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COMPACT TENSEGRITY ROBOTS CAPABLE OF LOCOMOTION THROUGH MASS-SHIFTING

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ABSTRACT

Robustness, compactness, and portability of tensegrity robots make them suitable candidates for locomotion on unknown terrains. Despite these advantages, challenges remain relating to simplicity of fabrication and locomotion. The paper introduces a design solution for fabricating tensegrity robots of varying morphologies with modular components created using rapid prototyping techniques, including 3D printing and laser-cutting. It explores different robot morphologies that attempt to balance structural complexity while facilitating smooth locomotion. The two The techniques are utilized to fabricate simple tensegrity structures, followed by tensegrity robots in icosahedron and half-circle arc morphologies. Locomotion strategies for such robots involve altering of the position of center-of-mass to induce 'tip-over'. Furthermore, the design of curved links of tensegrity mechanisms facilitates continuous change in the point of contact (along the curve) as compared to piece-wise continuous in the traditional straight links (point contact) which induces impulse reaction forces during locomotion. The resulting two tensegrity robots - six-straight strut icosahedron and two half-circle arc morphology - achieve locomotion through internal mass-shifting utilizing the presented modular mass-shifting mechanism. The curve-link tensegrity robot demonstrates smooth locomotion along with folding-unfolding capability.

Keywords: Tensegrity Mechanisms, Robot, Locomotion

INTRODUCTION

Tensegrity structures comprise of disconnected rigid compressive elements (struts) suspended by a network of pre-stressed tensile elements (cables) and are robust, compliant, and packable [1]. These qualities have attracted considerable attention from roboticists to design tensegrity structure mobile robots for space and exploration applications [2–14].

Tensegrity Prototyping. The geometrical analysis of tensegrity mechanisms has been substantially researched [15–18]. However, prototyping of tensegrity structures remains tedious and time-consuming [7,19]. This is due to the complexity of geometric morphologies that are challenging to visualize and requirement of prestress in cables. Currently, the design methodologies for utilize jogs, multiple set of hands and precise compatible fabrication to achieve symmetric cable tension and strut compression [9,19–21]. Recently, two-dimension to three-dimension solutions have been explored using flexible lattice networks which are excellent for fabricating known morphologies which may not be altered post-assembly [10,19]. The paper proposes a design solution employing modular and rapid-producible components that is applicable to variable morphologies without requiring precise component proportions, prestressed cables, and use of jigs.

Tensegrity Locomotion. Locomotion is a result of the optimization of frictional forces between the robot and its environment at different locations of the body [22]. In case of tensegrity robots, this is often achieved by altering the center-of-mass (CoM) of the robot to induce "tip-over" that subsequently results in change in the points of contact with the environment. In case of traditional straight-link tensegrity robots, the change in points of contact (edges of links) is sudden and results in impulse forces during "tip-over" sequences. The research presents a two curve-link tensegrity robot where the CoM alteration is induced by internally shifting mass along the link

FABRICATION METHODOLOGY

Tensegrity mechanisms comprise of compressive and tensile/compliant elements. The *compressive elements* (or struts) are made of rigid material, including wood [7], plastics [9], and metals [2,8,19,20]. While the *tensile and compliant elements* are fabricated using cables, metal extension springs [4–6, 13, 20, 21] and elastic cables comprised of various plastics [2, 10, 11, 19]. Here the springs may span the full cable length [4, 5], or pair in series with other robust cable materials [6, 20, 21]. *Integration* of these elements varies considerably, with some methods including hooks [5, 8, 21],knots [7], and even clamps [19]. Here, precision in fabrication and integration of component lengths is critical to achieve the desired balance of forces required by the mechanism. Connections are often semi-permanent and restrict passive cable modification (Bohm et al employed a notable exception [9]). These limitations can be mitigated by active cable control [7, 8, 12, 20]. However, for tensegrity structures lacking active cable control, achieving even force distribution presents a challenge. A conventional solution is to determine the required component lengths of a structure before assembly. This solution is time-consuming and limits experimentation with novel morphologies.

