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Loco-sheet: Morphing Inchworm Robot Across Rough-terrain

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***Abstract*—Inchworm, a kind of caterpillar, traverses various terrains by moving its center of mass (COM) with simple two-anchor crawling locomotion. Because of this advantage, many soft locomotion robots were developed to mimic this inchworm-like two-anchor crawling. However, most of these developed inchworm robots have difficulties in moving its COM in the vertical height direction, so these robots face difficulties in overcoming discrete high terrain, like stairs. In this paper, we propose a flexible sheet-based inchworm robot (Loco-sheet) that employs a novel locomotion mode made by morphing to overcome discrete high terrains, like stairs. In this novel mode, called the S-shape locomotion mode, the robot changes its body shape into an 'S' to lift the COM up, by exploiting bending stiffness of the flexible sheet to climb stairs. The bending stiffness of the sheet was designed to be sufficient to lift up the COM. The robot also does two-anchor crawling, called the omega-shape locomotion mode, to pass through low gaps. Loco-sheet is designed with anisotropic friction wheels and a mass distribution advantageous for omega-shaped locomotion without slippage. Morphing between two modes is reversible. Motor-tendon driven actuation system allows the robot to pull the far end of the sheet from the actuator to fold the body, and allows the robot to operate untethered from an external power supply with small volume actuators. The robot climbs a 90 mm stair, passes through 72 mm low gaps, and travels flat surfaces. Therefore, Loco-sheet is suitable for traveling a variety of undefined environments.**

***Index Terms*—Soft locomotion robot, Multi-modal locomotion robot, Inchworm robot, Morphing robot, Flexible sheet-based robot**

I. Introduction

Caterpillars are made up of soft bodies and can traverse various terrains [1], making soft locomotion robotics researchers attractive to imitation. To adapt to various terrains, caterpillars move their center of mass (COM) by morphing their flexible body. For example, two-anchor crawling, seen in the motion of inchworms', changes the position of their COM and points of anchoring to move by first folding the body into an omega-shape followed by spreading out. Due to the relative ease-of-design of this type of locomotion and its adaptability to wide range of different environments, robotics researchers have developed inchworm like robots that mimic two-anchor crawling [2]-[10]. Additionally, one caterpillar-like robot was developed that simulates a caterpillar that can roll quickly [11]. The guiding principle behind these robots is concentrated on the forward movement of the robot's COM position; resulting in locomotion on a continuous planes, like flat or inclined planes.

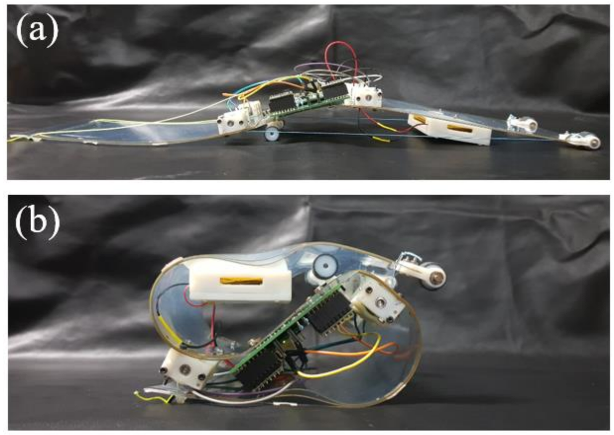

Figure 1. Loco-sheet (a) Omega-shape locomotion mode (b) S-shape locomotion mode.

However, terrain generally is not composed of only flat continuous surfaces but also discrete uneven terrains like a staircases. In order for inchworm robots to then climb these discrete uneven terrains, the anchoring points of the robot must have means to float above the ground to connect with high elevation anchoring points, and raise its COM higher than the target terrain. Since the COM of previous inchworm-like soft robot designs are situated away from the contact surface of the anchoring area with the ground, for these robots to lift their COM and one anchoring point above the target terrain stably, another anchoring point is needs to be fixed to the ground. Most developed inchworm robots' anchoring points are hard to fix to the ground, making discrete high terrain difficult to overcome. There are some inchworm robots that use artificial prolegs [12], magnets [13], or suction pads [14] to fix one anchoring point to the ground to lift another anchoring point and COM up, but these approaches are limited by surface materials.

