A Retrofit Passive Foldable Snow Shoe for a Legged Robot to Walk on Snowfield

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***Abstract*— A new attachment for a legged robot to help walking on snowfield is proposed. The device works like a snowshoe for human and prevents the robot from sinking in or slipping on the snow surface. Comparing to a bipedal human, a multi-legged robot has much larger numbers of legs and their ranges of movement are limited. For this reason, it was difficult to attach a large foot without making leg collision or stepping on an adjacent foot. To overcome these problems, this paper proposes an automatic retraction and expansion mechanism of wide snow-contacting framings which are passively operated by gravitation. Also, for the problem of stepping on an adjacent foot, we propose a passive downward-deflection mechanism which allows the lower shoe to smoothly exit from the upper shoe. The experiments to examine the performance of movement on some snowfields and the measurement of slip resistance force showed the effectiveness of our design. The proposed shoe does not rely on any external control logic. Therefore, it is easily attached to many existing legged robots.**

***Index Terms*— legged robot, rough terrain, snowfield, shoes for robots, retrofit device**

I. INTRODUCTION

As the people living in cold and snowy countries know, moving on a snowfield is a very hard problem. The stickiness of snow often makes many bumps on the surface. Soft snow sometimes causes deep hollow by applying little pressure on it. Hard and icy snow makes its surface very slippery.

All these characteristics make it difficult to move on the snowfield by using wheeled machines or legs. Instead, some specialized surface contact mechanisms are used that disperse a machine's pressure by its wide contact area so that the body does not sink in the snow.

Well-known examples are the crawler machines, such as snowmobiles, that have wide and long treads. A snow country rescue robot HimBot [1] is a typical crawler type robot. Blade Walker [2] is another proposal that uses very wide pads as ground contact and cyclically let them move like a crawler.

However, a crawler type robot has difficulty in running on a rough terrain [3]. A snowfield sometimes has large and hard bumps. Since a crawler usually does not have enough traction to climb up slippery snow bump, smaller machines tend to be unable to move over the terrain.

For this reason, another approach was proposed that uses legs having high stability. The capability of legs to step over and climb up obstacles is desirable to move on snowfield [4][5]. A famous example is BigDog [4] which is known to maintain stability even if it slips on an icy road and sinks into the shallow snow.

The problem of a legged machine that moves on a thick snowfield is the concentration of its weight on a small landing area. When it walks in the deep snow, it is likely to get stuck deeply and unable to move.

An attachment or a shoe that has a wide landing area may improve the stability of a leg and prevents it from getting stuck. However, a leg with a wide sole may collide with adjacent legs during a swing phase. Furthermore, such a wide sole may disturb smooth movement on hard and rugged grounds. Therefore, this extended sole should easily be attached or detached on legs of any machine without modifying control logic of the machine.

To provide a new sole attachment for mobile robots for snowfield that overcomes these problems, we have developed a new retrofit passive foldable snowshoe-like mechanism. Our approach is summarized as follows:

1. A sole that is lightweight and that has wide contact area on snow is proposed. It is designed by referring to the Japanese traditional snowshoe, called “Kanjiki.”
2. The sole is designed to automatically close by gravitation while lifting a leg. It expands and firmly supports the leg while it lands on the surface.
3. When the sole overlaps with an adjacent sole during the double-supporting phase, it deflects

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down passively and exits smoothly from beneath the other sole.

This paper is organized as follows: Firstly, the mechanical design of the proposed shoe (sole) is explained in detail. Then, the results of the experiments are shown. The experiments were conducted on snow by using a six-legged hexapod robot with the proposed shoes. We show the results of the performance of the movement of the robot on a variety of snow surfaces. Finally, we explain the effect of slip prevention by the shoe through the experiments.

II. Design of THe Snowshoe FOr Legged Robots

A. *A reference design: "Kanjiki" snow shoe*

Long ago in Japan, people living in snowy regions use snowshoes made of Bamboo framings as in Fig. 1.

The snowshoe is lightweight since it consists mainly of framing. However, it effectively prevents a person from sinking in the snow. Since snow is sticky, a lump of snow around the framing will become as if it is a hard padding attached to the framing. We think that this gives sufficient buoyancy on snow.

Figure 1. A traditional Japanese snow shoe "Kanjiki." It is made of a pair of "U-shaped" bamboo framings.

Referring to this, we designed our snowshoe for a legged robot as having U-shape framings toward four directions as in Fig. 2 and 3.

B. *Passive foldable desgin*

Fig. 2 shows a multi-legged robot with the proposed foldable shoes.