DESIGN SOLUTION

A design solution is presented for the assembly of tensegrity structures enabling use of untensioned cables of oversized lengths, and connections supporting "passive cable tuning".
Components. Struts are laser-cut from acrylic sheet stock, enabling varying geometries to be created quickly and precisely. Cables are cut from a spool of elastic nylon cord in oversized lengths. Nylon cables may be paired in series with metal extension springs to realize additional compliance. Fig. 1a illustrates one such combination.
Connections. For a given connection point, nylon cables route through a hole in the acrylic strut. The hole is sized so that as a bolt is inserted, the nylon cables are compressed slightly, and the bolt is secured with a nut, further compressing the nylon cables. The fit of the nut can be hand-tuned to vary level of compression desired to be applied to the nylon cables, thus, enabling the assembly to act as an adjustable clamp. Exploiting this feature, the nylon cables may be clamped sufficiently to remain in place under pretension tensile forces, while still enabling adjustment. With sufficiently oversized cable lengths, all connections may even be made on a flat surface, eliminating the need for jigs (Fig. 1b, 1c). In this way, all cable connections may be made without pretensioning, then tensioned individually to achieve a balanced structure (Fig. 1d). The presented design solution may also be employed to reduce the overall number of cables in a structure by using a single oversized cable as two cables. By clamping the midpoint of the oversized cable, each ends may act as an independent cable capable of being tensioned. Interestingly, while likely not practical, a single exceedingly length could serve as the entire cable network with this design solution by routing and being clamped at each hole (likely having to overlap itself at some points). The observed benefits of the proposed solution can be summarized as:

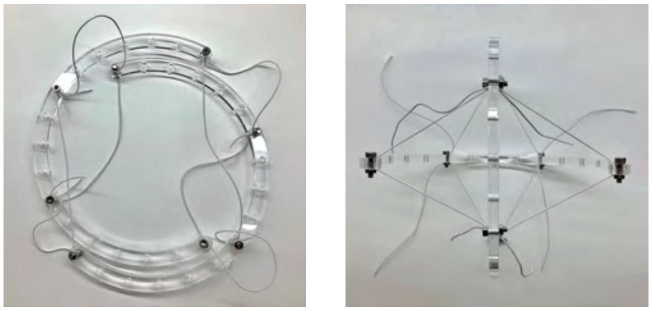
1. *Rapid prototyping and hassle-free assembly*. Components are quickly produced, applicable to a range of designs, and simple to assemble. Individual cables may be passively and independently clamped and removed without pretensioning.
2. *Cable manipulation capability*. Multiple cables may be clamped by a single connection, excess cable lengths may be trimmed, and single cables lengths may function as multiple cables. Individual cable tension and lengths may be passively modified during and after fabrication, enabling tunable levels of compliance within a structure.

The traditional straight strut morphologies were also successfully constructed as shown in Fig. 2a,2b : the 3-strut prism and the 6-strut icosahedron, which can be packed into a single combined strut.

MORPHOLOGY DESIGN FOR LOCOMOTION

Tensegrity structures adapted to mobile robots conventionally achieve locomotion through rolling about their entire body. Intuitively, morphologies resembling spheres facilitate planar rolling locomotion. However, those composed of straight struts (enabling uniaxial strut compression [1]) are limited in their ability to approximate a spheres curvature and achieve continuous change in the point of contact in an effort to achieve smooth rolling motion. Closer approximations require increased structural complexity (more links and connections). In order to balance rolling smoothness and structural complexity, the 6-strut icosahedron is frequently selected to achieve rolling locomotion [3, 5–7, 12, 13, 21]. This morphology enables planar locomotion, but motion is characterized by discontinuous "tip-over" impacts between triangular faces. Furthermore, these triangular faces are non-linearly sequenced, resulting in continuous "zig-zagging" directional change. This overall motion is described as "punctuated rolling motion" [23] achieved through "steps" [20] or "flops" [6]. As an example, the 3-strut prism, seen in Fig. 3a, while not well-suited for rolling locomotion, is notable for its simplicity and ability to be folded into a single combined strut. Similarly, the 6-strut, Fig. 3b, had its zig-

(a) COMPONENTS (b) STRUT END CONNECTIONS



(c) STRUT MIDDLE CONNECTIONS (d) CABLES PASSIVELY TENSIONED

(e) ASSEMBLED MECHANISM

FIGURE 1: ASSEMBLY OF A CURVED LINK TENSEGRITY MECHANISM.

(a) 3-STRUT PRISM (b) 6-STRUT ICOSAHEDRON

FIGURE 2: CONVENTIONAL STRAIGHT STRUT TENSEGRITY MORPHOLOGIES FABRICATED USING THE PROPOSED DESIGN METHODOLOGY.