In this paper, we propose a flexible sheet-based inchworm robot (Loco-sheet) with an additional 'S-shape' locomotion mode generated through morphing to overcome discrete high terrain, like stairs (Fig. 1). S-shape locomotion mode is defined by the unique "S-shape" of the robot during locomotion. During S-shape locomotion, the COM of the robot is situated directly above the contact surface of the anchoring area with ground, and bending stiffness makes

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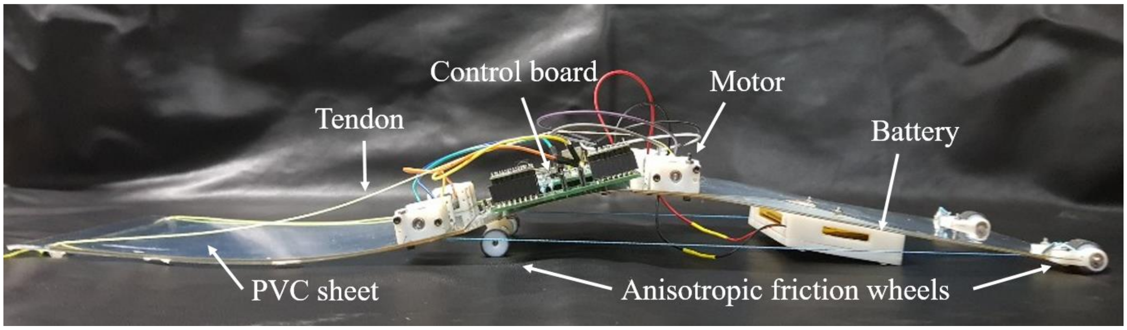

Figure 2. Strucutre of the Loco-sheet

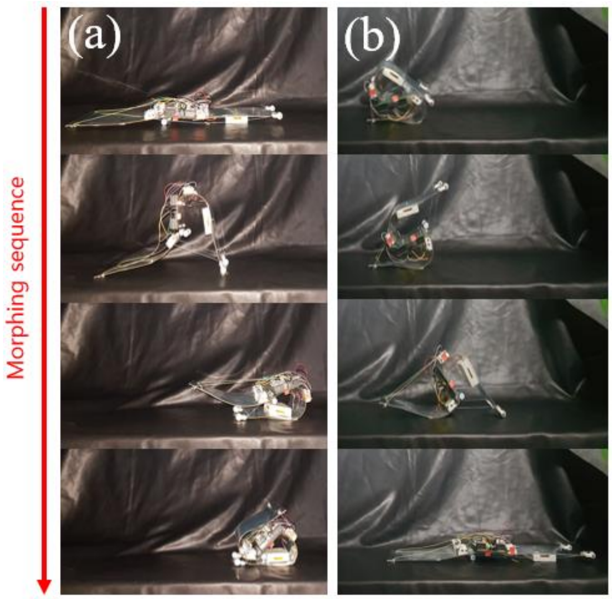

Figure 3. Morphing of Loco-sheet (a) Morphing from Omega-shape to S-shape (b) Morphing from S-shape to Omega-shape

