Gait Production in a Tensegrity Based Robot

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***Abstract*— The design of legged robots for movement has usually been based on a series of rigid links connected by actuated or passively compliant joints. However, the potential utility of *tensegrity*, in which form can be achieved using a disconnected set of rigid elements connected by a continuous network of tensile elements, has not been considered in the design of legged robots. This paper introduces the idea of a legged robot based on a tensegrity[1], and demonstrates that the dynamics of such structures can be utilized for locomotion. A mobile robot based on a triangular tensegrity prism is presented, which is actuated by contraction of its transverse cables. The automatic design of a controller architecture for forward locomotion is performed in simulation using a genetic algorithm which demonstrates that the structure can generate multiple effective gait patterns for forward locomotion. A real world tensegrity robot is implemented based on the simulated robot, which is shown to be capable of producing forward locomotion. The results suggest that a tensegrity structure can provide the basis for extremely lightweight and robust mobile robots.**

I. Introduction

Conventional design of legged robots is based on a series of rigid links which connected by prismatic or rotary joints. The joints are usually actuated using electric motors, pneumatic or hydraulic actuators. The majority of robots developed have been based on this design [9] [20]. In some cases, especially for robots which aim to produce dynamic gait the joints may be supplemented with series elastic elements, or some may simply have passive compliance [1] [19].

In this paper, the goal was to explore a new paradigm in the design of legged robots, based on the concept of tensegrity. Tensegrity structures are unique mechanical structures which are composed of a set of disconnected rigid elements connected by a continuous network of tensional members. Due to an intricate balance between the tensile and compression forces in the structure, the structure is maintained at equilibrium. Even when a moderate deforming force is applied at one point of the structure, only a transient change is effected in the global form, after which the structure once again returns to its equilibrium configuration.

Tensegrity structures were first invented by Snelson [22] in 1948 and formally patented by Buckminister Fuller in 1962 [5] [6], who coined the word tensegrity as an abbreviation of *tensile integrity*. Their ability to form the basis of lightweight and strong mechanical structures using a minimal amount of material, rapidly gained them widespread popularity in architectural design for structures such as bridges and geodesic domes [8]. Their utility was also recognized for the design of lightweight space structures such as deployable masts [7] and reflector antennas [24] [13].

With respect to the static properties of tensegrity structures, numerous theoretical investigations have been undertaken. In particular, the problem of *form finding*, that is determining the geometrical configuration of a tensegrity structure has received widespread attention [18] [17] [2] [24]. In addition to the static characteristics, the mechanics and motion control of tensegrity structures have also been investigated [3] [12] [4]. However, only Aldrich *et. al.* have studied motion control directly in the context of robotics, for trajectory tracking in a tensegrity based robotic manipulator [21].

The use of tensegrity structures in the context of locomotor robots has not been considered. This is potentially a considerable oversight. Tensegrity structures have been shown to closely resemble the cytoskeletons of single-celled organisms [11] [10], several of which are known to move. Tensegrity structures also bear resemblance to the musculo-skeletal systems of highly successful land based animals and the cytoskeletons of single-celled organisms. Cats, which can jump several meters in height without causing damage to their structure, and cheetahs, which can acheive maximum speeds of over 60 mph, are able perform these incredible feats due to the intricate incorporation of tensional elements in their musculo-skeletal system [25]. Their musculo-skeletal systems are made up of rigid links (bones) which are connected by a highly redundant network of tensile elements (tendons) with contractive elements (muscle fibers) in series. These elements work to maintain the integrity of the form, actuate the structure, and store energy, which makes it possible to resist large shocks and transfer energy from one bound to the next. In some special cases these elements have also been shown to explicitly create tensegrity in some parts of the musculo-skeletal system [14]. Thus, tensegrity structures could provide a suitable architectural basis for land based locomotion.

Tensegrity can also provide considerable benefits in terms of weight and strength-to-weight ratio. As recent years has seen a trend towards mobile robot applications in autonomous space exploration, operations in hazardous environments, military operations, and human assistive function, where the financial costs of transportability and the energetic costs of mobility are key issues in design, these areas could greatly benefit

[1] The term “legged” is used here in a general sense to represent systems that locomote using sequences of discrete contacts. This is in contrast to wheeled systems which use continuous rolling contact.

from advances in lightweight design techniques which do not require the sacrifice of strength or functionality.

