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Crawling by Body Deformation of Tensegrity Structure Robots

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Abstract— **In this paper, we describe the design of a deformable robot with a tensegrity structure that can crawl and we show the results of experiments showing the ability of these robots to crawl. We first describe a tensegrity structure, composed of struts and cables, and its characteristics. We next explain the principle of crawling by robot body deformation, followed by a classification of the methods by which a body can be deformed and the contact conditions of the robot through the cable-graph of the tensegrity structure. We also describe topological transition graphs that can visualize crawling from each initial contact condition. We then discuss the characteristics of the proposed robot in terms of design freedom. Finally, we show experimentally that the prototype of a tensegrity robot can crawl.**

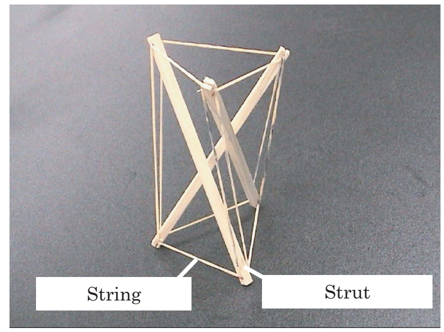

Fig. 1. Tensegrity structure

I. INTRODUCTION

Over the past several decades, many studies have been conducted on locomotion robots, which move by robotic body deformation. Snake-like robots and fish robots have focused on the generation and analysis of movement-applied physical interactions between the environment and a robotic body [1], [2], [3]; for example, a fish robot generates a propulsion force by applying physical interactions between its fins and the water.

More recently, robot locomotion has been assessed by applying the potential energy of deformable robots. These robots moved by applying gravitational potential energy gradients and the storing/restoring of their bending potential energy. For example, a deformable robot capable of crawling and jumping has been proposed [4], [5], [6]. This prototype robot consisted of a circular shell made of a spring metal, which could be deformed by a Shape Memory Alloy (SMA) coil to jump twice its diameter. These findings have led to the analysis of jumping and passive crawling by deformation of a robotic body [7], [8]. The jumping height caused by deformation of a body has been found, both by practical experiments and by analytic simulation, to depend on the impulse during jumping. These analyses have also revealed the appropriate shape of the robot before jumping, in terms of energy conversion efficiency from bending potential energy [8]. Robotic catapults have been designed based on closed elastic, which generates impulsive motions by active snap-through buckling [9], [10]. Robots, including robotic catapults, have also been shown to jump and swim. The motions of these robots have also been analyzed, by assuming the elastic strip was approximated by a serial chain of rigid bodies. Robot locomotion has also been assessed relative to the physical parameters of a robotic body. For example, a circular modular robot, with variable compliance mechanisms, has been designed [11]. A method for systematic optimization of the stiffness distribution of the robot has been developed, resulting in a fast and smooth rolling motion and a sudden stopping motion. Although both theoretic analyses and practical experiments have shown that locomotion can be generated by robotic body deformation, some existing body deformation robots [4], [9] 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 applied 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 [12]. The structure is maintained at equilibrium because of a balance between the tensile and compression forces in the structure. In this paper, we propose that a deformable robot with a tensegrity structure can crawl and describe its performance in practical experiments. We first show a tensegrity structure, made of struts and cables, and its characteristics. Second, we briefly explain the principle of crawling using robot body deformation. Next, we classify the methods by which a body can be deformed and the contact conditions of the robot through a cable-graph of the tensegrity structure. We also discuss the characteristics of the proposed robot in terms of design freedom. Finally, we show experimentally that the prototype of a tensegrity robot can crawl.

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II. 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 [13]. 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 [14]. In biology, the cells of living beings have been described as being made from tensegrity structures [15]. In robotics, lightweight robotic arms may be tensegrity structures, with tensegrity robots classified as a new type of tendon driven robotic system [16]. That paper focused on a method to determine the tendon force inputs from a set of admissible, non-saturating inputs, which can move a rigid body system from one point to another along a prescribed path in minimum time. Tensegrity structures have also been studied as locomotion robots. For example, a mobile robot was constructed based on a triangular tensegrity prism, which can be actuated by contraction of its transverse cables [17], [18], [19]. Using a generic algorithm, the automatic design of controller architecture for forward locomotion was simulated, suggesting that this structure can generate multiple effective gait patterns for forward locomotion. That robot was able to show a walking motion, considered an expansion of legged robots. That robot, however, did not actively utilize body deformation of a tensegrity robot. In addition, a spatial modular tensegrity mechanism has been kinematically and statically analyzed [20].

