Development of transformable mobile robot with mechanism of variable wheel diameter

Keiji NAGATANI[*1], Mitsuhiro KUZE[*2] and Kazuya YOSHIDA[*1]
[*1] Graduate School of Engineering, Tohoku University
6-6-01, Aramaki Aoba, Aoba-ku, Sendai 980-8579, Japan
[*2] Fuji Heavy-Industries 1-1, Subaru-machi, Ohta-city, Gunma 373-8555, Japan

March 1, 2007

Abstract

A demand of search and rescue operation using robotic technology increases to mitigate a natural disaster. In such search and rescue tasks, target environment is usually narrow and bumpy world. Therefore there exists a trade-off between high-capability of moving on bumpy environment (which requires large body) and exploration in narrow spaces (which requires small body). To solve such a problem, the authors developed "small-sized transformable mobile robot" that equips with a mechanism of variable wheel-diameter and variable stabilizer-length. The robot (minimized body) can be deployed through a narrow space , and it can surmount relatively large obstacles by expanding its wheel diameter. In this paper, details of the robot system are explained, and geometric analysis of capability of surmounting a step is discussed.

keywords: Mobile robot, Search and rescue, Rough terrain, Variable wheel-diameter

1 Introduction

Commonly, a field of earthquake hazard in urban area is an unstable and bumpy environment which has a danger of collapse of buildings (caused by aftershocks and so on). Therefore, it may cause a second disaster to a rescue crews. In such a dangerous area, a use of autonomous robots (particularly remote-control mobile robots for searching victims and collecting information of hazard-areas) instead of rescue crews is recently focused. In such environments, the robots had better be small-size (to go through narrow opening), and also it had better have high-capability of surmounting uneven grounds. Generally, the capability depends on the robots' size (particularly wheels' size), and there is a trade-off between them. To relax the both conditions as much as possible, our research group developed a transformable mobile robot that can change the sizes of wheels' diameter and stabilizer length mechanically (a bar to keep robot's body not to rotate) for adapting to various environments.

Fig.1 is a good example to explain our concept of developing robot. When the robot moves a narrow space, it reduce its wheel-diameter and its stabilizer-length to fit in the environment. Once the robot has to move on bumpy surfaces, it extends its wheel-diameter and its stabilizer-length to overcome it. In this research, we developed a prototype mobile robot which enables the above functions. In the Fig.1(a), the prototype-robot with minimum-wheel-diameter is shown, and in the Fig.1(b), the robot with maximum-wheel-diameter is shown.

In this research, we performed experiments of surmounting up-step using the prototype robot with various sizes of wheel diameters and stabilizer length. Through the experimental process, we understood that the stabilizer length was very important to surmount bumpy environment. In this paper, we describe a mechanism and system of the prototype robot, and we show experimental results. Also, we discuss a geometric capability for surmounting a step with different wheel diameters and with different stabilizer lengths in comparison with experimental results.

2 Related works

Related works are performed in many research institutes about mechanism of locomotion on uneven surface for search and rescue mission (particularly the target environment is urban earthquake hazard-area). The locomotion type of such rescue robots can be categorized by wheeled-type, crawler-type, snake-type and legged-type. Recent researches related to rescue robot including the above are

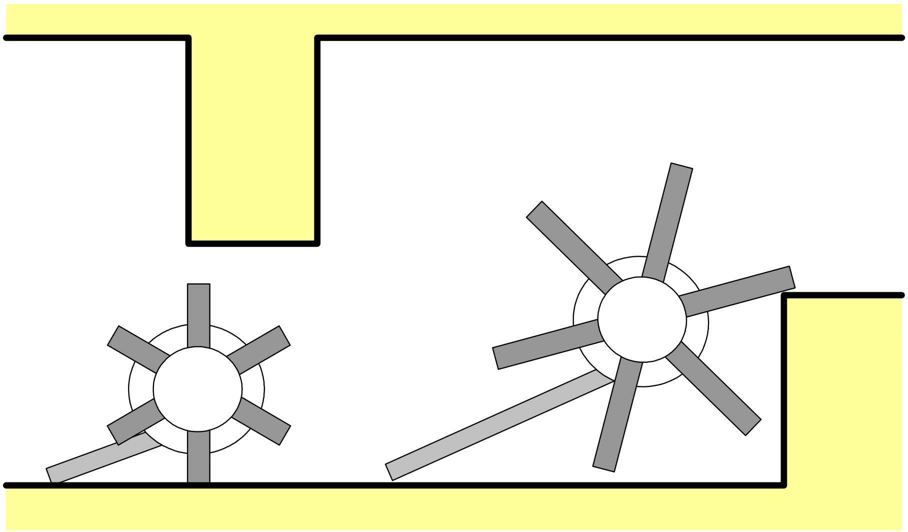


Figure 1: A desired capability of the proposed robot

Table 1: Specification of the target robot

Width	350–500 [mm]
Length	360–585 [mm]
Wheel-diameter	150–300 [mm]
Total weight	5.6 [kg]

gathered well in "the special edition of Journal of Japan Robotics Society (in Japanese)" [1] and "special issues in Journal of Advanced Robotics [2]".

