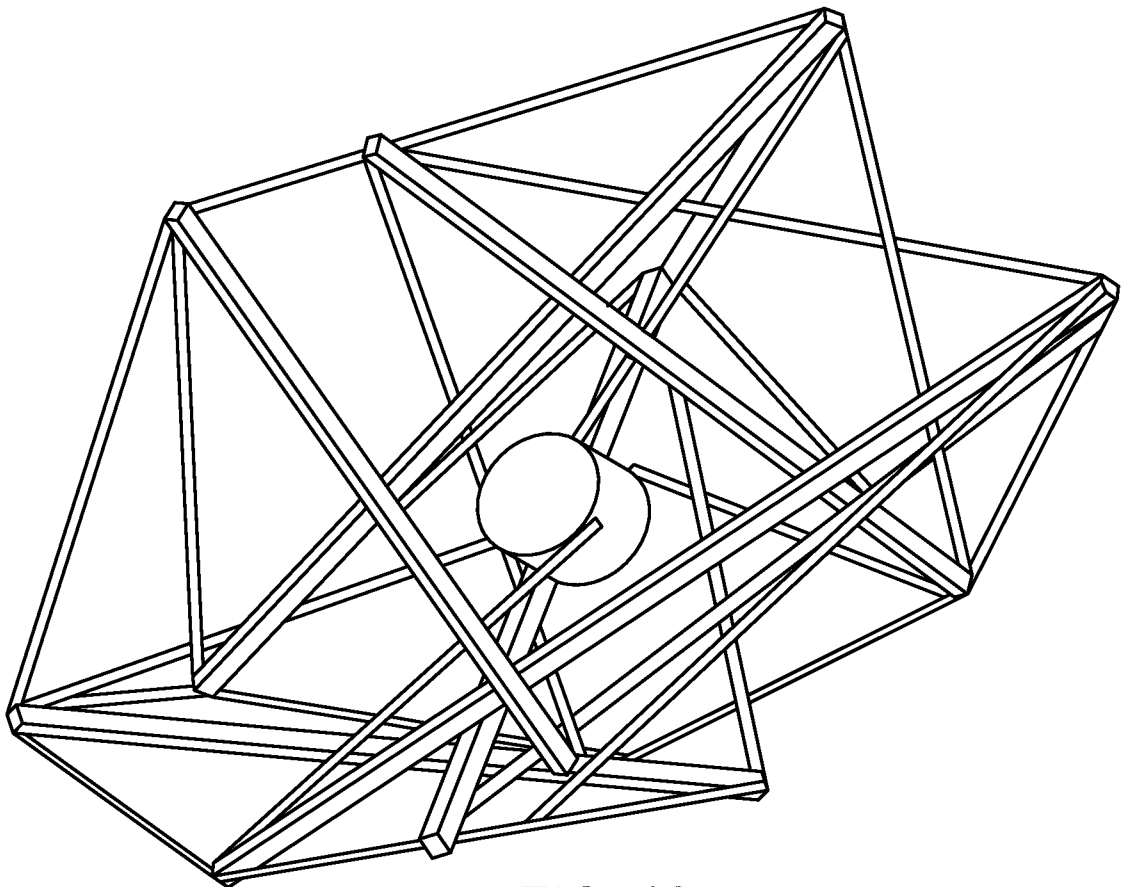
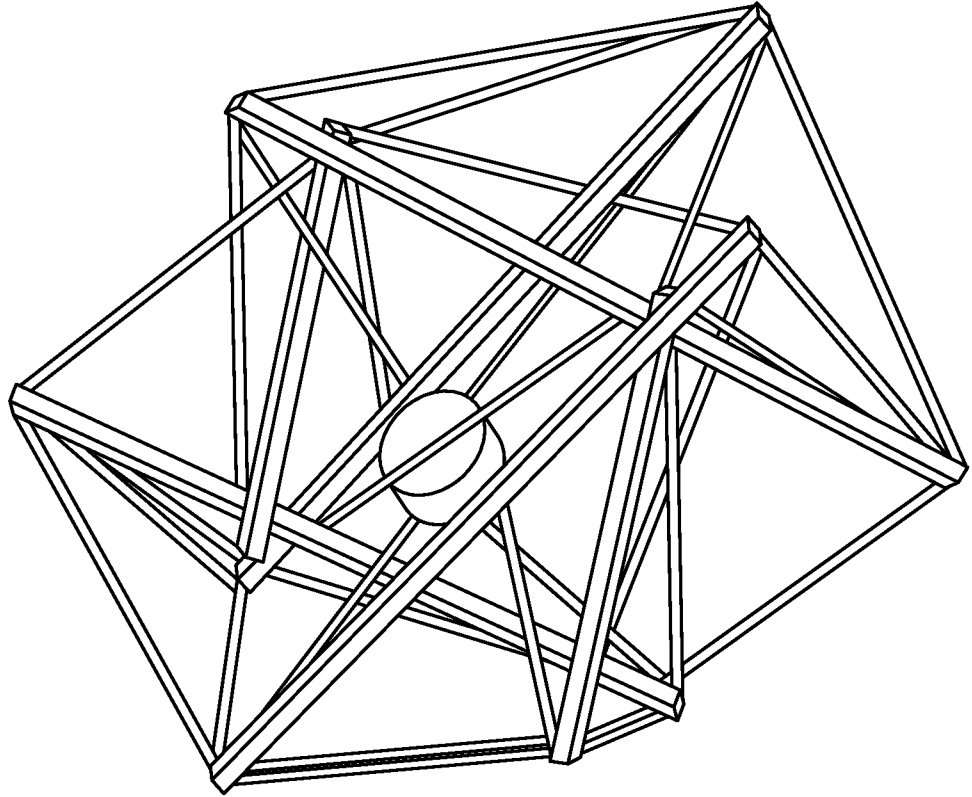