We realized locomotion of a tensegrity robot by body deformation. This robot utilized gravitational and tensile potential energy, enabling it to move on an irregular terrain efficiently and robustly using body deformation. Additionally, we focused 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 [4], [9], 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.

III. Crawling by body deformation

In this section, we briefly explain the principle of crawling by deformation of a robotic body. We then classify the methods by which the body of a robot with a tensegrity structure can be deformed.

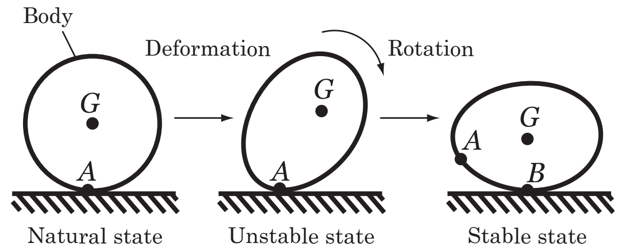


Fig. 2. Principle of crawling by body deformation

A. Principle of crawling

Crawling by body deformation of a locomotion robot can be accomplished by applying a change in gravitational potential energy caused by deformation [5]. Suppose a robot that composes a deformable body is stable on the ground, as illustrated in Figure 2. For simplicity, the body of the robot is made from a single material. Symbol A and G note the contact area between the robot and the ground in the natural state and at the center of gravity of the robot, respectively. 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. If the robot deforms from a stable to an unstable shape (Figure 2), it rotates clockwise and moves towards the right. The gravitational potential energy of the robot then reaches its minimum at contact with area B, which is different from area A. Successive deformation of the robot body, which can be generated by actuators, enables a continuous crawling motion along the ground.

B. Body deformation of tensegrity structure robots

In this section, we discuss the methods by which a robotic body with tensegrity structure, made of struts and strings, can be deformed. Figure 3 shows a cable-graph [12] of a three-strut tensegrity system. Node P_i shows an end point of a strut. For N strut components, there are $2N$ nodes P_i. In the figure, solid and dashed lines show the string and strut components of the tensegrity structure, respectively, indicating that a segment $P_{(2i-1)}P_{(2i)}(i = 1, \cdots, N)$ represents each strut component.

We classify the methods by which a robotic body with a tensegrity structure can be deformed into three processes (see Figure 4):

(a) Deformation of a string component.
(b) Deformation of a strut component.
(c) The relationship between two strut components is altered by the force of an external actuator.

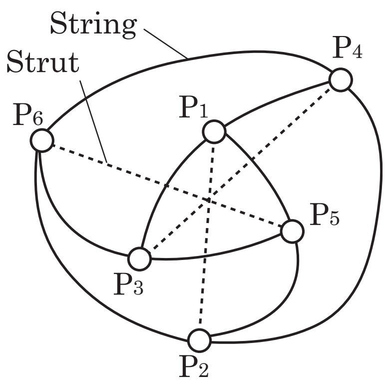


Fig. 3. Cable-graph of a three-strut tensegrity structure

In addition, process (c) can be classified in terms of the relationship between two strut components.

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

In process (a), a string component itself (e.g. string P_1P_3) is a prismatic actuator, for example, an SMA coil and a wire driven by a motor. This scheme has been implemented in a prototype consisting of wires driven by motors [17]. The change in length of one string causes deformation in the body of the tensegrity robot because the end point of one strut component fixes some string components. In process (b), a strut component itself (e.g. strut P_1P_2) is a prismatic actuator, for example, a pneumatic cylinder. Identical to process (a), the change in length of one strut causes deformation in the body of the tensegrity robot. In process (c-1), the arrangement of two strut components connected by the same string, for example, the distance between points P_1 and P_3 against struts P_1P_2 and P_3P_4 in Figure 3, is changed. A prismatic actuator can be fixed easily at the ends of the two struts along the connecting strings because string P_1P_3 is between points P_1 and P_3. In this scheme, a large deformation of the robotic body occurs in response to changes in a small number of struts. In process (c-2), the arrangement of two strut components that are not connected by the same strings is changed. Although Figure 3 cannot show this process, it must be considered if there are large numbers of strut components because the long distance between two struts may be deformed.

