

# Micro Rubber Structure Realizing Multi-Legged Passive Walking -Integration and Miniaturization by Micro Rubber Molding Process-

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**Abstract**— The final goal of this work is the development of functional rubber sheets with micro rubber structure such as friction free, adhesion, and impact adsorption rubbers, etc. In the previous report, we reported a micro rubber structure realizing flexible passive walking with 3 v-shaped units consisting of 4 legs to achieve very low friction. In this second report, we show the miniaturization and integration of this structure to realize a rubber sheet with 64 legs by micro rubber molding process using stereo lithography method. The prototype is designed and fabricated, and tested. Under some conditions, the 64 legged rubber sheet realizes flexible passive walking on a sloping road successfully.

## I. INTRODUCTION

LIVING things in nature have many types of soft micro structures, and realize some macro-functions such as a friction control, a stiffness control and an adhesion control [1, 2, 3, 4, 5]. For example, a gecko's leg has micro structures consisting of lamellas, setae, and spatulas which achieve a high adhesion force [6, 7, 8, 9]. Lady beetles have micro sucker structures which realize a friction control with specific liquid [10].

The final goal of this research is the development of functional rubbers with micro rubber structures such as friction free rubbers, adhesion rubbers, and impact adsorption rubbers. The functional rubbers have potentials to work as a flexible rubber robot body, a soft robot hand skin and a sole of walking robot foot [1].

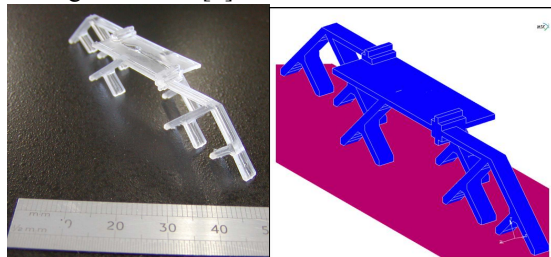


Fig. 1. V-shaped units made of rubber for flexible passive walking [1]

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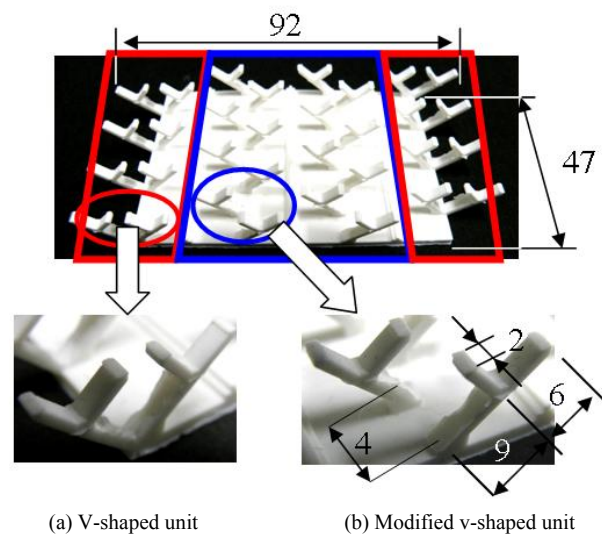
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In the previous report, we showed the first step of our project to achieve a rubber structure with very low friction by applying a passive walking mechanism [1]. The rubber structure called v-shaped unit which consists of 4 micro legs was developed as shown in Fig.1. It was found that the v-shaped unit realized successfully passive walking by the experiments with a high speed camera and a 3D motion capture.

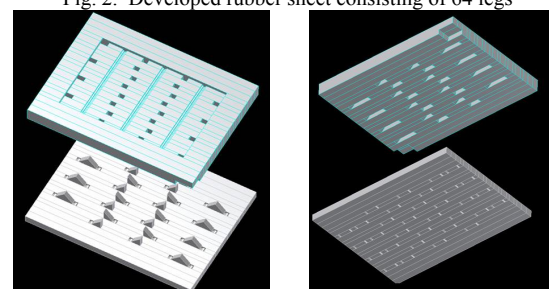
In this second report, we show the development of a micro multi-legged rubber sheet. The v-shaped units have been reduced in size to 3/4 of the original model and they are integrated to realize the 64 legged rubber structure as shown in Fig.2. A new micro rubber molding process has been introduced to the manufacturing process. This process combines the stereo lithography mold with a special molding process of a coating and a two-step molding/ demolding.