Figure 2. A multi-legged robot attached with the foldable snow shoes introduced in this paper.

Fig. 3 shows the composition of the proposed shoe. The upper side of the picture shows the entire view of the snowshoe. It consists of (1) a land contacting framings (down left) and (2) a set of connection linkages that connects four framings with a leg of a robot.

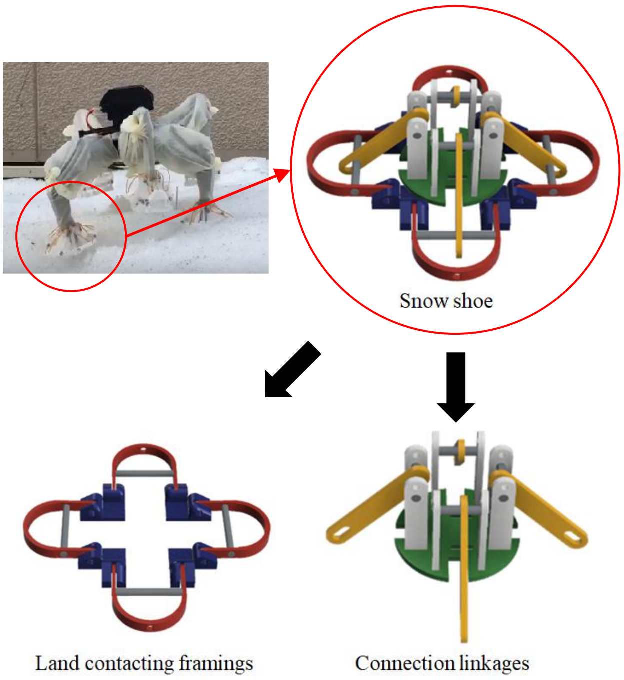

Figure 3. The composition of the proposed snow shoe.

Fig. 4 shows the connection of the shoe to the leg of a robot in detail. The leg is connected to the supporting disk (green plate) by a joint with 1 DOF. Each framing is connected by a linkage, which lifts up the framing while the supporting disk is lifted up at the beginning of the swing leg phase.

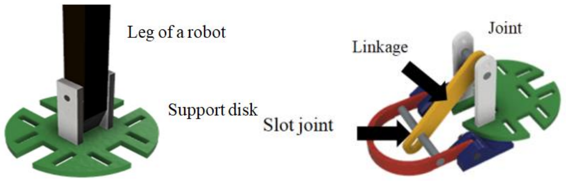

Figure 4. Details of leg and framing connection.

Fig. 5 (left to right) shows the process of folding by the lift of the leg in detail. As shown on the right side in the figure, while the leg is put down on the ground from the swing leg phase, four framing joints (blue parts) touch on the ground first. After that, the linkage (yellow part) pushes the framing (red part) down to the ground. Finally, after the leg firmly touches on the ground at the support disk (green part), the linkage firmly supports all the framings. Thus, the ground reaction forces from the frames and the support disk both support the leg.

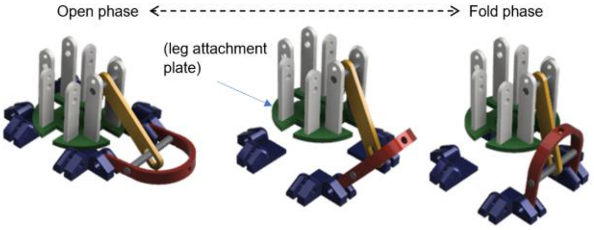

Figure 5. Sequence of passive folding according to the lift of the leg.

By the effect of buoyancy produced by the frames, the robot is expected to keep walking on snow. Also, the automatic folding mechanism contributes to avoiding collision of legs during swing phases. In the next section, we describe the effect of this automatic folding, and the mechanism corresponding to the smooth step under the shoe overwrapping situations in detail.

III. MECHANISM OF REALIZING OBSTRUCTION FREE FOOTSTEP

A. *Avoiding conflict of nearby legs*

As shown in Fig. 6, a shoe that occupies a wide region will easily collide with adjacent legs. In this case, the legged robot is not able to perform a sufficiently long stride. However, by using the automatic folding mechanism described in the previous chapter, the occupation area of the shoe will be kept small. For example, the shoe in Fig. 7 occupies about 2/3 of the areas when closed.