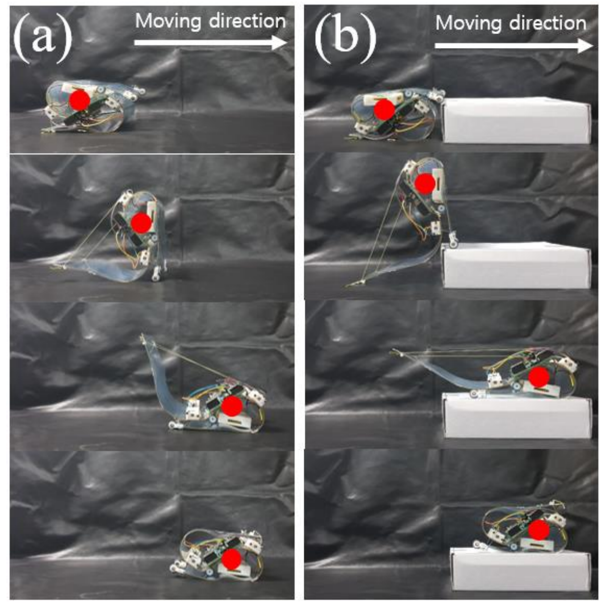

Figure 4. S-shape locomotion mode of Loco-sheet (a) A plain case (b) A stair(60 mm height) case. The red point is COM of the robot.

force in the height direction, so COM is raised stably. The body is composed of a flexible PVC sheet so morphing into another mode is possible by stroke adjustment of motor-tendon actuation system while having enough bending stiffness to lift up the robot over high terrain. The S-shape of the robot is still S when turned 180 degrees, so it moves repeatedly.

The Loco-sheet also does inchworm-like two-anchor crawling to pass through low gaps. The inchworm-like crawling mode is called omega-shape locomotion mode. Anisotropic friction wheels were attached to the robot and the mass distribution was designed to perform the two-anchor crawling without slipping.

Loco-sheet is fully untethered from an external source of power, rather, it is battery powered. The robot's height is 7 cm when fully folded, and the robot climbs steps up to 9 cm height. On a flat surface, it moves at a speed of 22 mm/s while in its S-shape locomotion mode and moves at a speed of 18 mm/s in its omega-shape locomotion mode. This robot crawls through narrow gaps with a minimum height of 7.2 cm. Therefore, Loco-sheet is suitable across a variety of rough terrain, and useful for exploring places including contaminated zones.

II. Loco-sheet Design

A. Design Overview

Loco-sheet is a sheet-based robot composed of an assembly of several parts mounted to a flexible PVC sheet (Fig. 2). The PVC sheet is flexible enough for morphing and it has enough bending stiffness to exploit stiffness to movement. In addition, it is possible to replace rigid links, bearings and springs with one sheet, which is simple and inexpensive. Loco-sheet is capable of locomotion in two modes, S-shape locomotion and omega-shape locomotion. Each motion is made by folding and unfolding the flexible sheet, but it should be noted that different shapes make different motions. And the difference in shape is generated by adjusting the amount the flexible sheet is folded (Fig 3). Morphing from one mode to another mode is reversible.

In the soft robotics field, dielectric actuators [15], [16], shape memory alloy (SMA) coils [17], [18], pneumatic actuators [19], [20] and motor-tendon driven actuation systems [3], [21] are used for actuation. Loco-sheet uses motor-tendon driven actuation system for actuation. This actuation pulls the far end of the sheet from actuators with tendons using small electrical motors to fold the body. And strokes are adjusted by modulating these tendons. Using an

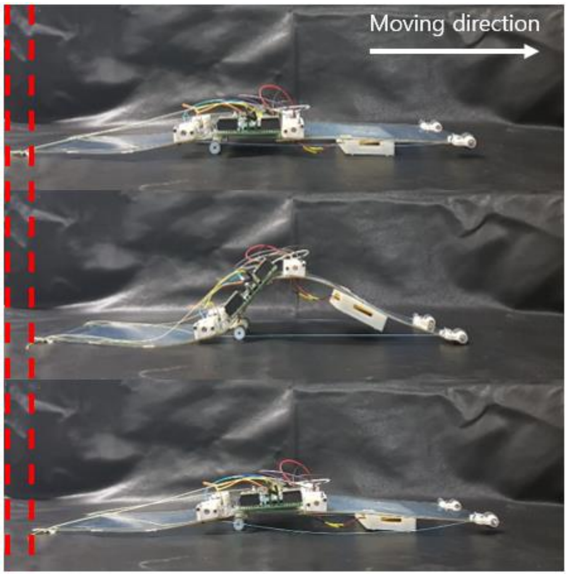

Figure 5. Omega-shape locomotion mode of Loco-sheet.

