How Object Softness Contributes to Robotics

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Abstract

This paper describes how object softness contributes to robotics, taking two research projects on locomotion and manipulation. First, I describe crawling and jumping by the deformation of a robot body. Second, I focus on the soft-fingered manipulation to show how fingertip softness realizes the secure grasping and manipulation of an object.

1. Introduction

Robotics has mainly focused on rigid body systems. Object softness has been interested in the literature of flexible arms, where softness was regarded as a barrier against good performance of a mechanical arm. Recently, through researches in my group, I recognize that object softness can improve the performance of mechanical systems. These approaches are referred to as *soft body robotics*. This paper describes our two research issues on soft body robotics to show how object softness contributes to the locomotion and the manipulation. First, I describe crawling and jumping by the deformation of a robot body. Second, I focus on the soft-fingered manipulation to show how fingertip softness realizes the secure grasping and manipulation of an object.

2. Locomotion by Deformation

2.1. Motivation

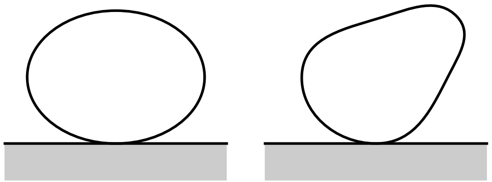
Rough terrain locomotion has mainly relied on rigid body systems, such as crawlers and leg mechanisms. Locomotion mechanisms consisting of rigid body systems have drawbacks: large weight that may cause impact to humans and difficulty in recovery from their overturning. Recently, mechanisms that can recover from their overturning have been studied [1, 2], but these mechanisms tend to be complicated. An alternative approach to light-weighted and simple mechanisms is thus required. Recent researches on soft actuators such as shape memory alloy (SMA) wires and polymer gel actuators has yielded impressive results [3, 4, 5]. Soft actuators have been used to drive leg mechanisms and soft body robots [6]. Locomotion mechanisms consisting of soft actuators can be light-weighted. Unfortunately, soft actuators still have drawbacks. They tend to generate a small force, and those that generate a large force need either a high driving voltage over 1,000V, making it difficult to build self-supporting robots, or a wet environment.

To overcome this problem, we have employed soft actuators to controllably deform a robot body, enabling it to crawl over and jump on rough terrain. Crawling and jumping using deformation can cope with rougher terrain than rigid body systems can. Additionally, soft body deformation reduces the damage in collision with humans.

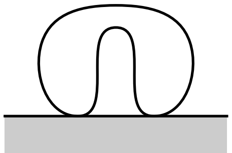
2.2. Principle of Crawling and Jumping by Deformation

Suppose a robot is in stable on the ground, as illustrated in Figure 1-(a). Self-deformation of the robot body generates a moment by a gravitational force around the area the robot is in contact with the ground. The moment causes the robot to move on the ground. If the robot deforms from a stable shape into an unstable shape described in Figure 1-(b), it rotates clockwise and moves towards the right. Successive deformation of the robot body, which can be generated by actuators, enables a continuous crawling motion along the ground. Thus, the proposed crawling approach uses gravitational potential energy.

Deformation allows elastic potential energy to be stored which, if released rapidly enough, can generate a force large enough to make the robot jump. Now suppose the robot deforms from one stable shape into another, which has large high potential energy as illustrated in Figure 1-(c). If the potential energy is released rapidly enough, the robot will jump. The high-energy shape shown in Figure 1-(c) turns, with a small disturbance, into the stable shape shown in Figure 1-(a), generating the force required for the jump. Thus, the proposed approach uses elastic potential energy. Actuators inside the robot body can be used to store this elastic energy. The forces required to store the elastic energy is generally much smaller than those required to perform a jump.



