2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Development of an unit type robot “KOHGA2” with stuck avoidance ability

Hitoshi Miyanaka[1], Norihiko Wada[1], Tetsushi Kamegawa[2], Noritaka Sato[1],
Shingo Tsukui[3], Hiroki Igarashi[4] and Fumitoshi Matsuno[1]

***Abstract*— To search victims in the narrow space at the disaster site, we have developed the snake-like rescue robot called “KOHGA”. The robot is constructed by connecting multiple crawler vehicles serially by active joints. KOHGA has a problem that obstacles are caught to the joints and then the robot is stuck. To solve this problem, we developed an unit assembled robot “KOHGA2” . It can be rearranged. The robot can swing crawler-arms and avoid the stuck. In this paper, we report the construction of the hardware and the control system of KOHGA2, the basic mobility performance, and the stuck avoidance strategy.**

I. Introduction

The rescue activity has received much attention to reduce damage caused by large-scale disasters such as Hanshin-Awaji (Kobe) Earthquake in 1995, the disastrous event of the NY World Trade Center in 2001, and the Sumatra coast earthquakes in 2004. In such a large-scale disaster site, it is difficult for human being to go into rubble, and the rescue workers who practice the rescue activity have risk suffered by the second disaster [1], [2]. Recently, it is necessary to prepare for not only a natural hazard but also a disaster by human errors and an artificial disaster such as terrorism. In any case the rescue robots that work quickly and accurately instead of the human being are expected [3].

We consider the robots which have a shape as long and thin as a snake is effective to search in a narrow space where is difficult for human being to enter. Then, we have developed the multi-vehicle connected crawler type rescue robot called “KOHGA” that is developed by considering the improvement of remote controllability, and we have done some basic operation verification for the robot [4]. However, KOHGA has a problem that the robot get stuck by catch the obstacles on the joint because the structure of KOHGA is simply connected some vehicles.

Not only KOHGA, many snake-like robots have been developed until now [5], [6]. For example, Hirose developed a multi-vehicle connected robot “Genbu” that uses active wheels and passive joints and verified the method of the stuck avoidance by classifying the stuck conditions and controlling all wheels individually [7]. However, there are few researches that address the method of the stuck avoidance for the multi-vehicle connected robots with crawlers and the active joints.

On the other hand, to improve the effectiveness of running performance for crawler vehicles, some rescue robots adopt the flipper mechanism or sub-crawlers mechanism [8]. These robots show high running performance in uneven terrain using them compared with the normal simple vehicle type robots. For example, Ma developed the crawler type robot which has two outputs with the planetary gear mechanism to drive and swing the crawler parts [9]. This robot shows high performance of climbing step by swinging crawlers around the center of rotation axis, and the robot is also possible to connect to the another vehicles to compose the multi-vehicle connected structure. However, in the paper [9], the stuck avoidance starategy is not considered.

Fig. 1. Pictures of KOHGA2 that can be rearranged

In this paper, we report the hardware and the control system configuration of newly developed multi-vehicle connected robot called “KOHGA2”, the basic movement performance, and the methods of the stuck avoidance by using the crawler-arms. KOHGA2 has the unit structure, so it is possible to rearrange its configuration. Moreover, it can taeke various forms by the swing motion of the crawler-arms, and avoids from various stuck conditions and shows the high mobility performance on an uneven terrain.

II. Mechanical construction

The overview of KOHGA2 is shown in Fig.1. KOHGA2 has the unit structure that consists of the crawler-arm-units, the joint-units, the terminal-units and the connecting parts as shown in Fig.2. The connecting part has 4 joints. The specification of each element is shown in Table I. The sensors such as cameras, lights, speakers, and microphones can be installed in the terminal-unit at both ends of KOHGA2. The motors which drive the crawler belt and the arm are installed in the crawler-arm-unit. The joint-unit has one degree of

[1]The University of Electro-Communications, Tokyo, Japan
[2]Okayama University, Okayama, Japan
[3]TOPY Industries, Ltd, Aichi, Japan
[4]SGI Japan, Tokyo, Japan