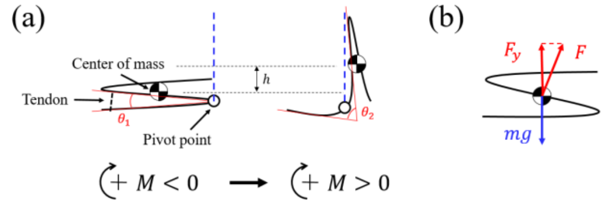

Figure 6. S-shape locomotion mechanism of Loco-sheet. (a) Moment change by releasing tendons. (b) Free body diagram of S-shape locomotion mode.

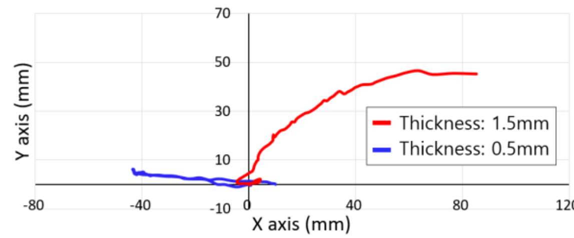

Figure 7. Center of mass trajectory of S-shape locomotion according to sheet thickness.

electric motor as an actuation system means that the robot can be completely untethered through the addition of batteries on board. Folding movements are made by pulling the tendon tied at the end of the sheet, and unfolding motions are created by the elasticity of the sheet when the tendon is released.

S-shape locomotion is a novel motion that lifts up the COM using the bending stiffness of PVC sheet (Fig. 4). For S-shape locomotion, morphing should be performed to form the S-shape as shown in Fig. 3 (a). Then, when the tendon connected to the folded sheet at the bottom is released, the bending stiffness of the sheet lifts the COM (red points in Fig. 4) of the robot upward and allows it to move forward. When pulling the released tendon again, it returns to an S-shape. The robot continues to move when this process is repeated. When climbing stairs, this robot adjusts the tendon length connected to the folded sheet at the top to anchor itself over the stairs. Then, the robot releases the tendon connected to the folded sheet at the bottom, causing the force generated by the bending stiffness of the sheet to lifts the COM of the robot upward and allowing it to climb stairs.

During omega-shape locomotion, the robot performs two-anchor crawling, folding and unfolding itself into an omega shape (Fig. 5). For omega-shape locomotion, the motor releases all the tendons and unfolds the sheet as shown in Fig. 3 (b). By pulling the tendon connected to the sheet in desired direction of motion moves the robot forward due to the friction difference between the anisotropic friction wheels and the surface in contact. If the tendon is loosened, the friction difference between the anisotropic friction wheels allows the robot to unfold without moving backward. The robot continues to crawl by repeating this process. Omega-shape locomotion permits the Loco-sheet to pass through low gaps that the robot has difficulty to pass through while in its S-shape locomotion.

B. Mechanical Design for S-shape Locomotion

In its S-shape locomotion, in order for Loco-sheet to move forward, it needs to move its COM until it exceeds the pivoting point and change the direction of the gravity induced moment to the clockwise direction by releasing the tendon as shown in Fig. 6 (a). For the COM of the robot to cross the pivoting point, the COM must be elevated at the time the sheet unfolds. The force of lifting the COM up is made by the bending stiffness of the sheet. As shown in Fig. 6 (b), the y-axis force of F due to bending stiffness must be greater than the gravity, mg, so that the COM can be elevated.