In pursuit of these potential benefits, the following work addresses the motion control of a tensegrity structure for robotic locomotion. For this purpose, precise trajectory tracking is not considered a high priority. Instead, the primary focus is the production of gait, defined as the generation of periodic motions which lead to non-zero movement of the center of mass [15]. In this paper, a genetic algorithm is employed to converge on periodic patterns of actuation for locomotion. This method is used for the control of the tensegrity robot TR-3 (**T**ensegrity **R**obot with **3** struts), which is based on a triangular tensegrity prism. The results demonstrate the successful production of static and dynamic gait patterns in the robot, and show that even simple tensegrity structures can harbor the potential for dynamic gait production. Thus, it suggests the potential utility of tensegrity for land based locomotor robots.

II. Tensegrity Prism

The triangular tensegrity prism is a tensegrity structure made of three struts and nine cables (Fig. 1). The cables lie along the edges of a triangular prism and the struts lie inside the prism. The struts are rigid bars and the cables may be elastic or inelastic cables. As in a prism, the lengths of the cables along the edges of the triangular faces have equal lengths, as well as the three the transverse cables. Here we refer to the equilibrium lengths of the former as S_1, and the latter as S_2. In equilibrium all the cables experience non-zero tension. Thus, if elastic cables are used, the equilibrium lengths of the cables are usually longer than their rest lengths. By varying the rest lengths of the cables, different aspect ratios between the width and length of the structure can be acheived. The values of the strut and cable lengths that are used here are shown in Table 1.

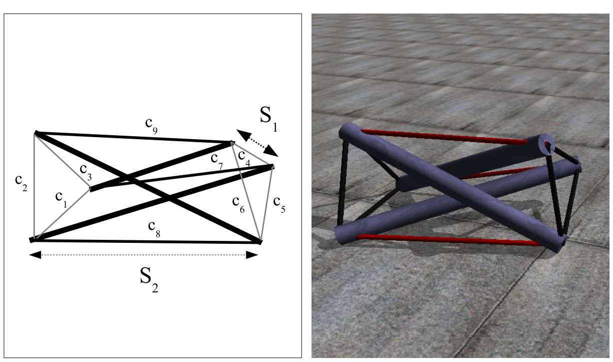

Fig. 1. a) Schematic of the 3-prism tensegrity structure. The thick black lines indicate the struts. The thin grey lines indicate the cables at the two ends of the prism. These are of length S_1. The thin black lines indicate the transverse cables connecting the two sides of the prism. These are of length S_2. b) The robot TR-3, based on the 3-prism tensegrity structure, in simulation.

Table 1 shows the values of the parameters in the implementation of the TR-3 robot.

TABLE I

Values of parameters for the TR-3 robot

strut length	1.008 m
cable spring constant k	0.7 N/m
cable damping constant c	10.0 Ns/m
cable rest length S_1^o (short)	0.347 m
cable rest length S_2^o (long)	0.441 m
equilibrium cable length S_1	0.440 m
equilibrium cable length S_2	0.880 m

III. Dynamics

As the dynamic motion control of tensegrity structures has not been of great relevance in previous applications, a full development of the equations of motion including the mass and inertial properties of the struts has not been performed. The only development of the equations of motion has been done by Kanchanasaratool and Williamson who have developed a constrained particle dynamic model, assuming zero mass struts, using the Lagrange method. However, in describing the dynamics of physical robots it is not appropriate to consider the rigid bodies as massless, and thus this model is not sufficient to represent the real dynamics of a tensegrity robot.

The Newton-Euler method is suitable for the development of the equations of motion considering the mass and inertial properties of the struts. Tensegrity structures with elastic cables do not have rigid joints to generate constraints, and thus in essence each strut can be considered a free body with a set of forces acting on it. Thus, the Newton-Euler method is more amenable to the analysis of such structures as in this method every body is treated as a free body.