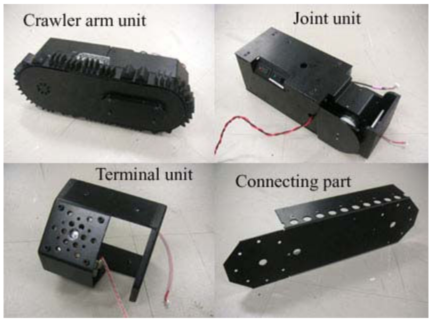


Fig. 2. Four kinds of components of KOHGA2

freedom. By assembling 2 joint-units with 90[deg] offset, a two-degrees-of-freedom joint is composed. The joint-unit has space for the batteries. The crawler-arm-units, the joint-units, and the terminal-units are fixed by the connecting parts.

Because of the unit structure, KOHGA2 can be rearranged. In addition, by changing the assembling positions of rotation axes of the crawler-arm-unit, KOHGA2 has a combination of different compositions. Fig.3 shows the 6 kinds of compositions. Each composition is defined as follows, “(a) 1 vehicle - 2 crawlers - non-coaxial type”, “(b) 1 vehicle - 4 crawlers - coaxial type”, “(c) 2 vehicles - non-coaxial type”, “(d) 2 vehicles - coaxial type”, “(e) 3 vehicles - non-coaxial type”, and “(f) 3 vehicles - coaxial type”. The assembling of the crawler-arm-unit to the connecting part has 2 possibility. One is the coaxial type and the other is non-coaxial type. The composition that the rotational axes of right and left crawler-arms are alternately attached to the vehicle is the non-coaxial type, and the composition that the rotational axes of both right and left crawler-arms are attached to the same end of the vehicle is the coaxial type. For example, in the case that KOHGA2 is the 3 vehicles version, the vehicle at both ends is assembled by 1 terminal-unit, 2 crawler-arm-units and 1 joint-unit, and the central vehicle is assembled by 2 crawler-arm-units and 2 joint-units. Features of KOHGA2 are mentioned below.

A. Unit structure

One of the features of KOHGA2 is the unit structure. KOHGA2 is composed by 4 kinds of unit as mentioned before.

It is easy to repair the robot at the disaster site by changing units when some parts of the robot are broken. So, it seems that the robot with the unit structure has the ability to accomplish the rescue activity smoothly. Namely it has following characteristic;

- Tolerance to breakdowns by changing the units

In addition, the unit structure has more characteristics as follow;

- Flexibility of the form change according to the situation
- Ability to extend the structure

So, the unit structure is very useful as the structure of the rescue robot.

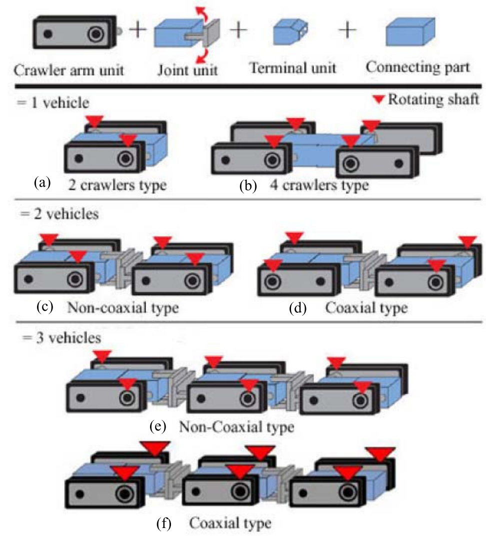


Fig. 3. Six configurations of KOHGA2

TABLE I
SPECIFICATIONS OF EACH UNIT

	Size[mm]	Weight[kg]
Crawler arm unit	$370 \times 119 \times 144$	3.8
Joint unit	$261 \times 93 \times 93$	1.8
Connecting part	$338 \times 102 \times 97$	0.5
Terminal unit	$78 \times 103 \times 93$	0.2

B. Crawler-arm

A crawler-arm is often called a flipper or a sub-crawler. There are not so many examples of the adoption of the crawler-arms for the multi-vehicle connected robots such as snake-like robots. On the other hands, the single-vehicles that have crawler-arms have been widely developed.

