MOVING STRATEGY OF TENSEGRITY ROBOTS WITH SEMIREGULAR POLYHEDRAL BODY

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This paper represents rolling of a deformable polyhedral robot with a tensegrity structure. In this paper, we make a prototype of a tensegrity locomotion robot, which corresponds with the right-handed snub cube. We show that a moving strategy of tensegrity locomotion robots using the body deformation depends on the structure itself through analyses of the gravitational potential energy. In the snub cube, the gravitational potential energy at four-point contact is smaller than one at three-point contact, which results in moving directionality.

Keywords: Tensegrity; Body Deformation; Gait; Semiregular Polyhedron.

1. Introduction

Recently, deformable locomotion robot by applying the potential energy has been conducted.[1,2] Several robots can move and jump by applying the gravitational potential energy gradients and the storing/restoring of their bending potential energy. We have realized rolling locomotion of a polyhedral robot with a tensegrity structure. Tensegrity is a mechanical structure composed of a set of disconnected rigid elements connected by continuous tensional members.[3] Applying the lightweight characteristic of the structure, tensegrity as a locomotion robot have been studied. Paul et al. have constructed a mobile robot based on a triangular tensegrity prism.[4] We have realized rolling locomotion of a regular icosahedron tensegrity robot by the body deformation,[5,6] which utilizes the gravitational potential energy gradients during the body deformation. In this paper, we deal with a tensegrity robot with a semiregular polyhedral body to determine a gait. We show that the moving strategy of tensegrity locomotion robots using the body deformation depends on the structure itself in terms of the gravitational potential energy, which results in moving directionality.

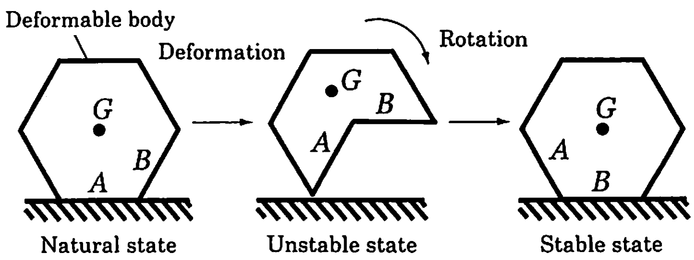


Fig. 1. Principle of rolling by body deformation

2. Moving strategy of a rolling tensegrity robot

2.1. *Rolling principle by body deformation*

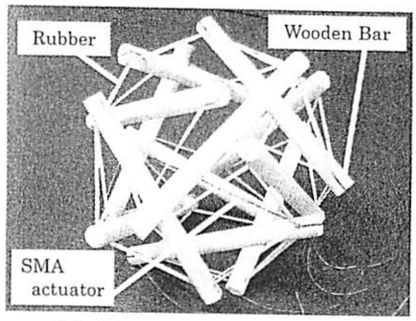
Deformation of the robot body results in gradient shifts in terms of gravitational potential energy (Figure 1). Hence, it generates a moment of gravitational force around the ground. The gravitational potential energy of the robot then reaches its minimum, results that the body is able to roll.[1] Using the body deformation rolling against a ground, the tensegrity robot we proposed could move.

2.2. *Tensegrity robot with semiregular polyhedral body*

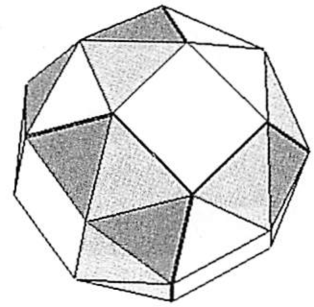
In this paper, we apply a 12-strut tensegrity to realize rolling motion using the body deformation (Figure 2-(a)). This structure consists of twelve struts and forty-eight strings, each of which is connected at the ends of two struts. Assuming that strut ends and strings are considered as vertices and edges of a semiregular polyhedron, the structure corresponds with a snub cube, a semiregular polyhedral body (Figure 2-(b)). Hence, stable configuration of this structure against the ground is as follows: (a) four-point contact (Figure 3-(a)), (b) three-point contact 1 (Figure 3-(b)), and (c) three-point contact 2 (Figure 3-(c)). Difference between (b) and (c) is directions of struts against a ground. In contact condition (b), the contact directions of three struts are symmetric configuration. Circles in these figures imply the contact points against the ground.