This method can be used to develop the equations of motion for an actuated tensegrity. In general, if a tensegrity structure has n struts, in 3D, each strut has 6 degrees of freedom. These include three position variables $[x_i, y_i, z_i]$ and three orientation variables $[\theta_i, \phi_i, \psi_i]$ for the ith strut, the latter of which specify angles with respect to the x, y and z axes respectively. Thus, the state vector for a system of n-struts is a vector $q \in \mathbb{R}^{6n}$, such that

$$q = [x_1, y_1, z_1, \theta_1, \phi_1, \psi_1, ..., x_n, y_n, z_n, \theta_n, \phi_n, \psi_n] \tag{1}$$

Depending on the configuration of the tensegrity every strut end is connected to three or four elastic cables which exert forces on the rigid struts. The set of cable forces is $\mathbf{F_C} = [\mathbf{F_{C1}}, \mathbf{F_{C2}}, ..., \mathbf{F_{C2m}}]$ where m is the number of cables. Note there are twice as many cable forces as cables, as each cable will actually produce two force vectors in equal and opposite directions, one on each strut to which it is attached. Each cable force magnitude is calculated as follows:

$$F_i = k(||\mathbf{r_j} - \mathbf{r_k}|| - l^r_{c_i}) - c(\frac{d||\mathbf{r_j} - \mathbf{r_k}||}{dt}) \tag{2}$$

where r_j and r_k are the position vectors of the strut ends to which the cable is attached and $l^r_{c_i}$ is the rest length of the cable which produces F_i. The force vector F_{Ci} produced at the strut end represented by position vector r_j due to the cable connected between strut ends r_j and r_k is

$$\mathbf{F_{Ci}} = F_i \cdot (\mathbf{r_k} - \mathbf{r_j}) \tag{3}$$

In addition to the cable forces, the rigid struts also experience occassional contact forces from the ground. Assuming that during normal behavior only one end of a strut contacts the ground at any time, the set of ground forces is $\mathbf{F_G} = [\mathbf{F_{G1}}, \mathbf{F_{G2}}, ..., \mathbf{F_{Gn}}]$. These forces are non-zero only upon contact, and can be calculated according to a standard spring-damper based ground model [23].

Thus, the Newton-Euler Equations for the tensegrity can be written in the following generalized form:

$$\mathbf{A}(\mathbf{q})\ddot{\mathbf{q}} = \mathbf{B}(\mathbf{q}, \dot{\mathbf{q}}, \mathbf{F_G}, \mathbf{F_C}) \tag{4}$$

where $\mathbf{A}(\mathbf{q})$ is the inertia matrix.

IV. Implementation

The tensegrity structure is implemented in the *Open Dynamics Engine* (ODE) simulation environment, which provides physics based simulation of rigid body motion. It includes implementation of the frictional characteristics of ground surfaces, gravity, and the dynamics of multi-link rigid bodies composed of various types of joints.

The struts of the tensegrity structures are implemented as rigid cylindrical bodies. They have a mass of m, length l, and radius r. The outer surfaces have elastic contact properties such that when in contact with another surface they generate forces which resist penetration. The cables in contrast are implemented as virtual objects whic are massless, volumeless, and do not have any contact characteristics. Each cable is represented by a pair of forces, one of which is applied at the end of each strut to which the cable is attached. The magnitude of the force F is based on a spring-damper model:

$$F = \frac{k}{l_o}(l - l_o) - c\dot{l} \tag{5}$$

where l is the current distance between the relevant strut endpoints, l_o is the spring rest length, k is the spring coefficient and c is the damping coefficient. The forces are applied along the instantaneous location of the line joining the end points of the two struts to which the cable is attached.

A. Actuation

Three methods of actuation are possible in a tensegrity structure: strut colocated actuation, cable colocated actuation, and non-colocated actuation. In strut colocated actuation, the actuators are responsible for altering the strut lengths, and as a result the overall geometry of the structure. In cable colocated actuation, the structure is modified by changing the effective rest length of the cables. In non-colocated actuation, actuation is applied between two struts, two cables, or a strut and a cable.

For the TR-3 robot, cable-colocated actuation was selected. This is similar to prior work on motion control of the tensegrity for a flight simulator in which the control variables were the rest lengths of some of the cables of the tensegrity. The cables were located on the longitudinal cables of the prisms as indicated in Figures 1 by the black cables (c_7-c_9). The actuators applied force on the structure by effecting a change in the rest length of these cables. The maximum change in the cable length was 0.10m. The control of the robot is accomplished by periodically changing the rest lengths of these cables from the maximum to a minimum value. In simulation, this change was considered to be instantaneous.

