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Development of Omni-directional Mobile Robot Under Unstructured Environment

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Mobile robots are expected to support relief activities, after a great scale disaster. These robots need ability to move on/in rubble in order to collect information related to victims and the conditions. In order to attain this purpose, we proposed a transformational mobile robot (CUBIC-R), which can traverse rubbles omnidirectionaly. The robot 's shape is hexahedron and each surface has a crawler unit with a couple of crawlers. As each surface is united by transformational mechanism which has 1DOF, it can overcome rough terrains (step, stairs, gap and so on) using transformation. Additionally, it can traverse terrains in the direction of the front, back, left or right without rotating the platform, because its shape is cross-shape. As the robot can traverse terrains in the left or right direction if it can not overcome obstacles in the front or back directions, stuck possibility of the robot may be small. Therefore we consider that CUBIC-R can be operated widely in the stricken-area. However, we found that there were several problems in CUBIC-R, such as the heavy weight, the complexity of the mechanism, the stability of the robot and the difficult robot operation. In this paper, we improve the robot mechanism and develop a fundamental robot/human interface in order to solve the above-mentioned problems.

Key Words: mobile robot, transformational, omni-directional, rescue operation

1. Introduction

After the Great Hanshin-Awaji Earthquake and the September 11 terrorist attacks in the U.S.A., disaster prevention systems and rescue systems [1), 2)] has come to attract attention. Early detection of disaster victims and quick decision-making are important items for mitigating damage. This decision-making includes determination of the rescue method, decision of victim's rescue order and presumption of secondary disaster possibility etc. this decision-making needs disaster information such as victims' existence, victims' position and the internal and external condition of buildings that have suffered serious damage. However, it is not easy to collect the information because of secondary collapses. Therefore, rescue robot are expected to collect disaster information in order to secure rescuer's safety and to perform rescue activities efficiently.

In previous research, several good mechanisms based on crawlers were proposed and expanded the range of robot activities in the stricken area [3)~10)]. Because contact area of crawler mechanisms to the ground is larger than that of other mechanisms, such as wheel type and walking type, crawler mechanisms can traverse the unstructured terrains made of the debris and rubble using simple control. Also, probability of secondary collapse caused by crawler mechanisms is expected to become smaller because pressure to the ground of crawler mechanisms is smaller than that of others. Therefore, crawler type mechanisms are focused in rescue robot. Crawler type mechanisms are focused in rescue robot research because of above mentioned reasons. However, there is a physical inconsistency for rescue robots. They need big bodies when they traverse big rubble, although they need small bodies when they enter to narrow space.

To solve this inconsistency, several crawler type robots, of which crawler platforms or crawler modules are connected sequentially, were proposed. These robots have high movement ability in an anteroposterior direction because they have long bodies [3)~7)]. Furthermore, they have high penetration ability in an anteroposterior direction, because their cross-sections in the direction are as small as an crawler platform or module.

Also, a crawler type robot which has an arm was proposed [8), 9)]. This robot integrated crawlers and an arm has high mobility than that of robots which consist of only crawlers. Furthermore, the robot has a locomotion strategy in which several units are connected using the arm. Consequently, the robot has high mobility about the same as conneced-vehicle type robots mentioned above.

On other hand, the one crawler vehicle has high mobility in an anteroposterior direction, however its rota-

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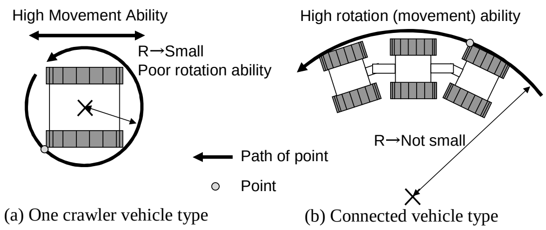


Fig. 1 Strategy of redirection on rough terrain

tion ability is not high (**Fig. 1**(a)). Therefore, the vehicle has the problem of change of the direction on unstructured terrain, where rotation ability means mobility in azimuth(yaw) direction of the vehicle.