FIG. 19

SUBSTITUTE SHEET (RULE 26)

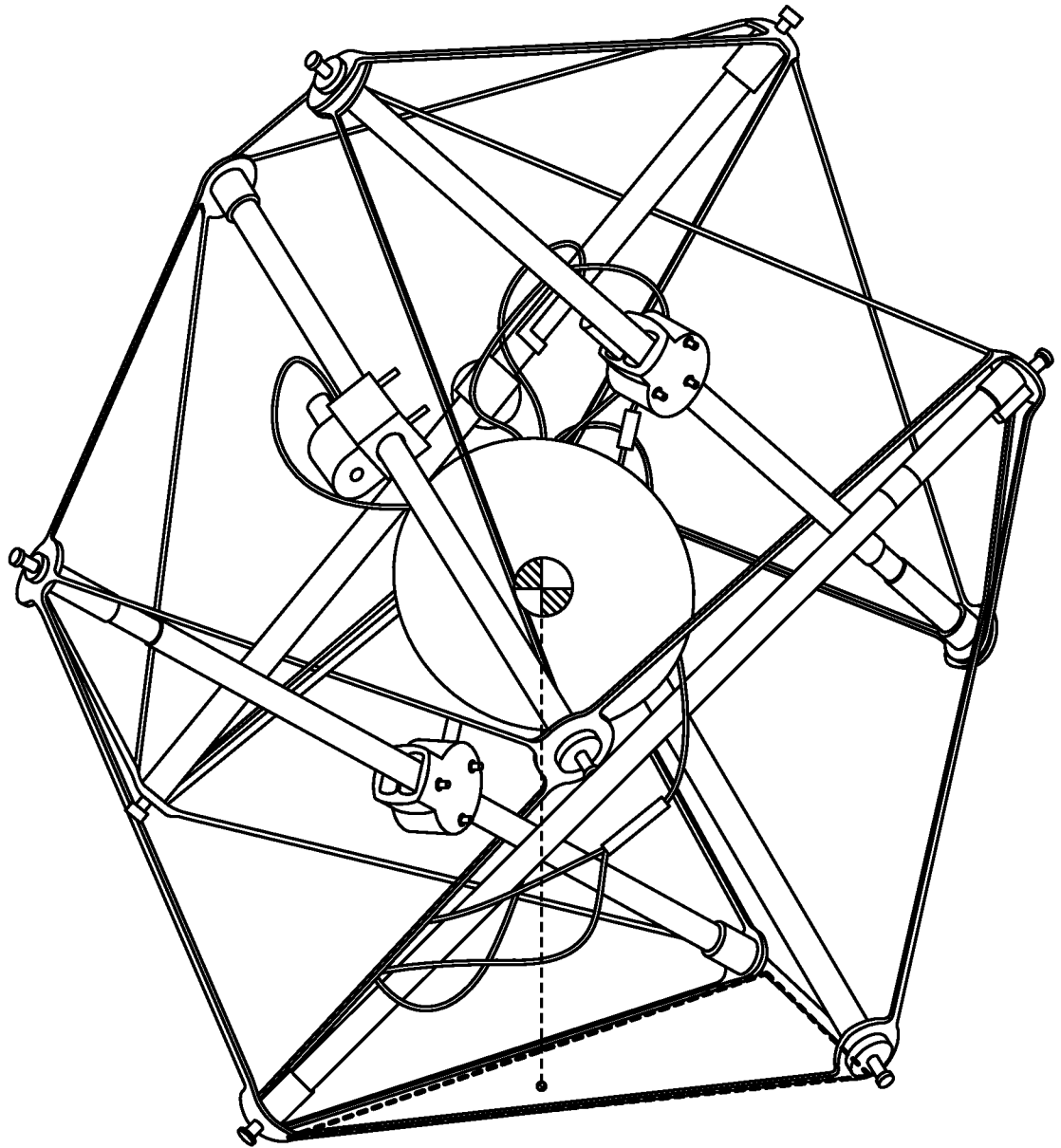


FIG. 19