V. Control

Each actuator was contracted once during each gait cycle. The point in the gait cycle at which the actuation begins, the duration of the contraction, and its amplitude are determined by the genetic algorithm independently for each actuator. The period of the gait is also determined by the genetic algorithm.

The relevant parameters in the control are:

λ	period of the gait cycle
α_i	amplitude of actuation for each cable
ϕ_i	phase of onset of actuation for each cable
δ_i	duration of actuation for each cable
$l^r_{c_i}$	current rest length of each cable
$l^o_{c_i}$	original rest length of each cable
t^o_i	time of onset in each cycle
t	time

The controller has the following form:

In each time step, for each cable c_i:

$$\textit{if } t \bmod \lambda = \phi_i, \textit{ set } t^o_i = t$$

$$l^r_{c_i} = \begin{cases} l^o_{c_i} - \alpha_i l^o_{c_i} & : \quad t < t^o_i + \delta_i \\ l^o_{c_i} & : \quad t > t^o_i + \delta_i \end{cases}$$

VI. The Genetic Algorithm

A genetic algorithm was used to search the space of possible controllers. Each agent in the population had a genome string with floating point values between 0 and 1. The first value in the string, p, encoded the period of the gait cycle. The rest of the genome string was composed of triples $[a_i, o_i, d_i]$ encoding the amplitude, phase and duration for each cable. The parameters λ, α_i, ϕ_i and δ_i were determined from these values as follows:

$$\lambda = \lambda_{min} + \lfloor p(\lambda_{max} - \lambda_{min}) \rfloor$$
$$\alpha_i = \lfloor a_i \alpha_{max} \rfloor, \quad \phi_i = \lfloor o_i \lambda \rfloor, \quad , \delta_i = \lfloor d_i \lambda \rfloor$$

where λ_{max} = 500, λ_{min} = 200, α_{max} = 0.10.

A fixed length genetic algorithm was used to evolve the controllers [16]. Each run of the genetic algorithm was conducted for 200 generations, using a population size of 200.

At the end of each generation, the 100 most fit genomes were preserved; the others were deleted. Tournament selection with a tournament size of three, is employed to probabilistically select genotypes from among those remaining for mutation and crossover. 25 pairwise one-point crossings produce 50 new genotypes: the remaining 50 new genotypes are mutated copies of genotypes from the previous generation. The mutation rate was set to generate an average of n mutations for each new genome created, where n was defined as a function of the genome length g_l, as $n = g_l/11$. Mutation involved the replacement of a single value with a new random value. Each genome contains floating-point values which are rounded to two decimal places and range between 0.00 and 1.00. The genome had 10 values. The first value represented the period of the gait cycle, and the rest of the genome consists of triples which represent phase, duration and amplitude of actuation for the three actuated cables.

During evolution each individual is evaluated for 10,000 time steps of the dynamics simulation. The initial condition for each individual at the first time step is at position [0, 0] in the x-y plane. The fitness of the individual is determined at the end of the evaluation period, and is considered to be the distance travelled in the y-direction with respect to the origin.

VII. Results

The results of the genetic algorithm resulted in a fitness history as shown in Figure 2. The graph shows a smooth increase in fitness for the first 40 generations, and then it reaches a relative plateau for the rest of the experiment, resulting in low final fitness. The pattern of actuation employed by the controller evolved in this experiment can be seen in Figure 3. This is a plot of the forces applied by all the cables of the tensegrity. The bottom three graphs plot the forces on the actuated cables. An instantaneous increase in cable force corresponds to activation of the actuator, which leads to an contraction of the cable. Conversely, an instaneous decrease in cable force corresponds to deactivation of the actuator. Referring back to Figure 1, cable c_7 and c_8 are the actuated cables close to the ground and cable c_9 is the one on top. Thus, as Figure 3 shows, the gait is produced roughly by activating the bottom two cables c_7 and c_8 for equal durations one after the other, while keeping the top actuator c_9 active, and then briefly relaxing all three actuators. If the actuators are labelled from front to back in Figure 1, c_8 is actuator 1, c_9 is actuator 2 and c_7 is actuator 3. The pattern of actuation can then be written as a sequence of binary states $[s_1, s_2, s_3]$, where s_i is a binary value corresponding to the state of actuator i. 0 corresponds to the actuator being relaxed, and 1 corresponds to the actuator being activated (contracted). Thus, the pattern of actuation in this gait can be seen a repeated loop through the states [0,1,1],[1,1,0][0,0,0]. The cable forces have been plotted for 1000 ms and in this duration of time, approximately three loops through this sequence of states is performed. Thus, the frequency of the gait cycle is approximately 3 Hz.

