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Wheel Transformer: A Miniaturized Terrain Adaptive Robot with Passively Transformed Wheels

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***Abstract*— A small mobile robot that uses round wheels has a stable ride ability on flat surfaces, but the robot cannot climb an obstacle whose height is greater than the length of its wheel radius. As an alternative, legged-wheel robots have been proposed for their better climbing performance. However, such legged-wheel robots have a poor driving performance on flat surfaces since their center of mass is vertically changed.**

Transformable wheels are used to make the robot drive with round wheels on flat surfaces and climb an obstacle with legged-wheels. However, the design of previously developed transformable wheels is complicated because it needs actuators for the transformation. Thus, it is not suitable for small robots.

In this paper, a simple robot platform called Wheel Transformer that uses a new kind of transformable wheel is described. The transformation process is passively operated by an external frictional force, so it does not need any actuators. We fabricate the transformable wheel as well as the robot platform based on analysis of transformation mechanism. The robot can climb an obstacle whose height is 2.6 times greater than its wheel radius.

I. INTRODUCTION

A small robot can reach the places which humans find hard to reach such as a collapse-endangered building. In such places, many small robots are particularly used for surveillance purpose and search and rescue missions (SAR) [1]. In SAR missions, the cooperation of small robots using a swarm robotic system is useful [2]. However, a small mobile robot that uses round wheels has limited climbing performance because most man-made obstacles are relatively larger than the size of the small robot. Furthermore, a round-wheeled robot cannot climb an obstacle taller than its wheel radius because the contact point between an obstacle and a wheel is not placed above the center of the wheel and thus it cannot generate sufficient torque to climb. For example, the robots in the Alice series that use round wheels have difficulty in moving over a complex terrain [3].

Previously, many different types of legged–wheel mobile robots have been proposed as an alternative because of their better climbing performance. Biologically inspired hexapod robot called Whegs has been designed based on the cockroach's walking gait [4] [5]. Whegs is able to climb an obstacle whose height is greater than the length of its legs. Mini-Whegs can also climb an obstacle greater than the length of its legs [6]. RHex uses semi-circular shaped legged-wheels and open loop control to climb stairs across a variety of stair geometries [7] [8]. However, all legged-wheel mobile robots may have rough rides on flat surfaces due to the vertical displacement of their centers of mass. To solve this problem, Whegs walks using a tripod gait [4] [5] and Mini-Whegs also uses four legs in an alternating diagonal gait [6].

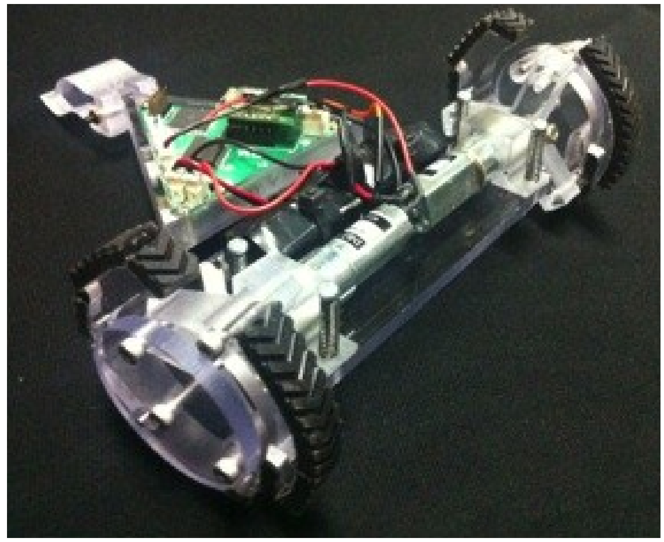

Fig. 1. Wheel Transformer, a miniaturized terrain adaptive robot with passively transformed wheel.

The design concept of a transformable wheel is terrain adaptiveness. It means that a transformable wheel keeps a round shape when the robots move on flat surfaces and transforms to a legged-wheel when the robots encounter an obstacle. In other words, a transformable wheel takes advantages of both round wheel and legged-wheel. Usually, the transformation process is operated by an additional actuator. One example is Quattroped [9]. It uses transformable wheels that directly change their morphology of the wheels into two degrees-of-freedom legs. However, it needs additional servo motors for active transformation at four wheels and it makes robot design and control algorithm become complex.