In the field of wheeled-type rescue robots which relates to our research deeply, SCOUT robots [3] and jumping robot [4] are cited in this paper. In the former research, robots have two wheels, and each of it can be controlled remotely. One feature of this research is that the robots can be launched by specific launcher to be thrown into a target environment. Therefore, the shape of each robot is a small-thin cylinder. To improve surmounting ability on rough terrain for such small robots, one of them have special wheels which sticks out many rods from wheels' surface. Our deformation wheels resemble this idea functionally. However the principle and the size of the extension-mechanism are different. Additionally, the a capability of surmounting a step is not discussed deeply in the previous research. In the latter research, wheeled robots have an ability not only to move on flat surfaces, but to jump over large obstacles. It has a great potential of locomotion on debris for small-size mobile robot. However, the jumping function can not be utilized in a narrow space (such as like a cave).

3 Development of transformable mobile robot

3.1 Requirement specification for target robot

At the beginning of robot's design, we set the following requirements for our robot in consideration of performing activities in hazard areas in collapsed Japanese houses made by wood.

- The robot can be thrown into a target house with passing through a narrow opening of rubble (minimum 150[mm]).
- The robot can surmount a step (maximum 300[mm]).

To satisfy the above contradictory requirements (small-size and high-traversing ability), we developed a transformable small-sized mobile robot which has mechanisms of "variable-wheel-diameter" and "variable-stabilizer-length". (A specification of the robot is shown in the table 1.) By reducing wheel-diameter and stabilizer-length using the above mechanisms, the robot is thrown into a target environment through narrow space and it moves in a narrow space. On the other hand, by expanding wheel-diameter and stabilizer-length, it moves on bumpy surface and stairs. In the following sub-sections, we explain details of the mechanisms.

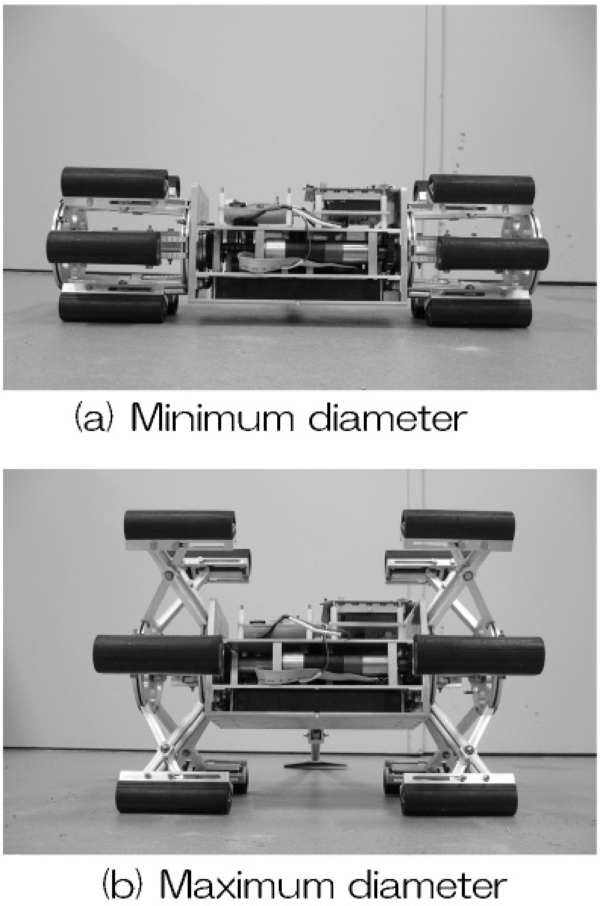


Figure 2: An overview of the robot

3.2 Mechanism of variable-wheel-diameter

Our mechanism of variable-wheel-diameter is composed of 6 equally angular-spaced pantographs (which transforms movement of horizontal direction to vertical direction). A series motion of one pantograph mechanism is shown in the Fig.4. In this figure, the length of the mechanism (vertical direction) is enlarged while the width of two disks in the bottom of the figure is shortened. To change the width between the two disks, we use linear actuator which is composed of trapezoidal-screw-thread and DC-motor (Maxon: A-max16, 110071). In our pantograph mechanism, a maximum range of each pantograph in vertical direction is 75[mm]. Therefore, the total range of wheel-diameter is from minimum $\phi = 150$ [mm] to maximum $\phi = 300$ [mm]. Fig.5 shows a series of expansion motion of the wheel.