The motions of the flexible passive walking of this model are analyzed experimentally.



(a) V-shaped unit (b) Modified v-shaped unit

Fig. 2. Developed rubber sheet consisting of 64 legs



(a) Obverse (b) Reverse

Fig. 3. The master molds for 64 legs rubber sheet

## II. DESIGN OF MICRO RUBBER STRUCTURE AND ITS MOLDING PROCESS

### A. Design of 64 legged rubber sheet

We design a 64 legged rubber sheet. The basic design of the v-shaped unit as shown in Fig.1 is expanded to this new design. The legs are arranged as the eight v-shaped units on the outside and as the eight modified v-shaped units on the inside not to occur the interferences of the legs as shown in Fig.2. This sheet is  $42 \times 92 \times 8$  [mm] in the size and 9.87[g] in the mass. Compared to the previous model of the rubber structure as shown in Fig.1, this rubber sheet is integrated to 64 legs from 12 legs and miniaturized to 3/4 from the previous model.

The master molds of the 64 legged rubber sheet consist of two molds which are an upper-mold and a lower-mold as shown in Fig.3. These are made of photo-curable epoxy resin (SCR735, D-MEC, Japan), and fabricated by stereo lithography process. The bottom surface of the upper-mold and both surfaces of the lower-mold are devised, so it is easy to demold the molded rubber sheet. As a mold method of the rubber sheet, the upper-mold and the lower-mold are assembled as shown in Fig.4. This assemble method makes demold with complex shapes easy.

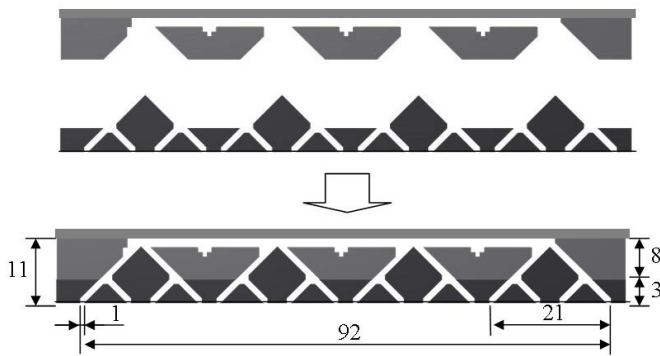


Fig. 4. Assembling upper-mold and lower-mold (unit: mm)

### B. Micro Rubber Molding Process

We newly introduce micro rubber molding process for complex shaped structure, which consists of 8 steps as shown in Fig.5.

- (1) Teflon coating on the surfaces of the lower-mold and the upper-mold.
- (2) Casting to the coated lower-mold with liquid rubber after putting it on the plate base, and vacuum deforming.
- (3) Assembling the lower-mold and the coated upper-mold.
- (4) Casting the upper-mold.
- (5) Vacuum deforming of both master molds. The top surface of the assembled master molds is covered with a plate.
- (6) Demolding the lower-mold after polymerization.
- (7) Demolding the upper-mold.
- (8) Completion of 64 legged rubber sheet.

Teflon (Polytetrafluoroethylene: PTFE) works as a mold lubricant. The liquid rubber of a condensed type silicone rubber (KE1415, Shin-Etsu Silicones, Japan) is used. Condensed type liquid silicone rubber with low viscosity is selected for micro rubber molding. After finishing the polymerization in the master molds, the top surface of them is covered with another plate. Master molds, the top plate, and the bottom plate are fixed with a vise to remove the burrs getting from molding. When the master molds are demolded, these two plates are taken off firstly. Figure 6(a) shows the step (6), and Fig.6(b) shows the step (7).