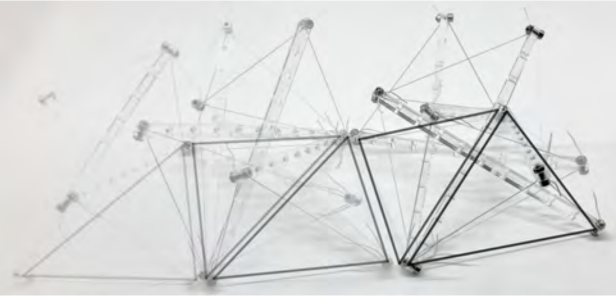
zag, “flopping” locomotion observed through hand rolling. Mitigating these problems has been explored through careful control [6, 7] and further increased structural complexity to feature 12-struts (rhombicuboctahedron-like morphology) which “steps” between linearly sequenced square faces to eliminate directional change [20].

An emerging approach towards achieving smooth rolling locomotion is found by directly introducing curvature to struts. Here, the curvature introduces additional bending moment to struts (perhaps straining the definition of tensegrity). However, Böhm et al [4, 9, 24] have demonstrated smooth uniaxial rolling motion with their novel morphology composed of two curved struts. Interestingly, this morphology is not analogous to a sphere, but more closely resembles a condensed sphericon. A sphericon is a geometric roller formed by two orthogonal half-arcs meeting at the same center of curvature [25] that is capable of uniaxial rolling. Furthermore, it has been found that an improved geometric roller may be created through modification of the arc length of these arcs and the distance between their respective centers of curvature [24]. This geometric roller may be adapted towards a tensegrity morphology capable of smooth uniaxial rolling and full planar locomotion with the addition of conventional “tip-over” operations [9]. These results invite further exploration into other curved strut morphologies potentially suitable for tensegrity robot locomotion.

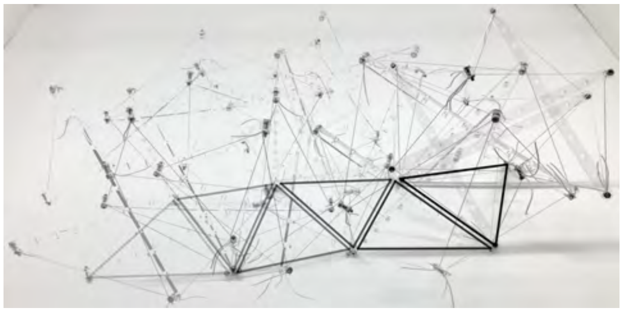
Exploring curved link morphologies. The two-arc roller as illustrated in Fig. 4a is a variation on Böhm-morphology [9] where the centers of the arcs don’t coincide. This was observed to have similar dual-axial locomotion with a slight wobble (Fig. 4a). The oloid (Fig. 4b) further varies the arc angle of the arc beyond 180 deg is a uniaxial roller - it demonstrates wobble locomotion, but along a one axis as shown in Fig. 5b. The two-disc roller (Fig. 4c) is an oloid where the centers of the arcs coincide - the resulting oloid-like locomotion as along its outer edges was hindered at its poles. The extra link, curved 3-strut structure (Fig. 4d) behaved similar to the straight 3-strut prism, with still inefficient, but somewhat improved rolling locomotion. Addition of non-structural curved features to these modified morphologies (Fig. 6) displayed reduction in wobble. The additional features functioned as an exterior shell for the structure, filling in portions of the open spaces between struts.

LOCOMOTION AND TENSEGRITY ROBOTS

Controlled rolling locomotion in tensegrity robots is conventionally achieved through altering of their CoM that is either achieved through deformation of the body [3] or internal shifting



(a) ROLLING LOCOMOTION OF 3-STRUT PRISM



(b) ROLLING LOCOMOTION OF 6-STRUT PRISM

FIGURE 3: PUNCTUATED ROLLING MOTION ALONG THE FACES OF STRAIGHT-STRUT TENSEGRITY MECHANISMS RESULTING IN CONTINUOUS ZIG-ZAG.

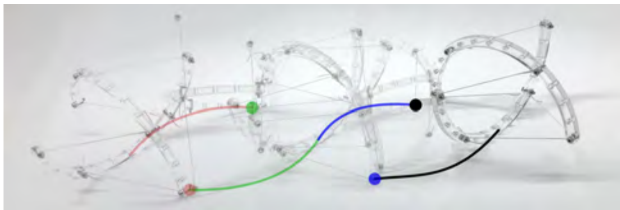
of the mass [4,9]. Through coordinated cable actuation, the body deformation results in change in robots CoM and ground contact surface, causing the body to rotate. Here, actuating the numerous cables involved requires a large control effort [9]. Internal mass-shifting strategy alters the robots CoM without deforming the body and facilitating smooth rolling locomotion. Mass-shifting mechanisms only require a single actuator, and may be incorporated directly into existing struts, independent of tensile cable networks. Furthermore, this approach has been demonstrated to achieve high-speed locomotion with reduced control complexity and minimal actuation.