IV. EXPERIMENT

In this section, we confirm that the robot we proposed can crawl experimentally. We classify the contact conditions of the robot against a floor in terms of the struts contacting the floor in our prototype. We then confirm that the prototype can crawl from each contact condition. We also depict transition graphs to describe the experimental results.

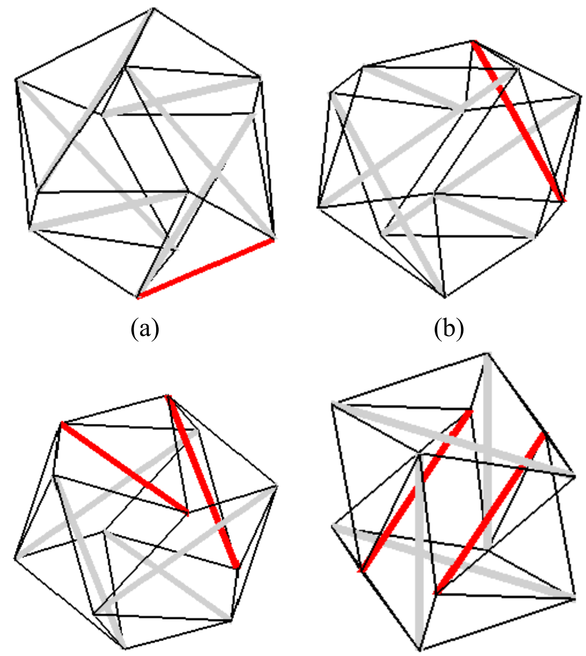


Fig. 4. Deformation of tensile structure

A. Prototype

Figure 5 shows a prototype of a tensegrity structure robot, which was composed of six struts and 24 strings, with 12 nodes in a cable-graph. Figure 6 shows a cable-graph of the six-strut tensegrity system we have proposed. The meaning of the nodes and solid lines is the same as in Figure Figure 3. For viewability, the dashed lines are not shown in the figure, implying that a segment $P_{(2i-1)}P_{(2i)}(i = 1, \cdots, N)$ is each strut component. Each strut is made of 150mm of acrylic pipe (diameter: 8 mm), and each string is made of a rubber band with a coefficient of rigidity of 13.1N/m. This prototype has a total weight of 25.2 g. In this prototype, three pairs of parallel struts are arranged to maintain the equilibrium shape of the robot (e.g. struts P_1P_2 and P_7P_8 are in parallel arrangement). The actuators are made from BMX150 shape memory alloy (SMA) coil (TOKI Corporation, Japan). The SMAs are arranged along the strings as shown in the figure to deform the body of the robot. Both ends of the SMA coil are fixed to the ends of the two struts that connect with strings, as shown in Figure 4-(c–1). The SMAs shrink by turning on electricity, generating heat.

B. Transition patterns from contact conditions

The shape of our prototype is similar to that of a regular icosahedron. Hence, any four end points of the robotic body are noncoplanar. The six-strut tensegrity robot contacts the floor at three end points, the minimum number of points that form a plain. There are two contact conditions in our