When several connected-vehicle type robots turn, their shape is transformed from straight line to an arc using joint mechanisms and the area for a turning radius is needed [4),5),7)] (Fig. 1(b)). There are various ground situations in the stricken area. For example, we consider a situation in which a robot crawls up from a groove when it is running the bottom of a groove shown in **Fig. 2**(a). As for the connected vehicle type robot, it is susceptible to instability around roll axis. As there are various situations in the stricken area, in order to correspond to these situations, we consider that it is desirable that rescue robots can move with same mobility in four directions (front, back, left and right) without rotating (Fig. 2(b)). According to this concept, we proposed a novel movement mechanism, CUBIC-R(CUBIC Robot for Rescue), which can traverse terrains in the direction of front, back, left or right [10)].

In this paper, Section 2 outlines the architecture and the locomotion strategies for CUBIC-R. Section 3 describes problems of CUBIC-R and its improvement. Section 4 describes development of human/robot interface for improvement CUBIC-R (CUBIC-R+). Section 5 development of improvement CUBIC-R+, and examines it. Section 6 concludes this paper.

2. Development of CUBIC-R

2.1 Architecture

Fig. 3 shows architecture of proposed CUBIC-R. Its body at "Home mode" is regular hexahedron and its each surface has a crawler unit which consists of independent crawlers on the left and right sides, as shown in Fig. 3(a). As CUBIC-R can transform its shape corresponding to terrain by controlling the transformational mechanism which has one degree of freedom and is installed between connected plates, it can traverse the terrain and enter narrow space composed of big and small rubble with relative ease. Also, the uniting mechanism unites the crawler unit and the platform, and it has one passive degree of freedom and a brake in the direction of the yaw axis. A relative angle between a crawler unit and united plate can be arbitrarily controlled by this mechanism and turning grounding crawler unit. And the angle can be kept by activating the brake.

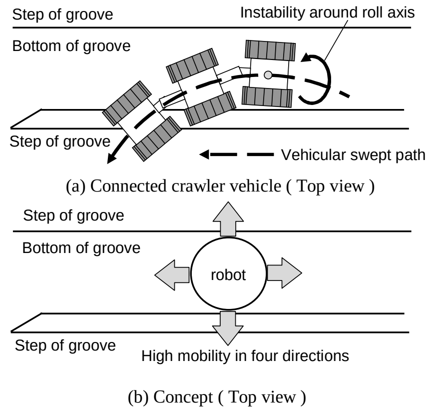


Fig. 2 Concept of development

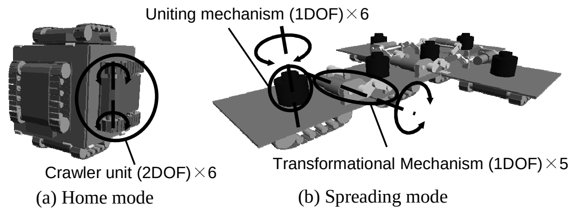


Fig. 3 Omni-directional mobile robot(CUBIC-R)

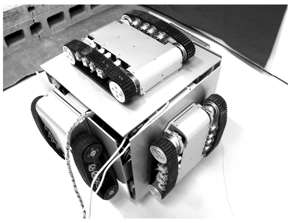
2.2 Locomotion Strategies

First of all, the active area of CUBIC-R is assumed to be inside of the partially destroyed house where secondary collapse might occur. Furthermore, we assumed that CUBIC-R can travel from safety area to the house and gather the disaster information inside of the house.

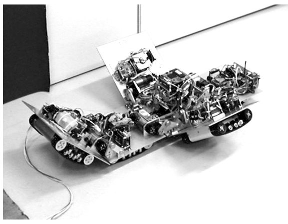
As for smooth roads and downward slopes, CUBIC-R moves with home mode. CUBIC-R has the ability to turn in the smallest radius at home mode, because the robot can carry out spot rotation by driving the grounding crawler unit as shown in Fig. 1(a).