Locomotion Solution. Proposed mass-shifting approach involving a modular pulley system draws inspiration from Böhm et als refined prototypes [9]. The internal mass-shifting is achieved through a pulley system that can directly be integrated onto the links, enabling modular design of tensegrity robots capable of locomotion. The Fig. 7 illustrates the mass-shifting pulley system on a straight strut. Here, the mass holder surrounds the strut and is capable of sliding along it. A pulley cable (same as tensile cables) is attached to the mass holder which is fed through a gearbox of a motor at one end and looped around the other end. The gearbox is created out of laser-cut acrylic components and consists of a driving pinion and idler gear, which grip the cable

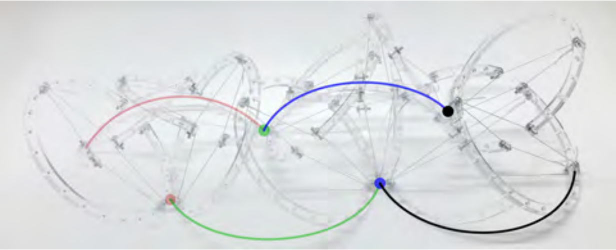
(a) TWO-ARC ROLLER (b) OLOID

(c) TWO-DISC ROLLER (d) CURVED 3-STRUT

FIGURE 4: CURVED STRUT TENSEGRITY MORPHOLOGIES



(a) DUAL-AXIS WOBBLE LOCOMOTION OF CURVED 2-STRUT.



(b) UNIAXIAL LOCOMOTION OF OLOID.

FIGURE 5: ROLLING LOCOMOTION ALONG THE FACES OF CURVE-STRUT TENSEGRITY MECHANISMS. FACES CONTACTING THE GROUND DURING MOTION ARE TRACED.

(a) MODIFIED CURVED 3-STRUT (b) MODIFIED TWO DISC ROLLER

FIGURE 6: CURVED STRUT STRUCTURES MODIFIED WITH NON-STRUCTURAL CURVED FEATURES

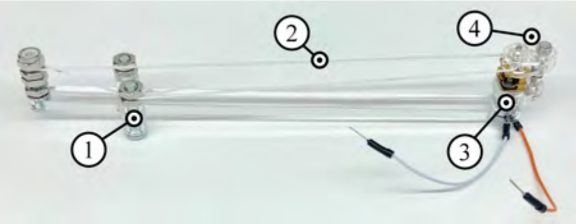
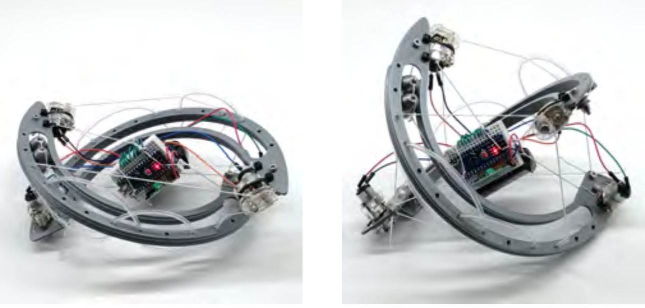


FIGURE 7: PULLEY SYSTEM COMPOSED OF SLIDING MASS HOLDER (1), NYLON CABLE PULLEY (2), MOTOR (3), AND ACRYLIC GEARBOX (4)



(a) PACKED ORIENTATION (b) DEPLOYED ORIENTATION

FIGURE 8: FOLDING OF TENSEGRITY ROBOT ACHIEVED THROUGH MOTION OF STRUTS ALONG THE CABLES.

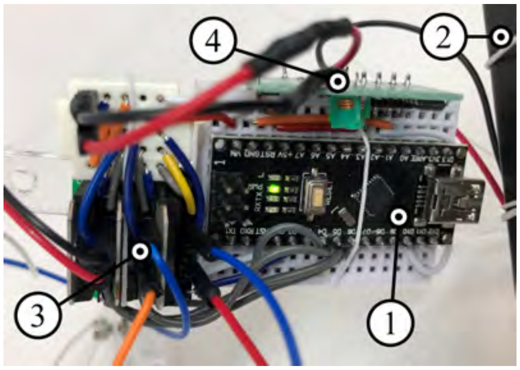


FIGURE 9: CONTROL PAYLOAD CONSISTING OF A MICROCONTROLLER (1), BATTERY (2), MOTOR DRIVERS (3), AND RADIO MODULE (4)

as they rotate. The non-backdrivable high torque motors provide a firm grip on the cable while both powered and unpowered. The current prototype uses a derivative of a Pololu Micro Metal Gearmotor. The pulley system is further adapted to modified curved struts as illustrated in in Fig. 8. Here, the pulley cable is inlaid inside the channels following the strut's curvature and the masses are directly held between the two curved sections while an end spool was employed to mitigate frictional forces. The housing components are 3D printed.