In this way, this micro rubber molding process realizes a simplified molding of the micro rubber structure with complex shapes.

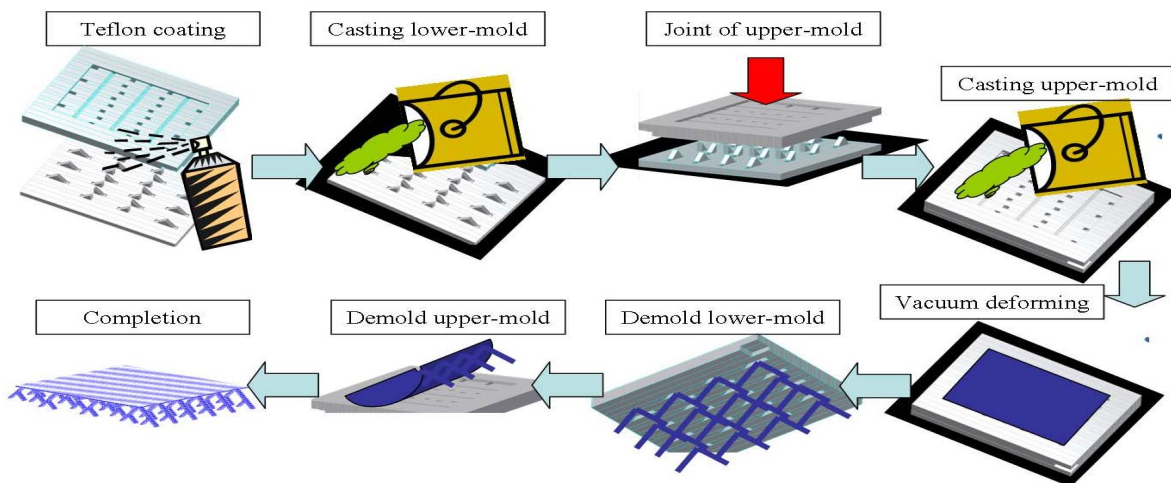
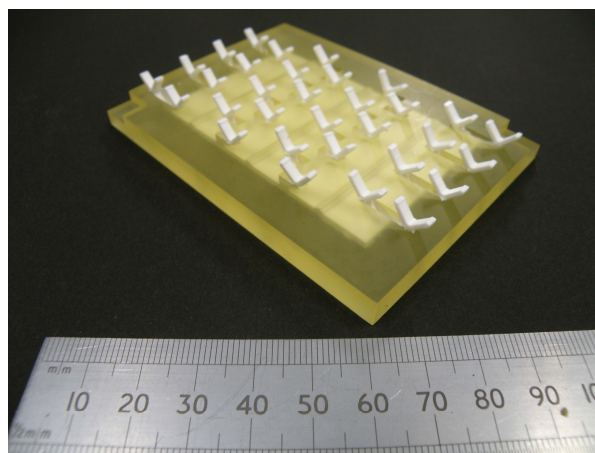
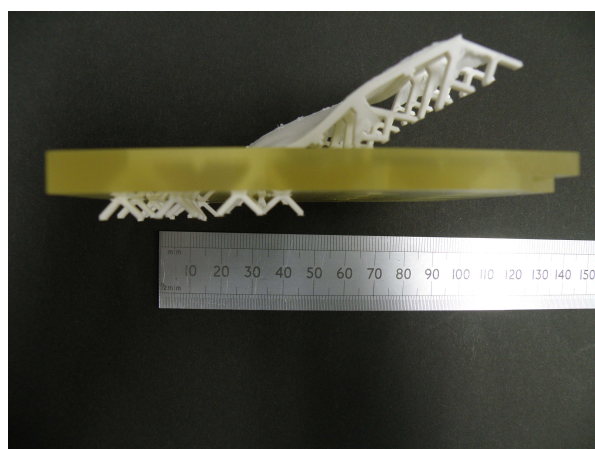