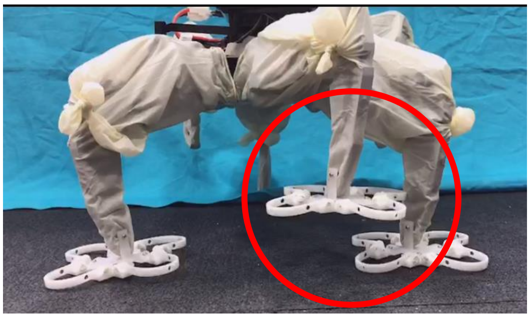

Figure 6. Collision of a wide shoe with nearby legs.

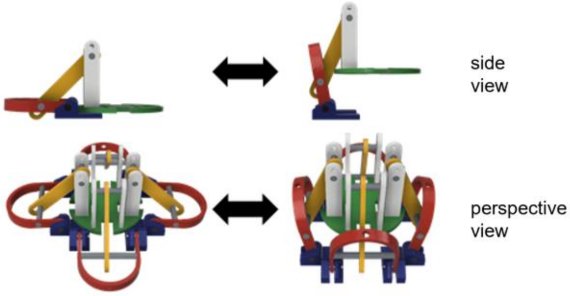

Figure 7. Overview of folding and opening of the shoe.

An important point of this mechanism is that the shoe expansion and fold actions are performed without the help of the robot's controller logic. Therefore, the introduction of the shoe to the robot's leg is done by just fixing the shoe to the end of its leg.

B. *Realizing smooth escape from the situation of a shoe stepped by another shoe*

A legged robot must have a double-supporting phase, where two adjacent legs land at the same time at a close rage. At this phase, it is likely that the shoe of a stance leg will overlap with the shoe of a swing leg. Fig. 8 shows a typical situation.

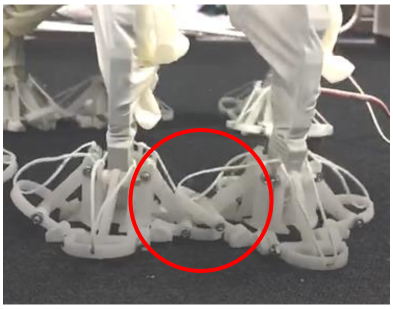

Figure 8. The shoe of a stance leg overlapping with the shoe of a swing leg.

To let the shoe smoothly exit from the overlapping shoe, we realized the joint of a framing by the slit-joint as in Fig. 9.

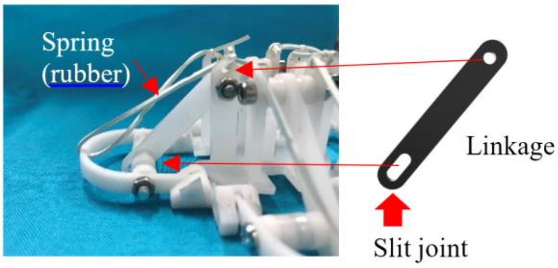

Figure 9. A slit joint that allows downward flop of a framing.

Fig. 10 shows the sequence of exiting from the overlapping situation. As in this figure, the shoe underneath the other shoe deflects the framing downward as it lifts. Then, the shoe gets back to the normal folded position by the traction force given by the spring (rubber, in this case). This is realized by the lower joint of the framing that slides down the slit. In the case of the support phase, the joint of the framing comes to the upper end of the slit. Therefore, it passes the ground reaction force to the leg without loss.

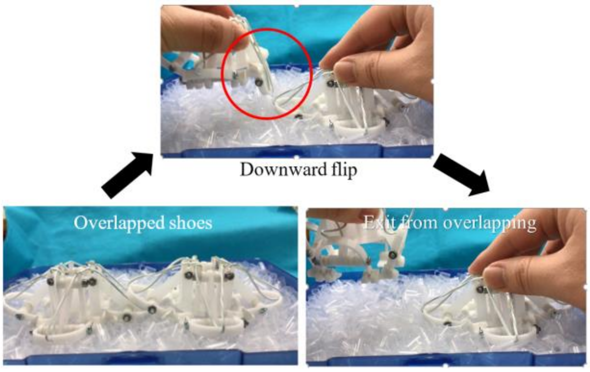

Figure 10. Exit from overlapping position by downward flip.

Fig. 11 shows the detail of the escape motion. This figure clearly shows the position of the link of the framing in the slit.


Fist, the framing flips downwards as it lifts. By this, an overlapping shoe will be able to escape.

After the overlapping shoe has escaped, the framing is folded back again.

Figure 11. The detail of flipping and retracting of the shoe.