(a) stable shape (b) unstable shape



(c) stable shape with high potential energy

Figure 1: Principle of crawling and jumping

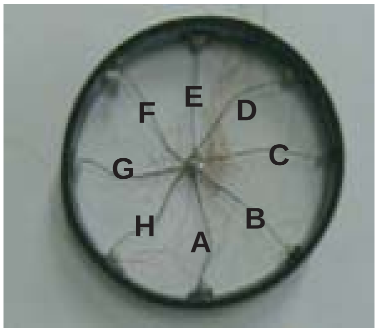
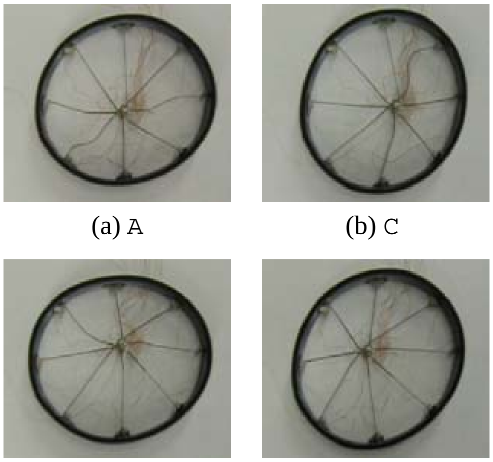


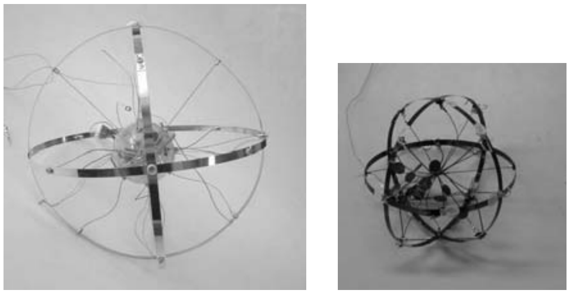
Figure 2: Prototype of a circular soft robot



(a) A (b) C

(c) E (d) G

Figure 3: Deformation of a circular soft robot



(a) (b)

Figure 4: Prototypes of spherical soft robot

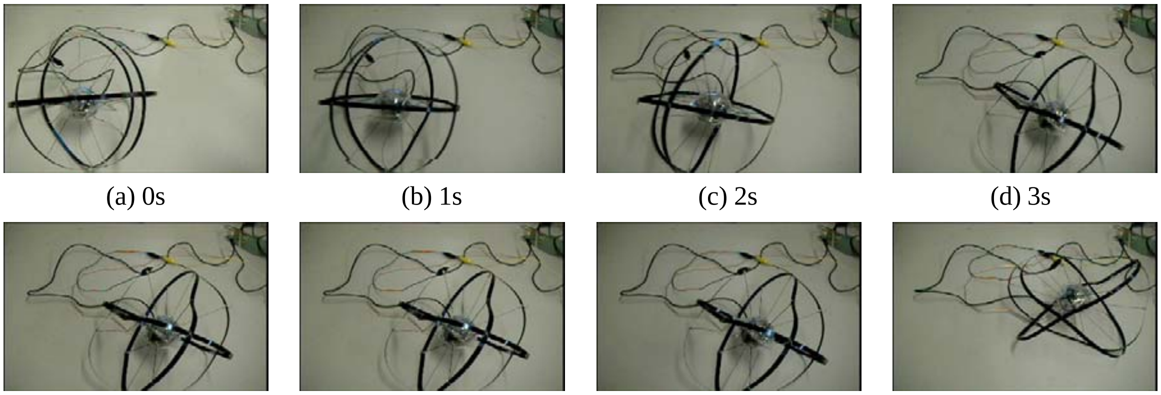
2.3. Experimental Results

Figure 2 shows a prototype of a circular soft robot, which consists of eight BMX100 SMA coils, labelled A through H, attached to the inside of a circular rubber shell. When voltage is applied to a coil, it contracts, causing the circular rubber to deform as shown in Figure 3. Each figure corresponds to the deformation caused by the contraction of an individual coil, namely coil A, C, E, or G.

We build two prototypes of a spherical soft robot to assess experimentally the feasibility of a deformable robot crawling and jumping. The prototypes are shown in Figure 4. The body of a prototype consists of three circular shells intersecting orthogonally. Prototype shown in Figure 4-(a), which is referred to as prototype A, is for crawling. This prototype consists of 18 SMA coils and shells made of spring steel. The diameter of the the spherical body is 200mm and the prototype weighs 137g. The core inside the spherical body includes circuits to drive SMA coils, a microprocessor, and a serial communication circuit. The core weighs 75g. Prototype shown in Fig.4-(b), which is referred to as prototype B, is for both crawling and jumping. This prototype consists of 22 SMA coils - 18 for crawling and jumping and 4 for jumping. The diameter of the spherical body is 90mm and the prototype weighs 5g. Circuits to drive SMA coils and a microcomputer are outside of the prototype.