Fig. 5. Micro Rubber Molding Process; (1) Teflon coating of the master mold, (2) casting the lower-mold and vacuum deforming, (3) assembling the lower-mold and the upper-mold, (4) casting the upper-mold, (5) vacuum deforming both molds, (6) demolding the lower-mold, (7) demolding the upper-mold, and (8) completion

| Property           | Value   |
|--------------------|---------|
| Durometer hardness | 20      |
| Tensile strength   | 4.2 MPa |
| Stretch            | 400 %   |
| Tearing strength   | 18 kN/m |



(a) After demolding the lower-mold



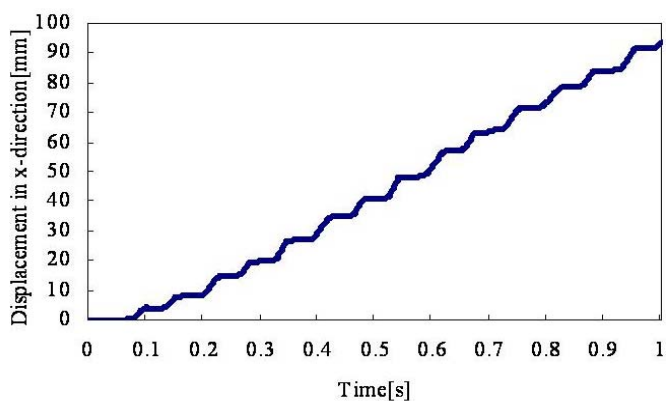
(b) Demold the rubber from the upper-mold

Fig. 6. Demold process of rubber from the molds, which is a process of a micro rubber molding process

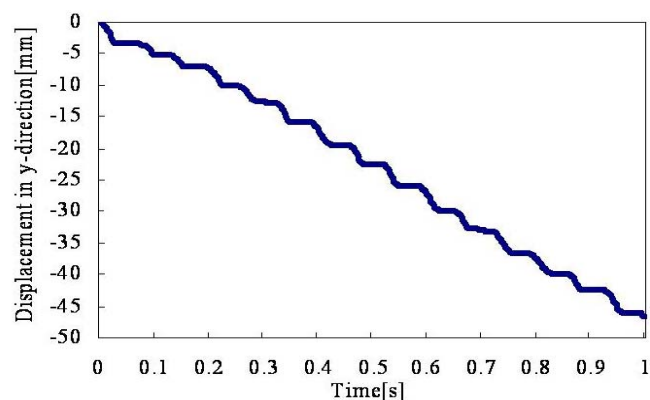
### III. PASSIVE WALKING EXPERIMENTS

#### A. Experimental setup

The passive walking experiments are carried on under various conditions using the 64 legged rubber sheet. Figure 7 shows flexible passive walking of v-shaped units analyzed by non-linear FEM [1]. It shows staircase patterns, which we expect the prototype to realize. The experiment system is composed of an acrylic board and a base as shown in Fig.8. The rubber sheet is experimented for the angle variation. A height of the base is  $a$  [mm], and the length of the acrylic board is  $b$  [mm]. The variable  $x$  [mm] represents the bottom length of a triangle consisting of the base, the acrylic board, and the ground as shown in Fig.8. The angle between a ground and the acrylic board  $\theta$  [deg] is calculated with  $x$ ,  $a$ ,



(a) Ideal leg motion in x-direction by non-linear FEM.



(b) Ideal Leg motion in y-direction by non-linear FEM.

Fig. 7. Ideal leg motions by non-linear FEM analytical results[1].