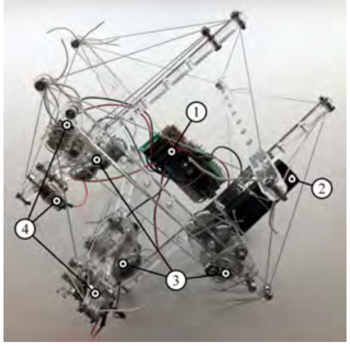
Packing-Deployment Solution. Active folding of tensegrity robots has been actively folded as explored by the SUPERball tensegrity robot [12] (6-strut straight link icosahedron). This enables compact storage of tensegrity robots and subsequent active deployment which is highly desirable for space applications and disaster relief scenarios. Folding of these robots has conventionally been achieved through active cable length change [6].

An alternative method involving motion of strut ends along cables is proposed as illustrated in Fig. 8. The cables are fed through gearboxes (the same employed for mass-shifting) attached to motors at strut ends, the strut ends may move up and down the cable lengths. Folding is achieved by coordinating the motors at both strut ends for the two-arc roller in Fig. 8.

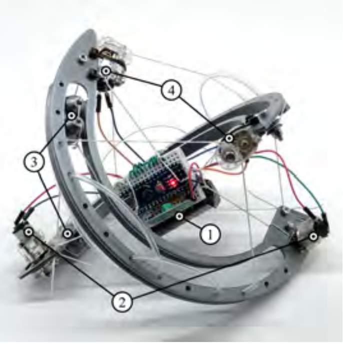
Control Payload Solution. Available options of providing power and control to tensegrity robots present limiting factors in their design. A tethered robot may be simpler and lightweight, but is limited in range - either by the length of its cord, or the likelihood tangling of the cord while rolling. Untethered robots require self-contained electronics, and potentially significant battery payloads. The presented control solution is created in pursuit of the minimum requirements of weight, size, and complexity to achieve a modular untethered system. The Fig. 9 illustrates the control payload that executes open-loop control commands wirelessly sent by an external controller.

Tensegrity Robots. Integration of the presented systems result in the creation of two mobile tensegrity robots that are capable of locomotion through internal mass shifting - the six-strut straight link icosahedron and the two half-arc curved strut.

Six-strut icosahedron morphology tensegrity. The three orthogonal struts were modified to incorporate mass-shifting systems and the electronics payload was distributed over two additional struts as highlighted in Fig. 10a. Locomotion challenges included optimizing the weight of the masses required for lo-



(a) SIX-STRUT TENSEGRITY ROBOT



(b) HALF-ARC CURVED STRUT TENSEGRITY ROBOT

FIGURE 10: TENSEGRITY ROBOTS CAPABLE OF LOCOMOTION THROUGH INTERNAL MASS-SHIFTING. THEY INTEGRATE (1) SUSPENDEDCONTROL PAYLOAD , (2) PULLEY SYSTEM WITH (3) SLIDING MASSES, AND (4) FOLDING MOTORS.

comotion with the motor (size and power). Mechatronics challenges arose from the scale of the morphology - excessively electronics and the mass-shifting systems collided at times.

Two half-arc curved strut tensegrity robot. This morphology overcomes challenges faced for the previous case and incorporates mass-shifting systems into both curved struts while the electronics payload was bundled and suspended in the center of the robot as illustrated in Fig. 10b. This morphology resulted in highly efficient locomotion (also observed by [9, 24]). By following the curvature of the robot, the masses are furthest from the geometric center of the robot and facilitate efficient altering the robots CoM. The curved struts enable smooth rolling motion by continuous change in points of contact with the variation of CoM. As the morphology only consists of two struts, folding systems is incorporated without greatly increasing the required number of actuators showing considerable reduction in volume during packed orientation.

CONCLUSION

The paper presents a design solution for fabricating tensegrity robots of varying morphologies with modular components creating used rapid prototyping techniques, including 3D printing and laser-cutting. It involved exploration of morphologies desirable for locomotion which included investigation of their shapes (staright, curved), their placement (location of center of link arcs), number of links and even non-structural elements. The resulting two tensegrity robots - six-straight strut icosahedron and two half-circle arc morphology - achieve locomotion through internal mass-shifting utilizing the presented mass-shifting mechanism. The curve-link tensegrity robot demonstrates smooth locomotion and folding packing behavior with folding-deployment orientations.

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