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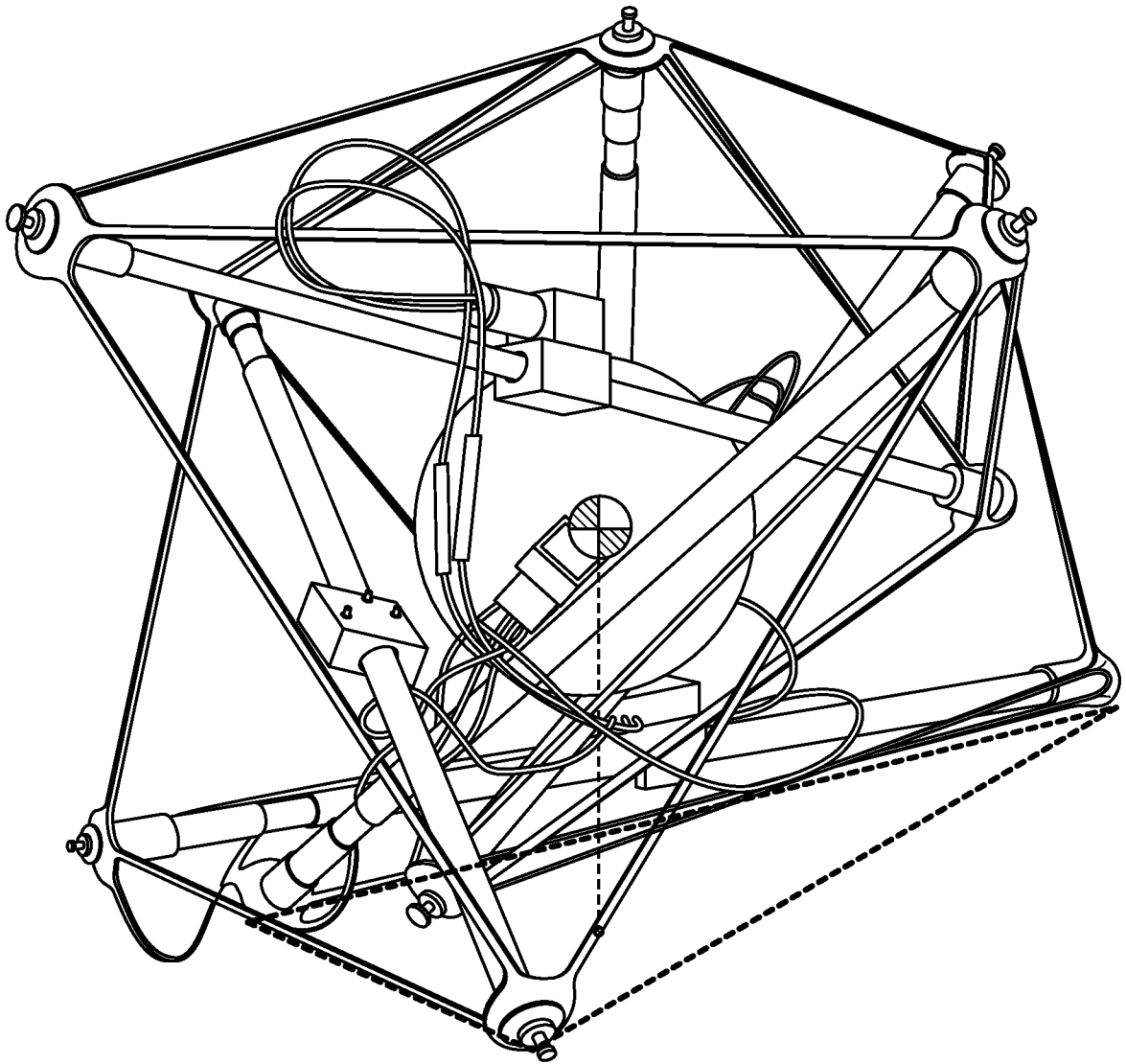