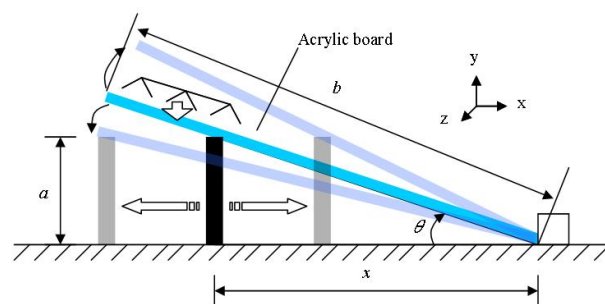


Fig. 8. The experimental setup for Micro Rubber Structure passive walking. Under the various conditions, the performance evaluating experiments are performed.

and  $b$ . Sequential pictures in a successful case are as shown in Fig.9. This micro rubber structure as shown in Fig.9 is found to work, realizing a passive walking on the sloping road successfully. In this experiment, leg motions of the rubber structure are observed from the bottom of the transparent acrylic slope using a 3D motion capture and a high speed camera.

The results of the walking experiments depend on many parameters such as dropping height, leg posture at the initial contact, and the material property of the rubber and the slope. At the current moment we success the passive walking under specific conditions.

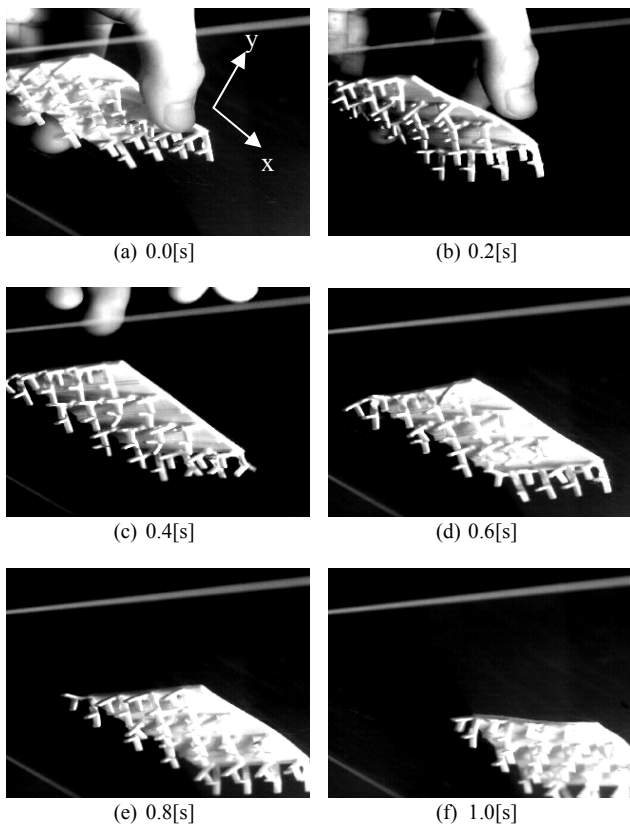


Fig. 9. Sequential high-speed photographs taken from the bottom of the acrylic. The Micro Rubber Structure is walking down on a sloping road successfully.

### B. Passive walking experiments for various slope angle

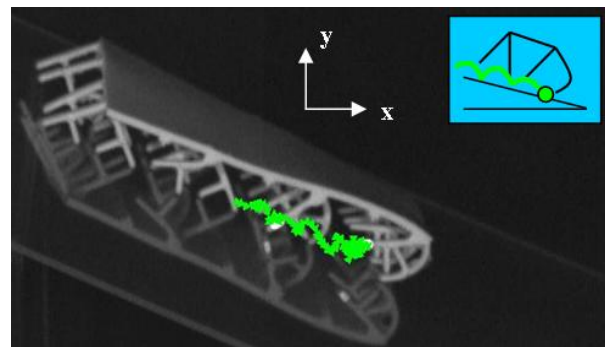
Passive walking of the 64 legged rubber sheet is tested under various conditions. Figure 10 shows the leg motions of the rubber sheet with the experiment system and method as shown in Fig.8. Green lines in Fig.10 represent the trajectories of the front leg tip, which are obtained by the 3D motion capture.

Figure 10(a) shows the experimental result of the leg trajectory on the slope of  $\theta = 24$ . In this experiment, the rubber sheet stopped on the middle of the sloping road. The reason is that the front side legs are involved in the sloping road as shown in the figure. So, passive walking is not realized with the slope of  $\theta = 24$ .

