Rolling Locomotion of Deformable Tensegrity Structure

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In this paper, we propose that a deformable robot with a tensegrity structure can crawl and describe its performance in practical experiments and a gait description. We apply Miller index in crystallography to describe the gait of a prototype, and then classify two contact conditions of the prototype. We demonstrate rolling of a six-strut tensegrity to confirm the movement of the prototype from each contact condition.

Keywords: Tensegrity; Body Deformation; Gait description; Miller index.

1. Introduction

More recently, robot locomotion has been assessed by applying the potential energy of deformable robots.[1,2] These robots moved by applying gravitational potential energy gradients and the storing/restoring of their bending potential energy. Although both theoretic analyses and practical experiments have shown that locomotion can be generated by robotic body deformation, some existing body deformation robots have had to deal with degree-of freedom problems because these robot bodies were made of a single material, indicating that rigidity and mass cannot be selected independently. To expand the freedom of design, we apply a tensegrity structure in designing the deformable body of a locomotion robot. Tensegrity is a mechanical structure composed of a set of disconnected rigid elements connected by continuous tensional members.[3] Tensegrity structures have also been studied as locomotion robots in terms of the lightweight.[4] That robot, however, did not actively utilize body deformation of a tensegrity robot. We realized rolling locomotion of a tensegrity robot by body deformation, which utilizes gravitational and tensile potential energy.[5] In this paper, we propose that a deformable robot with a tensegrity structure can crawl and

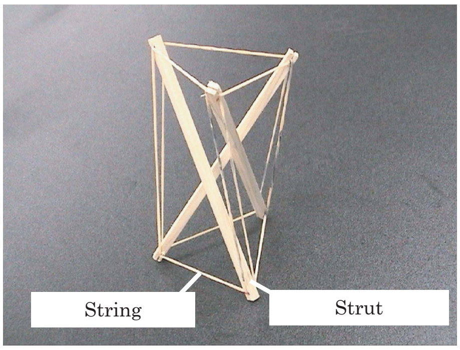


Fig. 1. A three-strut tensegrity structure

describe its performance in practical experiments and the gait description.

2. Tensegrity structure

Tensegrity structures are mechanical structures composed of a set of disconnected rigid elements connected by continuous tensional members. As an example, Figure 1 shows a three-strut tensegrity structure with nine strings. The structure is maintained at equilibrium because of a balance between the tensile and compression forces in the structure. Tensegrity structures were first discovered and developed in architecture. The word tensegrity is an abbreviation of *tensile integrity*. Their ability to form the basis of lightweight and strong mechanical structures using a minimal amount of material has been applied to architectural designs for structures such as bridges and domes. In architecture, there have been many studies of the characteristics and the forms of these structures. We focuse on a feature of tensegrity structure, in that the strut components should be separate from the string components. It was difficult to select the rigidity and mass independently in existing body deformation robots,[1,2] because the bodies of these robots were made of single materials. Therefore, the robot body should be smaller in size in order to reduce its weight. Because the rigidity of the structure was dependent on the rigidity of the string components, the weight of the tensegrity structure can be reduced while maintaining body size by reducing the weight of the strut components. We show that tensegrity structures can be utilized for the bodies of deformable robots in terms of design freedom.

3. Rolling Tensegrity

3.1. *Rolling by body deformation*

Rolling by body deformation of the tensegrity robot can be accomplished by applying a change in gravitational potential energy caused by deformation. In the natural state, the gravitational potential energy of the robot is at its minimum; i.e., the energy gradient is zero. Deformation of the robot body results in gradient changes in gravitational potential energy. Hence, it generates a moment of gravitational force around the area in which the robot is in contact with the ground. This moment causes the robot to move on the ground. The deformation lengths of actuators and the deformation volume of the body to roll the body depend on the number of tensegrity strut. In case of a three-strut tensegrity, the deformation lengths of actuators to roll the body are larger than one of a six-strut tensegrity. In addition, the body of more complex tensegrity dose not very deform against the deformation lengths of actuators. Hence, we took a six-strut tensegrity as an example in this prototype.

3.2. *Body deformation with tensegrity structure robots*

There are some kinds of ways of body deformation because the robot is composed by two kinds of components, struts and strings. In this section, we discuss ways of deforming a robotic body with tensegrity structures. We classify ways of deformation of the robotic body with a tensegrity structure into three processes as follows (see Figure 2):

[1] A string component itself is deformed.
[2] A strut component itself is deformed.
[3] Arrangement between two strut components is changed by force of an external actuator.

In addition, process (c) is classified in terms of connection relationships between two strut components.

(c–1) The two strut components are connected by a cable directly.
(c–2) The two strut components are not connected by a cable directly.

In the figures, relevant components in deformation are depicted using deep color.