As for rough terrain composed of big rubble such as steps, stairs or upward slopes, it traverses by transforming its shapes corresponding to the situation of the terrain. More details about CUBIC-R locomotion strategies in the partially destroyed house were described in previous paper [10)].

The mechanisms of CUBIC-R are similar to the connected-vehicle type robot. CUBIC-R needs no open space for changing the traveling direction, because the robot has the crawler unit which can turn in yaw axis



(a) Home mode



(a) Spreading mode

Photo. 1 Experimental CUBIC-R

Table 1 Specification of experimental CUBIC-R

Total Weight	31.0kg
The number of actuators	23
Rated output power of actuators	12∼18W
Cubic Size (Without Crawler unit)	260 × 260 × 260mm
Robot Size (Standard mode)	360 × 360 × 360mm
(Full expansion mode)	1040 × 780 × 210mm

on each surface and then the traveling direction can be changed without rotating whole robot platform. This is main characteristic of CUBIC-R. However, the penetration ability is less than that of the connected-vehicle type robot due to smaller DOFs of transformational mechanism and larger cross-section.

2.3 Experimental CUBIC-R

We produced experimental CUBIC-R shown in **Photo. 1**, in order to evaluate the realization possibility of proposed mechanism. And **Table 1** shows outline of produced experimental CUBIC-R.

The robot has Ni-H battery of which capacity is 7.2Ah so that the robot can work for 40 minutes.

We confirmed fundamental mobility of experimental model of CUBIC-R, and checked experimentally whether this robot has enough mobility under envisioned rough terrains [10]. However, several problems of CUBIC-R became clear through these experiments. The following section describes details.

3. The Problems of CUBIC-R and the Improvements

In this section, the problems of CUBIC-R which became clear by the experiments and the improvement points are described.

3.1 Problems of CUBIC-R

(1)Weight

Weight of the robot is 31kg as shown in Table 1 and it is a little heavy. Generally, making the robot lighter will improve mobility and the buffer impact when the robot falls from above to the terrain. For rescue operations, the robot must become lighter.

(2)The Human/Robot Interface

Previously, we controlled the robot using personal computer keyboard during the experiments. A key on keyboard was assigned into a motion of an actuator. As CUBIC-R has 23 actuators, we made rules so that robot control became simple. For example, while crawler units are controlled, the uniting mechanisms on same surfaces are not activated (brake-off). However, it is unrelated to the robot configuration and assignment of key, therefore keyboard control is less intuitive and very complex. Therefore, an intuitive human/robot interface is needed.

(3)Balance

The robot has long side and short side as shown in **Fig. 4**. It is difficult for robot operator to estimate position of the center of gravity, because the center of gravity is slightly close to Surface 5. When the robot climbs a step or traverse across a gap, the operator must judge whether the gravity point is on the step or whether length of the gap which the robot can traverse. As the robot operation is premised on remote control, the robot must be the configuration which operators readily recognize the position of the gravity point.

Secondly, when the robot changes the activated surfaces along from Long side to Short side, the robot balance becomes instable around the roll axis in Short side direction. For example, we consider that the robot runs bottom of the groove using Long side, and then the robot escapes from the groove using the surfaces along Short side (**Fig. 5**). At that moment, the surfaces along Long side are closed in order to shift the center of gravity on center of Surface 1, so that the robot moves stably around the roll axis in Short side direction. In addition, while controlling above, the operator makes surfaces neighboring Surface 1 along Short side to touch the step of groove so that the robot can not roll, as shown in Fig. 5(b). This additional control is cumbersome.

During the robot runs using the surface along the Short side, the surfaces along long side are always closed as mentioned above. These operations are redundant in the rescue operation. Additionally, when the robot closes the surfaces along the Long side, the center of gravity shifts to a higher position and the robot balance becomes instable in the roll and pitches over the axis.

Finally, presence of the Long side complicates robot control. Because the open/close control of Surface 6 depends on the relative angle θ_{1-5} between Surface 5 and Surface 1 whereas other surfaces depend on the relative angle between itself and surface 1. The relative angle θ_{1-6} between Surface 6 and Surface 1 is expressed as follows.