IV. EXPERIMENTS OF PERFORMANCE MEASUREMENT BY ACTUAL AND ARTIFICIAL SNOW

A. *Identification of the types of snow*

Snow has different characteristics according to the conditions such as the temperature, particle size, and the shape of the snowflakes [6]. Therefore, the condition of the snow must be explicitly indicated in each experiment.

According to the previous studies, it is known that the general characteristics of snow are estimated by measuring the hardness of the snow [7][8][9]. The hardness of snow is observed by measuring the repulsion force during a small disk is poked in the snow. Fig. 12 shows the digital force gauge (A&D Company, AD-4932A-50N) and the terminal attachment (7 mm diameter). An actual measurement is shown in Fig. 13 (left).

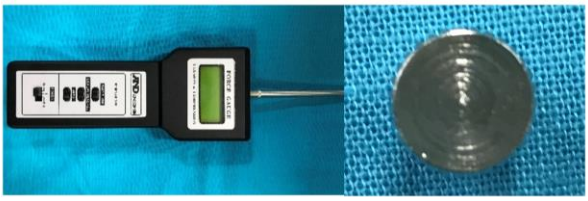

Figure 12. The force gauge and the terminal attachment to measure snow hardness.

Fig. 13 shows typical hard and soft snow (Fig. 13 (middle and right)). On the measurement with the force gauge, the typical soft snow showed 1.03 to 8.84 kPa, and the hard snow showed 13.0 to 22.1 kPa during five times of measurements. In this paper, we show the reading of the force gauge for the snow on which each experiment was conducted.

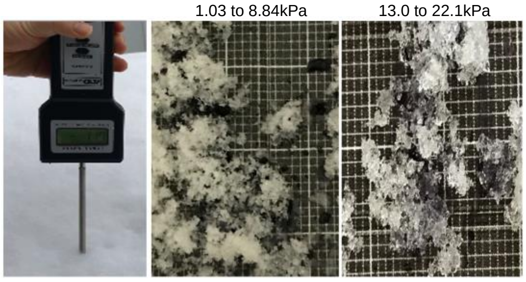

Figure 13. The method of hardness measurement (left). The typical soft snow (middle) and the hard snow (right).

B. *Hexapod legged robot*

We used a small hexapod legged robot (KMR-M6, Kondo Kagaku Co. Ltd.) (Fig. 14). The size is H:182 mm × W:336 mm × D:223 mm, and the weight is 1.06 kg.

Figure 14. The hexapod robot KMR-M6 with water resist cover.

C. Experiments of the ability of movement

To examine the ability of movement on a flat snowfield, we conducted the experiments by the robot with the proposed shoe and without it. Fig. 15 shows the size of the foot of the robot without the shoe.

Figure 15. The size of the foot of the robot.

Fig. 16 (right and left) show the difference of the distance with the three strides by the robot with the proposed shoe and without it. The hardness of the snow was 1.04 kPa (right) and 3.12 kPa (left), which should be classified in soft snow. The proposed shoes could achieve sufficiently long strides, while the leg without the shoe did not achieve any movement.

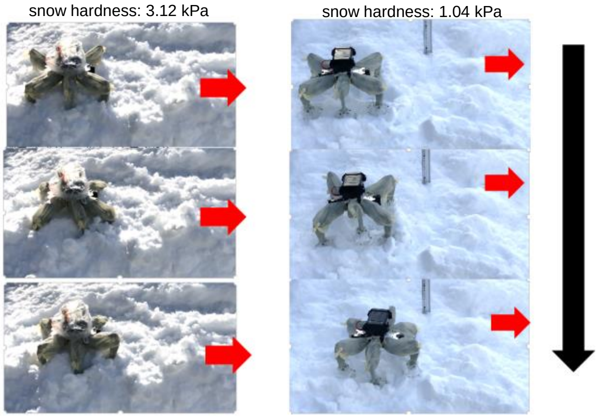

Figure 16. Movement of the robot with the proposed shoe (right) and without it.

Fig. 17 shows a sequence of the middle leg from the swing phase to the stance phase (left to right). As in this figure, the shoe in the swing phase is folded, and it is extended as the leg touched on the snow.

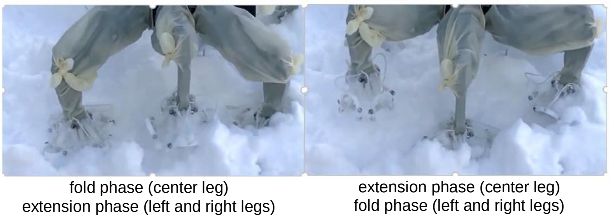

Figure 17. Passive fold and extension of the shoe in the experiment on the soft snow.