2.3. *Transition of gravitational potential energy*

We investigate the movement from each initial condition as shown in previous section through analyses of the gravitational potential energy; assuming that the movement is quasi-static and the robot do not deform during the



(a) 12-strut tensegrity robot



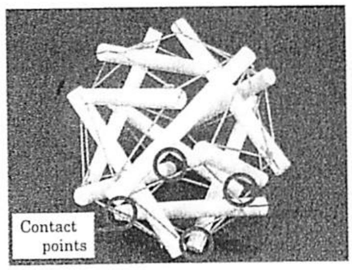
(b) Snub cube

Fig. 2. Polyhedral tensegrity structures

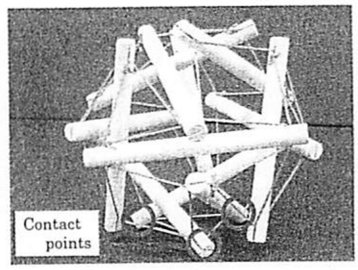
moving. Gravitational potential energy E_g of tensegrity robots is calculated under acceleration of gravity g as follows:

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

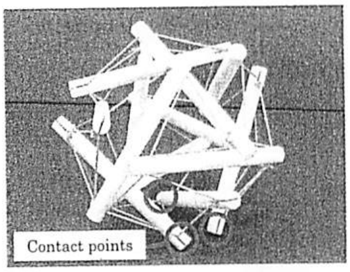
where m_i and h_i are mass and height of center of gravity of the i-th strut, respectively. In this paper, the number of struts N is twelve. Figure 4 shows transition of gravitational potential energy. In the figure, horizontal and vertical axes imply rotational angle of the robot and the gravitational potential energy, respectively, normalizing as the tensegrity of weight 1, which is inscribed on the sphere of diameter 1. In a snub cube, the gravitational potential energy at four-point contact is smaller than one at three-point contact, which determines moving direction. Conditions at four-point contact are stable in comparison with three-point contact, that is, these results predict that it is easy to be four-point contact after rolling in practice. Based on the result, we can determine the gait of the snub cube tensegrity locomotion robot using contact condition 1, the four-point contact. A snub cube has 6 square surfaces, and the surfaces are vector equilibrium such as a regular hexahedron. Figure 5 shows movable directions of the prototype of 12-strut tensegrity robot. Assuming that the contact condition of the robot reaches condition 1 at stable configuration, the robot can roll at the cross and horizontal directions in this figure, which results in determining a gait based on these stable configurations. Enantiomerism exists in snub cube. We discuss the gait determination method both in right-handed and left-handed snub cube. The gait as shown in Figure 5 depends on the structure of the polyhedral locomotion robot itself. In 6-strut tensegrity locomotion



(a) Pattern 1



(b) Pattern 2



(c) Pattern 3

Fig. 3. Contact conditions of 12-strut tensegrity against a ground

robot, this gait determination is not applied. There are two contact conditions against a ground in 6-struts tensegrity (Figure 6). Figure 7 shows transition of gravitational potential energy in terms of a regular icosahedron tensegrity robot. In the tensegrity robot, the gravitational potential energies at all stable conditions coincide.

3. Experiment

3.1. *Prototype*

A prototype of a twelve-strut tensegrity structure robot is shown in Figure 8. This protoyepe is a right-handed snub cube. Each strut is made from 110 mm length of an wooden bar (diameter: 10 mm), and each string is made from a rubber band that has 38 N/m coefficient of rigidity. The prototype of a tensegrity robot is 53.0 g weights. The actuators are made from BMX150 shape memory alloy (SMA) coil (TOKI Corporation, Japan), which is 0.15 mm wire diameter. Both end of the SMA coil is fixed at the ends of the two struts that connect with strings. The SMAs shrinks by turning on electricity, generating heat.