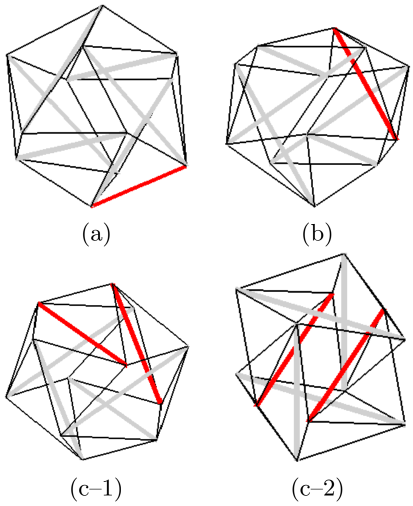


Fig. 2. Deformation of tensegrity structure

3.3. *Prototype*

We deal with a six-strut tensegrity robot to realize rolling locomotion, which was composed by six struts and twenty four strings. A prototype of a six-strut tensegrity structure robot is shown in Figure 3. Each strut is made from 150 mm length of an acrylic pipe (diameter: 8 mm), and each string is made from a rubber band that has 13.1 N/m coefficient of rigidity. The prototype of a tensegrity robot is 25.2 g weights. The actuators are made from shape memory alloy (SMA) coil, which is 0.15 mm wire diameter. We used twenty-four SMA coils in this prototype. We arranged the SMAs along the strings as shown in the figure to deform the body of the robot. That is, we applied the body deformation method (c–1) in the privious section in this prototype. Both end of the SMA coil is fixed at the ends of the two struts that connect with strings.

3.4. *Description of gait*

This six-strut tensegrity is a regular icosahedron excepting the six edges; we consider the tensegrity as a regular icosahedron. We apply Miller index[6] to describe the plane of the tensegrity. Miller index is a notation method to describe the plane of crystals. Based on Miller index, the planes are classified as two types form {111} and form {210}. That is, twenty faces of an icosahedron are denoted as (111), ($\bar{1}$11), (1$\bar{1}$1), (11$\bar{1}$), ($\bar{1}\bar{1}$1), ($\bar{1}$1$\bar{1}$),

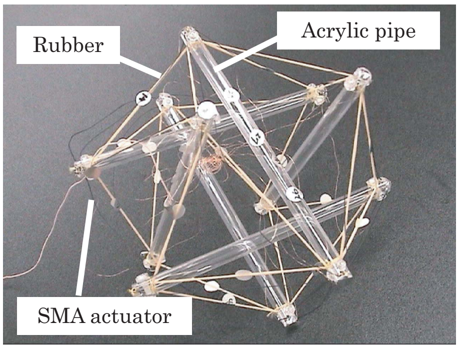


Fig. 3. Prototype of deformable robot with tensegrity structure

$(1\bar{1}\bar{1})$, $(\bar{1}\bar{1}\bar{1})$, (210), $(\bar{2}10)$, $(2\bar{1}0)$, $(\bar{2}\bar{1}0)$, (102), $(\bar{1}02)$, $(10\bar{2})$, $(\bar{1}0\bar{2})$, (021), $(0\bar{2}1)$, $(02\bar{1})$, and $(0\bar{2}\bar{1})$ by Miller indices. These form can describe two contact conditions of the robot as shown in Fig. 5. We also denote each face and vertex based on the Miller index of an icosahedron (see Fig. 6). We can describe a gait of the robot using these notations. We assume that the tensegrity robot rotate using the edge of the polyhedron, and then the moving configurations are classified as following three types: $\{111\} \rightarrow \{210\}$, $\{210\} \rightarrow \{111\}$, and $\{210\} \rightarrow \{210\}$.

3.5. *Transition of gravitational potential energy*

We investigate the movement from each initial condition in terms of gravitational potential energy based on the previous classifications. We assume that the movement is quasi-static and the robot do not deform during the translation. Gravitational potential energy E_g of tensegrity robots is calculated under acceleration of gravity g as follows:

$$E_g = \sum_{i=1}^{N} \Big(m_i \, g \, h_i \Big), \tag{1}$$

where m_i and h_i are mass and height of center of gravity of the i-th strut, respectively. We can check gravitational potential energy of the robot at any condition based on Eq.1 using node positions of the polyhedron. Figure 4 shows transition of gravitational potential energy. In the figure, horizontal and vertical axes imply rotational angle of the robot and the gravitational potential energy, respectively, normalizing as the tensegrity of weight 1, which is inscribed on the sphere of diameter 1. Struts are composed by homogeneous material so that the gravitational potential energy transitions

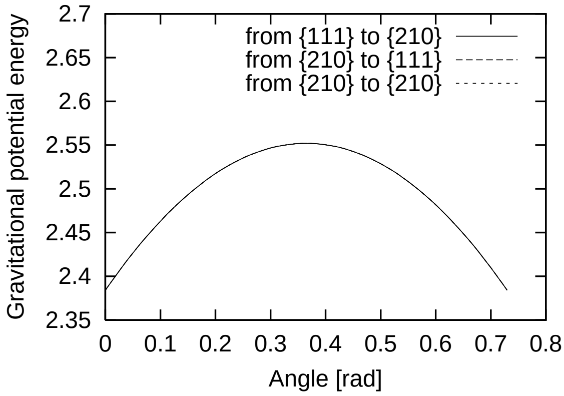
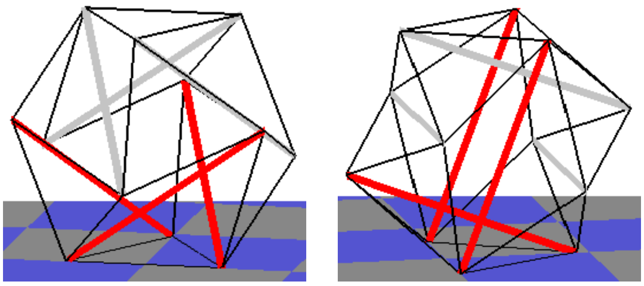