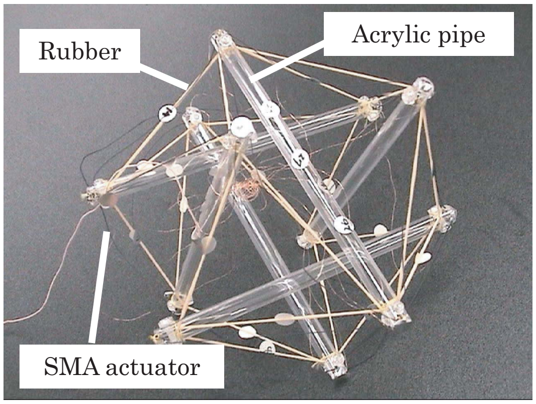


Fig. 5. Prototype of a deformable robot with tensile structure

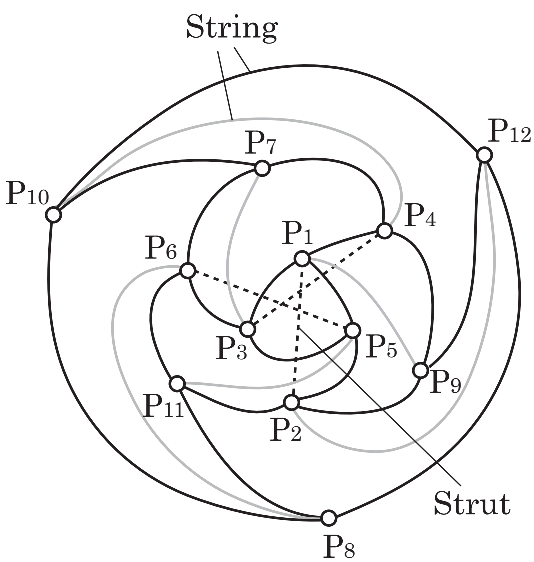


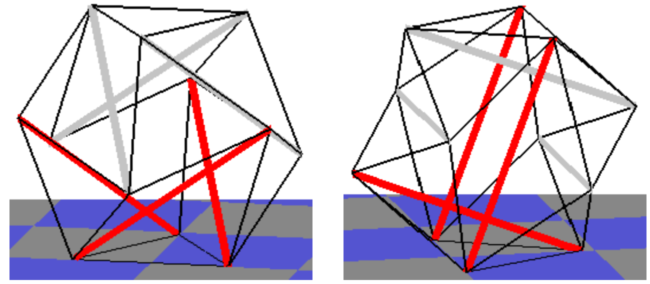
Fig. 6. Cable-graph of a six-strut tensegrity structure

prototype:

(α) Three struts without a pair of parallel struts (Figure 7-(a)).

(β) A pair of parallel struts and one other strut (Figure 7-(b)).

Points $P_1P_3P_5$ and $P_1P_3P_7$ are considered examples of cases (a) and (b), respectively, in Figure 6. We consider crawling of the prototype at each contact condition. Figure 8 shows the transition graphs of the crawling pattern at each initial contact condition. Vertices of a triangle in the figure indicate the contact points of the robot in a stable state. The number in the triangle indicates the number of times that the robot can translate the contact conditions for crawling times M. The number 0 indicates that the robot is at its initial state. In Figure 8-(a), points P_1, P_3, and P_5 are in contact with the floor at initial state. Due to space limitations, we show only the transition state at M=3 from each contact condition. The six-strut tensegrity robot cannot move in any direction because its body is a regular icosahedron without



(a) Pattern 1 (b) Pattern 2

Fig. 7. Contact conditions between the floor and the tensile structure

some vertices. The dashed lines indicate that the robot cannot transition through the edge. For example, the robot can move to state $P_1P_3P_9$ and $P_3P_6P_7$ but not $P_1P_4P_7$ at initial state in Figure 8-(b) (see Figure 6). As stated above, we can describe the crawling as a topological graph.

C. Experimental results

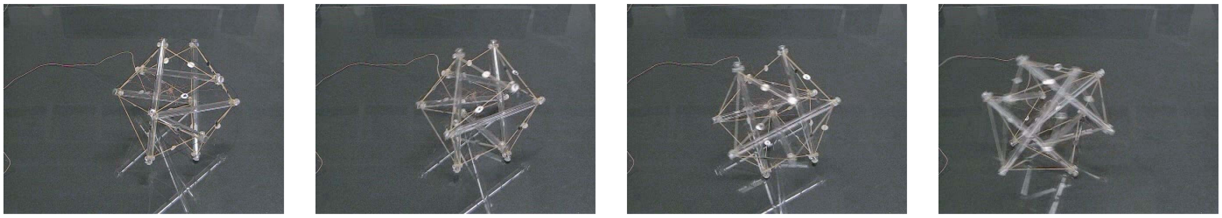
Figures 9 and 10 show successive images of experimental crawling from each contact condition, types $P_1P_3P_5$ and $P_1P_3P_7$, respectively. In Figure 9, we show that the tensegrity robot translates from initial contact condition $P_1P_3P_5$ (Figure 9-(a)) to stable contact condition $P_1P_3P_6$ (Figure 9-(d)) through $P_1P_3P_7$ (Figure 9-(c)) applied by actuators along segment P_3P_5 (Figure 9-(b)) due to the effect of gravitational potential energy. We confirmed experimentally that contact condition type $P_1P_3P_5$ was more stable than condition type $P_1P_3P_7$ because condition $P_1P_3P_6$ was classified as type $P_1P_3P_5$. In Figure 10, the robot translates from initial contact condition $P_1P_3P_7$ (Figure 10-(a)) to stable contact condition $P_3P_6P_7$ (Figure 10-(d)) applied by actuators along segment P_4P_7 (Figure 10-(b) and (c)). Condition $P_3P_6P_7$ was classified as type $P_1P_3P_5$. As shown in these figures, the tensegrity robot we propose can crawl on a floor at each contact condition.

