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Tensegrity robot dynamic simulation and kinetic strategy programming

Changhong Lin, Daiwei Li, and Yongjia Zhao

***Abstract*—Tensegrity structures are prestressed structures consisting of a set of discontinuous compressed members (struts) and continuous tensile elements (cables). Because of their unique advantages of self-deformation, foldability and light-weighting, tensegrity structures have aroused researcher's intense interest in the field of robotics. In this paper, dynamic simulation for 6-strut tensegrity robot is conducted, and is focused on locomotion control strategy by calculating continuous kinematic workspace in advance. In the simulation, the scenario that the robot rolls on the uneven terrain is designed and results show our strategy is capable of dealing with tough terrain as well as planar ground. We also developed a prototype hardware system based on rope twisting mechanism to prove the validity of our method in this paper.**

I. Introduction

Tensegrity structures are prestressed structures consisting of continuous tensile cables and discontinuous compressed struts. They have some characteristics such as high strength, light weight, deformability and impact resistibility. Tensegrity structures have been applied to the design of mobile robot, making the robot have some advantages over those traditional wheeled mobile robots and walking robots, such as the ability of adapting to complexity terrain, obstacle avoidance, shock resistance and providing protection to effective payloads located inside the structures.

The term "tensegrity", which came from a contraction of tensional integrity, was first proposed by American architect Fuller [1]. Paul proposed a 3-strut tensegrity robot and his work focused on gait production [2] and dynamic control for locomotion [3] while precise trajectory tracking was not considered. Dynamic equations for tensegrity structures were given in some research and corresponding locomotion strategy was realized [5]. For instance, a 6-strut tensegrity robot with 6 struts and 24 cables can roll over a flat ground based the locomotion policies and achieve discontinuous movement [6] [7]. The NIAC (NASA Innovative Advanced Concepts) Program employed Bullet Physics simulation engine for crash simulation with their probe Superball bot, which is developed to be used in further Titan exploration [8].

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Since the tensegrity robots have complicated parallel mechanical structure and highly coupled nature, it is difficult to control it using traditional methods. Their equilibrium state can be affected easily by even small cable actuation or tiny external disturbance [9]. It is hard to figure out the optimum actuation strategy by inverse kinematics calculation. For example, the robot is actuated based on the transformable relationship between actuator pairs and 20 situations of contact ground [10]. However, such a movement strategy makes the control parameters discontinuous. As a result, it cannot realize the continuous gait of movement. Also, this method cannot work well when the robot deforms to a singular configuration.

To deal this problem, we propose a straightforward and easy-to-implement method to work out the movement strategy for 6-strut tensegrity robot. With the proposed method, continuous and smooth locomotion can be achieved based on the kinematic workspace of tensegrity robot. We apply a series of forces to tighten cables which are classified into 12 actuator pairs, and calculate the movement of gravity center, that is to say, we work out the kinematic workspace of the tensegrity robot. We can find out how to actuate these cables to change the gravity center of tensegrity robot to desired position. By doing so, the locomotion of robot become more effective. A physical prototype is then developed based on the simulation models as a proof of our method, in this prototype, we use 24 rope twisting mechanisms as the 24 actuators of tensegrity robot.

The rest of this paper is organized as follows. Section II describes the dynamic simulation of 6-strut tensegrity robot. Section III introduces the process to find out the best locomotion strategy of tensegrity robot to realize continuous movement. Section IV shows experimental results generated by rolling a tensegrity robot base on our strategy. Finally, Section V provides conclusion and future works.

II. Geometry Description and Dynamic Modeling

A. The Geometry Description of Tensegrity Robot

Fig. 1 show the morphology of 6-strut tensegrity robot. The thick lines indicate the struts. The thin lines indicate the cables. The icosahedral has 12 vertices belonged to 6 struts. The 12 vertices are numbered according to [7]. The 6-strut tensegrity structure is geometrically similar to an icosahedron but only 24 edges have real cables. So the 6-struct tensegrity structure consists two kinds of triangles one is equilateral triangle comprised of 3 real cables and other is isosceles triangle comprised 2 real cables. Then the structure has 8 equilateral triangles and 12 isosceles triangles. To describe the state of a strut, we build a body coordination on each strut, as

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shown in Fig. 2. The origin is in the center of strut, and the x-axis is along the axial direction.