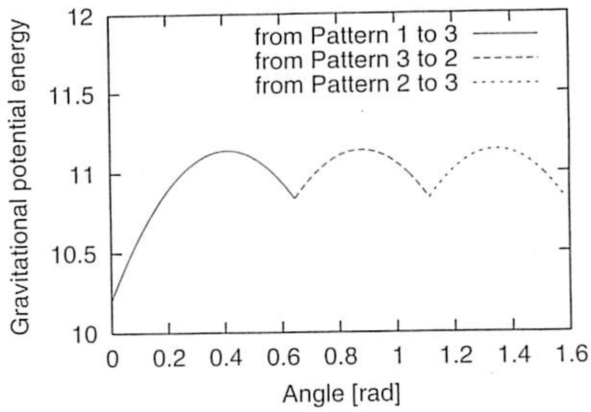


Fig. 4. Transition of gravitational potential energy

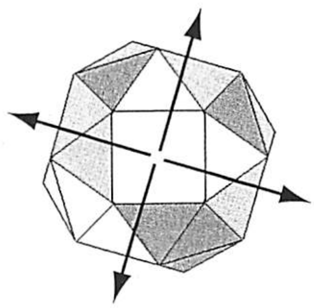
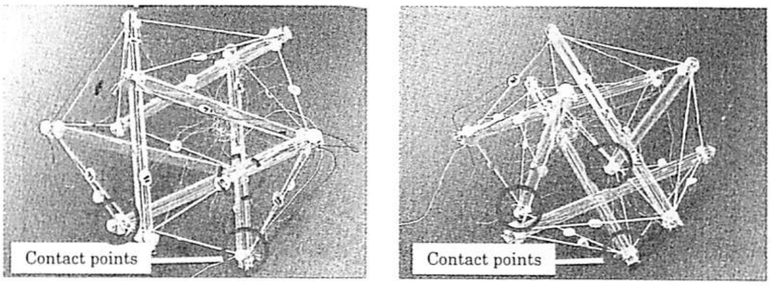


Fig. 5. Movable directions of the prototype of 12-strut tensegrity robot

3.2. *Experimental results*

We confirm the translation from contact condition 1 and 2 to evaluate the validity of the analyses. Figures 9 and 10 show successive images of experimental rolling from each contact condition, type 1 and 2, respectively. The actuators to deform the body are made from BMX150 shape memory alloy (SMA) coil (TOKI Corporation, Japan). In Figure 9, we show that the tensegrity robot transits from the initial contact condition 1 (Figure 9-(a)) to stable contact condition 1 (Figure 9-(d)) with the body deformation (Figure 9-(b)). In this rolling, the robot did not remain still at contact condition 2. In Figure 10, we show that the tensegrity robot transits from the initial contact condition 2 (Figure 10-(a)) to stable contact condition 1



(a) Pattern 1 (b) Pattern 2

Fig. 6. Contact conditions between floor and 6-strut tensegrity structure[6]

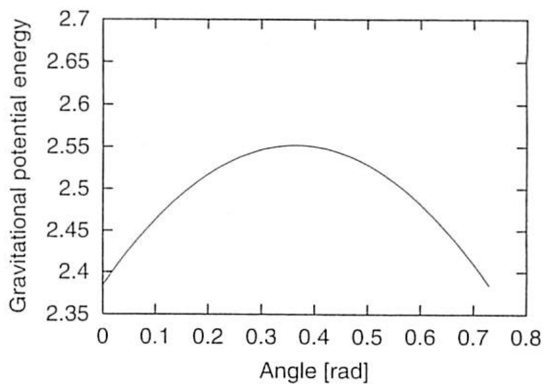


Fig. 7. Transition of gravitational potential energy[6]

(Figure 10-(d)) with the body deformation (Figure 10-(b)). In this rolling, the robot also did not remain still at contact condition 2. These experimental results reinforce the previous analyses.

4. Summary

This paper has described a moving strategy of tensegrity rolling robots. In a kind of tensegrity structure such as the type of snub cube, some planes has more smaller local minimum of the gravitational potential energy against a ground than other ones. Based on these planes, we could make a moving strategy. In the snub cube, the gravitational potential energy at four-point contact is smaller than one at three-point contact, which results in moving directionality. The robot can roll at the cross and horizontal directions. We also have confirmed the availability of the moving strategy experimentally. In the future, we will analyze a moving strategy taking the weight/inertia of the robot body into consideration.