In order to satisfy the bending stiffness condition of the F_y greater than mg, the robot body was fabricated by attaching three sheets of 0.5T PVC. Fig. 7 compares the trajectory of the COM of robots made of one PVC sheet and made of three sheets. In the blue trajectory shown in Fig. 7, the COM of a robot made of one PVC sheet moves backward. Since the bending stiffness of one PVC sheet is not high enough to lift the COM up, the stiffness pushes the COM backward. Whereas, in the red trajectory, a robot made of three PVC sheets lifts the COM up and permits it to move forward.

C. Mechanical Design for Omega-shape Locomotion

During omega-shape locomotion, to crawl without slip using the folding and unfolding of the sheet, there must be a difference in the friction between the front and back contact points with the ground when pulling and releasing the tendons. The difference in the friction coefficients was made by attaching anisotropic friction wheels in the front and rear. The normal force acting on each wheel was balanced similarly so that the force difference was a direct function of the friction coefficient.

Fig. 8 shows the crawling principle of the Loco-sheet. In Fig. 8 (a), the normal force acting on wheel 1 is dominantly depend on m_1, and the normal force acting on wheel 2 is dominantly depend on m_2. In order to make normal forces N_1 and N_2 similar, a control board and actuators (180.9g) were placed in m_1 and a battery (143.4g) was placed in m_2.

The front and rear anisotropic friction wheels were made using one-way clutches. The one-way clutch is a bearing that travels only in one direction. Both wheels are designed so that

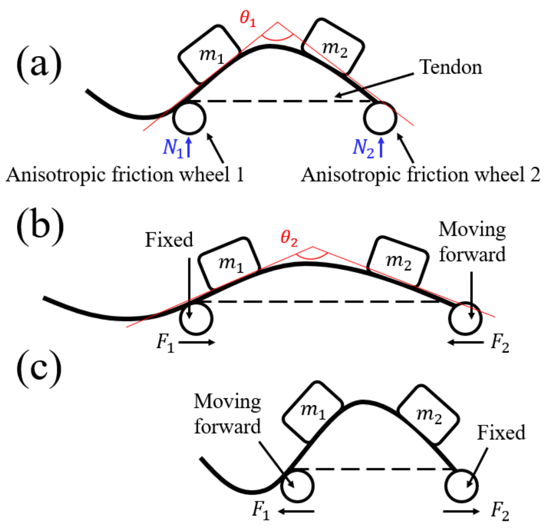

Figure 8. Omega-shape locomotion mechanism of Loco-sheet. (a) Folded state of omega-shape locomotion mode. (b) Unfolded state by releasing tendon. (c) Folded state by pulling tendon.

they roll forward but not backward. In Fig. 8 (a), when the tendon is released, wheel 1 is powered backward and wheel 2 is powered forward. The one-way clutch of wheel 1 is deactivated, and the one-way clutch of wheel 2 is activated because both wheels don't roll back. Then,

$$\mu_1 \gg \mu_2 \quad (1)$$

where μ_1 and μ_2 are friction coefficients of anisotropic friction wheels with ground. Since the normal force is similar,

$$\mu_1 N_1 > \mu_2 N_2 \quad (2)$$

$$F_1 > F_2 \quad (3)$$

Thus, wheel 2 moves forward and wheel 1 is fixed as shown in Fig. 8 (b). Similarly, when pulling the tendon in state (b), the one-way clutch of wheel 1 is activated and the one-way clutch of wheel 2 is deactivated because both wheels don't roll back. Then,

$$\mu_1 \ll \mu_2 \quad (4)$$

Since the normal force is similar,

$$\mu_1 N_1 < \mu_2 N_2 \quad (5)$$

$$F_1 < F_2 \quad (6)$$

Thus, as shown in Fig. 8 (c), wheel 1 moves forward and wheel 2 is fixed. By repeating these two steps, the robot crawls without slip.