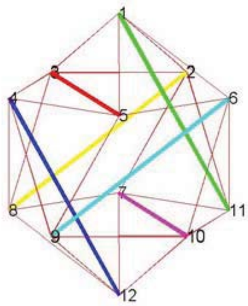

Figure 1. Abstract structure of tensegrity robot. The fine lines in brown represent cables, while other thick lines in different colors represent struts

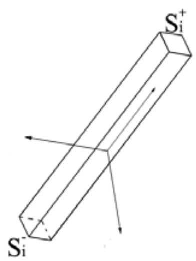

Figure 2. Body coordination system for a strut

B. Kinematic and Dynamic Description to Single Strut

1) Kinematic Description

Due to the mass distribution of strut can be considered as even-distribution. So we assume the center of a strut coincides with the gravity center of a strut. Denote $\boldsymbol{q}$ as the quaternion rotated from ground coordinate to body coordinate. Then we can calculate the rotation matrix R.

Vectors $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{c}$ denote the unit vector of body coordinate, and $\boldsymbol{c}$ is the unit vector along the axial direction of strut, then the position and speed of vertices of struts can be worked out, the positional vectors of both vertices of i-th strut are $\boldsymbol{x}_i + L\boldsymbol{c}_i, \boldsymbol{x}_i - L\boldsymbol{c}_i$, and the velocity vectors of both vertices of i-th strut are $\dot{\boldsymbol{x}}_i + L\dot{\boldsymbol{c}}_i, \dot{\boldsymbol{x}}_i - L\dot{\boldsymbol{c}}_i$. Where L is the half length of a strut. We can describe the translational motion of the i-th strut with $\ddot{\boldsymbol{x}}_i$, the $\ddot{\boldsymbol{x}}_i$ could be obtained according to Newton second law of motion. And we can describe the rotation of the i-th strut with $\ddot{\boldsymbol{q}}_i$, the $\ddot{\boldsymbol{q}}_i$ could be obtained by Lagrange equation of motion.

2) The Force Applied on Strut

We consider the cable is actuated by pneumatic muscle. Pneumatic muscle change its length by change the air pressure in its inner airbag. A pneumatic muscle can be considered as a spring obeyed Hook law when the air pressure in airbag is stable. Its stiffness($K=\frac{dF}{dl}$) is proportional to air pressure. So its mechanical characteristics can be described as[12]:

$$\mathrm{F} = K_g P'(L - L_{\min}) \tag{1}$$

where K_g is a constant, P' is the relative air pressure, $L_{\min}$ is the minimum of pneumatic muscle theoretically (when F=0) .

Every vertice is connected by 4 cables, so the tensile force of every cable should be calculated before calculating the resultant force and resultant torque of struts.

We can work out the j-th cable's length l_j and the time derivative of cable length $\dot{l}_j$, the tensile force is described as followed[8]:

$$f_j = K(l_j^a - L^a) + B\dot{l}_j + A(P_j) \tag{2}$$

Take the i-th strut into account, there are 8 tensile forces apply on the i-th strut. Defined f_i as the resultant force of i-th strut, and $\boldsymbol{\tau}_i$ as the torque of i-th strut. Then $\boldsymbol{f}_i$ can be described as:

$$\boldsymbol{f}_i = \sum_{j \in E} \boldsymbol{f}_j + [0, 0, -1]^T mg \tag{3}$$

where E is a set consisting the cable numbers connected to the vertices of i-th strut. The $\boldsymbol{f}_i$ is described in ground coordinate. The $\boldsymbol{\tau}_i$ can be described as:

$$\boldsymbol{\tau}_i = [0, 0, L]^T \times R_i^T \boldsymbol{f}_i^+ + [0, 0, -L]^T \times R_i^T \boldsymbol{f}_i^- \tag{4}$$

where R_i^T is the rotation matrix of i-th strut, $\boldsymbol{f}_i^+$ and $\boldsymbol{f}_i^-$ is the resultance force of the two vertices of i-th strut. $\boldsymbol{\tau}_i$ is described in body coordinate.