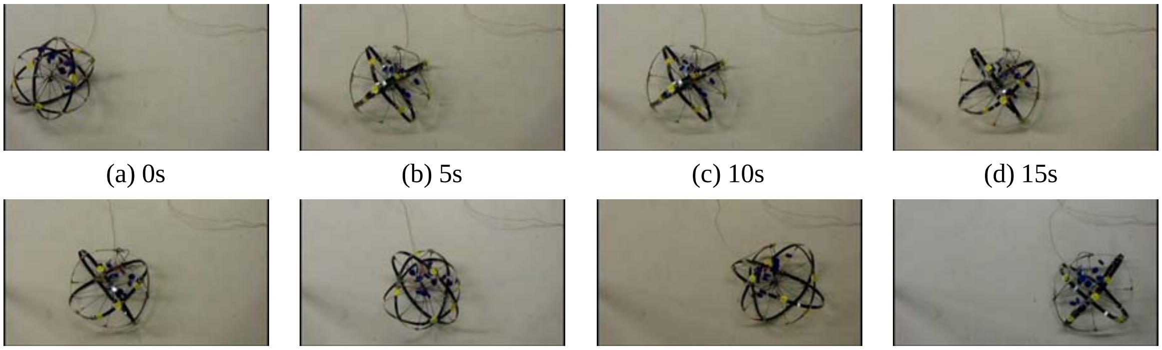
Figure 5 shows SMA coils attached to a spherical prototype. Figure 5-(a), (b), and (c) show the top, side, and front view of the prototype, respectively. All the SMA coils used for crawling are illustrated in these figures. As can be seen in the figures, the SMA coils for crawling are attached between the center of the sphere and the three circular shells labelled C1, C2, and C3. The 18 SMA coils used for crawling are labelled A100 and $A\bar{1}00$ through A001 and $A00\bar{1}$ as well as the digital sum of each adjacent pair. Figure 5-(d) shows the bottom of the prototype. Four SMA coils for jumping are attached along a square The SMA coils for jumping are labelled $B10\bar{1}$, $B01\bar{1}$, $B\bar{1}0\bar{1}$, and $B0\bar{1}\bar{1}$.

Crawling Figure 6 describes the crawling of a prototype A on a flat ground. Fig.7 describes the crawling of a proto-


(a) 0s (b) 1s (c) 2s (d) 3s

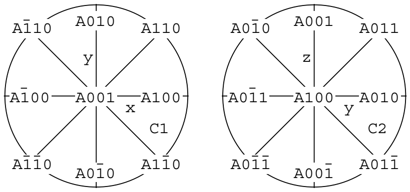
(e) 4s (f) 5s (g) 8s (h) 16s

Figure 6: Spherical soft robot crawling (prototype A)

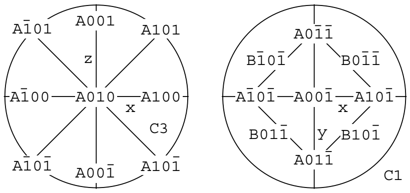

(a) 0s (b) 5s (c) 10s (d) 15s

(e) 20s (f) 30s (g) 40s (h) 50s

Figure 7: Spherical soft robot crawling (prototype B)



(a) top view (b) side view



(c) front view (d) bottom view

Figure 5: SMA coils attached to spherical prototype

type B on a flat ground. As shown in the figures, the spherical robots can crawl on a flat ground.