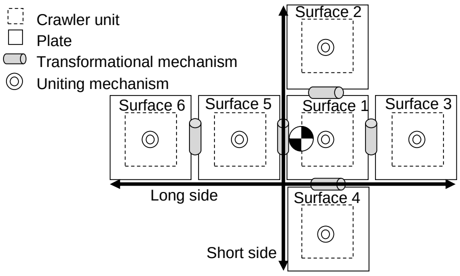


Fig. 4 Identification of surfaces(Top view)

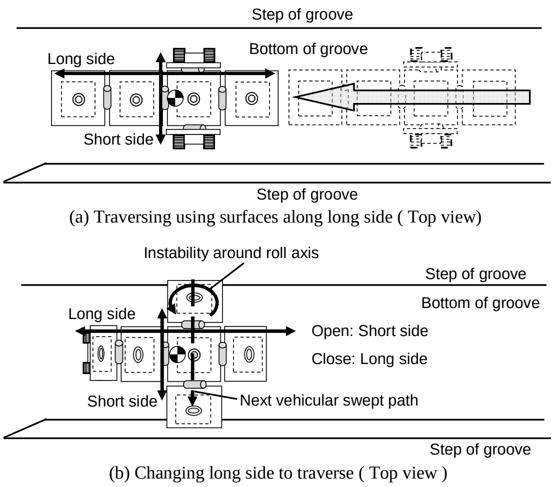


Fig. 5 Motion of escaping from a groove

$$\theta_{1-6} = \theta_{1-5} + \theta_{5-6} \tag{1}$$

where, θ_{5-6} is relative angle between Surface 5 and Surface. It is difficult for operator to control Surface 6 in real time during rescue operations.

(4)Driving Force to Terrain

As each crawler unit is included within each surface as shown in Fig. 4, a plate sometimes touches obstacles and the robot cannot traverse rubble. Especially, this accident occurs at spreading mode and the robot cannot traverse rubble. In order to break out this situation, additional operations for surfaces and crawlers are needed. This additional control is cumbersome.

A more serious situation arises in the experiment of traversing stairs. When the forward plate gets stuck with next step, the robot cannot climb next step. In order to break out of this situation, the operator controls the shape of the robot and crawlers so that the forward plate does not get stuck with next step and the robot does not fall from existing step. These complex operations may be impossible in the rescue operations.

3. 2 Approach to Problem Solving

To solve problems of CUBIC-R mentioned above, we reconsidered the robot configuration. However it must be maintained that the main characteristic of CUBIC-R, i.e., it can traverse in the multiple directions (front, back, left and right). Therefore, as one solution of the problems, we modified CUBIC-R configuration, as shown in **Fig. 6**, **7**. Details of configuration of modified CUBIC-R which call CUBIC-R+ and the improvements are described below.

(1)Removed Surface 6

As shown in Fig. 7, CUBIC-R+ is removed Surface 6 from CUBIC-R shown in Fig. 4. CUBIC-R+ configuration becomes symmetrical structure composed of five surfaces which the gravity point of the robot is on the center of Surface 1 as shown in Fig. 7(b). Basically, the plate, crawler unit, uniting mechanism, transformational mechanism and these motor controllers of Surface 6 are removed from CUBIC-R.

Consequently, improved items are follows.

- The trimmed weight is approximately one surface. Generally, weight saving makes improvements of the robot mobility and it is desirable for rescue operations.
- The human/robot interface is simplified slightly due to reduction of the number of actuators.
- As the height of the gravity point becomes lower, the robot can traverse the terrain in stable.
- As the position of gravity point is same as that of the center of Surface 1 and the robot on the flat(Fig. 7(b)), operator can estimate the gravity point more easily.
- The robot balance in the roll direction is more stable than that of CUBIC-R due to symmetrical structure, when the surfaces are activated.
- The operator does not need to distinguish the control methods of Short side and Long side due to symmetrical structure.

As discussed previously, weight, human/robot interface and robot balance are improved except the robot described in 3.1(4) by refined the robot structure. Especially, all problems of the robot balance may be improved.