To consider wheel's rotation, an actuator of wheel-rotation should be independent from wheel-expansion, so we embedded a trapezoidal screw thread for wheel expansion's actuator into a hollow shaft which supports wheels. The wheel itself is rotated by actuation of spur gears. In this research, FAULHABER's DC-motor is used for rotation of the wheel. A schematic of basic concept of it is shown in Fig.3.

3.3 Mechanism of variable-stabilizer-length

A robot which has only two driving wheels (such as our robot shown in the figure 2) requires a constraint mechanism not to rotate the body. Usually, the mechanism can be just a bar (shown in the figure 1), and we call it "stabilizer". A function of the stabilizer-length corresponds to wheelbase of conventional automobile. Therefore, the longer the stabilizer-length is, the better stability the robot performs in case of its moving on a bumpy surface. However in practical case, there is a minimum length of the stabilizer to surmount a certain height of step, in geometric analysis. Furthermore, the length had better be minimum in consideration of energy-consumption and obstacles' interference with the stabilizer. Therefore, we developed a mechanism of variable-stabilizer-length to respond to various heights of steps and to keep the stabilizer length short. Fig.6 shows an overview of variable-stabilizer-length. It is composed of trapezoidal-screw-thread and DC-motor (Maxon: A-max16) that

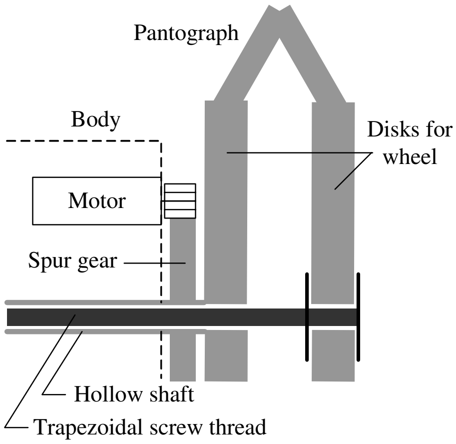


Figure 3: Basic concept of actuation mechanism

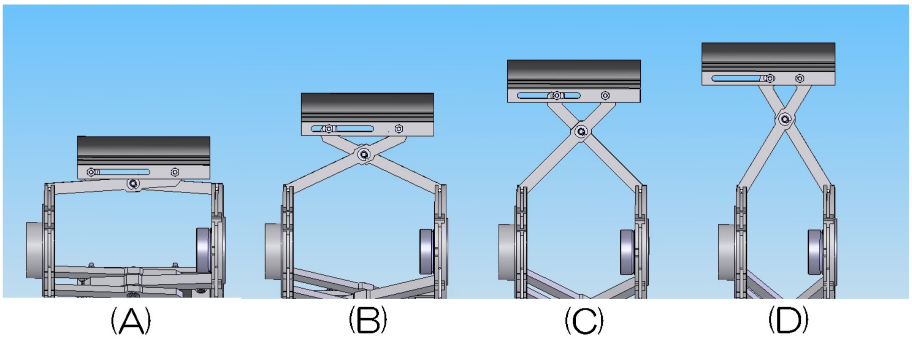


Figure 4: Mechanism of variable-wheel-diameter

converts from rotational motion to translational motion (to extend the stabilizer). The range of the length is from 230[mm] to 380[mm].

3.4 Control system

We are now developing a control system for our robot which consists of (1) CPU module, (2) motor drivers, and (C) power supply. SH7046 CPU board with FPGA is used for CPU module to generate PWM (and direction) signal and reading encoders' data. For motor drivers, we use a commercial motor drivers (iMCs03 : iXs Research). The electric power is supplied by a battery (YUASA NP2-12) and DC/DC converter (5V from 12V to supply controller's power source). Our plan is that the control system communicates with operators via wireless communication, and the robot is controlled remotely (but not implemented). In the experimental section to evaluate capability of surmounting a step, we do not use the above intelligent system, but use low level control.

4 Geometric analysis of surmounting a step

To surmount a step by mobile robots, we divided the motion into two different phases, called "approaching phase" and "surmounting phase", shown in the Fig.7. In the "approaching phase", the robot contacts one of the tip of wheel's rod to the step's edge. Next in the "surmounting phase", the robot rotates its wheel to lift up its body. In this research, we study a kinematic relationship among wheel-diameter, stabilizer-length and capability of surmounting a step in each phase.