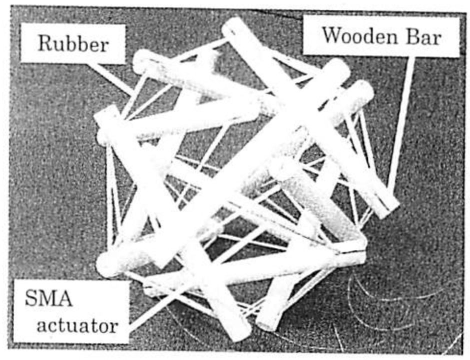
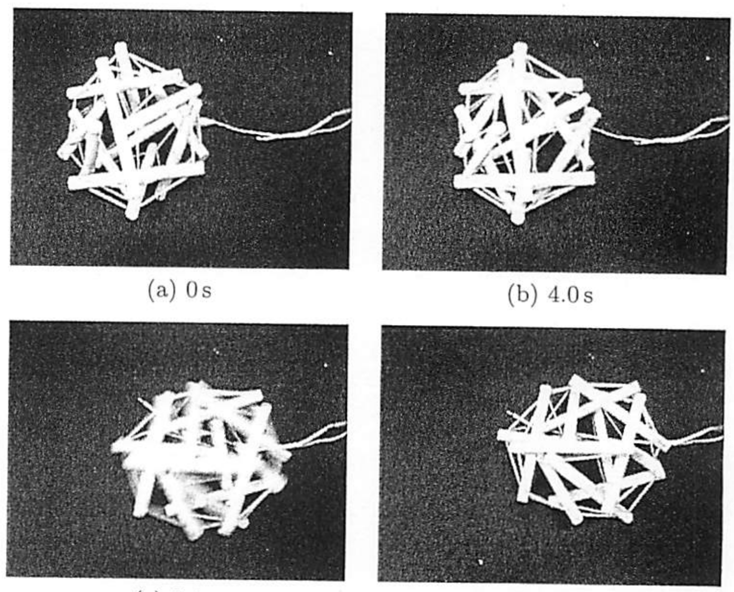


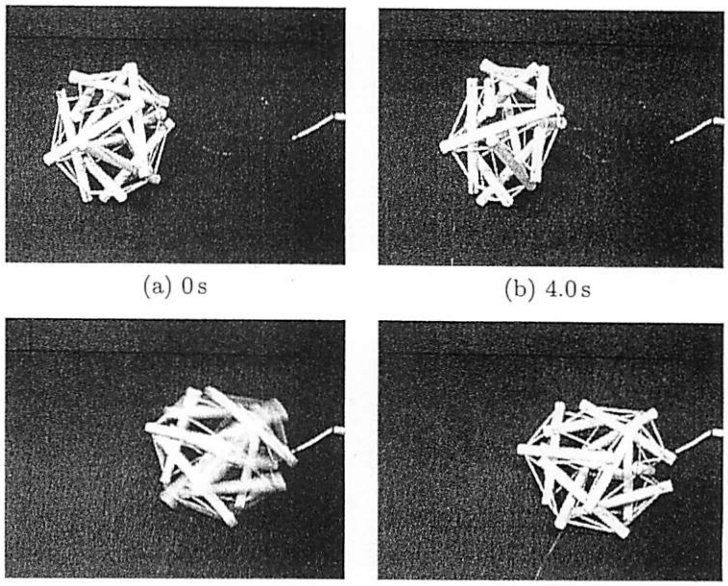
Fig. 8. Prototype of deformable robot with tensegrity structure (12 struts)



(a) 0 s (b) 4.0 s

(c) 5.0 s (d) 5.2 s

Fig. 9. Crawling by body deformation from initial condition 1



(a) 0 s (b) 4.0 s

(c) 6.0 s (d) 7.0 s

Fig. 10. Crawling by body deformation from initial condition 2

Acknowledgment

This research was partly supported by a fund for Grants-in-Aid for Scientific Research in Japan Society for the Promotion of Science (No, 21760210).

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