3) Flow Chart of Dynamic Simulation

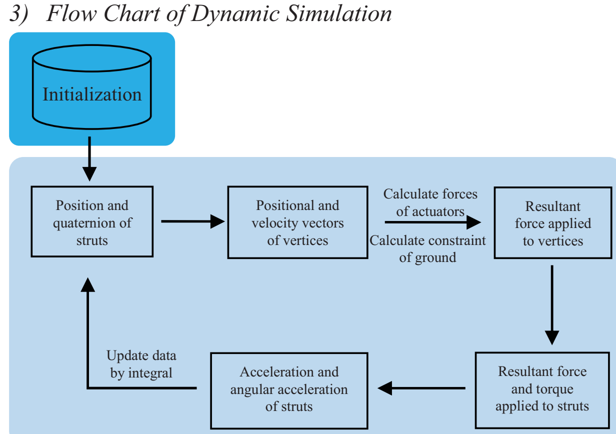

Figure 3. Simulation system pipeline

Our simulation system is illustrated in Fig. 3. At the beginning of simulation program, the initialization of the six struts (including position of gravity center and orientation of struts) are set. The positional and velocity vectors of all the 12 vertices are obtained by kinematic formula introduced above.

After that, the forces arose by 24 pneumatic muscles can be obtained based on the data of vertices. Then the accelerations and angle accelerations of six struts are computed. Subsequently simulation system updates the position and orientation data of six strut using acceleration data. Then simulation system starts new iterative with new data.

III. Kinematic Strategy Programing

In this section, we will discuss how to perform locomotion based on the dynamic model introduced in Section II. Because the tensegrity robots have no legs or wheels, the only way to make the robots move is to change their shape by change the length of the struts or cables. In this paper, we only consider the latter, which is to actuate the motor to lengthen or shorten the rest length of specified cables in each locomotion step. Shape change leads to move of the relative position between projection on the ground of the robot's center of gravity and edges of supporting triangle. Once the projective position of the robot's center of gravity move out of the scope of the supporting triangle, the robot performs the rolling locomotion.

Because the physical prototype we designed can perform continuous actuation based on a rope-twisting mechanism, we use the same actuator pairs as is used in [9], but extend it in a continuous kinematic workspace. To illustrate the strategy in the next section, we mark several actuator pair in Fig. 4.

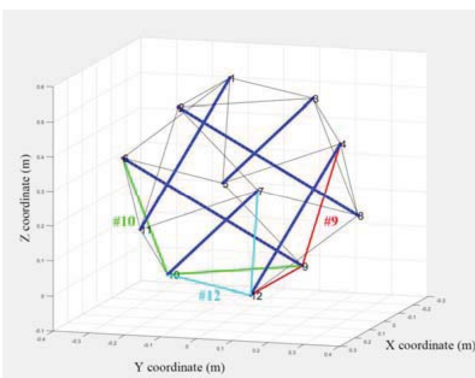

Figure 4. Parts of actuator pairs

A. Description of Kinematic Workspace

Because of the symmetry of the tensegrity structures, only two kinds of contact situations, isosceles contact and equilateral contact, need to be taken into account. By calculating the kinematic workspace of these two contact situations given continuous actuation for all the actuator pairs listed above, we can obtain the relationship between center of gravity and actuator pairs for other 18 contact situations using a mapping method.

In order to describe the kinematic workspace accurately, we establish a supporting triangle coordinate system as shown in Fig. 5, the origin of this coordinate is placed onto the center of gravity of supporting triangle. The *y*-axis crosses one of vertex of supporting triangle, *x*-axis is on the plane of supporting triangle and perpendicular to *y*-axis, and *z*-axis is perpendicular to the plane of supporting triangle.

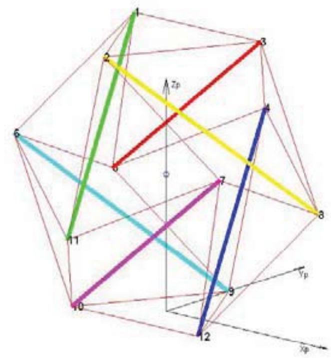

Figure 5. Supporting triangle coordinate

Because the internal forces created by cable's tension is much bigger than forces caused by contact with the ground in the case of rolling on planar ground, we ignore the friction forces. As a result, the tensegrity robot can maintain the ideal icosahedral shape if all the actuators remain their initial state. We define the kinematic workspace as a set of gravity center position under the continuous actuation given different actuator pairs. In fact, when the certain force applies on the tensegrity robot, the structure would oscillate at first, which leads to the instability of the position of gravity center. To solve this problem, we average the position of strut's gravity center computed in every iterative of simulation system, naming the average nominal gravity center. Finally, the nominal gravity center is regarded as the final gravity center caused by certain force.