FIG. 19
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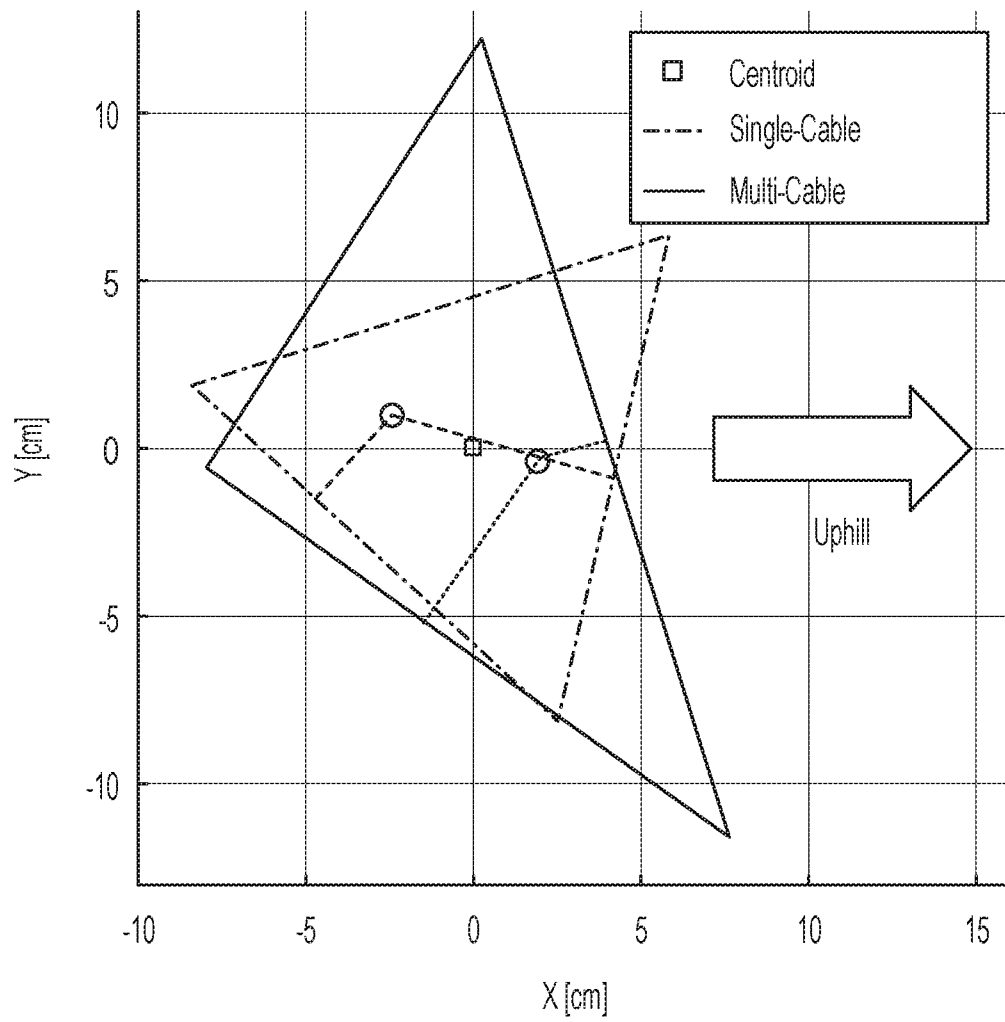