However, CUBIC-R+ needs countermeasure for overturn accident, because Surface 6 has been removed. In addition, as the robot length along Long side becomes shorter, the robot mobility becomes lower such as traversing a gap. It is a serious problem for rescue robot to be stuck in a dead-end situation due to overturn accident. This problem and remaining problem described in 3.1(4) are discussed below.

(2)Improvement of Driving Force to Terrain

To solve the remaining problem of robot described in 3.1(4), the shape of the plate (Fig. 4) has been redesigned like half-moon, as shown in Fig. 6, 7. Consequently, as a part of the crawlers are located outside of the plane, the crawlers get into touch with obstacles. Therefore, driving

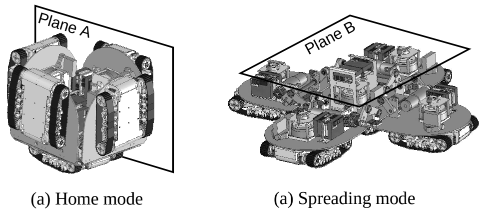


Fig. 6 Improved CUBIC-R(CUBIC-R+)

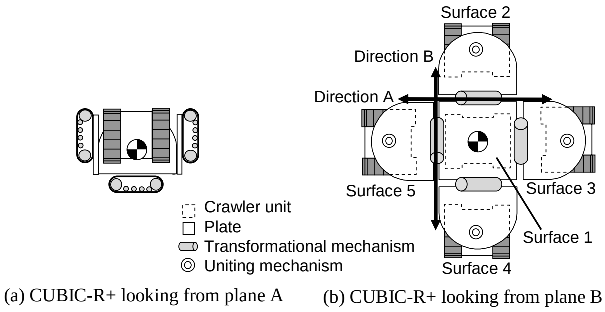


Fig. 7 Rough sketch of CUBIC-R+ in Fig.6

force of crawlers is transmitted more surely to the rough terrain than before.

(3)The Countermeasure for Overturn Accidents

Locating the crawlers outside of the plane is also one of countermeasure for overturn accident. For example, **Fig. 8**(a) shows the situation which CUIBC-R+ has overturned. Before the robot overturning, the operator has to notice that CUBIC-R+ gets off balance and then has to make CUBIC-R+ transform to home mode shown in Fig. 6(a). At that time, if CUBIC-R+ advances in the direction A or B as shown in Fig. 7(b), crawlers will contact on the terrain as shown in Fig. 8(a) because the parts of crawlers are located outside of the planes. In this case, as the robot can run, the crawlers get into touch with the obstacles and the driving force of crawlers rotates the body around pitch axis, as shown in Fig. 8(a)-(b). The robot continues to drive the crawlers and then the pitch angle of the robot becomes large as shown in Fig. 8(b)-(c). The robot can return to the original condition(Fig. 6(a)), if the center o gravity moves in back of the grounding point, as shown in Fig. 8(c)-(d). This strategy is based on pitching motion of CUBIC-R in experiment of traversing step [10].

4. Development of the Human/Robot Interface

As discussed in 3.1(2), the keyboard on PC has been used for the robot operation, and it is difficult to control directly. For improvement of human/robot interface, we develop new interface employing PlayStation2 (SCE video game) controller shown in **Fig. 9**. The reasons for

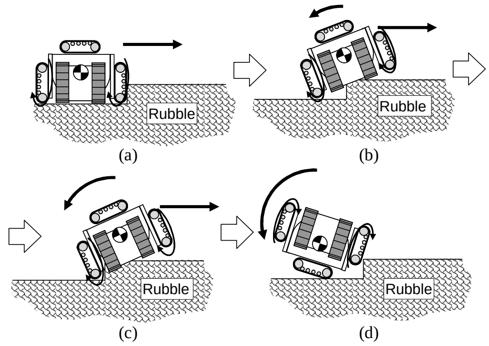


Fig. 8 Return Motion (strategy)

the choice are described as follows.