In small robots, the number of usable robotic components is limited because of their size, thus a simple design is important. A complex design will increase the robot size and complexity of control algorithm. Specifically in SAR missions, simplicity of robot design is critical since swarm robotic system that consists of small robots is needed in SAR missions. For example, many small robots will be spread to

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find something or deliver something together. Group food retrieval in some ant species is already investigated as a role model of multi-robot collective transport strategies in this viewpoint [10]. Thus, the simplest design with a low number of usable robotic components that provides the robot with necessary functions is an additional goal of this paper.

A simple robot platform, Wheel Transformer (Fig. 1), described in this paper uses two modes: a driving mode with round wheels and a climbing mode with legged-wheels. Thus, it can avoid the rough ride on flat surfaces and improve the climbing ability. Furthermore, for a simple robot design, the transformation process is passively operated when it encounters an obstacle. Wheel Transformer employs two dc motors to drive two transformable wheels and it can change its moving direction without additional servo motors.

In the following sections, we will report on the design, modeling, manufacturing and performance of the transformable wheel in more detail. We will also provide a passive transformation process the robot adopts to climb an obstacle. We will present a simple robot platform design, Wheel Transformer, which uses transformable wheels. We will conclude with discussion about the performance of our transformable wheel and robot platform.

II. TRANSFORMABLE WHEEL DESIGN

A. Features of the transformable wheel

The transformable wheel consists of five components – the wheel-base, the three legs and the force transmitter (Fig. 2). One of the three legs, called the trigger leg, is not the same as the other two; the trigger leg has a pin and the other two legs have slides. The force transmitter contains one slide and two pins and it links the three legs. The role of the wheel-base is to place the other components in the right position and to fix the wheel to the motor axle.

There are two design issues in the transformable wheel: a one degree-of-freedom transformation and a small trigger force. All three legs are linked to each other to make one degree-of-freedom by pin and slide linkage system. Therefore, if the trigger leg is rotated, the other two legs are also rotated. Furthermore, since external forces should cause this passive transformation, the necessary trigger force should be small.

B. Pin and slide arrangement

When an external trigger force rotates the trigger leg, the trigger leg also rotates the force transmitter. Sequentially, the force transmitter also rotates other two legs and then, all three legs are unfolded. Pins and slides could be placed on the legs or the force transmitter. Fig. 3(a) shows the pin driving system and Fig. 3(b) shows the slide driving system. In Fig. 3(a), arrow1 indicates the rotating force of the pin and arrow2 indicates the desirable path of the slide. When the pin rotates the slide, an initial contact point is placed where the angle between arrow1 and arrow2 is less than 90 degrees. In comparison, in Fig. 3(b), arrow3 indicates the desirable path of the pin and arrow4 indicates the rotating force of the slide. When the slide rotates the pin, arrow4 is perpendicular to arrow3, so the rotating force of the slide cannot have an effect on the desirable path of the pin. Because the transformation rate is its maximum when the angle between arrow3 and arrow4 at the start and end point of rotation is 90 degrees, the slide driving system (Fig. 3(b)) is not suitable for the transformable wheel design. Therefore, we asymmetrically place the pins and slides at the legs and the force transmitter so that the pin rotates the slide at all three points (Fig. 4) (see video). A simulated result (performed by Recurdyne) also shows the same result (Fig. 5). As indicated in the graph, a necessary trigger torque for transformation in the pin driving system is about 20 Nmm. However the necessary trigger torque in the slide driving system is about 120 Nmm.

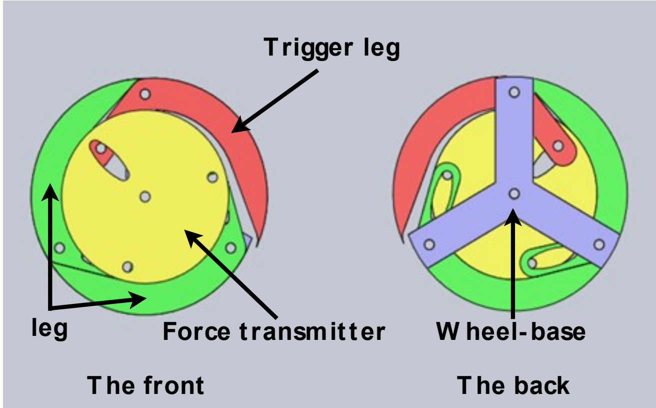

Fig. 2. The feature of the transformable wheel.