4.1 Capability of surmounting a step in "approaching phase"

In the "approaching phase", the robot contacts its tip of wheel's rod to the edge of the step. To realize this motion, the wheel's diameter R must satisfy the following geometric constraint which relates to the height of the step H_1,

$$H_1 \leqq kR, \tag{1}$$

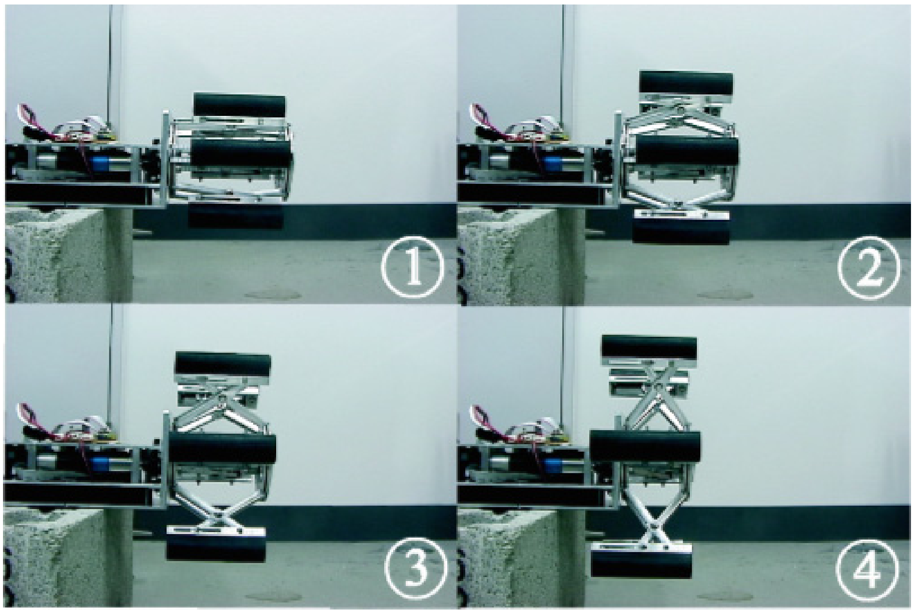


Figure 5: Sequence of expanding wheel diameter

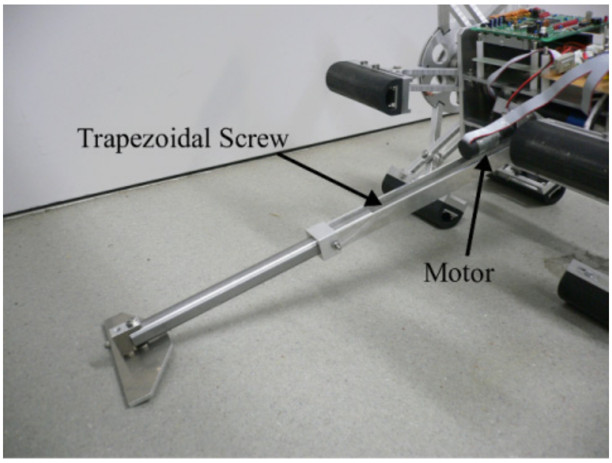


Figure 6: The mechanism of variable stabilizer length

where the k is determined by the number of rods.

It is difficult to formulate the coefficient k because it depends on not only "the angle" which a rod forms with a neighbor rod but "interference" between rods and the step (or the ground). Therefore, in this paper, k is calculated based on each individual geometric constraint.

For example, when the number of rods is 3 (which is shown in the Fig.8-a), wheel's diameter R must satisfy the following equation,

$$H_1 \; 5 \; \frac{R}{2}\sin(60^\circ)\cdot 2 = \frac{\sqrt{3}}{2}R. \tag{2}$$

In case of our robot, the number of rods is 6. Therefore, based on the geometric constraint shown in the Fig.8-(b), the necessary condition of R to surmount a step height H_1 is calculated by the following equation,

$$H_1 \; 5 \; \frac{R}{2} + \frac{R}{2}\sin(30^\circ) = \frac{3}{4}R. \tag{3}$$

The equation shows that the maximum-approach-height is 75 % of wheels' diameter.

4.2 Capability of surmounting a step in "surmounting phase"

In the "surmounting phase", the robot lifts its body up and forwards it to the front by rotating its wheel. To realize this motion, the stabilizer-length L must satisfy the following geometric constraint