KOHGA2 adopts the crawler-arms as a movement mechanism. The aim of this research is to examine the improvement of the mobility for the rough terrain by rearranging the robot configuration of the crawler-arm-units. Especially, in this paper, the stuck avoidance strategy using the swing motion of the crawler-arms to solve the problem for the multi-vehicle connected robots is described.

III. System Configuration

In this chapter, the system configuration of KOHGA2 is described.

It is necessary for KOHGA2 to achieve easy separation and re-composition of the units, we introduce decentralized system architecture. A slave microcomputer is installed in an unit which has the actuators, namely the crawler-arm-unit and the joint-unit. A host microcomputer that sends and receives data to slave microcomputers is installed in the terminal-unit of KOHGA2. Moreover, the communication between a PC on the operator side and the robot is achieved by a wireless system.

The remote control system of KOHGA2 is shown in Fig.4. A game pad of SONY Playstation2 is used as the control

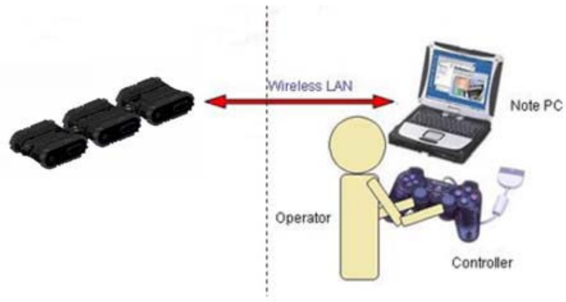


Fig. 4. Control system of KOHGA2

TABLE II
BASIC PERFORMANCE OF KOHGA2

Max speed	0.21 [m/s]
Minimum turning radius	1.28 [m]

input device. This device is easy to use because it is familiar to many people. Commands from the operator are transmitted by 5.2GHz wireless LAN.

A TITech SH2 Tiny Controller produced by the HiBot Company is adopted as a microcomputer in the crawler-arm-unit and the joint-unit. The microcomputer is very small size of 50mm∑ 20mm. Moreover, the communication between each microcomputers is achieved by CAN(Controller Area Network) which is a function of the microcomputer. An ID is set to each slave microcomputer, and the host microcomputer transmits the message to the slave microcomputers according to the ID. It is very easy to connect and disconnect a slave microcomputer to the CAN bus. A host microcomputer can easy communicate to slave microcomputers for the units which are connected to the CAN bus. As a result, the connection and the disconnection of the communication related to the mechanical connection and disconnection becomes very easy by using CAN bus.

IV. BASIC PERFORMANCE OF KOHGA2

The basic performance of KOHGA2 is shown in Table II. The minimum turning radius is measured when KOHGA2 is the 3 vehicles version.

4 basic mobility experiments of A∼D were conducted for 6 kinds of compositions by the unit rearrangement of KOHGA2. Moreover, we evaluated the performance for the each composition in the case that crawler-arms are fixed and crawler-arms are used, respectively. The state that crawler-arms are not moved is called "usual state". Fig.5 shows the another possible configuration of each robot in Fig.3$(a),(c),\cdots,(f)$. All joints of the crawler-arms in Fig.3$(a),(c),\cdots,(f)$ rotate to the ceiling direction, we obtain another shape of the robots shown in Fig.5$(a),(c),\cdots,(f)$, respectively. The total length of each configuration of the robot is shown in Table III. The obtained basic performance by the experiment is shown in Table IV. The details of each experiment are explained as follows.