- The controller has many buttons and joysticks. Therefore, many motions of CUBIC-R+ can be assigned into the buttons or joysticks.
- As arrangement of 'Cross' buttons is similar to the configuration of CUBIC-R+, each surface expect Surface 1 is assigned to each button in 'Cross' buttons. The robot is controlled more intuitively by using the controller.
- As the controller has two joysticks, it is similar to proportional R/C system for operating the mobile system such as car, tank and aircraft.
- As the controller is compact size and lightweight, the operator operate the robot while standing.

The basic operation flow of CUBIC-R+ is that the operator selects active surfaces and selects the actions of crawler units or/and transformational mechanism. As each action for unit(s) or mechanism(s) is assigned into button(s) or joystick(s), the robot control becomes more intuitive control.

Fig. 9 and **Table 2** show the assignment of the operations and the details are follows.

A. Selection of the Active Surface

The operator can select one or more surfaces.

a)Selection of one Surface

The operator selects one active surface. Each surface except Surface 1 is assigned to each button in 'Cross' buttons shown in Fig. 9. The button is assigned into the surface in the correct relative position.

b)Selection of the Surfaces along some Direction

When the operator would like to control the surfaces along some direction at a same time, the operator selects this operation. In this case, the operator selects one of surface along direction A or B.

c)Selection of all Surfaces

When the operator would like to control all surfaces at a same time, the operator selects this oper-

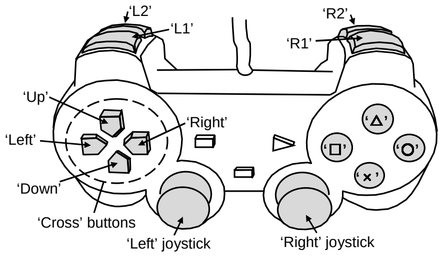
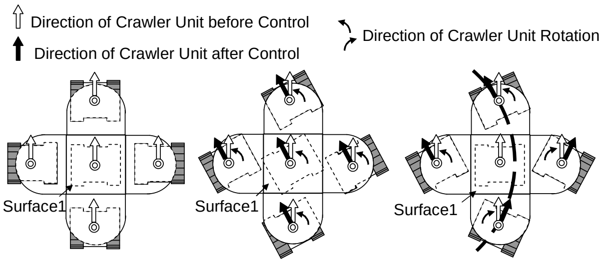


Fig. 9 Identification of buttons and joysticks

Table 2 Assignment of the robot operation

Surface(s)	Assigned Button	Motion	Assigned Button or Joystick
Selection of Active Surface(s)		**Motion of Surface(s)**	
All Surfaces	'R2'	Open	'O'
		Close	'×'
Surface1	'R1'	(direction A)	'Up' or 'Down' and
		Open	'△'
	'Cross' Buttons	Close	'□'
		(direction B)	'Left' or 'Right' and
Surface2	'Right'	Open	'△'
		Close	'□'
Surface3	'Up'	**Direction Control of Crawler Unit(s)**	
Surface4	'Left'	Turn	'Right' Joystick
		'Cancer'	'L2' and
Surface5	'Down'	(See Fig.10(b))	'Right' Joystick
		'Snake'	'L1' and
		(See Fig.10(c))	'Right' Joystick
		Movement Control of CUBIC-R+	
		Forward or Backward Movement	'Left' Joystick



(a) Before Control (b) 'Cancer' Control (c) 'Snake' Control

Fig. 10 Direction control

ation. For example, in order to avoid overturn accident, the operator selects and closes all surfaces for a short time.

B. Selection of Actions

The operator selects the commands of the motions for selected surfaces. In this case, the operator pushes the button of motion while pushing the one of activated surfaces.

a)Open/close of the Surfaces

The buttons for the motions of the Surface are a different arrangement from that of the surfaces along some direction. The reason is the same buttons for selection of the surface and the surfaces along some direction are assigned. While the surfaces do this motion, all brakes in uniting mechanism are activated so that the crawler units cannot rotate. The open/close motion of the surfaces along some direction is a useful motion for going up/down steps [5), 10)]. Therefore, the motions are especially assigned into the buttons.

b)Direction Control of the Crawler Units

This motion is used for change of the direction of the robot. The operator controls the turn of any crawler unit or multiple crawler units. In either case, the brakes in uniting mechanism on selected surfaces are not activated.