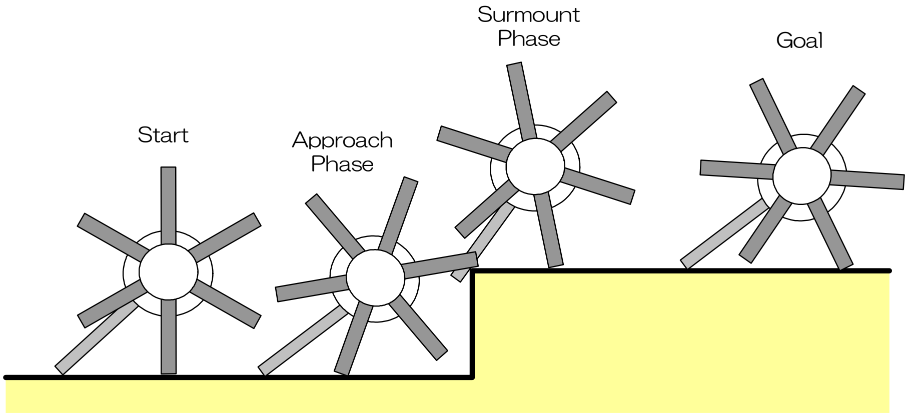
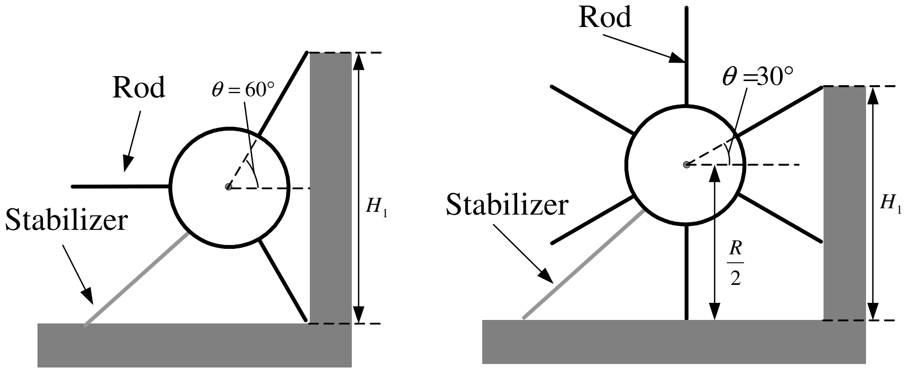


Figure 7: Surmount sequence



(a) The number of rods = 3 (b) The number of rods = 6

Figure 8: Limitation of the wheel diameter

which relates to the height of the step H_2 and the length of the wheel's diameter R.

$$H_2 + \frac{R}{2} \; 5 \; L + s. \tag{4}$$

Where the s is the length between the center of the wheel and the base of the stabilizer. Fig.9 shows a geometric schema of the above calculation.

4.3 Graph of capability of surmounting a step

As shown in the above subsections, there are two constraints for surmounting a step in "approaching phase" and "surmounting phase". The equations (1) and (4)) can be rewrited in the following equations according to H_1 and H_2,

$$H_1 \quad 5 \quad kR \tag{5}$$

$$H_2 \quad 5 \quad L + s - \frac{R}{2} \tag{6}$$

and The equation can be plotted in a graph shown in the Fig.10. In this graph, the robot can surmount the step in case of the area 4. To surmount a step, we can choose a set of (H, R) in the area 4, and minimum L can be calculated by the equation 6.

5 Experiments

To evaluate geometric capability of surmounting a step for transformable mobile robot shown in the above section, we performed several experiments using our mobile robot in several cases of changing wheel radius and stabilizer length.