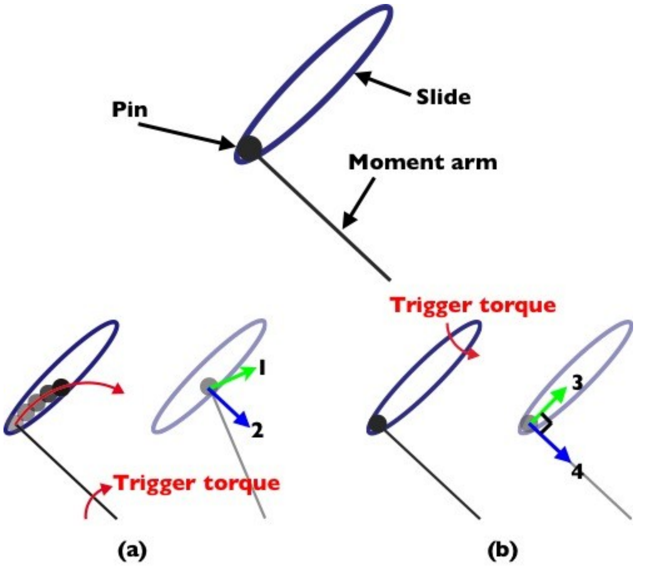

Fig. 3. The rotating mechanism in the pin and slide linkage system: (a) The pin driving system. (b) The slide driving system.

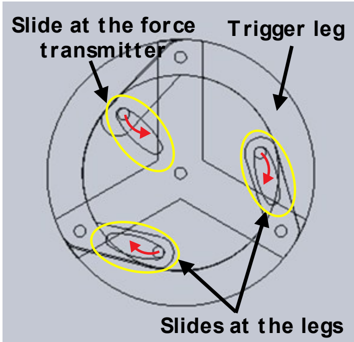

Fig. 4. The asymmetric pins and slides arrangement.

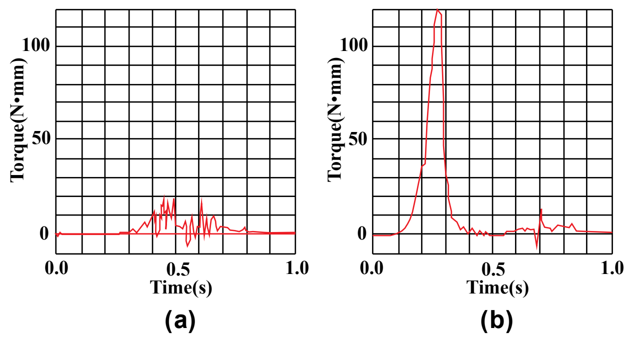

Fig. 5. A simulated result of necessary torque for the transformation: (a) The pin driving system. (b) The slide driving system.

C. Slide design for minimum interference

A slide bounded by straight lines is not suitable for rotation since the pin path is an arc and it will increase necessary trigger force due to interference between the pin path and the slide path. Fig. 6 shows the features of slide whose boundary shape is an arc. Specifically, the arc boundary comes from the pin path so that the pin smoothly rotates the slide with a small amount of necessary trigger force.

III. Robot Platform Design

A very simple robot platform called Wheel Transformer that uses the transformable wheels was developed. The robot design should be simple for its small size.

A. Suspension

Fig. 7 schematically shows the collision occurring between the leg and the ground surface because the robot's center of mass is vertically changed when the robot is in a legged-wheel mode.