FIG. 20

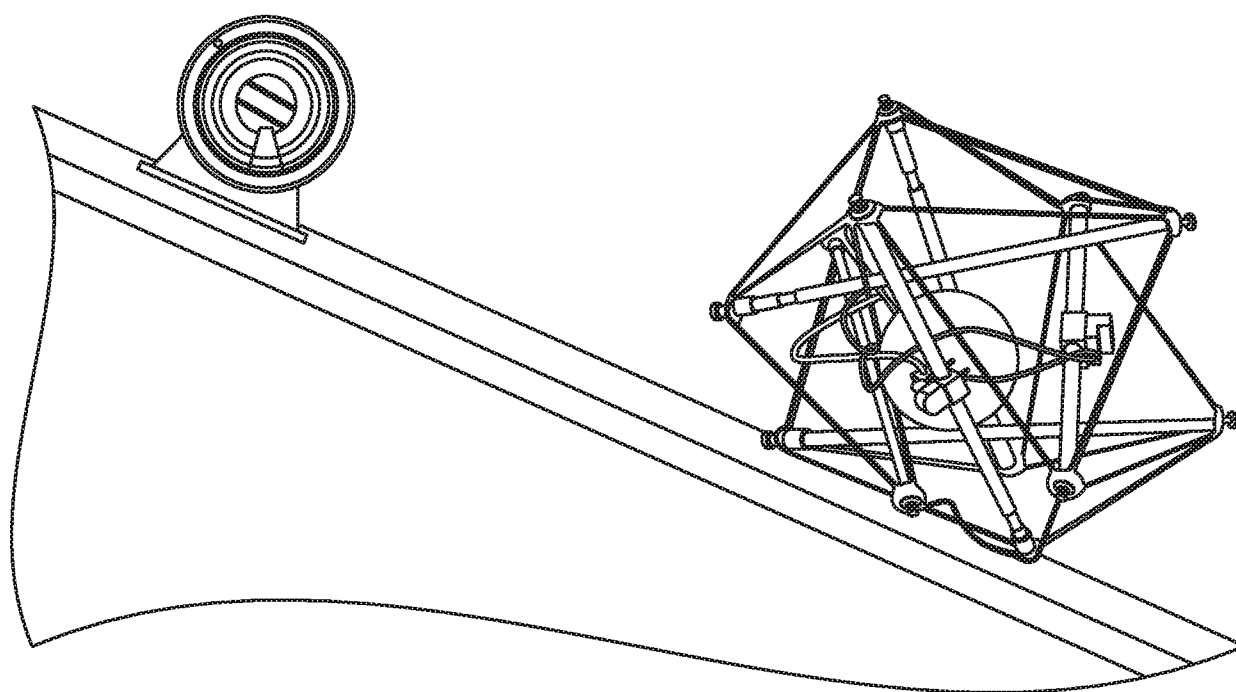


FIG. 21

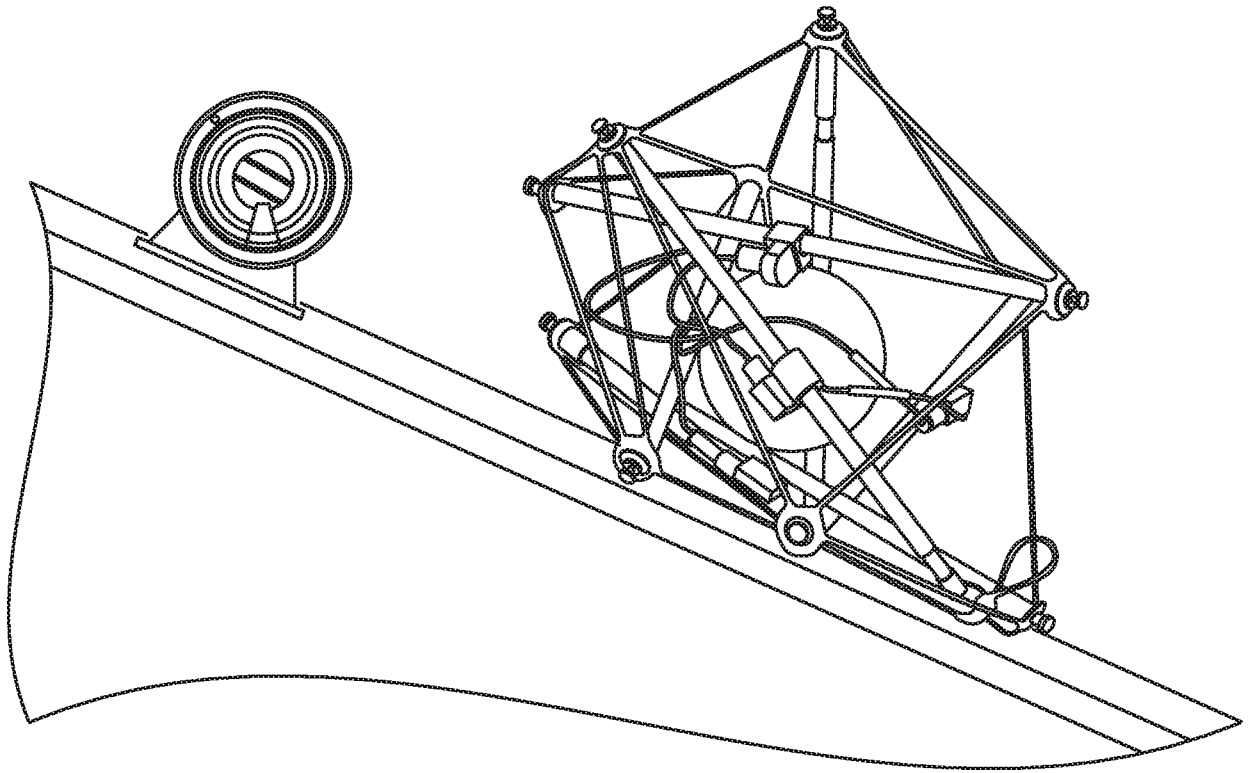