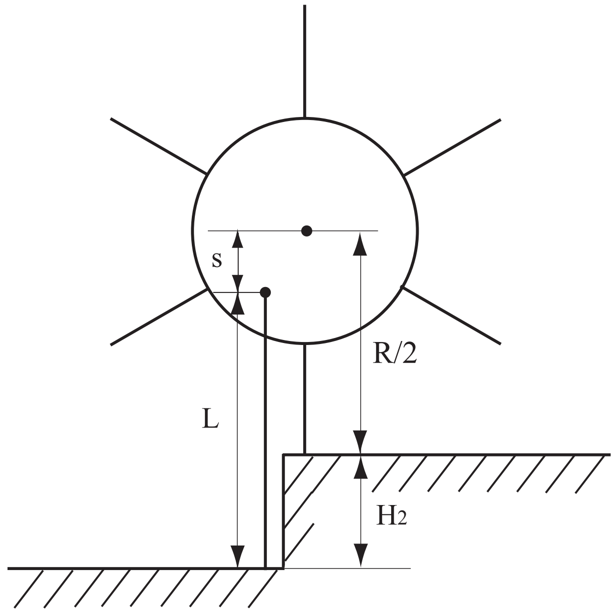


Figure 9: Limitation of the stabilizer length

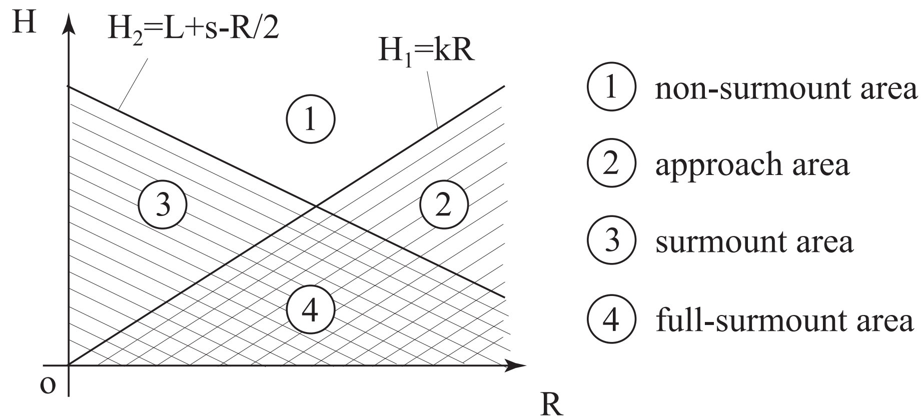


Figure 10: Surmount Diagram

5.1 Experimental conditions

In these experiments, we used a height-adjustable-step and confirmed the maximum height of the step which the robot surmounted in various patterns of wheels' diameter and stabilizer length (total 60 patterns). Diameter of the robot-wheels is set from 165[mm] to 300[mm] in every 15[mm] step. Stabilizer length is set from 230[mm] to 380[mm] in every 30[mm] step. When the robot approaches to the step, the phase of both wheels must be synchronized to maximize performance. In this experiment, both wheels are rotated by open-loop, so the phase was synchronized at the beginning of wheels' rotation.

5.2 Experimental results and discussion

Fig.11 shows the graph of the maximum height of the step (which robot can surmounted) from the point of view of wheels' diameter in the stabilizer length.

On the other hand, when the length of the stabilizer is long enough, the maximum height of the step is monotonously increased according to increasing of the length of the wheels' diameter.

Fig.12 shows three typical series of photographs which the robot tries to surmount a step (height is $H = 200$ [mm]). The left column of the figure shows that the wheels' diameter is $R = 240$ [mm] and the stabilizer length is $L = 380$ [mm]. In this case, the robot could not contact its tip of wheel's rod to the edge of the step in the "approaching phase". The center column of the figure shows that the wheels' diameter is $R = 300$ [mm] and the stabilizer length is also $L = 380$ [mm]. In this case, the robot contacted its tip of wheel's rod to the edge of the step in the "approaching phase".

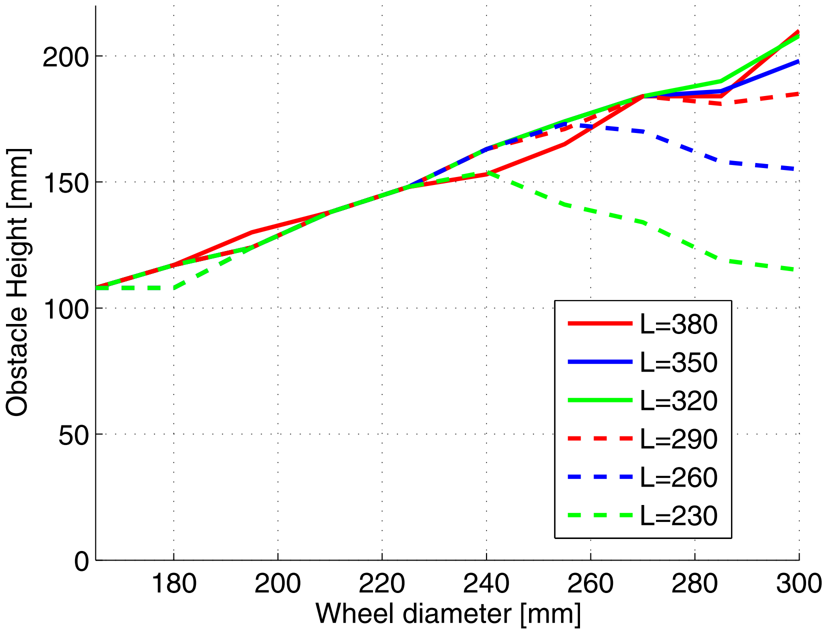


Figure 11: Results classified by stabilizer length

Next the wheels lifted the robot up and forwarded the body in the "surmounting phase" while the stabilizer supported robot's body not to be flipped. The right column of the figure shows that the wheels' diameter is $R = 300$ [mm], but the stabilizer length is only $L = 200$ [mm]. In this case, the robot completed "approaching phase". However it did not forward the body in "surmounting phase" because of the lack of the stabilizer's length.

Based on the above, it becomes clear that it is very important to consider not only the wheels' diameter but the length of the stabilizer to surmount steps.