Figure 4 shows the foot contact data corresponding to the 1000 ms of actuation plotted in the Figure 3. This pattern of actuation leads to a slow, relatively static gait in which all three contact points are on the ground for large parts of the gait cycle. The gait can be understood as the robot dragging two of its struts along, using the third as a pick axe. The contact data shows that the gait pattern is not perfectly periodic, unlike the pattern of control inputs. However, a rough periodicity can be

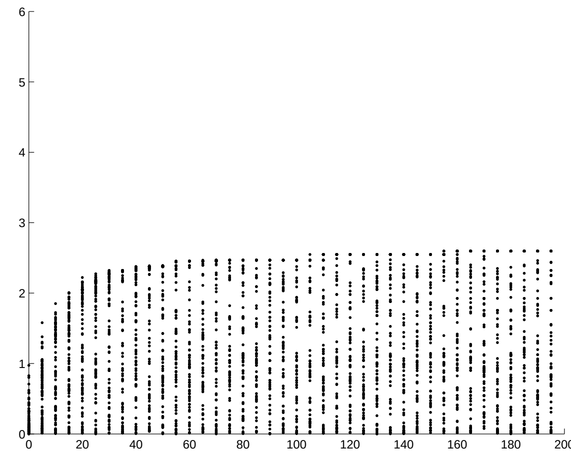

Fig. 2. **Evolutionary fitness history, TR-3** This graph plots the fitness of each agent in the population, once every five generations, over the 200 generations over which the experiment was conducted. The x-axis indicates the generation number, and the y-axis indicates the fitness of the agent, which was the distance travelled in the forward direction in 10s.

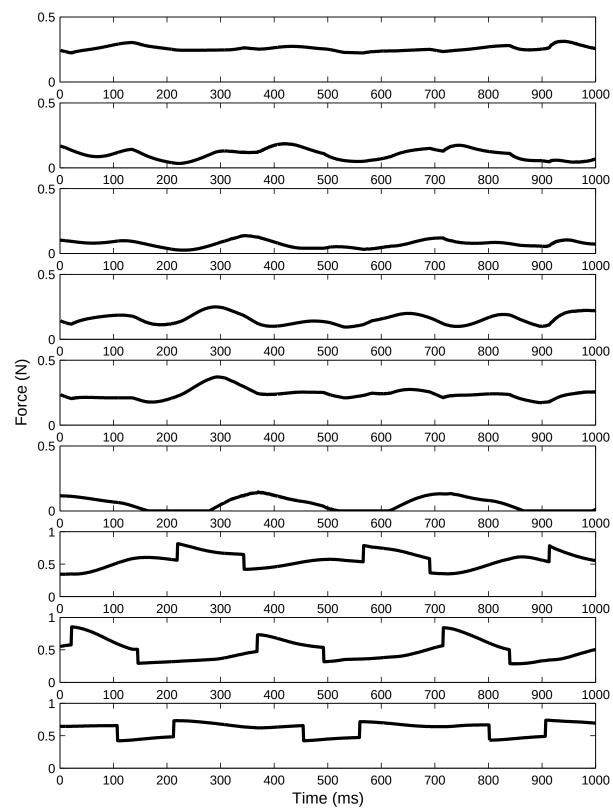

Fig. 3. **Cable Forces** Cable forces as function of time for 1000ms, plotted from top to bottom for cables c_1- c_9 (Fig. 1) respectively.

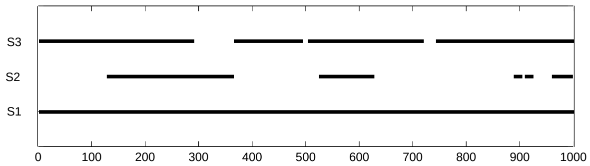

Fig. 4. **Contact Data** Ground contact information is plotted for struts S_1, S_2 and S_3 for 1000ms. Dark portions of the lines indicate when a strut is in contact with the ground, and the absence indicates loss of ground contact.