·Direction Control of any Crawler Unit

This control is selected, when the operator makes a crawler unit to turn around yaw axis. The operator selects relevant surface and moves 'Right' joystick left or right in desired direction. As the crawler unit has two independent crawlers, the crawler unit can turn in any direction.

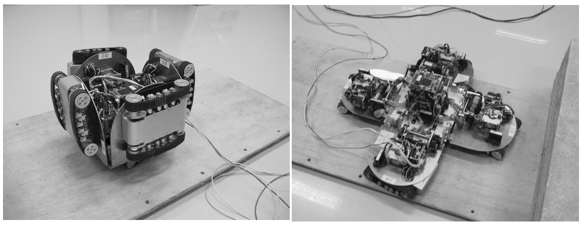
·Direction Control of multiple Crawler Units

The operator is able to select two motions, 'Cancer' or 'Snake' control. This motion uses two different buttons and 'Right' joystick. **Fig. 10** shows the behavior of the crawler units in each motion, when all crawler units contact on ground and the operator moves 'Right' joystick left. Where, Fig. 10(a) shows the configuration before direction control and Fig. 10(b) and Fig. 10(c) show the configuration after 'Cancer' and 'Snake' control, respectively. As motor controllers measure the number of revolutions of crawler, not relative angle between a crawler unit and united plate, the robot needs the control that all crawler units are directed in same direction as shown in Fig. 10(a) before the operator selects 'Cancer' or 'Snake' control. In the future work, the relative angle will be controlled by using potentiometer in a uniting mechanism.

As for 'Cancer' control, all crawlers turn in the same direction, as shown in Fig. 10(b). The robot can traverse the terrain (at least, on flat plane) in the all directions without rotating the robot platform. This motion is unique among connected-vehicle type and needs no open space for change of direction.

In this case, the operator selects 'L2' button and move 'Right' joystick left or right in desired direction.

As for 'Snake' control, the crawler units on the surfaces along some direction turn so that the crawler units give form to an arc in the direction, as shown in Fig. 10(c). For changing the robot di-



(a) Home mode (a) Spreading mode

Photo. 2 Experimental CUBIC-R+

Table 3 Specification of experimental CUBIC-R+

Total Weight	22.0kg
The number of actuators	19
Rated output power of actuators	12∼18W
Cubic Size (Without Crawler unit)	248 × 248 × 220mm
Robot Size (Standard mode)	348 × 348 × 270mm
(Full expansion mode)	681 × 681 × 210mm

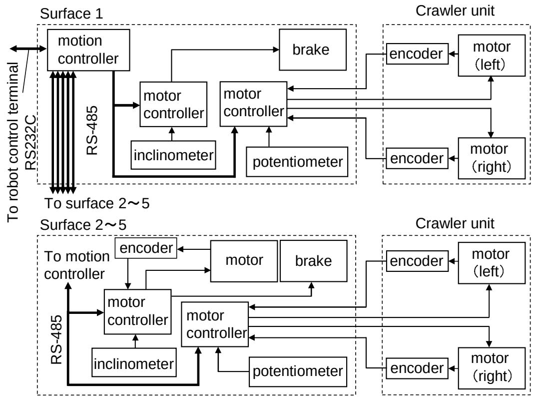


Fig. 11 System block diagram

Table 4 Results of experiments(CUBIC-R+ and CUBIC-R)

Item	Result	
	CUBIC-R+	CUBIC-R
Going up a slope	Inclination 37 degrees	38 degrees
Traversing a step	Height 240 mm	320 mm
Traversing the stairs	Angle of flight 35 degrees (rise 160 mm, tread 230 mm)	Same as the left
Traversing across a gap	Width 350 mm	400 mm
Escaping from a groove	Width 500 mm Depth above 200 mm	Same as the left

rection, the crawlers on two more surfaces along direction A or B (Fig. 7(b)) must be in contact with the terrain, and the crawlers in the lateral direction must not be in contact with the terrain. This motion is similar to the redirection motion of the connected-vehicle type as shown in Fig. 1(b).