Fig.13 shows a comparison between the above experimental result and the theoretical graph of capability of surmounting a step (which is shown in the section 4.3).

In this figure, the maximum height of the step seems almost the same tendency as the theoretical graph of capability of surmounting a step. However there is a small gap between experimental result and theoretical calculations. In an assumption in the geometric discussion, each tip of the rod is assumed to be a point, and it can generate an enough friction force. However, the above result shows an enough measure of validity of the simple geometric analysis which is discussed in the section 4.

6 Conclusion and future works

In this paper, we introduced our mobile robot for search in disaster environment which has a mechanism of variable wheel-diameter and stabilizer-length. It aims to relax a trade-off between high-capability of moving in bumpy environment (which requires large body) and exploration in narrow spaces (which requires small body). Also we performed an analysis of geometric relationship between the maximum height of the step in case of variabilities of wheel-diameter and stabilizer length. Finally, we performed several experiments to measure the maximum height of a step using our developing robot, and confirmed a validity of the geometric analysis. Basically, a continual motion of climbing over steps enables climbing up stairs, and we performed its motion recently. Fig.14 shows a sequence of photographs of its scene.

In this research, we completed only a geometric analysis of capability for the target robot, but it was not sufficient in a strict sense. In our future works, we should consider a dynamics of such kind of robot in case of surmounting a step. We also continue to maintain the control system of the robot, and we will put several sensors to detect surroundings of it in consideration of an actual mission of search in disaster environments.

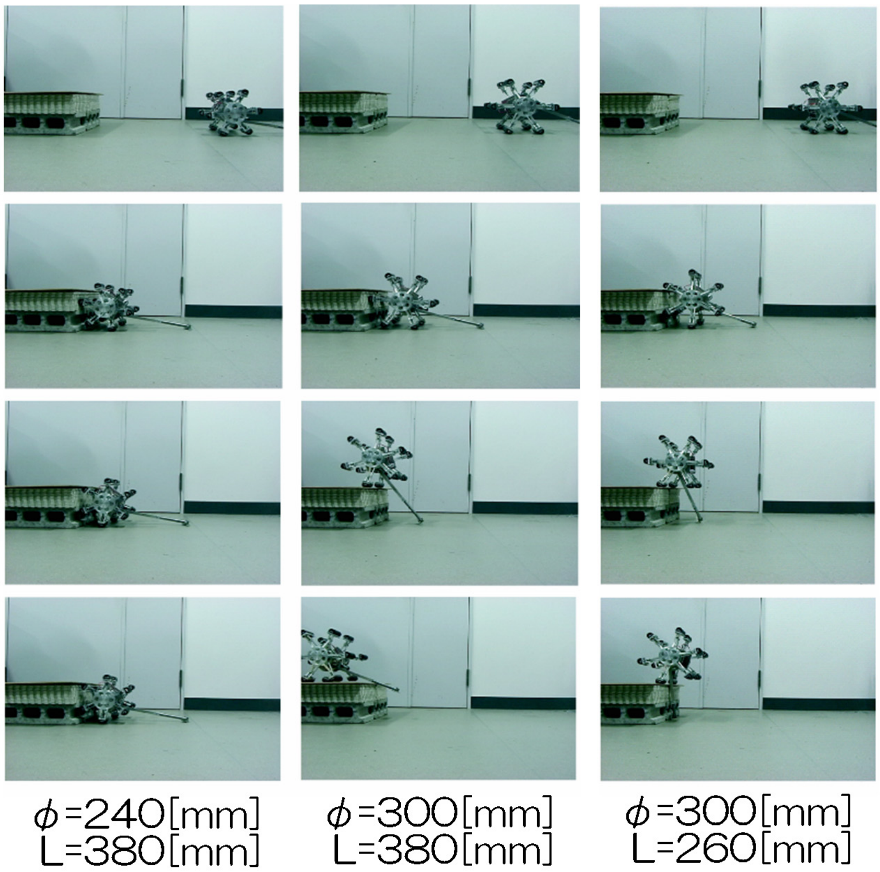


Figure 12: Experimental scenes of different parameters

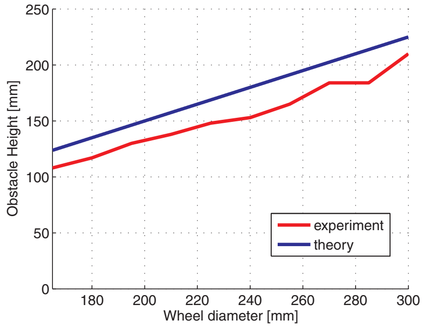
References

[1] Special issue: Special project for earthquake disaster mitigation in urban areas development of advanced robots and information systems for disaster response. *Journal of Robotics Society in Japan (in Japanese)*, Vol. 22, No. 5, pp. 1–44, 2004.