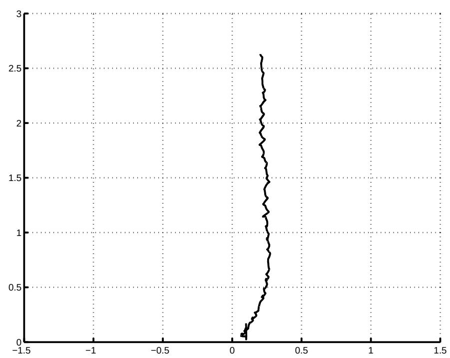

Fig. 5. **Position of CoM** The trajectory of the Center of Mass of the TR-3 robot is plotted over 10 seconds of operation timeActuator placement on the T-CUBE2 robot.

observed if the data is plotted for 10s.

The position of the Center of Mass of the robot over 10s is plotted in Figure 5. The trajectory is curved in the initial transient phase, but then tracks a straight line. The slight aperiodic nature of the gait is apparent on close observation, in that not every step produces exactly the same change in the position of the center of mass. However, it is nonetheless effective in transporting the robot at an approximate speed of 0.26 m/s.

VIII. Physical Robot

To test the feasibility of a tensegrity robot in the real world, a physical robot was developed inspired by the TR-3 robot simulation (Fig 7). Aluminum tubes were used for the struts, and nylon covered rubber elastic cable was used for the cables. The struts were 0.4m (16”) long and the cables lengths S_1 and S_2 were 0.14m (5.6”) and 0.21m (8.5”) at rest, and 0.15m (6”) and 0.33m (13”) in the equilibrium configuration. This lead to a structure with overall length, width and height of 0.36m (14.25”), 0.21m (8.5”) and 0.23 (9”) respectively. The overall weight of the structure was 680g (1.5 lbs). The physical parameters of the physical robot are slightly different from that of the simulation: the struts are slightly heavier, the cables have slightly higher elasticity, and the floor has higher friction, due to our particular choice of materials and test environment. However, it was not considered particularly important to create an exact correspondance between the simulation and the real robot, but to develop a platform that would validate the feasibility of a tensegrity robot.

The transverse cables of the robot were actuated as in the TR-3 robot simulation, using Hitec HS-625MG servomotors mounted on the struts. The servmotor axle was fitted with a 2.54cm (1”) plastic arm to which the cable was attached using a nut, bolt and washer fitting and heavy duty fishing line. The motor had a range of motion of 45°. During walking each servomotor was controlled to alternate between its maximum and minimum position value, producing an approximately 2cm change in the length of the cable. The actuators are labelled [1, 2, 3] as can be seen in Fig. 7. 1 corresponds to the servomotor towards the front of the image. 2 corresponds to the one in the middle at the top and 3 corresponds to the one behind and on the bottom. When each actuator is at its minimum position so that the cable was relaxed, it is considered to be in state 0. When it was in its maximum position, exerting force on the cable it was considered to be in state 1. A periodic pattern of actuation corresponding to looping through the states in the following order [1, 0, 0], [1, 0, 1], [1, 1, 0] [1, 1, 1], [0, 0, 0] [0, 0, 1], [0, 1, 0], [0, 1, 1]. Using this controller, the robot was able to produce gait in the longitudinal direction at a speed of 60cm/min[2].

IX. Discussion

The simulation results demonstrate that a simple tensegrity robot based on a tensegrity prism has the ability to produce gait on level terrain. The development of the physical robot, albeit demonstrating a relatively slow gait, provides a preliminary validation of the concept. The results show that a robot based on a tensegrity structure can be used for locomotion. It opens the door to a new technology in the design of mobile robots. Tensegrity robots can present numerous advantages. They can be lightweight, due to the fact that the structure achieves its rigidity based on a high number of tensile elements and a relatively small number of rigid elements. Moreover, as only a small number of actuators are used relative to the degrees of freedom, this leads to additional reductions in weight. Tensegrity robots also have a very high strength to weight ratio and are effective at absorbing shocks.

Another feature of tensegrity structures is the fact that application of a force on one part of the structure causes a global deformation in the structure, resulting in changes to various extents in all of the tensional members. Thus, different actuators can be used to cause actuate a single cable. This leads to the possibility for a small number of actuators to cause a global movement pattern, and for multiple subsets of actuators to be used to produce the same behavioral outcome. The redundancy of actuation also gives rise to robustness to control failures.