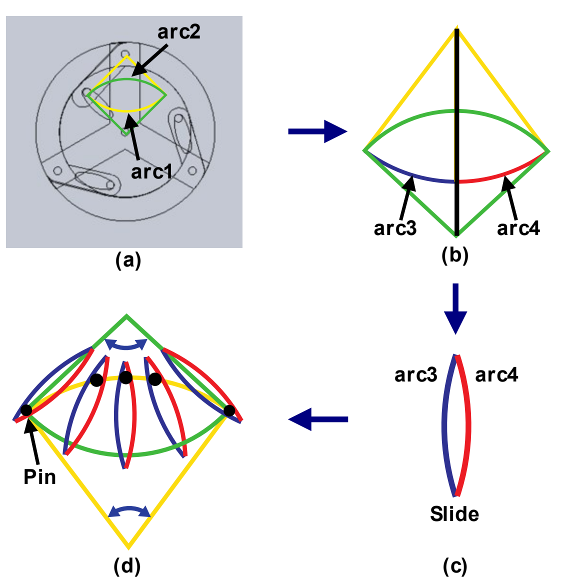

Fig. 6. A process of slide boundary design: (a) Arc1 indicates the pin path and arc2 indicates the slide path. (b) Arc1 consists of arc3 and acr4 that indicate the half portion of the pin path. (c) The curvature of boundary arc is identical with the curvature of the pin path. (d) The pin smoothly glides into the slide.

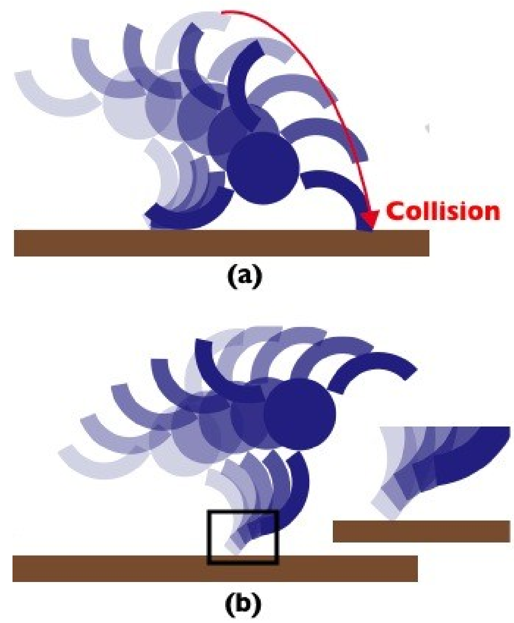

Fig. 7. A schematic sketch of the collision: (a) A collision between the leg and the ground surface. (b) Non-attachment phase of three legs in same time.

If the motor rotates very quickly, the repulsive force is so big that all three legs are simultaneously in a non-attachment phase. As a result, the robot cannot drive forwards because of the absence of a ground reaction force. Moreover, Wheel Transformer uses only two wheels, so the absence of a ground reaction force is even more critical than in hexapod robots such as Whegs. Thus we used linear springs at the motor mount for shock absorption. They will make a stable contact between the legs and terrain.

B. Body

The dimensions of Wheel Transformer are determined by a geometric analysis to prevent overturning when it climbs an obstacle. When only one wheel is transformed during climbing, the body is tilted in a lateral direction, so it is possible for it to be overturned. In the same way, the body could be overturned in a longitudinal direction because it will be tilted while climbing an obstacle. When it comes to body flexion, this is inspired by biological principle; a cockroach makes a stable contact by changing its body posture while climbing an obstacle [11]. In the same way, the body of Wheel Transformer is passively bent because of the weight of its tail so that it makes a stable contact with the upper surface of an obstacle.

C. Steering

Wheel Transformer can easily change its moving direction since it uses just two wheels. When the left motor rotates backwards and the right motor rotates forwards, the robot turns its head towards the left. The robot also turns right when the motors rotate in the opposite directions.

D. Electronics

Two 7.2 V lithium polymer batteries were used as power sources. As a microprocessor, ATmega 128 controls the motor power using PWM method. The robot communicates with a remote computer by Bluetooth.

IV. Transformation Mechanism

A. A schematic process of climbing

The transformable wheel is optimized to climb a vertical obstacle such as stairs. Since the transformable wheel does not contain any actuators for transformation, an external force is needed to cause the transformation. Fig. 8 shows a schematic process of climbing. Point A indicates the contact point between the wheel and the ground surface. Point B indicates the contact point between the trigger leg and the side surface of an obstacle. Point C indicates the end part of the trigger leg. We analyzed each step to realize passive transformation. In order to climb the highest obstacle, the legs should start unfolding when the transformable wheel makes contact with the side surface of an obstacle. Step 1 describes the initial contact state and the frictional forces at point A and point B start to unfold the trigger leg. In step 2, point C should not slip while the wheel rotation is continued. In step 3, the following leg climbs the obstacle and in step 4, the wheel goes into its folded state again to drive as a round wheel.