Fig. 4. Transition of gravitational potential energy



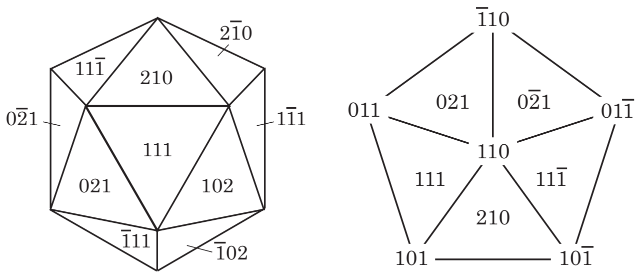
(a) Pattern {111} (b) Pattern {210}

Fig. 5. Contact conditions between floor and tensegrity structure

of all moving configurations are corresponding. We found that all transitions of gravitational potential energy coincide through the analysis. Three curves in Figure 4 are superimposed and hence indistinguishable. In this analysis, because we consider a regular icosahedron as a model of a six-strut tensegrity, the transition from any contact conditions are described as all same rolling.

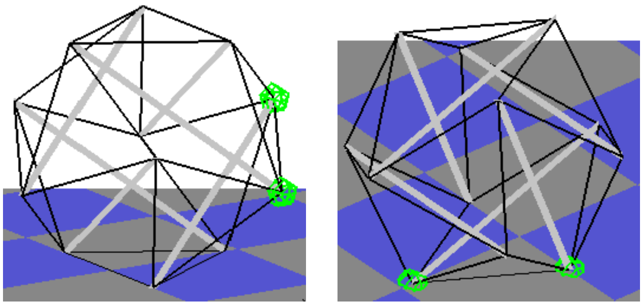
4. Experiment

In this paper, we investigate transitions from conditions {111} and {210} to confirm the mobility. Figure 7 shows relevant nodes in deformation, which are depicted using color balls. Figure 8 and 9 show successive images of



(a) Faces (b) Nodes

Fig. 6. Naming convention of a six-strut tensegrity



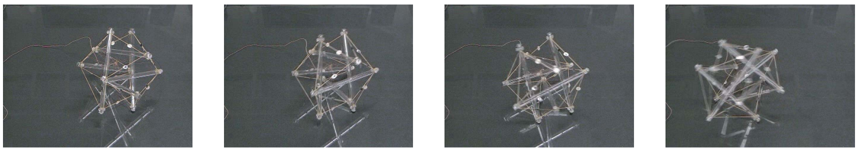
(a) Pattern {111} (b) Pattern {210}

Fig. 7. Arrangement for deformation

experimental results from initial condition {111} and {210}, respectively (Figure 8-(a) and Figure 9-(a)). In Figure 8, the tensegrity robot began to deforming its body at 4.0 s (Figure 8-(b)), and then went through contact condition {210} (Figure 8-(c)), finally, became static at contact condition {111} (Figure 8-(d)). In Figure 9, the tensegrity robot began to deforming its body at 4.0 s (Figure 9-(b)), and then translated contact condition {111} (Figure 9-(c)), finally, remained the contact condition {111} (Figure 9-(d)). As shown in these figures, the tensegrity robot we propose can crawl on a floor at each contact condition.

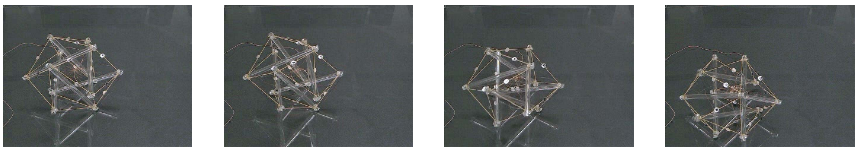
5. Summary

In this paper, we proposed that a deformable robot with a tensegrity structure could crawl and describe its performance in practical experiments and



(a) 0 s (b) 4.0 s (c) 5.0 s (d) 5.2 s

Fig. 8. Crawling by body deformation from initial condition {111}



(a) 0 s (b) 4.0 s (c) 6.0 s (d) 7.0 s

Fig. 9. Crawling by body deformation from initial condition {210}

a gait description. We applied Miller index based on crystallography to describe a gait of the robot, and then classified two contact conditions of the prototype. We demonstrated rolling of a six-strut tensegrity to confirm the movement of the prototype from each contact condition. Through the analysis, we could explain the characteristics of our prototype by the notation. We hope that this notation system is basis on describing of moving configurations of polyhedron locomotion robots.

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