These robots have the possibility for low volume stowage and self-deployability. These are new features in the realm of robotics, which were not easily achievable using conventional technology. While the use of these features may be limited to certain application domains, they nonetheless broaden the range of possibilities for robots.

However, as with all technologies, tensegrity robots also have some limitations. The tensegrity based robots as designed

[2]The performance of the robot can be observed in the video supplied along with the paper.

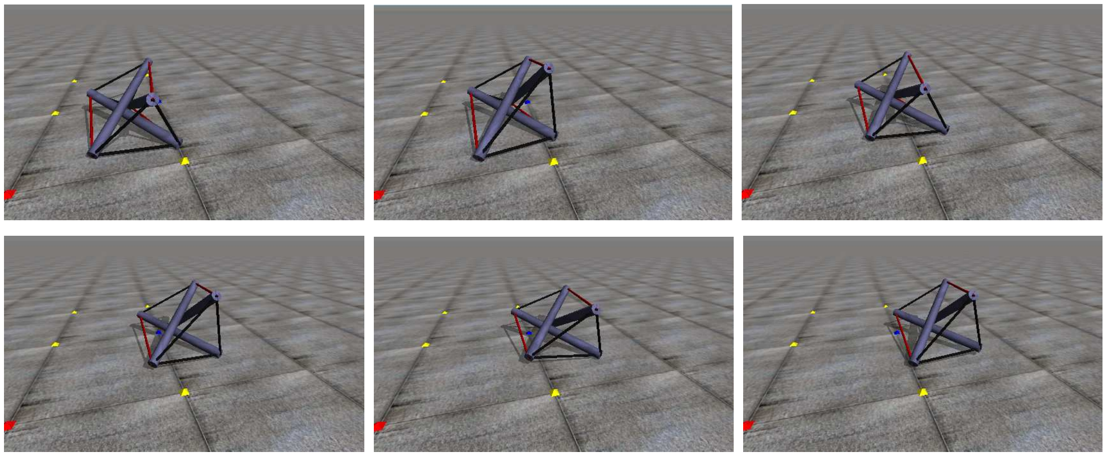

Fig. 6. Still frames extracted from video of TR-3 robot locomotion.

here are not suitable for highly precision movements. Due to the lower pre-stress conditions which enable sufficient kinematic maneuverability the structure is subject to significant vibrations, which require high bandwidth control to subdue. Thus, only tasks which can tolerate a certain measure of imprecision in trajectory tracking, or which obviate the need for trajectories are suitable for such robots. Locomotion represents a suitable task domain as joint trajectories are not always particularly important, as long as the movement produces a non-zero motion of the center of mass in the appropriate direction.

However, the requirement for precise control in locomotion can become more critical when stability issues arise. In the work presented, the TR-3 robot was statically stable and thus, within a large range of movement resisted falling. However, if the aspect ratios of the structure were much higher, leading to longer and narrower structures, then stability in a vertical orientation would be much more difficult. In such a situation, the control of postural stability may face some challenges due to the inherent elastic vibrations in the structure. The development of new theoretical methods would be required to deal with these challenges.

Fig. 7. A robot resembling TR-3 implemented in the real world.

A. Future Work

In this work, a simple tensegrity prism was selected for the basis of a tensegrity robot. However, it is likely that more ideal forms exist for locomotion. One direction of future work will focus on the design of more optimal forms for high speed locomotion, focusing on aspects including topology, pre-stress, and actuator placement.

Another issue is that the control employed in this work was purely open loop. It is likely that feedback will be necessary to acheive more stable limit cycles, and enable better control of directionality. Thus, future challenges will include the use of sensory information for feedback based control, as well more high level problems such as path-following.

A future application of tensegrity robots may be in the design of reconfigurable machines, which use actuators on the struts to change the overall geometry of the machine, and then use actuators on the cables for dynamic locomotion. This would enable the development of systems which can reconfigure their morphology with respect to the task environment and yet maintain the ability for dynamic movement.

X. Conclusion

This paper introduced the concept of using a tensegrity structure as the basis for land based locomotor robots. A tensegrity robot, based on a triangular tensegrity prism was designed in simulation and evolutionary optimization was used to obtain periodic gait controllers. It was demonstrated that such a robot had the potential to generate gait. A physical robot was designed based on the 3-prism tensegrity structure. This robot demonstrated the ability to produce forward locomotion, providing a conceptual validation of the results from simulation. The results suggest that tensegrity structures can be used to form the basis of lightweight and physically robust robots for locomotion.