In this case, the operator selects 'L1' button and move 'Right' joystick left or right in desired direction, and holds by the rule mentioned above.

c)Movement Control

In this control, all crawlers are driven in the same direction regardless of the directions of the crawler units.

The reason for driving all crawlers is that the robot can travel on the rough terrain. Because the crawlers transmit the driving force on the obstacles if the crawlers which do not contribute to movement get in touch with the obstacle. While the robot does this action, all brakes are activated so that the crawler units cannot turn.

In this case, the operator moves a 'left' joystick up or down in desired direction.

5. Production of CUBIC-R+

We produced prototype CUBIC-R+ according to description in section 3. **Photo. 2** and **Table 3** show the photographs and specification of prototype CUBIC-R+. The system block diagram is shown in **Fig. 11**. CUBIC-R+ was reconstructed from CUBIC-R. Therefore, the robot had no battery due to the small space for installing. On this account, although CUBIC-R+ is lighter than CUBIC-R by approximately 9kg from Table 1 and Table 3, actual reduced weight is 6kg by considering the battery weight, 3kg.

We confirmed fundamental mobility of prototype CUBIC-R+ under assumed rough terrains inside of the partially destroyed house. The results of the experiments of CUBIC-R and CUBIC-R+ are shown in **Table 4**. As for experiments for traversing the step and across the gap, the mobility is less than that of CUBIC-R, because the robot size is shorter than that of CUBIC-R due to reducing the number of the surface along Long side. The penetration ability at full expansion mode is 681mm × 210mm aperture size from Table 3, and this is the size that a male adult can barely enter. Furthermore, the ability may be improved by reducing the cross-section, if the robot enters narrow space in the direction A or B (Fig. 7(b)) and close the surfaces in the lateral direction.

Finally, **Photo. 3**(a)-(j) shows the experiment of the return motion discussed in 3.2(3). In the experiment, we confirmed that the robot could overturn. Here, the height of the step was 160mm in this experiment. Additionally, the center of gravity of CUBIC-R+ was lower than that of CUBIC-R shown in **Fig. 12**. Therefore, if the robot did not fall upside down completely, the robot could return to the original condition by vibrating, as shown in Photo. 3(f)-(j). As this result, we expect that the robot can get back by itself, if getting off the balance.

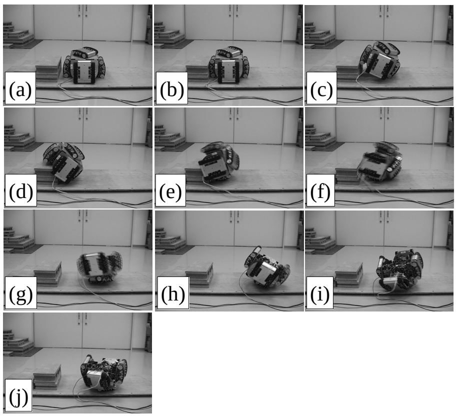


Photo. 3 Return Motion(experiment)

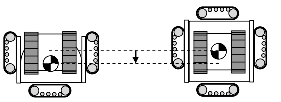


Fig. 12 Downward shift of center of gravity

6. Conclusions

In this paper, we outlined the proposed movement mechanism CUBIC-R which has high mobility on rough terrain composed of big rubble and penetration ability for narrow space in four directions. Secondly, the problems which were found in previous movement experiments and the solutions are described. Thirdly, we developed the improved human/robot interface by using video game controller and explained the robot operation. Finally, we produced prototype CUBIC-R+, and then examined and confirmed the mobility of the robot on fundamental rough terrains and the countermeasure of the robot for overturn accident. In our future work, we will improve the operation interface which enables us to control the CUBIC-R more easily and remotely. For this purpose, we will analyze dynamic behavior and use the graphical interface. Our goal is to realize control algorithm of basic movement strategies under various rough terrains.

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