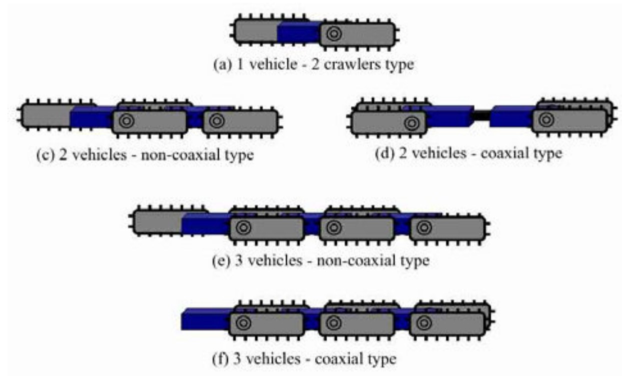


Fig. 5. The configurations using the crawler-arms

TABLE III
THE TOTAL LENGTH OF EACH CONFIGURATION

Configuration	Total length [mm]	Figure No.
1vehicle-usual	370	Fig.3(a)
1-2crawlers	826	Fig.5(a)
1-4crawlers	826	Fig.3(b)
2vehicles-usual	795	Fig.3(c)
2-Non-coaxial	1391	Fig.5(c)
2-Coaxial	1093	Fig.5(d)
3vehicles-usual	1245	Fig.3(e)
3-Non-coaxial	1841	Fig.5(e)
3-Coaxial	1543	Fig.5(f)

A. Vertical step climbing

In this experiment, as the number of the connected vehicles increases, the robot can climb over a higher step. For the 1 vehicle case, the robot can climb over the 60[mm] height step in the usual state, 250[mm] in the 2 crawlers type, and 290[mm] in the 4 crawlers type. In this case, the stability of the 4 crawlers type is better than the 2 crawlers type because it has 2 crawler-arms both front and back sides, and the 4 crawlers type can obtain a big driving power in addition. For the 2 vehicles case, the robot can climb over the 310[mm] height step in the usual state, 450[mm] in the non-coaxial type, and 480[mm] in the coaxial type. For the 3 vehicles case, the robot can climb over the 550[mm] height step in the usual state, 660[mm] in the non-coaxial type, and 720[mm] in the coaxial type.

From these results, the total length of the robot is essential for climbing ability of the high step. For the active joint position of crawler-arm-unit, we conclude that the coaxial type construction is better. Movement of the coaxial type robots is stable for the climbing step task because the moment balance of it is better than that of the non-coaxial type robots.

B. Stairs climbing

KOHGA2 is able to climb up and down stairs when the robot is constructed by 2 vehicles, 3 vehicles, and the 1 vehicle - 4 crawlers type, except for the case of the non-coaxial type.

In the case of the non-coaxial types, because both ends of the robot have only 1 crawler in the right side or the left

TABLE IV

EXPERIMENTAL RESULTS

Configuration	A	B	C	D
1vehicle-usual	60[mm]	Σ		180[mm]
1-2crawlers	250[mm]	Σ	33[deg]	320[mm]
1-4crawlers	290[mm]	”		360[mm]
2vehicles-usual	310[mm]	”		350[mm]
2-Non-coaxial	450[mm]	Σ	35[deg]	430[mm]
2-Coaxial	480[mm]	”		500[mm]
3vehicles-usual	550[mm]	”		570[mm]
3-Non-coaxial	660[mm]	Σ	40[deg]	650[mm]
3-Coaxial	720[mm]	”		630[mm]

A : Vertical step climbing B : Stairs climbing
C : Slope climbing D : Trench crossing

side, it is less stable than the coaxial type. If the front 1 crawler touches the edge of the step, the moment around the central body line will generate, the robot will rotate. So the non-coaxial type cannot climb stairs.

C. Slope climbing

The slope climbing experiment was conducted without swinging crawler-arms. The maximum slope angles that the robot can climb is following; 33[deg] for the 1 vehicle type, 35[deg] for the 2 vehicles type, 40[deg] for the 3 vehicles type. So it is expected if the number of vehicles increases, the robot can climb the slope with large angle. This is because if the number of crawler-arms increases, the area that the crawlers touch to the ground increase and the robot can get large friction force.

D. Trench crossing

When KOHGA2 doesn't use crawler-arms, the width of the trench that the robot can cross is 180[mm] for the 1 vehicle type, 350[mm] for the 2 vehicles type, and 570[mm] for the 3 vehicles type. In this experiment, as the number of connected vehicles increases, the robot can cross larger width of the trench. Moreover, the total length of robot becomes long when the robot uses the crawler-arms, so the trench crossing performance is improved.