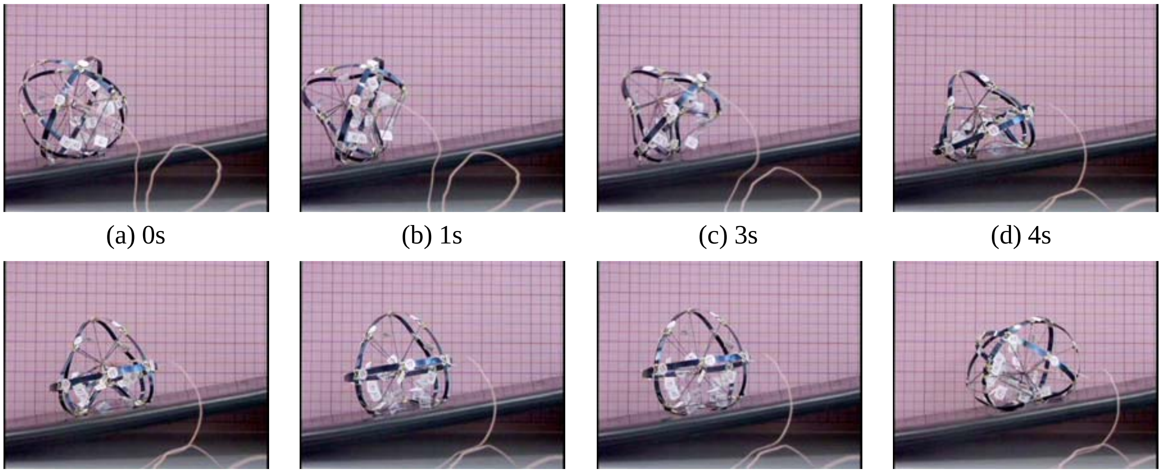
Slope-climbing Figure 8 describes the slope-climbing of a prototype B. The prototype can climb up a slope of 10 °.

Jumping Figure 9 shows the jump of a prototype B. The prototype can jump 180mm, which is twice of the diameter of the prototype.

3. Soft-fingered Manipulation

3.1. Motivation

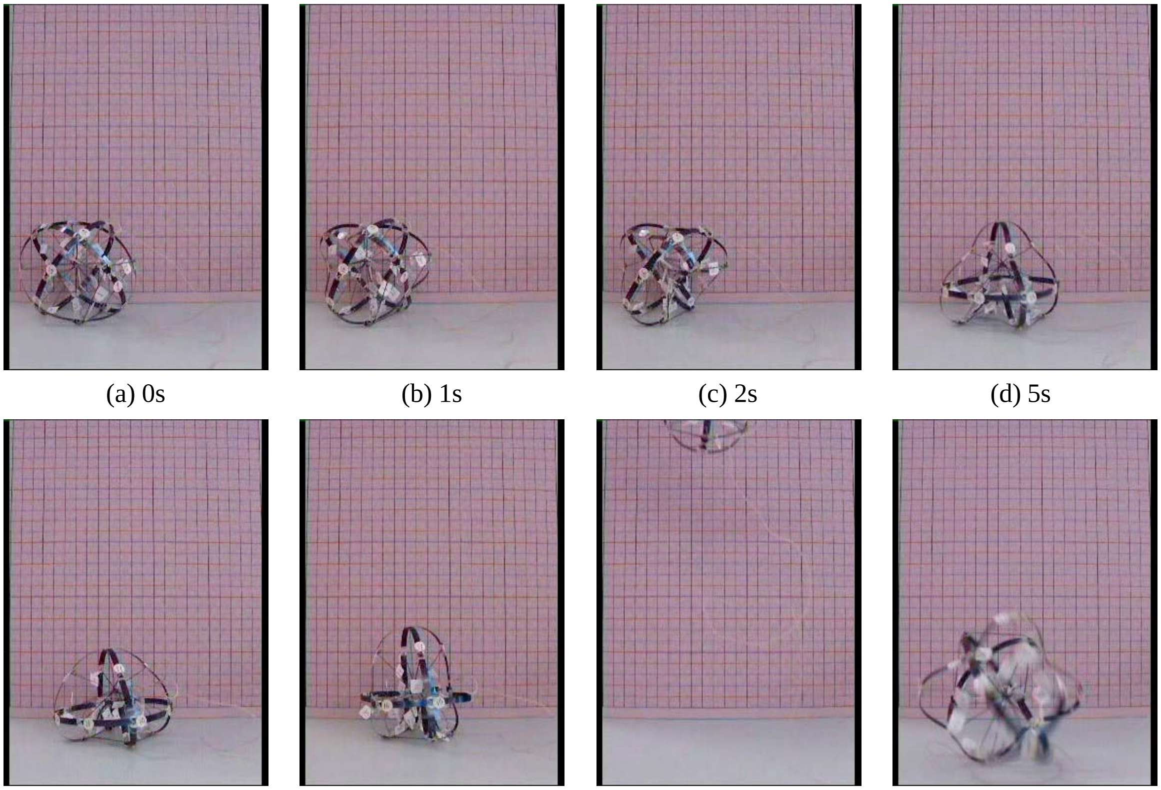
Many researches on object grasping and manipulation have assumed a point-contact between an object and rigid fingertips. Since the grasped object moves and rolls on the fingertip, it is comparatively easy to analytically describe position and velocity equations based on a geometrical relationship, which are required for the stability analysis of the grasped object. On the contrary, soft fingertips tend to deform easily and largely due to their softness. This deformation con-