For example, we apply air pressure of 0.4Mpa, 0.8Mpa, … , 2.4Mpa in sequence to actuator pair #10, at the same time position of gravity center is recorded, as seen in Fig. 6. The point cloud represent gravity center position during the whole process, and the circle is the corresponding nominal gravity center.

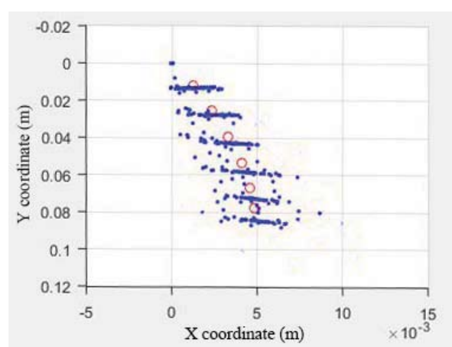

Figure 6. Gravity center path when #10 worked

A curve line describing the evolution of gravity center can be fitted using the series of nominal gravity center, so the corresponding relationships between air pressure and gravity center change can be obtained. After computing all the gravity center change curve, we combine them together and the kinematic workspace is obtained, as shown in Fig. 7. It is easy to find out that some actuator pairs such as #9, #10 and #12 can cause large migration of gravity center, while #4，#6 and #7 and cause less migration.

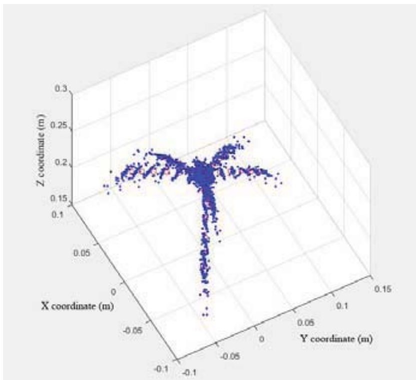

Figure 7. Descripton of kinematic workspace

B. The Principle of Rolling

We have assumed that all the friction of tensegrity robot is static friction, and the force caused by pneumatic muscle is much larger than gravity, so the influence to the robot shape caused by gravity can be ignored. That is to say, whether the robot can realize rolling is determined by the relative position between the projection of gravity center on contacted plane and the supporting triangle. When the projection of gravity center is out of the supporting triangle, the robot starts rolling.

As shown in the Fig. 8, the projection of gravity center is inside contact triangle, so the current robot could stand stable, but in the Fig. 9, the projection of gravity center is out of the contact triangle, so the robot would start to roll in the direction which is represented by arrow in Fig. 9.

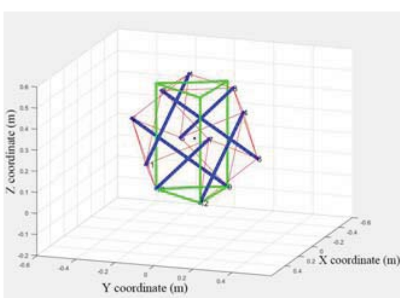

Figure 8. Stable state of robot

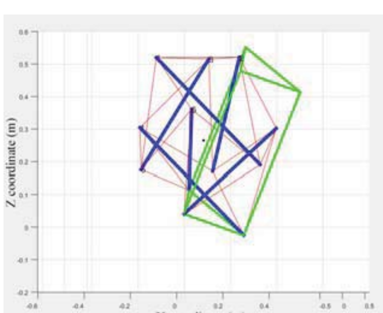

Figure 9. Rolling state of robot

C. Strategy of Continuous Movement

In order to realize continuous moving, we divide the whole rolling process into four steps, as followed:

1. Judge the situation of contact ground by sensors, then calculate the current position of gravity center.

2. Search in the kinematic workspace under the current situation.

3. Compare the target direction and current orientation of robot, Choose the best actuate strategy base on kinematic workspace worked out by step 2.

4. Implement actuate strategy to make the robot rolling.

By repeating the 4 steps above, the tensegrity robot can realize continuous movement.

For example, in the Fig. 8, the robot is contacted with the ground by the equilateral triangle consisting of vertices 9, 10 and 12(we can represent the triangle as (9, 10, and 12)). If we want to roll the robot in the direction represented by the arrow shown in the Fig. 8, the strategy will search in the kinematic workspace. As a result, it is easy to find out that the locomotion can be realized by apply air pressure of 4.2Mpa to the actuator pair #10.