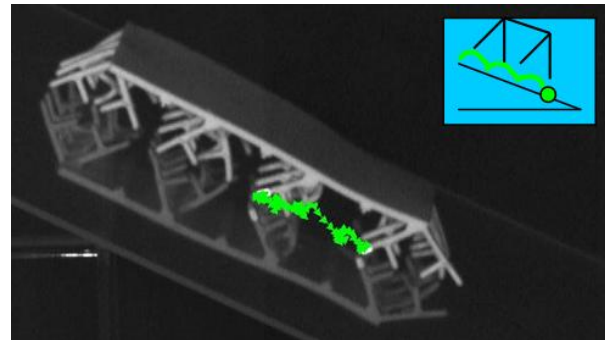
Figure 10(b) shows another experimental result on the slope of  $\theta = 26$ . In this experiment, the rubber sheet also stopped on the middle of the sloping road. But the involvement of the legs doesn't occur. The reason is that the angle of the slope is not enough. Passive walking failed because of the friction.

Figure 10(c) shows the experimental result on the slope of  $\theta = 28$ . In this experiment, the rubber sheet is successfully moving down on the sloping road smoothly.

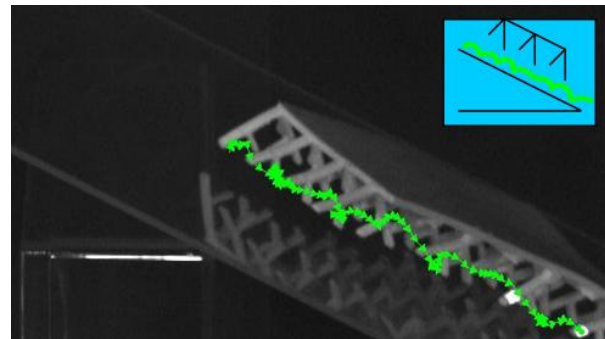
Figure 10(d) shows the experimental result on the slope of  $\theta = 36$ . In this experiment, the rubber sheet is moving down on the sloping road. It is not walking but more like hopping



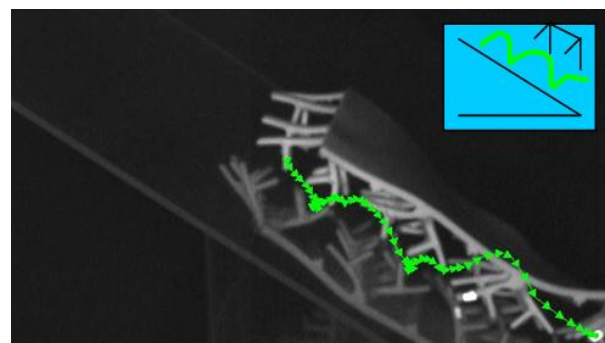
(a) A leg motion on the slope of 24 degree



(b) A leg motion on the slope of 26 degree



(c) A leg motion on the slope of 28 degree



(d) A leg motion on the slope of 36 degree

Fig. 10. Experimental results of the rubber sheet on the various slope angles. Green lines show the trajectories of the front leg tip.

and falling down the slope because the slope angle is too big.

These passive walking experiments were carried out under the slope angles of 20 to 38 degree. The best motion is found with the angle of 28 degree. For the angle of 20 to 26 degree, the rubber sheet stops. For the angle of 30 to 38 degree, it doesn't walk but jumps.