(a) 0s (b) 1s (c) 3s (d) 4s

(e) 9s (f) 12s (g) 15s (h) 18s

Figure 8: Spherical prototype climbing a slope (prototype B)



(a) 0s (b) 1s (c) 2s (d) 5s

(e) 15s (f) 45s (g) 46s (h) 47s

Figure 9: Spherical soft robot jumping (prototype B)

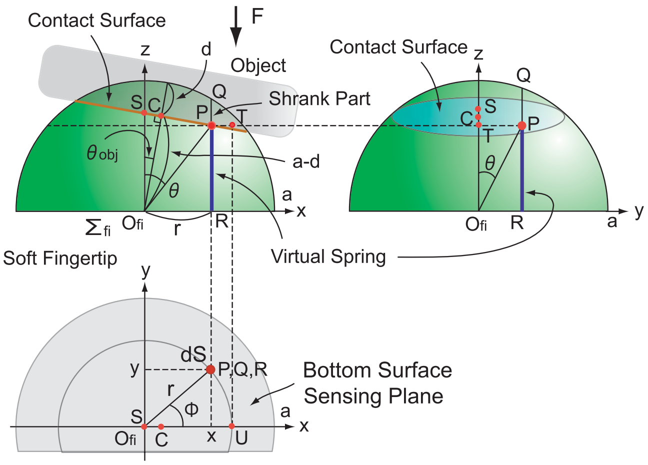


Figure 10: Translational contact

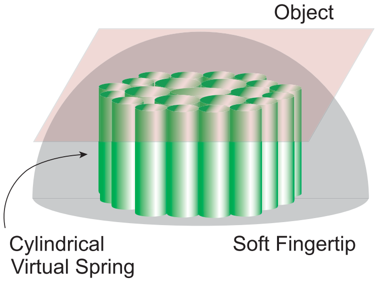
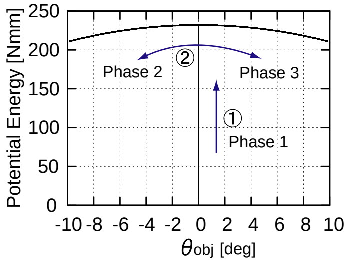


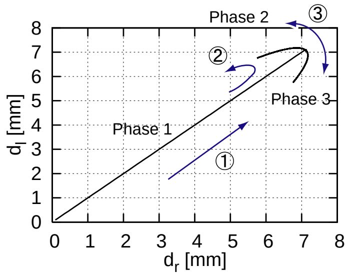
Figure 11: Cylindrical virtual spring components

tributes to grasping and manipulation of an object. In fact, the plane-contact is necessary for humans to achieve stable grasping and manipulation of the object, as the elastic force acting on the soft fingertip disperses widely to the object. This suggests that we should introduce soft fingertips to realize secure grasping and manipulation by a mechanical hand, and build an analytical model of soft fingertips to investigate how the deformation of fingertips contributes to the grasping and manipulation.

Several researches associated with the grasping using a soft fingertip have been studied recently. Xydas and Kao have shown an exact deformation shape of a *hemispherical soft fingertip* using FE analysis[7, 8, 9]. These studies have focused on deriving an exact deformation model, and have proposed the vertical contact deformation of the soft fingertip alone. Arimoto et al. have formulated *dynamics* in pinching by a pair of fingers with soft tips[10]. They have proposed a simple deformation model of a soft fingertip in order to use analytical mechanics theory in control[11]. Based on a concept of *stability on a manifold*, they have theoretically shown that a pair of a 2-DOF finger and a 1-DOF finger realizes secure grasping and posture control. More-