FIG. 21
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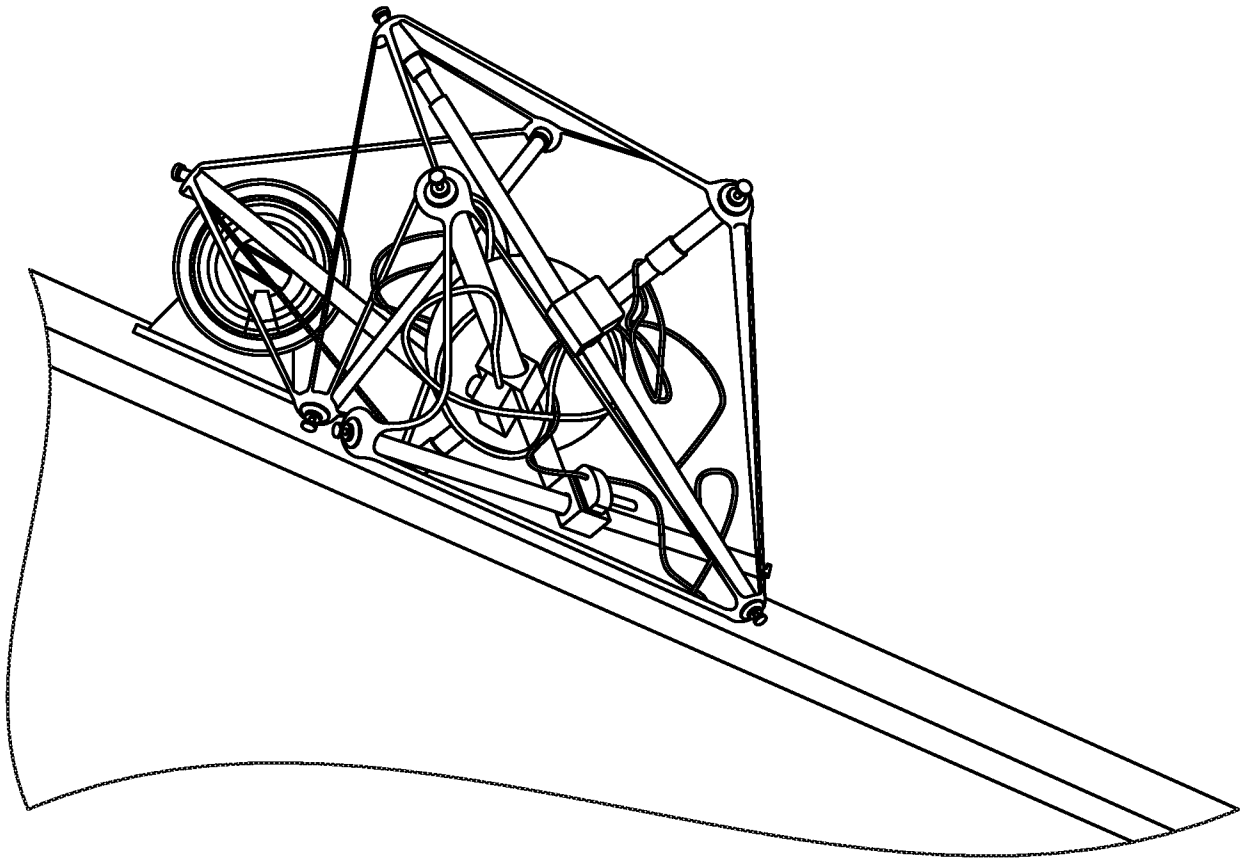