D. Experiment of measuring the ability of slip protection of the proposed shoe

It is known that another important characteristic of the “Kanjiki” snowshoes for a human is the protection of slip on the hard snow surface. To examine this functionality on the proposed shoe, we conducted simple experiments.

In the experiments, we compared two different types of the shoe. One is the proposed shoe which has U-shape frames. The other is the same shoe, but the bottom of the U-shape frames are covered by planar plastic plates.

Fig. 18 shows the original and the modified shoe that is covered by flat plates at the bottom.

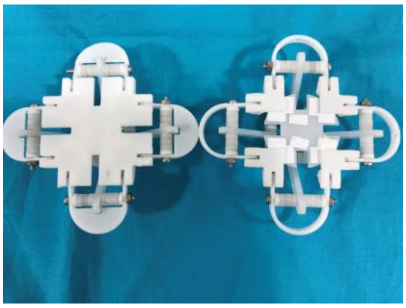

Figure 18. An original shoe with framings (right) and the shoe for the comparison which is covered by flat plates at the bottom (left).

The experiments were conducted using artificial snow. The artificial snow was made of a pile of thin plastic pipes with 5 mm diameter and 1 cm length. The hardness of this artificial snow was about 9 kPa. It should be classified as medium snow. When pressure is applied, the plastic pipes aggregate together as if they are a bunch of snow.

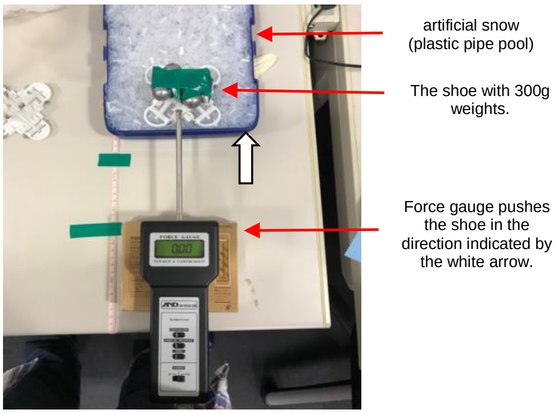

Figure 19. Configuration of the measurement of slip resistance force. A weight is put on the shoe and the force gauge records the maximum force during pushing the shoe.

Fig. 19 shows a configuration of the experiments. The targeted shoe was put on the artificial snow with the load of 300 g. The force gauge pushed the shoe for three seconds to the direction parallel to the surface of the artificial snow. The maximum force was recorded which represents the degree of resistance of the shoe against slipping on a snow surface.

Table 1 and 2 show the maximum resistance force for the proposed shoe and the shoe with a flat bottom. We measured the forces for eight trials. As shown in the tables, the shoe with U-shape framings is slightly better than the flat planar bottom for the performance of resistance against slip.

TABLE 1. THE MAXIMUM RESISTANCE FORCE BY A SHOE WITH FRAMINGS

Trial	1	2	3	4	5	6	7	8
Max resistance force (N)	1.1	1.0	1.1	1.2	1.3	1.3	1.1	1.0

TABLE 2. THE MAXIMUM RESISTANCE FORCE BY A SHOE WITH FLAT PLANAR BOTTOMS

Trial	1	2	3	4	5	6	7	8
Max resistance force (N)	0.9	0.9	0.9	1.1	0.8	1.0	0.9	0.9

V. CONCLUSION

A new retrofit device for a legged robot that helps the robot to walk on snowfield was proposed. The device has a similar effect to the snowshoe for a human and prevents the robot from sinking in or slipping on the surface of the snow.

Compared to a bipedal human, a multi-legged robot has a much larger number of legs. Thus, the range of movement for each leg is limited. For this reason, it was difficult to attach a large foot without causing leg collision or stepping on an adjacent foot.

To these problems, this paper proposed an automatic retraction and extension mechanism of large snow-contacting framings, which is passively driven by gravitation. Furthermore, we showed a mechanism that allows the shoe behind the other shoe to smoothly exit from it. The mechanism is realized by passively deflecting the framings to downwards.

The experiments of the performance of movement on the snowfield and the measurement of slip resistance force showed the effectiveness of the design.

It should be noted that these mechanisms do not rely on any external control logic. Therefore, the device is expected to be easily applied to many existing legged robots.

Since the current design is aiming at the environment of a soft and hard flat snowfield, we are planning to re-design the shoe to be used on a bumpier snowfield. Also, we are planning to investigate the preferable size and shape of the snow contacting framings.

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