V. Discussion

The approach shown here can be used to design a tensegrity structure robot that can crawl. To crawl and jump efficiently, locomotion robot requires a lightweight body. Large energy applied against a lightweight body generates high-speed movement and high jumping of the robots. However, some existing body deformation robots [4], [9] 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. For example, a previously designed body deformation robot [4] can jump by applying bending potential energy U_{flex} as follows:

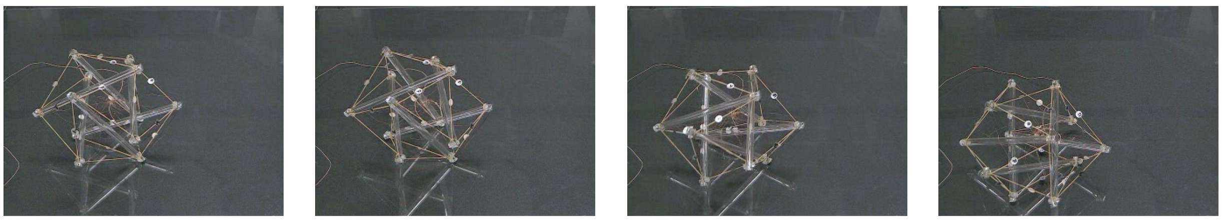
$$U_{\text{flex}} = \int_0^L \frac{1}{2} R_{\text{flex}} \left(\frac{\mathrm{d}\theta}{\mathrm{d}s} \right)^2 \mathrm{d}s, \qquad (1)$$

where R_{flex} and L are the rigidity and entire length of the robotic body, respectively (see Figure 12), indicating that a highly rigid robot can jump quite high. However, the rigidity R_{flex} is defined as Young's modulus E multiplied



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

Fig. 9. Crawling by body deformation (type $P_1P_3P_5$)



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

Fig. 10. Crawling by body deformation (type $P_1P_3P_7$)

by the geometrical moment of inertia I. That is, conduction of the robot, which has the different rigidity in the same size by a single material, is difficult. In contrast, the rigidity of a tensegrity robot depends on the rigidity of the strings, assuming that the struts do not deform. Thus, by using lighter weight struts, the entire weight can be reduced while keeping the same size. The tensile potential energy E_s of a tensegrity robot can be calculated as:

$$E_s = \sum_{i=1}^{N} \Big(\frac{1}{2} \, k_i \, d_i^2 \Big), \tag{2}$$

where k_i and d_i are rigidity coefficient and dilation of the i-th string, respectively. The condition in Equation Eq.2 does not include the mass properties of the material so that a lighter weight tensegrity robot can jump higher.

Figure 11 shows a six-strut tensegrity robot, in which the compressed struts are made from aluminum pipes, of the same length as in the prototype shown in Figure 5. In addition, the initial length and Young's modulus are the same as in the previous prototype, implying that the prototype in Figure 11 is heavier and of the same rigidity and size as the prototype in Figure 5. The heavier prototype weighs 53.8 g, twice that of the previous prototype. We also experimentally confirmed that the heavier tensegrity robot could crawl on a floor, indicating that a battery and a driving motor can be mounted inside the body of a six-strut tensegrity robot. The design freedom can be widely expanded in applying tensegrity structures for locomotion robots.