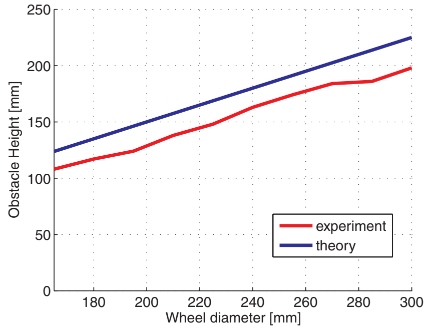
[2] Special issue of advanced robotics: Advanced research and development of robotics for search and rescue. *Journal of Advanced Robotics*, Vol. 19, No. 3, pp. 219–347, 2005.

[3] Brad Kratochvil Bradley J. Nelson Nikolaos Papanikolopoulos Andrew Drenner, Ian Burt and Kemal Berk Yesin. Communication and mobility enhancements to the scout robot. In *Proceedings of the the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 865–870, Lausanne, Switzerland, 2002.

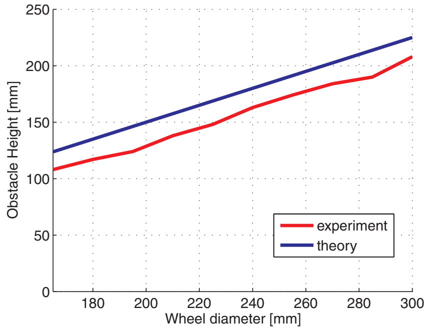
[4] M.Sasaki T.Tanaka A.Kitagawa H.Tsukagoshi, Y.Mori. Development of jumping & rolling inspector to improve the debris traverse ability. *Journal of Robotics and Mechatronics*, Vol. 15, No. 5, pp. 482–490, 2003.



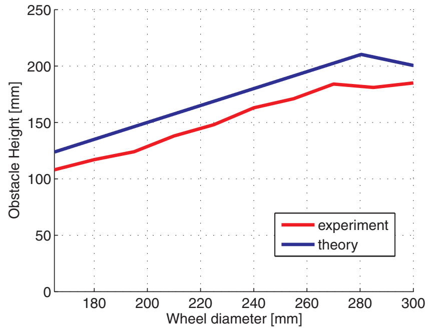
(a) L = 380 [mm]



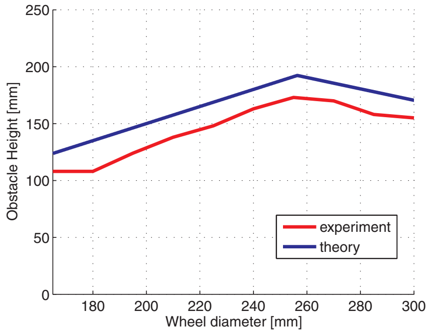
(b) L = 350 [mm]



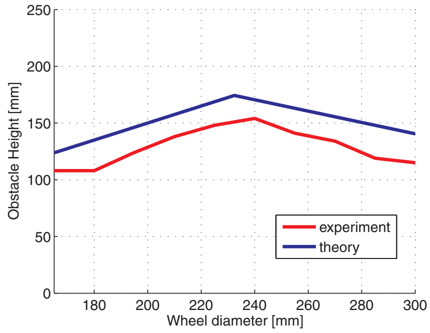
(c) L = 320 [mm]



(d) L = 290 [mm]



(e) L = 260 [mm]



(f) L = 230 [mm]

Figure 13: Comparison between experimental results and the proposed theory

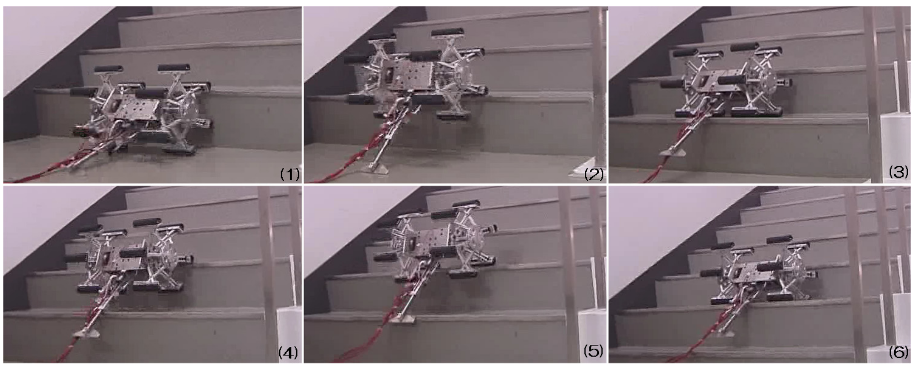


Figure 14: Stair climbing