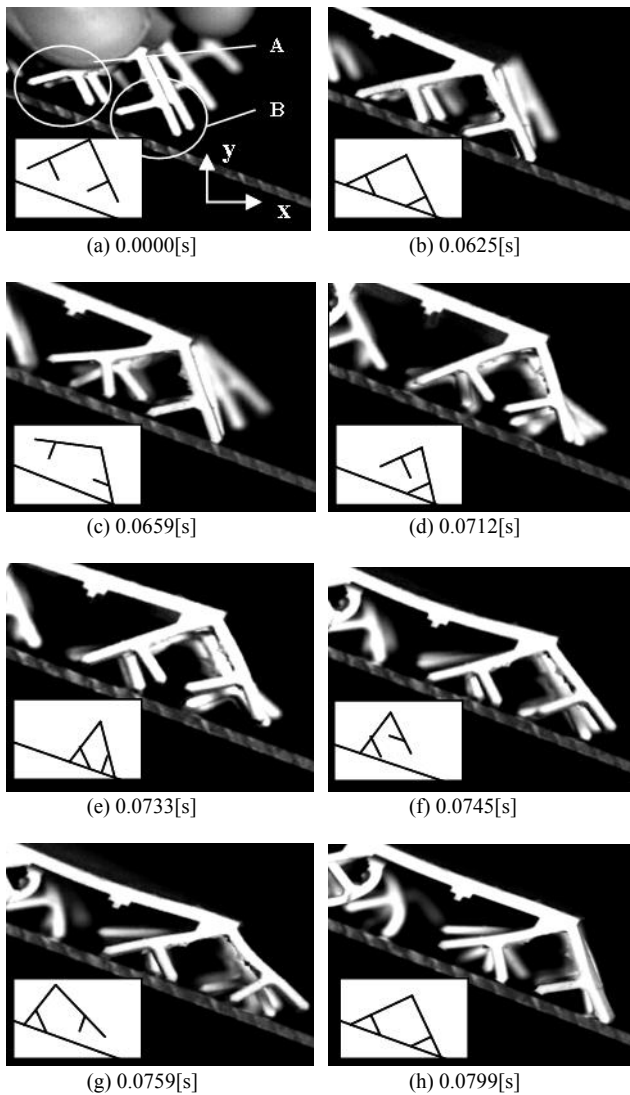


Fig. 11. Experimental results of passive walking on the slope of 28 degree, observed by the high speed camera. Flexible passive walking is recognized with sequential six leg cycles.

### C. Motion Analysis of the leg

A leg cycle motion is examined in more detail on the slope of 28 degree. The result is as shown in Fig. 11, where the front two v-shaped units as shown as A and B, respectively in Fig. 11(a) are discussed, for example.

At the time of  $t = 0$ , the rubber sheet is released and it starts walking as shown in Fig. 11(a).

Figure 11(b) shows the 1st step of the flexible passive walking cycle, where both units A and B are in standing phase on the ground and the v-shaped units are in normal phase. Figure 11(c) shows the 2nd step, where unit A is in swinging phase and unit B is in standing phase. Figure 11(d) shows the 3rd step, where unit A is moving in the forward direction in swinging phase. Figure 11(e) shows the 4th step, where unit A gets down on the slope and both units A and B are in standing phase. These two v-shaped units are located close. Figure 11(f) shows the 5th step, where unit A is in standing phase and unit B is in swinging phase. Figure 11(g)

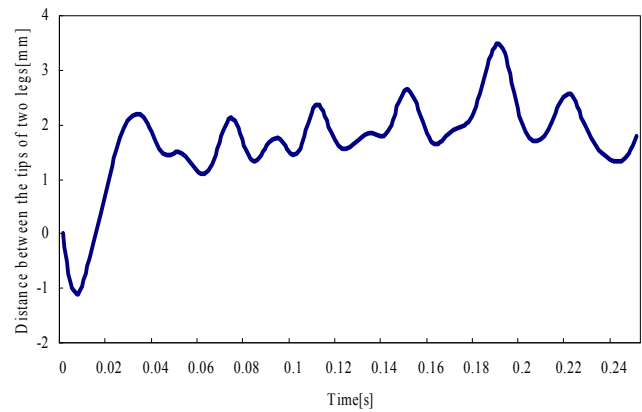


Fig. 12. Experimental results of the distance between the tips of two legs in the successful passive walking on the slope of 28 degree, measured by a 3D motion capture