B. Passive transformation 1 : Unfolding mechanism

Fig. 9(a) and (b) show a schematic sketch in the step 1 and 2. To make the trigger leg unfold, frictional forces at point A and point B are essential. Generally, a frictional force is generated by a vertical reaction force at the surface where the contact occurs. Thus, the frictional force at point B is generated by the vertical reaction force at the same point. At point A, the driving force is generated by motor torque. The driving force generates reaction force at point B and this reaction force also generates frictional force that causes the initial unfolded state of the trigger leg. Actually, in a three dimensional view, the contact point between the wheel and an obstacle is a line so it is not a stable contact. To make a stable contact, point A and point B are converted to flat surfaces. In the same way, point C also becomes to a flat surface so that it can prevent any slippery movement of the trigger leg (Fig. 9(c)).

To model the behavior of the transformation mechanism, a geometrical analysis was performed. Fig. 10(a) and (b) respectively indicate the initial position and an arbitrary position in transformation process. The torque at the joint of the leg (T_3) is given as

$$T_3 = \frac{T_1}{2}\,\frac{ma_s1}{ma_p1}\,\frac{ma_s2}{ma_p2}\times \frac{1}{\sqrt{\left(1+\left(\frac{\cos(\alpha)\sin(2\theta)-\sin(\theta)}{\cos(\theta)-\cos(\alpha)\cos(2\theta)}\right)^2\right)}}\times \frac{1}{\sqrt{\left(1+\left(\frac{\sin(\alpha)\sin(2\delta)-\sin(\delta)}{\cos(\delta)-\sin(\alpha)\cos(2\delta)}\right)^2\right)}} \quad (1)$$

where T_1 is the torque at the joint of the trigger leg, ma_s1 is the moment arm of slide on the force transmitter, ma_p1 is the moment arm of pin on the trigger leg, ma_s2 is the moment arm of slide on the other leg, ma_p2 is the moment arm of pin on the force transmitter, α is the designed angle of the trigger leg, which is 45 degrees, θ is a variable which indicates the rotation angle of the trigger leg ranging from $-\alpha$ to $+\alpha$ and δ is a variable which indicates the rotation angle of the force transmitter ranging from $-\alpha$ to $+\alpha$. All components in (1) except r and α are expressed in terms of θ, so the ratio of T_3 to T_1 is given as a function of θ (Fig. 11).

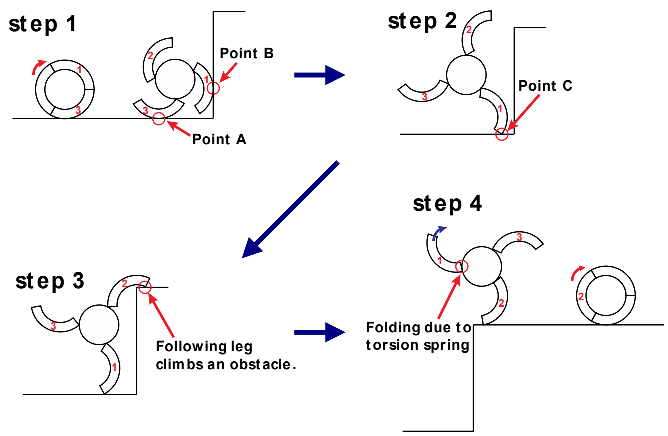

Fig. 8. A schematic process of climbing. The point A, B and C take important roles in Transformation mechanism. Trigger leg is indicated as leg 1.