FIG. 21
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2018/020966**A. CLASSIFICATION OF SUBJECT MATTER****B25J 9/00(2006.01)i, B22F 9/10(2006.01)i, B25J 11/00(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B25J 9/00; B64B 1/14; E04B 1/34; E04B 1/19; B64G 1/22; B64B 1/08; B22F 9/10; B25J 11/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: tensegrity robot, compressive, interconnect, tensile, lattice

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KIM KYUNAM et al., `Rapid prototyping design and control of tensegrity soft robot for locomotion.` In: International Conference on Robotics and Biomimetics, 2014, IEEE, pp. 7-14. see page 7, left column - page 13, right column; and figures 1-2.	1-3, 19-20
Y		14-17
Y	US 2017-0021907 A1 (RAPPORT, NATHAN) 26 January 2017 See paragraph [0054]; and figure 2.	14-17
A	US 2015-0151854 A1 (SCOLAMIERO et al.) 04 June 2015 See paragraphs [0049]-[0095]; and figures 1-3.	1-3, 14-17, 19-20
A	US 2015-0000213 A1 (NADEAU, GERARD F.) 01 January 2015 See paragraphs [0057]-[0062]; and figures 1-5.	1-3, 14-17, 19-20
A	WO 2014-029896 A1 (UNIVERSIDAD DE CANTABRIA) 27 February 2014 See claims 1-13; and figures 1-14.	1-3, 14-17, 19-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

25 June 2018 (25.06.2018)

Date of mailing of the international search report

26 June 2018 (26.06.2018)

Name and mailing address of the ISA/KR

International Application Division

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INTERNATIONAL SEARCH REPORTInternational application No.
PCT/US2018/020966**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☒ Claims Nos.: 10, 13
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claims 10 and 13 are not clear because they refer to claims 9 and 12 respectively, which do not comply with PCT Rule 6.4(a).
3. ☒ Claims Nos.: 4-9, 11-12, 18
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2018/020966

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2017-0021907 A1	26/01/2017	None	
US 2015-0151854 A1	04/06/2015	EP 2828928 A1 EP 2828928 B1 ES 2582481 T3 US 9815574 B2 WO 2013-140201 A1	28/01/2015 18/05/2016 13/09/2016 14/11/2017 26/09/2013
US 2015-0000213 A1	01/01/2015	US 8833000 B1 US 9546478 B2	16/09/2014 17/01/2017
WO 2014-029896 A1	27/02/2014	ES 2482365 A1 ES 2482365 B2	01/08/2014 21/01/2015