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REFERENCES

[1] Buehler, M., Battaglia, R., Cocosco, A., Hawker, G., Sarkis, J. and Yamazaki, K. Scout: A simple quadruped that walks, climbs and runs In: *Proc. Int. Conf on Robotics and Automation*, 1998, p. 1707-1712.

[2] R. Connelly and A. Black, "Mathematics of Tensegrity," *American Scientist*, Vol. 86, 1998

[3] de Jager, B. and Skelton, R. E. Input/output selection for planar tensegrity models. Proceedings of the 40th IEEE Conference on Decision and Control, Orlando, Florida, USA, December 2001

[4] Domer, B., Raphael, B., Shea, K., Smith, I. F. C. Comparing two stochastic search techniques for structural control, ASCE Journal of Computing in Civil Engineerin (accepted).

[5] Fuller, R. (1961). Tensegrity. Portfolio and Artnews Annual, 4, 112–127.

[6] Fuller, R. B., Tensile-integrity structures, United States Patent 3,063,521, November 13, 1962.

[7] H. Furuya, "Concept of Deployable Tensegrity Structures in Space Applications," Int. J. Space Structures, 7:2, pp 143-151, 1992

[8] Hanaor, A. "Aspects of Design of Double Layer Tensegrity Domes" International Journal of Space Structure, Vol. 7, No. 2, 1992 pp 101-103

[9] Hirai, K., Hirose, M., Haikawa, Y., and Takenaka, T. (1998) The development of Honda humanoid robot In *IEEE Proc. Conference on Robotics and Automation*.

[10] D. E. Ingber, "Architecture of Life," Scientific American, Jan. pp. 48-57, 1998

[11] Ingber, D.E., "Cellular tensegrity: defining new rules of biological design that govern the cytoskeleton," Journal of Cell Science, Vol. 104, 1993.

[12] N. Kanchanasaratool and D. Williamson, "Modelling and Control of Class NSP Tensegrity Structures," Int. J. Control, 75:2, pp 123-139, 2002

[13] Knight, B.F., Deployable Antenna Kinematics using Tensegrity Structure Design, Doctor of Philosophy Dissertation, University of Florida, Gainesville, 2000.

[14] Levin, S. M., The tensegrity-truss as a model for spinal mechanics: Biotensegrity, Journal of Mechanics in Medicine and Biology, Vol. 2, No. 3, 2002, pp 375-388

[15] McIsaac, K. A., and Ostrowski, J. P. Motion Planning for Aunguilliform Locomotion, IEEE Transactions on Robotics and Automation, Vol. 19, No. 4, August 2003.

[16] Mitchell, M. An Introduction to Genetic Algorithms. MIT Press, Cambridge, MA USA, 1996

[17] Pellegrino, S. Mechanics of kinematically indeterminate structures, PhD. dissertaion, University of Cambridge, U.K., 1986.

[18] Pugh, A., An Introduction to Tensegrity, University of California Press, 1976.

[19] Raibert, M. H. (1986) *Legged Robots That Balance*. MIT Press, Cambridge, Massachusetts.

[20] Ridderstrom, C. Legged locomotion: Balance, control and tools - from equation to action. PhD thesis, The Royal Inst. of Technology, 100 44 Stockholm, Sweden, May 2003

[21] Aldrich, J. B., Skelton, R. E. and Kreutz-Delgado, K. Control Synthesis for a Class of Light and Agile Robotic Tensegrity Structures, Proceedings of the IEEE American Control Conference, Denver, Coloradao, USA, June 4-6, 2003

[22] Snelson, K. D., Continuous tension, discontinuous compression structures, United States Patent 3,169,611, February 16, 1965.

[23] Taga, G., Yamaguchi Y. and H. Shimizu. (1991) Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment In *Biological Cybernetics*, 65, pages 147-159.

[24] Tibert A. G. and Pellegrino, S. "Review of Form-Finding Methods for Tensegrity Structures", International Journal of Space Structures, 18:4(2003), pp 209-223

[25] Vogel, S. Cat's Paws and Catapults, W. W. Norton Company Inc, NY, USA, 1998