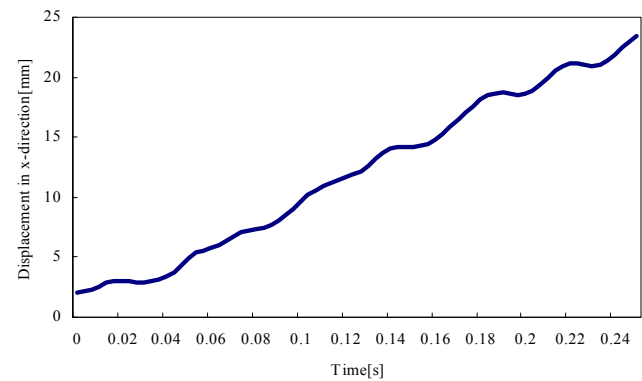


Fig. 13. Experimental results of the leg tip in x direction, in the successful passive walking on the slope of 28 degree, traced by a 3D motion capture

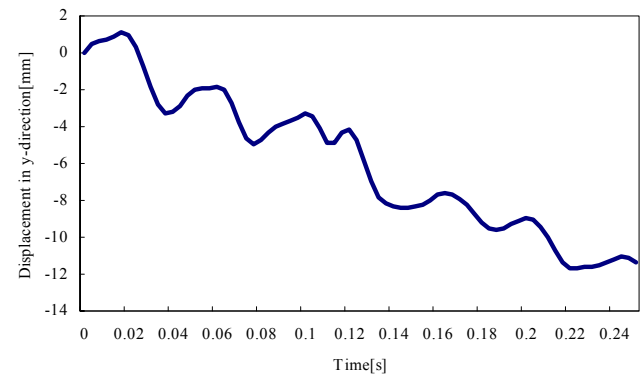


Fig. 14. Experimental results of the leg tip in y direction, in the successful passive walking on the slope of 28 degree, traced by a 3D motion capture

shows the 6th step, where unit B moves forward in swinging phase. Then the units return to the 1st step again as shown in Fig. 11(h) after unit B gets down the slope. In this way, flexible passive walking cycle is repeated. Figures 12, 13, and 14 show the experimental results obtained by the 3D motion capture. Figure 12 shows the distance between the tips of two front legs on the slope of 28 degree. We can find the periodical motions of the two legs. Figure 13 shows the displacement of a leg tip in x direction, and Fig. 14 shows the displacement of a leg tip in y direction on the slope of 28 degree. Waves in x direction show walking steps of flexible

passive walking, and waves in  $y$  direction show up/down motions of the leg tip from the ground in swing/standing phase. These figures show staircase patterns ideally, which is confirmed by the FEM analysis in the previous report as shown in Fig.7 [1]. The experimental results in Figs.13 and 14 show that the rubber sheet almost realizes flexible passive walking.

#### IV. CONCLUSION

As the second step of our project to develop micro rubber structures realizing functional rubber mechanisms, a 64 legged rubber sheet is proposed and fabricated by Micro Rubber Molding Process. Passive walking by 64 legged rubber sheet is realized under regulated conditions. The results of this paper are summarized as follows;

(1) By expanding the idea of v-shaped units shown in the previous report, a multi-legged rubber sheet of the miniaturization and the integration of the 64 legs is designed. This rubber sheet consists of 8 v-shaped units and 8 modified v-shaped units. V-shaped unit consists of 4 legs, resulting in the 64 legged rubber sheet.

(2) The 64 legged rubber sheet is fabricated by Micro Rubber Molding Process. This process is made of stereo lithography fabrication process and the 8 steps molding process using the two master molds.

(3) Passive walking of the rubber sheet is experimented under various conditions. The result shows that passive walking on the sloping road of 28 degree is successfully realized.

(4) Flexible passive walking cycle which is consisting of 6 patterns walking mechanism is almost confirmed by the experimental analyses using a 3D image capture and a high speed camera.

#### ACKNOWLEDGMENT

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