However, when the 1 vehicle - 2 crawlers type and the 2 vehicles - non-coaxial type and the 3 vehicles - non-coaxial type use crawler-arms, the width of the trench that the robot can cross is shorter compared with the total length of the robot. Because only 1 crawler-arm at both ends of the robot hitches to the corner in the trench, the impellent in both ends of the robot is smaller and stability to the moving direction is lower than the coaxial type. On the other hand, the high performance of trench crossing is obtained in 1 vehicle - 4 crawlers type and 2 vehicles - coaxial type because of big impellent and high stability by both right and left crawler-arms of the robot hitching to the corner in trench.

Consideration about the basic movement performance

As for the experiments of vertical step climbing and trench crossing, each performance is improved by using crawler-arms. It is effective to the improvement of the mobility performance to adopt crawler-arms for the multi-vehicle connected robot.

However, especially in the experiment of stairs climbing, the performance of the non-coaxial type is lower than the coaxial type. Because the non-coaxial type hitches only 1 crawler-arm to the corner of step or trench at both ends of the robot, the stability to the moving direction is low and the impellent in both ends of the robot becomes small. So, it is considered that the coaxial type is more effective composition than the non-coaxial type.

In addition, the problem of KOHGA2 is that the width of crawler belt is very thin compared with the width of robot, so this problem is seems to be the cause of low impellent. Therefore, the impellent should be improved by changing to the wider crawler belt and then the mobility performance will be improved.

V. STUCK AVOIDANCE

For the multi-vehicle connected robots, there is a problem of getting stuck because the connection joint of the multi-vehicles is caught to the obstacle. In this chapter, the expected stuck conditions when the robots run uneven terrain are classified. The strategy of the stuck avoidance using the form change of the robot by swinging of the crawler-arms is discussed. Some experimental results are shown. In this chapter, the non-coaxial type and the coaxial type of 3 vehicles are considered. We distinguish the initial states as follows, the ungrounded state: the 1st vehicle doesn't ground and the grounded state: the 1st vehicle grounds. In Fig.6∼11, the moving directions of the robot is the right side of the figures, and the vehicles are numbered from the 1st to 3rd from the moving direction.

In this experiment, the height of obstacle is 115mm. The communication between the robot and PC for control and the power supply are wired.

A. Joint stuck avoidance in the high ceiling environment

In this section, we consider the stuck avoidance for the obstacle in high ceiling environment. When the robot gets trapped into this kind of obstacle as shown in Fig.6(a), it is very hard to avoid the stuck by rotational movement of the crawler belts. Because there is no actuator at the joint which can lift up the stuck joint. To avoid this stuck, we propose the method that the robot lifts up the joint by swinging all crawler-arms to the direction of the ceiling. The crawlers can contact with the obstacle by swinging crawler-arms, the stuck joint is lifted up and then the robot avoids the stuck as shown in Fig.6(b).

From the experimental results, we find that both the non-coaxial type and the coaxial type are able to avoid the stuck as shown in Fig.7 by both of the proposed methods.

Even if both two joints get stuck, by swinging all crawler arms to the direction of the ceiling, the crawlers can contact with obstacles and the stuck joints are lifted up. So the robot can avoid stuck by the poposed methods.

B. Joint stuck avoidance in the low ceiling environment

In this section, we consider the stuck avoidance for the obstacle in the low ceiling environment. The crawler-arms collide with the ceiling if the method of the stuck avoidance

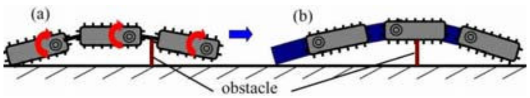
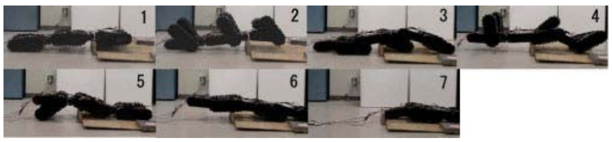


Fig. 6. The method of joint stuck avoidance in the high ceiling environment

(a) Non-coaxial type



(b) Coaxial type

Fig. 7. Stuck avoidance of joint in high ceiling environment

proposed in the previous section is used, so the stuck avoidance cannot be achieved for this stuck condition.