D. Locomotion Strategy in Different Terrain

Because the tensegrity robot contacts ground with triangle including three single vertices, and these vertices can determine a plane. As uneven terrain can be modeled as continuous slope triangles. If we want to make the robot roll along the slope, the strategy is move the projection of gravity center on the contact plane outside the supporting triangle based on the same kinematic workspace pre-computed. But to the project position, in slope situation, gravity center project on slope in the direction of gravity as shown in Fig. 10.

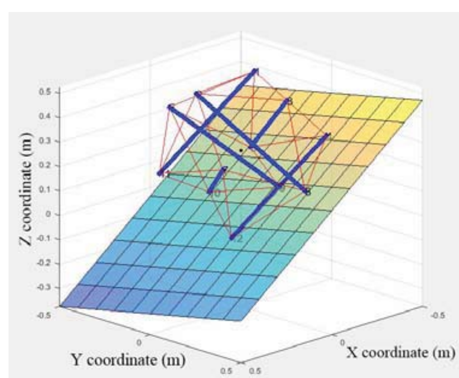

Figure 10. Slope situation

IV. EXPERIMENT

In order to verify the movement strategy, we build a physical prototype system and use spring and motor to form a rope twisting mechanism instead of pneumatic muscle[13][14]. Considering that the mechanical property of spring and pneumatic muscle are basically the same, both of them obey Hook law, when cable is twisted by motor, the force-deformation curve is similar to pneumatic muscle's force-deformation curve. The physical model is shown in Fig. 11.

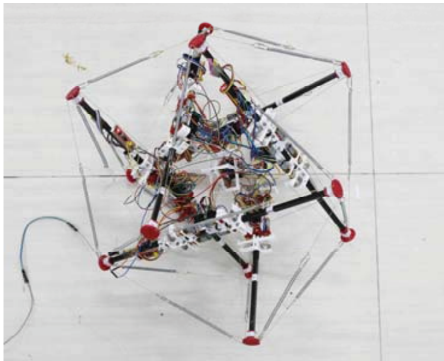

Figure 11. Physical model

A. Model Architecture

Cables of this physical model consist of springs and aromatic polyamide fibers. 24 DC motors work as actuators by enwinding cables onto the spools to change the length of cables. And six 50cm-length carbon tube work as six compress struts. The length ratio of strut and cable is 1.633.

B. Experiment

We have done experiment in physical model. The physical model can change its shape by actuate rope twisting mechanism. It can work well when it rolls according to kinematic workspace. As shown in Fig. 11, the robot stands on equilateral triangle (9, 10, 12), apply DC motors of actuator pairs #10 with voltage 11.1V, the robot start rolling, when it stand on isosceles triangle (10, 11, 12), then apply DC motors of actuator pairs #11 with voltage 6V, robot continue to roll to (6, 10, 11).

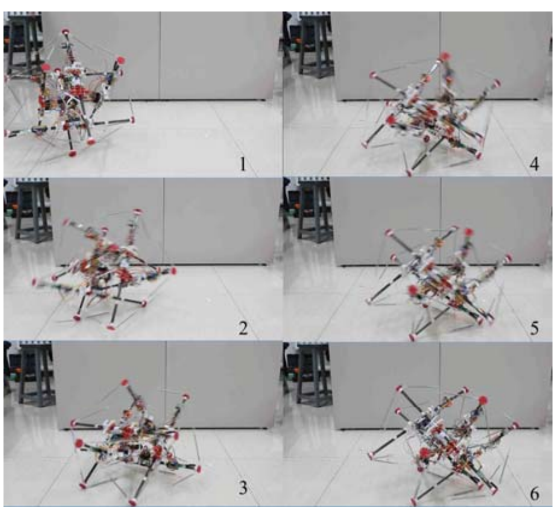

Figure 12. Experiment on physical model

V. Conclusion

This paper have established a dynamic simulation to analyze the locomotion method of 6-strut tensegrity robot. The kinematic workspace is worked out by applying series of actuation to cables and recording the changing of gravity center. We have finally proposed an effective method to realize continuous movement. We have also established a physical model to verify the locomotion strategy, the experiment have proved that the strategy we worked out in this paper is effective.

After established the cable-twisting physical model, we will continue to make a larger physical model using pneumatic muscle, and try to perform an overall verification for dynamic model and locomotion strategy. Also, we will mount a camera in the center of tensegrity robot to detect the terrain situation by visual identity [15], and predict the locomotion of robot.

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