Future work includes the selection of an appropriate actuator and a method to control the direction of crawling. The frictional force between a floor and a contact point must be considered when choosing a method to control the direction of crawling. One of the key terms in crawling by robotic body deformation is gravitational potential energy during transition. The gravitational potential energy Eg of tensegrity robots can be calculated under acceleration of gravity g as:

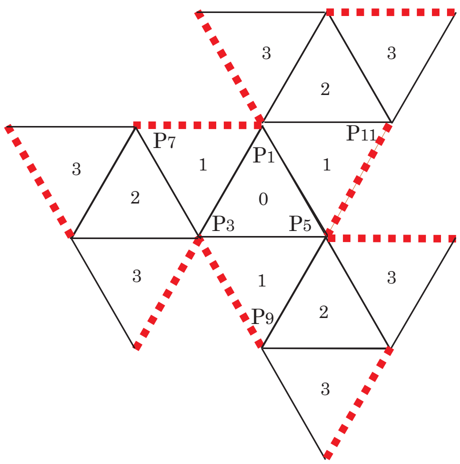
$$E_g = \sum_{i=1}^{N} \Big(m_i \, g \, h_i \Big), \tag{3}$$

where m_i and h_i are the mass and height of the center of gravity of the i-th strut, respectively. We can therefore determine gravitational potential energy of the robot at any condition based on Eq.3.

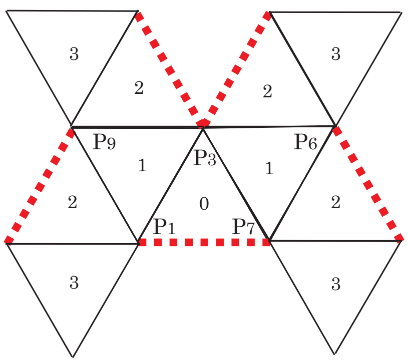
VI. Summary

In this paper, we have shown that a deformable robot with a tensegrity structure can be designed so that it can move by crawling, and we described the performance of prototype robots in practical experiments. First, we showed a tensegrity structure, made of struts and cables, and its characteristics. Second, we briefly explained the principle of crawling using robot body deformation. Next, we classified the methods of causing body deformation and the contact conditions of the robot through a cable-graph of the tensegrity structure. We also described a topological transition graph that can be used to visualize crawling from each initial contact condition. We then discussed the characteristics of the proposed robot in terms of design freedom. Finally, we showed experimentally that the prototype of a tensegrity robot could crawl.

Future work includes showing that a tensegrity robot can jump in response to body deformation. The potential energy stored in the body of a deformable robot is significant. Moreover, the jumping height generated by body deformation of a circular deformable robot has been shown to depend on the initial shape of the robot before jumping [8]. Using these results, we will design an appropriate shape in which potential energy can be stored and restored by body deformation. We need to contrive various ways of generating



(a) From $P_1P_3P_5$ pattern



(b) From $P_1P_3P_7$ pattern

Fig. 8. Transition graphs of crawling pattern

body deformation in order to realize the appropriate shape for jumping.

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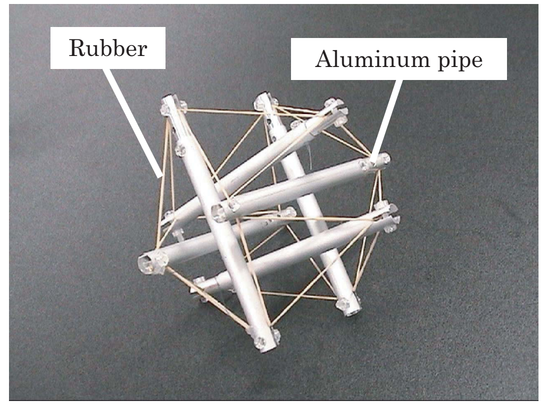

Fig. 11. Prototype (heavy weight type)

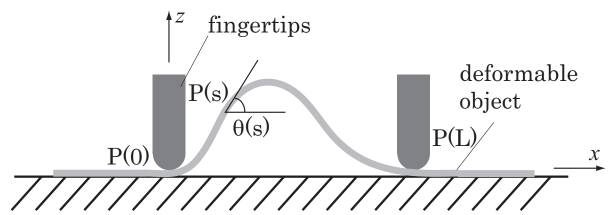

Fig. 12. Potential energy of an object by bending deformation

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