In this case, we propose the method of the stuck avoidance by making the shape of the robot as an arc. By winding the pitch joints to the direction of ground, the stuck joint is lifted up from the obstacle (Fig.8(a)). However, this method requires the necessary condition that the 1st and 3rd vehicles ground, if either cannot be grounded, this method is not useful. Therefore, we propose other methods of the stuck avoidance. For the non-coaxial type robot, the stuck joint is lifted up from the obstacle by swinging the crawler-arms of the 1st vehicle to the direction of the ground (Fig.8(b)). And for the coaxial type robot, the stuck joint is lifted up from the obstacle by swinging all crawler-arms to the direction of ground (Fig.8(c)).

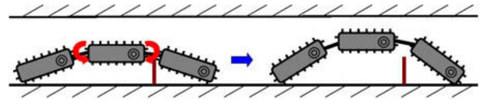
In the experiment, we set the height of the ceiling as 400[mm]. Fig.9 shows the snapshot of the joint stuck avoidance for the proposed 3 strategies.

However, the balance of the non-coaxial type robot is bad, so the stuck avoidance is not so easy. On the other hand, it is easy to avoid the joint stuck for the coaxial type robot. As the crawler-arm rotational axes are the same axis, the balance of the coaxial type is good. The coaxial type robot is better to avoid the joint stuck.

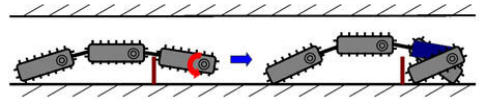
If crawler arms can contact to the ground and the stuck joints can be lifted up, the robot can avoid stuck by all proposed methods when both two joints get stuck.

C. Stuck avoidance for main body running aground on rubble

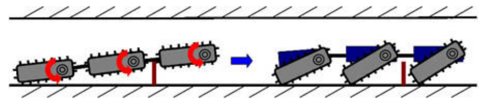
In this section, we consider the stuck condition that bodies of the robot are aground on the obstacle in rough terrain. For this body stuck, we propose the following method of the stuck avoidance. By swinging all crawler-arms to the direction of ground, the body of the robot is lifted up (Fig.10).



(a) Stuck avoidance with joints



(b) Non-coaxial type

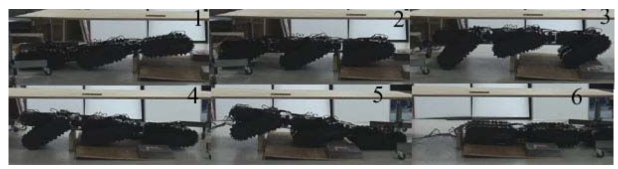


(c) Coaxial type

Fig. 8. The method of joint stuck avoidance in the low ceiling environment

(a) Stuck avoidance with joint

(b) Non-coaxial type



(c) Coaxial type

Fig. 9. Joint stuck avoidance in the low ceiling environment

In the experiment, we set the initial state as follows. The robot body is aground on the obstacle whose width is 100[mm] and height is 115[mm]. The width of the obstacle is narrower than that of the robot body. All crawler-arms are swung to the direction of the ground and the body stuck is avoided by lifting body in both the non-coaxial type and robot the coaxial type robot as shown in Fig.11. However, for the coaxial type robot, the load torque of the pitch joints during the avoidance movement is larger than that of the non-coaxial type robot. Because the moment around the pitch joint of the coaxial type robot related to the reaction force from the grounded is larger than that of the non-coaxial type robot.

Consideration about stuck avoidance

The experiment results are summarized in Table V. In these experiments, KOHGA2 achieved stuck avoidance by swinging the crawler-arms to the direction of the ceiling for the stuck condition that the joint is caught to the obstacle in the high ceiling environment, and also by swinging crawler-arms in the direction of the ground for the stuck condition that the joint is caught to the obstacle in the low ceiling environment. The time required of the stuck avoidance for the

Fig. 10. A form for stuck avoidance from hard rubble

(a) Non-coaxial type

(b) Coaxial type

Fig. 11. Stuck avoidance for main body running aground on rubble

stuck condition in the low ceiling environment was shorter. However, the method of stuck avoidance by lifting up the robot body is not useful when crawler-arms of the 1st and the 2nd vehicle cannot ground. So when the robot get stuck with the obstacle and the crawler-arms of the 1st and the 2nd vehicle cannot ground in the high ceiling environment, the method of stuck avoidance by swinging the crawler-arms to the direction of ceiling is suitable.