(a) potential energy



(b) displacements of fingertips

Figure 13: Simulation results

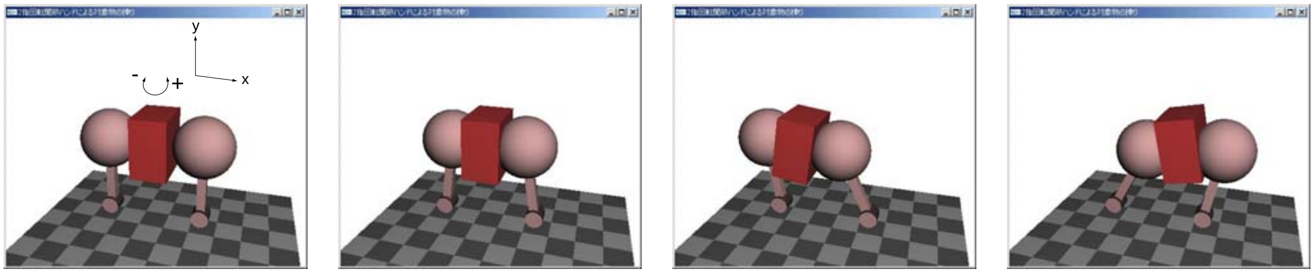
over, Arimoto and Doulgeri have formulated *rolling contact* between a grasped object and fingers with rigid tips and shown that a pair of a 2-DOF finger and a 1-DOF finger realizes secure grasping and posture control as well [12, 13]. This implies that rolling contact between an object and fingertips is a key to stable grasping and posture control. One additional DOF is needed to achieve the equilibrium of moments acting on a grasped object.

Our preliminary experiment suggests that a pair of two 1-DOF fingers with soft tips can perform secure grasping and posture control. In the above articles, the deformation model assumes that all the elastic forces acting on the soft fingertip face toward the origin of the fingertip. The gap between the above theory and our preliminary experiment comes from the deformation model of a soft fingertip rather than a control law for secure grasping and posture control. We need a new model of soft fingertips in order to theoretically show that a pair of two 1-DOF fingers with soft tips can perform secure grasping and posture control.

3.2. Fingertip Model

Figure 10 illustrates the translational contact between a rigid object and a hemispherical fingertip. Let d be the maximum displacement of a fingertip, θ_{obj} be the relative orientation between an object and the fingertip, and a be the radius of the fingertip.

In contact model, the infinite number of virtual springs are introduced along vertical direction, whose individual spring constants are different for each other due to their nat-



(a) phase 0 (b) phase 1 (c) phase 2 (d) phase 3

Figure 12: Motion of grasped object

ural lengths that stem from the hemispherical shape of the fingertip, as shown in Figure 11. Let E denotes Young's modulus of the fingertip material. Based on the contact model, we can compute the elastic potential energy stored in a fingertip in contact with a rigid object. The elastic potential energy can be written by

$$U(d,\theta_{obj}) = \int_S \frac{1}{2} E \lambda(x,y,d,\theta_{obj}) \,\mathrm{d}S,$$

where

$$\begin{aligned}\lambda(x,y,d,\theta_{obj}) &= \Bigg\{ \sqrt[4]{a^2-(x^2+y^2)} \\ &- \frac{a-d-x\cdot\sin\theta_{obj}}{\cos\theta_{obj}\sqrt[4]{a^2-(x^2+y^2)}} \Bigg\}^2.\end{aligned}$$

Set S is an ellipsoid region of point (x,y) satisfying the following two inequalities:

$$\begin{aligned}\big(x-(a-d)\sin\theta_{obj}\big)^2 \leq (a^2-(a-d)^2)\cos^2\theta_{obj} &= 0, \\ y^2 \leq a^2-(a-d)^2 - \frac{\{x-(a-d)\sin\theta_{obj}\}^2}{\cos^2\theta_{obj}} &= 0.\end{aligned}$$

We should stress that the potential energy depends on not only the maximum displacement d but the relative orientation between an object and a fingertip θ_{obj}. This dependency originates from the structure of a fingertip: a hemispherical soft tip with a rigid plate behind. Note that this structure is similar to a human fingertip: a soft tip with a hard nail. So, this dependency is referred to as *nail effect*.