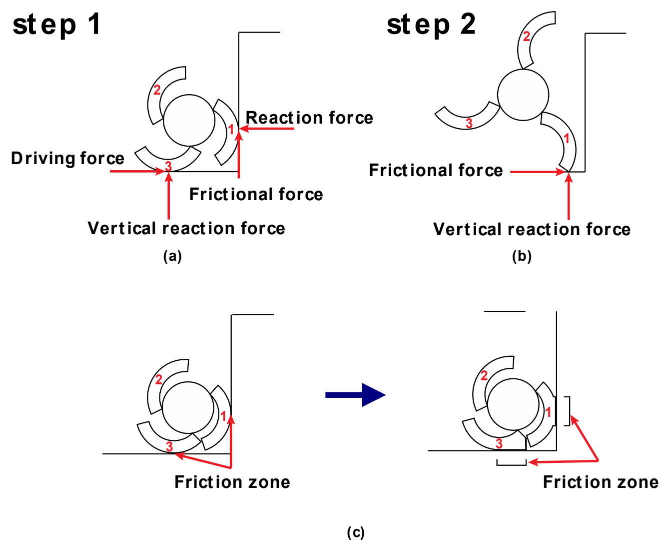

Fig. 9. (a) A schematic sketch in step 1. (b) A schematic sketch in step 2. (c) A comparison between contact state of a line and a flat surface.

In Fig. 11, the y value remains 0 until θ = -26 degrees because the trigger leg rotates without any contact point with the force transmitter. The ratio has the smallest value at θ = 0 degree, which indicates that only 10 % of T_1 has an effect on T_3. That is to say, the largest force is needed at this nadir for transformation. This result is consistent with the tendency of torque reaching its maximum at time = 0.5 seconds, as shown above in fig. 5(a).

C. Passive transformation 2 : Folding mechanism

After the robot climbs an obstacle, the transformable wheel should be folded again to make a round wheel for driving on flat surfaces. A torsion spring is placed at the joint between the trigger leg and the wheel-base so that it folds the trigger leg (Fig. 12). Sequentially, the force transmitter is rotated by

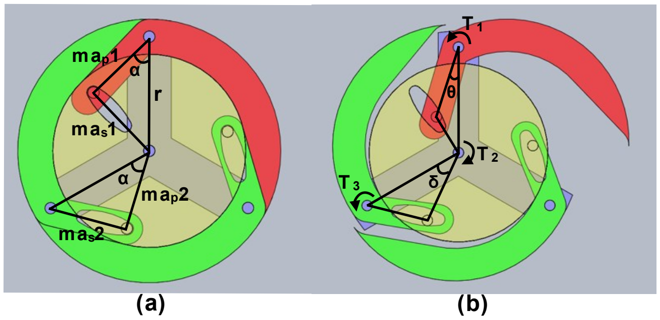

Fig. 10. The modeling of behavior of the transformation mechanism: (a) The initial position. (b) The position when trigger leg makes first contact on force transmitter.

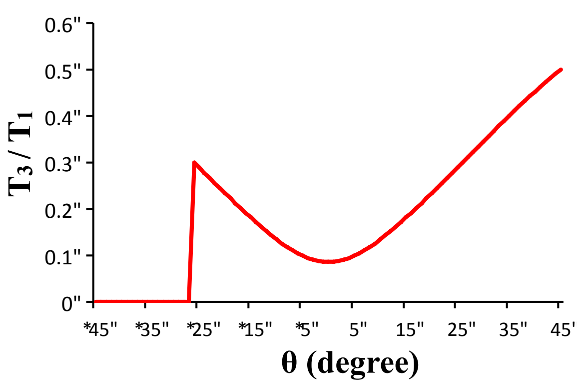

Fig. 11. The ratio of T_3 to T_1.

trigger leg and also folds the other two legs. The joint is the only point where a torsion spring could be placed because only the trigger leg can fold the other two legs using the same mechanism as when it unfolds the other legs. Furthermore, its spring constant should be as low as possible since it has a negative effect on the transformation when the trigger leg is unfolded by an external force. Since the role of the torsion spring is just as a trigger for folding, it does not need to perfectly fold the trigger leg. If it starts to fold the trigger leg, the trigger leg is perfectly folded because of the robot's own weight when the trigger leg makes a contact with ground surfaces.