D. Materials and Fabrication Process

Loco-sheet's body was made by attaching three sheets of 0.5T PVC. Actuators, electric components, anisotropic friction wheels and body were assembled with bolts and nuts, and holes for assembly were cut using a laser cutter.

The actuation system consists of motors, pulleys and motor casings. To maintain its folded shape without applying current, the motor should not be back-drivable so that the tension of the tendon made by bending stiffness is not lost. Micro metal gear motors (HPCB, gear ratio 298: 1) of Pololu with a stall torque of 3.4 kg · cm was used.

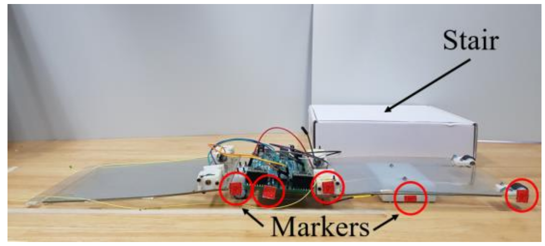

Figure 9. Experimental set-up

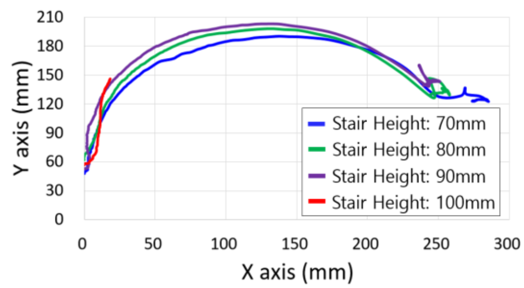

Figure 10. Trajectories of center of the robot on various stair heights.

III. Experiments & Results

Loco-sheet moves across both flat ground and stairs when the robot is in its S-shape locomotion mode, by moving the COM up and by adjusting the anchoring points. Loco-sheet also performs omega-shape locomotion to move under low gaps. In this section, experiments were conducted on the two locomotion modes of the Loco-sheet.

Fig. 9 shows the experimental set-up. Markers were attached to the position where the trajectory and velocity were to be measured and the position which is the center of rotation. Experimental images were taken. Analysis of all the markers were performed using ProAnalyst motion analysis software (Xcitex).

A. Locomotion Ability on Rough Terrains

The reason for adding an S-shape locomotion mode to the two-anchor crawler is to overcome discrete high terrain like stairs. An experiment that tested the maximum height stairs that Loco-sheet overcomes was conducted. The experiment was carried out by measuring the trajectory of the center of the robot with respect to the height of the various stairs. The experimental results are shown in Fig. 10. The results show that the maximum stair height the robot climb is 9 cm (the purple line). For higher stair (10 cm), the bending stiffness of the sheet is too weak to push the robot's COM forward beyond the pivot point, so the direction of the moment is opposite to the direction in which the robot ascends the stairs.

Loco-sheet uses the omega-shape locomotion to pass through low gaps. An experiment testing the minimum height of the gap which the robot crawl was conducted. Since the height of highest point when the robot folds to the omega-shape is the minimum height of the low gap that is traversed by omega-shape locomotion, the trajectory of this point was measured experimentally (Fig. 11). Results show, that the smallest gap height that Loco-sheet crawl under is 72 mm. The gap of this height is difficult to pass by S-shape

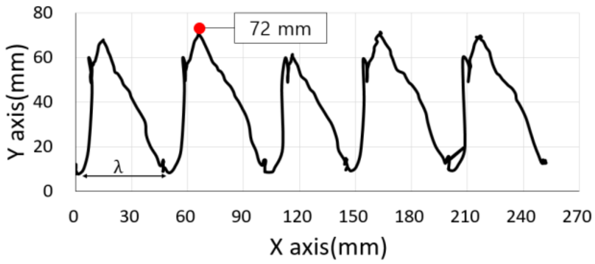

Figure 11. Trajectory of point of maximum height during Omega-shape locomotion.

locomotion mode, justifying the omega-shape locomotion mode as necessary.