3.3. Simulation

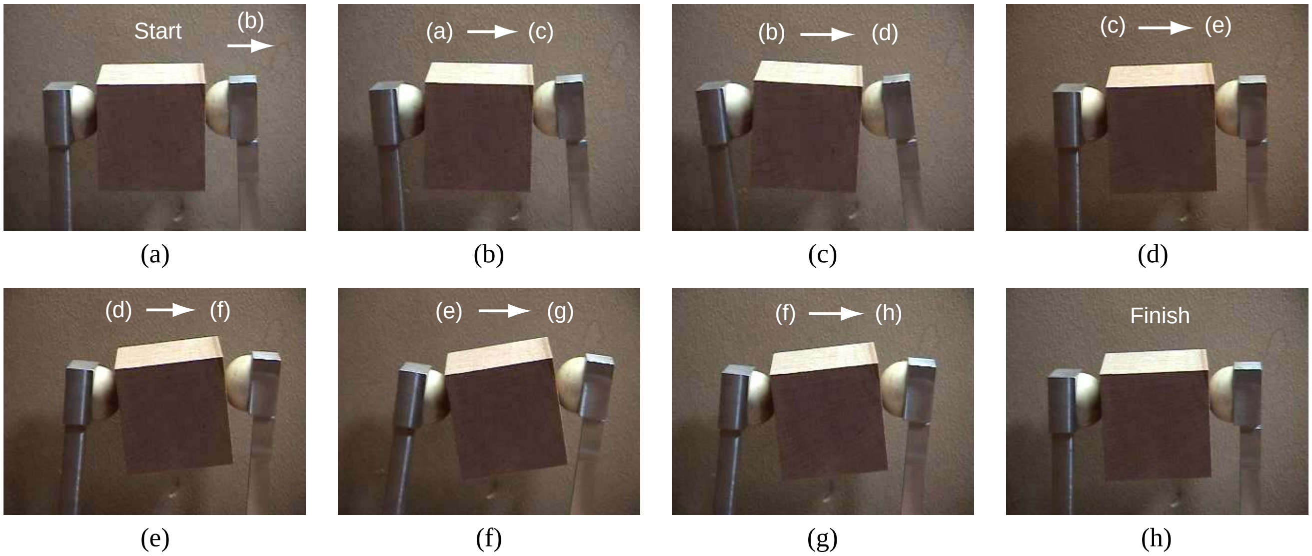
We simulate our proposed model and show a quasi-static manipulation process based on the theory of the local minimum of the elastic potential energy of the soft fingertip.

In this simulation, we set that both fingers face each other in parallel in the initial condition, as shown in Figure 12-(a). We assume that Young's modulus, E, is 0.30MPa that is measured by a tension test of several specimens made of identical material with the soft fingertip, and its diameter is 40mm. The width and height, w and h, from the center of the object are zero to avoid the complexity. Also, the length of the finger, L, is set as 51mm, and the mass of the all parts is negligible in this simulation.

As shown in Figure 12-(b) and Figure 13-(a), the total elastic potential energy by both fingers gradually increases as both fingers rotate toward inner side by 8deg, and the posture of the grasped object does not change. Continuously, when both fingers rotate toward counterclockwise direction by 20deg and rotate to opposite direction by 20deg, the object moves an opposite direction against the motion of both fingers. That is, the object slightly moves toward clockwise direction when both fingers rotate toward counterclockwise direction, and vice versa, as shown in Figure 12-(c) and (d). Additionally, after passed the maximum value shown in Figure 13-(a), the potential energy iterates a transition between maximum and minimum values, which corresponds to phase 2 and phase 3 shown in Figure 12. Furthermore, as shown in Figure 13-(b), each maximum displacement d_r and d_l of the right and left fingertips is completely equal at the case between phase 0 and phase 1. After that, d_l is larger than d_r in phase 2, and on the contrary, d_r becomes larger than d_l in phase 3.

Note that the position of center of gravity x_{obj} and y_{obj} and the orientation angle θ_{obj} can be decided while the total potential energy of both fingertips converges to its local minimum. Thus, we have obtained the quasi-static sequence motion of the grasped object by computing the variables x_{obj}, y_{obj}, and θ_{obj} consecutively at every infinitesimal angle of both fingers. This shows that the orientation of a grasped object can be controlled by joint angles of both 1-DOF rotational fingers.

Based on a contact model where the elastic energy depends on the maximum displacement d alone, it has been shown that a pair of 1-DOF fingers with soft fingertips cannot control the orientation of an object. Our model shows that a pair of 1-DOF fingers can control the object orientation. This ability originates from the *nail effect*.