V. Results

A miniaturized terrain adaptive robot with passively transformed wheels called Wheel Transformer and a new

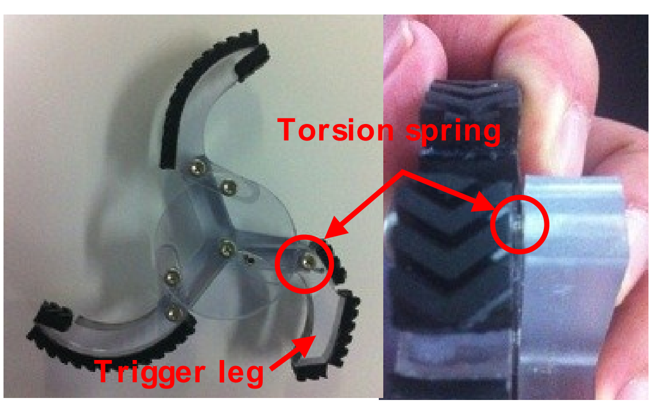

Fig. 12. Folding the transformable wheel using torsion spring. Because only trigger leg can fold all legs, just one torsion spring is needed.

kind of transformable wheel were fabricated (Fig. 1 and Fig. 13). The radius of the transformable wheel was 35mm and its weight was 50 g and the material used was polycarbonate. When it was unfolded, the radius was 60 mm and transformation rate was 171 %. All its components were fabricated using CNC milling machine. Transformable wheel was assembled using bolt and screw thread holes on the wheel-base. To increase its frictional force, a V-shaped anti-slip rubber pad (Misumi Corporation) was attached at the contacting surface of the wheel. The width of Wheel Transformer was 190 mm, its length was 210 mm and its total weight was 350 g. Its dimensions were determined base on geometrical analysis to prevent it from overturning during climbing.

Wheel transformer can move using round wheels on flat surfaces and can climb an obstacle with legged–wheels (see video). The transformation is passively operated by an external trigger force and torsion spring. It can climb up to a 90 mm height obstacle (Fig. 14). The turning radius during steering is nearly zero.

TABLE I. Physical Parameters for Wheel Transformer

Wheel radius (fold)	35 mm
Wheel radius (unfold)	60 mm
Body size	190 x 210 x 70 mm
Body mass	350 g (including batteries and electronics)
DC motors	DnJ hobby motors x 2 (gear ratio : 1/316)
Batteries	lithium polymer x 2 (3.7 V, 400 mAh per pack)

Fig. 13. The features of transformable wheel.

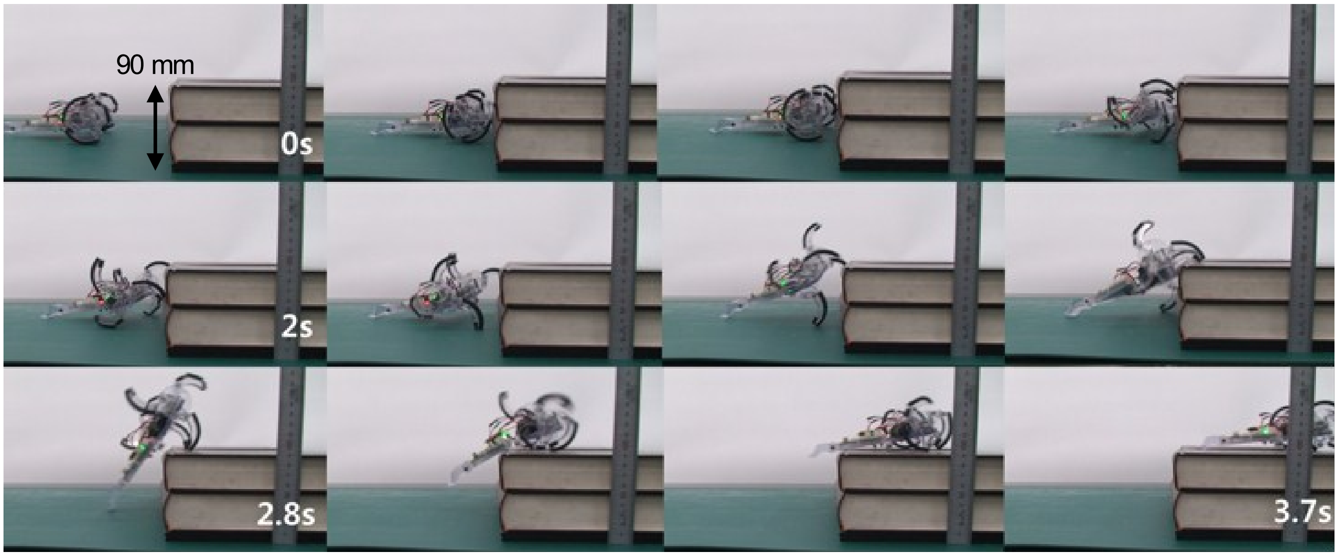

Fig. 14. The process of climbing 90 mm height obstacle.