B. *Locomotion velocity in each mode*

For locomotion robots, speed is one of the most important factors. The velocity of S-shape locomotion and omega-shape locomotion on a flat surface was measured. Each velocity was measured from the center of Loco-sheet. In order to consider only shape effects of each locomotion mode, the motor was actuated with maximum power in both modes. The resulting mean velocity measured was 22 mm/s in its S-shape locomotion mode and 18 mm/s in its omega-shape locomotion mode. S-shape locomotion mode is inefficient because the robot lifts COM up when moving, so we anticipate that the S-shape locomotion is slower than the omega-shape locomotion. However, S-shape locomotion is faster than the omega-shape locomotion. The reason why the S-shape locomotion is faster than the omega-shape locomotion is because when the COM of the robot is in the right side than pivoting point, the robot is assisted by gravity force, so the center of the robot moves quickly.

C. *Cost of Transport*

Since S-shape locomotion is a novel locomotion that moves the COM upward by using bending stiffness of the sheet, we calculated the mechanical cost of transport (COT) to quantify the energy efficiency of this mode. Because S-shape locomotion lifts COM up, COT is expected to be higher than omega-shape locomotion's COT. Each mode's COT is calculated and compared.

Mechanical COT is the work required to move the unit mass of robot unit distance. In S-shape locomotion mode, Loco-sheet uses potential energy stored in the folded sheet as shown in Fig. 6 when the robot lifts its COM up. And when COM is located on the right side of the pivoting point, the robot then does not use energy because gravity moves the robot. Thus, in Fig. 6, the work that the Loco-sheet used to go forward in S-shape locomotion mode is

$$W = \int_{\theta_1}^{\theta_2} k_{bending}(\theta)\theta d\theta \tag{7}$$

This bending potential energy is equal to the sum of the potential energy and the kinetic energy at $\theta_2$when the robot's sheet is instantaneously loosened from θ_1 to θ_2. Therefore,

$$\begin{aligned} \mathrm{W} &= mgh + \frac{1}{2}\left(\sum I\right) w^2 \\ &= mgh + \frac{1}{2}\left(\sum \int r^2 \rho dr\right) w^2 \\ &= 0.591J \end{aligned} \tag{8}$$

TABLE I. VALUES FOR CALCUATION OF MOMENT OF INERTIA *I* IN S-SHAPE LOCOMOTION MODE

Components	$r(m)$	$\rho(g/m)$	$I(gm^2)$
Sheet	0~0.13, 0~0.18	319	1.47
Motor & board	0.1~0.15	1790	1.94
Battery	0.05~0.15	2820	2.23

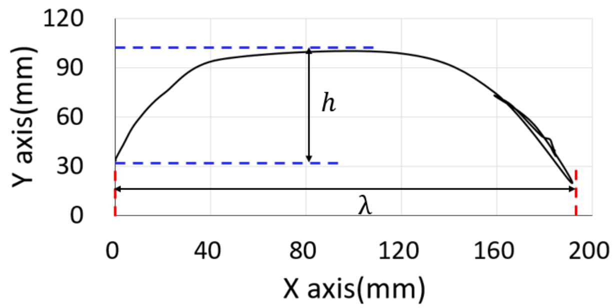

Figure 12. Trajectory of COM of Loco-sheet in S-shape locomotion.

In Eq. (8), the moment of inertia I of Loco-sheet is calculated as the sum of I about the pivoting point which is the center of rotation of the S-shape locomotion mode, the values for the calculation are in Table 1. An experiment of testing the instantaneous spreading of the sheet was carried out, and the values of r and w for θ_2 were measured by the motion analysis software (Xcitex). The value of h is obtained from the trajectory of center of Loco-sheet in while in its S-shape mode (Fig. 12). If the moving distance of the robot's COM is λ, the COT for S-shape locomotion is calculated as,

$$COT = \frac{W}{mg\lambda} = \frac{0.591}{0.481 \times 9.81 \times 0.0468} = 0.681 \tag{9}$$

Where the value λ is obtained from the trajectory (Fig. 12) of the robot's center during S-shape locomotion on the flat surface.