(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 14: Experimental results

3.4. Experiment

We evaluate the motion of the grasped object by two rotational fingers, and demonstrate that the object moves and tilts as well as the simulation results. We made a simple apparatus and a hemispherical soft fingertip, which is able to rotate freely by human hand motion as shown in Figure 14. The soft fingertip is made of polyurethane gel, and its diameter is 26mm. The length of each finger is 105mm, and the object is made of wood. Its shape is cube, and the mass is approximately 30g.

First, two rotational fingers are located at a parallel location, and rotate by a given angle toward inner side. The swing motion of both fingers is repeated several times. Figure 14 shows experimental results, in which the sequence motion of the object follows the arrows from (a) to (h). The grasped object moves from side to side as the fingers rotate simultaneously. The most important point is that the object tilts toward opposite direction of rotation of the fingers as well as the simulation result.

4. Summary and Conclusions

In this paper, I described two research issues on soft body robotics to show how object softness contributes to the locomotion and the manipulation. First, I introduced crawling and jumping by the deformation of a robot body. The deformable robot body works as a mechanical capacitor: elastic potential energy is stored in and released from the body during the jumping. I should stress that the SMA coils cannot generate sufficient impulse for the jumping. Releasing the potential energy stored in the body rapidly, we obtain an enough impulse for the jumping. Second, I described the grasping and posture control of a rigid object by a pair of 1-DOF fingers with soft fingertips. Up to now, it is believed that a pair of 1-DOF fingers can regulate the grasping force but cannot control the orientation of a grasped object. Here, I show that a pair of 1-DOF fingers can control the orientation of a grasped object through physical simulation and experiment. This ability originates from *nail effect*: the structure of a hemispherical soft fingertip with a rigid plate behind.

Through these two research issues, I found that object softness can improve the performance of mechanical systems. Theoretical investigation on the soft body robotics is now developing based on the static and dynamic modeling of deformable soft objects. Professor Tanaka and I have organized a research group on the *reality-based modeling of deformable soft objects based on their internal sensing*. We have developed an FE model of inelastic deformation, as shown in Figures 15 and 16. We are also building an internal sensing system using a CT scanner and MEMS-based force sensors. I believe that this modeling technique enables us to analyze theoretically how object softness contributes to the performance of mechanical systems.

I have omitted the detailed discussion in this paper. See details in [14] for crawling and jumping and in [15, 16] for soft-fingered manipulation.

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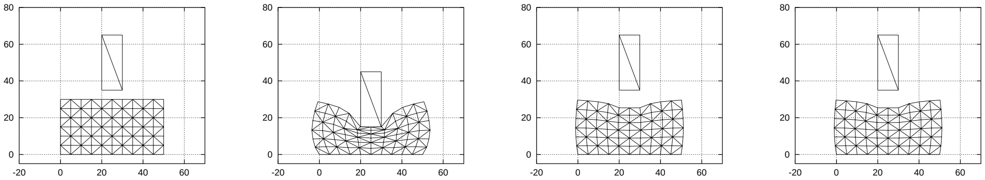
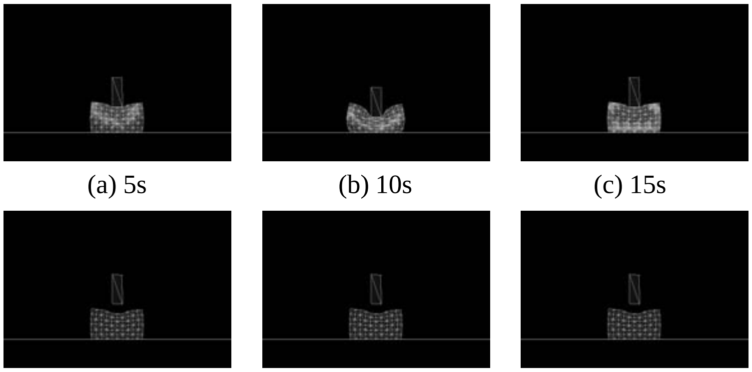


(a) 0s (b) 10s (c) 20s (d) 30s

Figure 15: Computation of 2D rheological deformation using FEM



(a) 5s (b) 10s (c) 15s

(d) 20s (e) 25s (f) 30s

Figure 16: Computed stress in 2D rheological deformation

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