VI. CONCLUSIONS

The transformable wheel takes the favorable features of two different types of wheels: the stable ride ability of a round wheel and the better climbing ability of a legged-wheel. Since the transformable wheel can keep its round wheel on flat surfaces, the robot can accelerate without vertical displacement of its center of mass. When it encounters an obstacle, it passively transforms to a legged–wheel to climb the obstacle. It can be transformed without actuators because it uses an external frictional force as its trigger force. A very simple robot platform is fabricated and it can climb an obstacle whose height is 2.6 times the radius of the wheels. This result can be compared to Whegs and Mini-Whegs that can climb an obstacle at most 1.5 times the length of their legs.

Wheel Transformer's very short turning radius enables it to follow the shortest path. It also helps the robot to cope with immediate path changes. Quadruped robot Mini-Whegs has a turning radius at least twice its body length. In comparison, Wheel Transformer has an almost zero turning radius since both dc motors rotate in opposite directions when it turns its moving direction (see video).

One of application areas of the small robots is SAR mission. Swarm robots are favorable in SAR mission because the mission needs a cooperation of small robots. The passive transformation of wheels enables a simple design of robot platform and the fabrication of small robots becomes easy.

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REFERENCES

[1] Matsuno, F., Tadokoro, S., "Rescue robots and systems in japan," in Proceedings of 2004 IEEE Int. Conf. on Robotics and Biomimetics (ROBIO '04), pp.12-20.
[2] Stormont, D.P., "Autonomous rescue robot swarms for first responders," in Proceedings of the 2005 IEEE Int. Conf. on Computational Intelligence for Homeland Security and Personal Safety (CIHSPS '05), pp. 151-157.
[3] Caprari. G., Arras, K.O., Siegwart, R., "The autonomous miniature robot alice: from prototypes to applications," in Proceedings of 2001 IEEE Int. Conf. on Robotics and Automation (ICRA '01), Vol.4, pp. 3643-3649.
[4] Quinn, R.D., Offi, J.T., Kingsley, D.A., Ritzmann, R.E., "Improved mobility through abstracted biological principles," in Proceedings of the 2002 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS '02), Lausanne, Switzerland, pp. 2652-2657.
[5] Allen, T.J., Quinn, R.D., Bachmann, R.J., Ritzmann, R.E., "Abstracted biological principles applied with reduced actuation improve mobility of legged vehicles," in Proceedings of the 2003 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS '03), Las Vegas, Nevada, pp. 1370-1375.
[6] Morrey, J.M., Lambrecht, B., Horchler, A.D., Ritzmann, R.E., Quinn, R.D., "Highly mobile and robust small quadruped robots," in Proceedings of the 2003 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS '03), Las Vegas, Nevada, pp. 82-87.
[7] Moore, E.Z., Campbell, D., Grimminger, F., Buehler, M., "Reliable stair climbing in the simple hexapod 'RHex'," in Proceedings of the 2002 IEEE Int. Conf. on Robotics and Automation (ICRA '02), Washington D.C., USA, pp. 2222-2227.
[8] Saranli, U., Buehler, M. Koditscheck, D., "RHex: a simple and highly mobile hexapod robot," Int. J. Robotics Research, vol. 20, pp.616-631.
[9] Shen. S.Y., Li, C.H., Cheng, C.C., Lu, J.C., Wang, S.F., Lin, P.C., "Design of a leg-wheel hybrid mobile platform," in Proceedings of 2009 IEEE/RSJ Int. Conf. on Robotics and Systems (IROS '09), St. Louis, USA, pp. 4682-4687.
[10] Berman, S., Lindsey, Q., Sakar, M.S., Kumar, V., Pratt, S.C., "Experimental study and modeling of group retrieval in ants as an approach to collective transport in swarm robotic system," Proceedings of the IEEE, vol. 99, pp.1470-1481.
[11] Wastson, J.T., Ritzmann, R.E., Zil, S.N., Pollack, A.J. (2002), "Control of obstacle climbing in the cockroach, Blaberus discoidalis: I. Kinematics," J. Comp. Physiology Vol. 188: 39-53.