The COT of the omega-shape locomotion is calculated to be similar to S-shape locomotion mode. The work used to go forward which is the sum of potential energy stored in the folded sheet and friction between wheel and ground as shown in Fig. 8 is

$$W = \int_{\theta_1}^{\theta_2} k_{bending}(\theta)\theta d\theta + F_{friction}\lambda \tag{10}$$

The value λ is moving distance during omega-shape locomotion. The bending potential energy is equal to the kinetic energy at θ_2 when the robot's sheet is instantaneously loosened from θ_1 to θ_2.Therefore,

$$\begin{aligned} \mathrm{W} &= \frac{1}{2}\left(\sum I\right) w^2 + \frac{1}{2}mv^2 + F_{friction}\lambda \\ &= \frac{1}{2}\left(\sum \int r^2 \rho dr\right) w^2 + \frac{1}{2}mv^2 + \mu mg\lambda \\ &= 0.108J + \mu mg\lambda \end{aligned} \tag{11}$$

In Eq. (11), the moment of inertia I of Loco-sheet is calculated as sum of I about the center of rotation of the sheet in Omega-shape locomotion mode, values for the calculation are in Table 2. The experiment of spreading the sheet

TABLE II. VALUES FOR CALCUATION OF MOMENT OF INERTIA *I* IN OMEGA-SHAPE LOCOMOTION MODE

Components	$r(m)$	$\rho(g/m)$	$I(gm^2)$
Sheet	0~0.1, 0~0.19	319	0.836
Motor & board	0.02~0.12	1790	1.03
Battery	0.07~0.12	2820	1.30

instantaneously was carried out, and the values were measured by the motion analysis software (Xcitex). COT of S-shape locomotion is

$$COT = \frac{W}{mg\lambda} = \frac{0.108}{0.481 \times 9.81 \times 0.0468} + \mu \\ = 0.489 + \mu \tag{12}$$

If μ is bigger than 0.192, COT of omega-shape mode is bigger than S-shape mode. However, Loco-sheet uses an anisotropic friction wheel as its friction mechanism, so the coefficient of friction between wheel and the ground is very small. Therefore, the COT of omega-shape locomotion is less than 0.681.

IV. CONCLUSION AND FUTURE WORKS

This paper presents Loco-sheet which is a flexible sheet-based two-anchor crawling robot that has a novel mode generated by morphing its shape to overcome discrete high terrains. In its S-shape locomotion mode, the robot lifts its COM up and adjusts the anchoring point to climb stairs. Since the S-shape of the robot is still S when turned 180 degrees, this shape allows the robot to move repeatedly. In its omega-shape locomotion mode, the robot folds its body in an omega-shape to crawl like the usual inchworm robots. Morphing between two modes is reversible.

The bending stiffness of the flexible PVC sheet which was used as the body of the robot is high enough to lift the COM up. Motor-tendon driven actuation allows the robot to pull the far end of the sheet from the actuators, small electrical motors, to fold its body. This actuation allows stroke control and the fabrication of untethered robots by adding batteries. Anisotropic friction wheels with one-way clutches and mass distribution on the sheet create an effective friction difference, allowing two-anchor crawling without slipping.

The proposed robot perform fully untethered locomotion robot including the ability to climb stairs, pass through low gaps, and travel flat surfaces. Therefore, Loco-sheet is suitable for rough terrains outside the laboratory, and is possibly useful for explorations.

This paper is a basic study on an inchworm robot that travel across rough terrain by morphing. In the future, design optimization of morphing and control with sensors will be performed.

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