In the case that KOHGA2 is the 2 vehicles version, the robot also can avoid stuck by all proposed methods. However, for the joint stuck avoidance strategies, the ability of the stuck avoidance declines because the performance of vertical step climbing falls off if the number of the connected vehicles is small.

Let us compare the stuck avoidance performance with the non-coaxial type robot and the coaxial type robot. In the high ceiling environment, the coaxial type robot in the ungrounded state is able to achieve stuck avoidance while it is difficult to achieve stuck avoidance for the non-coaxial type if it is not in the grounded state. So, it is observed that the coaxial type robot is more effective in the state that a joint gets stuck with an obstacle of height to which the 1st vehicle is not able to ground. Moreover, because the rotational axes of the crawler-arms are the same axis, the stability of the coaxial type robot is higher than that of the non-coaxial type robot. Therefore, we find that the coaxial type robot is more effective to the stuck avoidance than the non-coaxial type robot.

VI. Conclusion

In this paper, the hardware and the control system configuration of multi-vehicle connected robot KOHGA2 are described. KOHGA2 has rearrangement structure with the unit structure, and it has stuck avoidance ability with crawler-arms. The basic mobility performance that had been obtained by the experiment to 6 kinds of compositions is described. Moreover, we classified the stuck conditions expected when the multi-vehicle connected robots run on uneven terrain, and the methods of stuck avoidance using the swinging motion of the crawler-arms are described.

TABLE V

Experimental results

A	B	C	D	E
Joint	Non-coaxial	Grounded	-	Height:115
	Coaxial	Ungrounded		
Joint	Non-coaxial	Ungrounded	400	Height:115
	Coaxial			
Main body	Non-coaxial	Ungrounded	-	Height:115 Width:100
	Coaxial			

A : Kind of stuck B : Configuration
C : Initial state of robot D : Height of ceiling [mm]
E : Size of obstacle [mm]

Fig. 12. KOHGA2 for RoboCup2006

To improve the mobility performance, we designed a new wide width crawler belt which covers the entire width of the crawler-arm-unit. The 1 vehicle - 4 crawlers - coaxial type robot (Fig.12) that the new crawlers are used awarded the 1st prize of the Locomotion Challenge in the rescue robot league of RoboCup International Competition 2006.

The improvement of the user interface for remote control, detail theoretical analysis of proposed stuck avoidance and strategies for other stuck situations such as the case that the robot gets stuck in the side are future works.

References

[1] S. Tadokoro, T. Takamori, S. Tsurutani and K. Osuka: "On robotic rescue facilities for disastrous earthquakes – form the Great Hanshin Awaji (Kobe) Earthquake –", J. Robotics and Mechatronics, vol.9, no.1, pp.46-56, 1997.

[2] F. Matsuno and S. Tadokoro: "Rescue Robots and Systems in Japan", Proc. IEEE International Conference on Robotics and Biomimetics, 2004.

[3] "Special topic: Robotics for the disaster", Japan Society Of Mechanical Engineers magazine, vol.106, no. 1019, pp.759-814, 2003

[4] Tetsushi Kamegawa, Tatsuhiro Yamasaki, Hiroki Igarashi and Fumitoshi Matsuno: "Development of The Snake-like Rescue Robot “KOHGA”", Proc. IEEE International Conference on Robotics and Automation, 2004

[5] S. Hirose and T. Takayama: "Souryu-I : Connected Crawler Vehicle for Inspection of Narrow and Winding Space", Proc. ROBOMEC, 1CI4-1, 1998. (in Japanese)

[6] H. Kitajima and K. Osuka: "Articulated Vehicle with Four Side Crawler for Inspection of Narrow and Winding Space", Proc. SICE SI2002(I), pp.245-246, 2002. (in Japanese)

[7] Hitoshi Kimura, Shigeo Hirose and Keisuke Shimizu: "Stuck evasion control for Active-Wheel Passive-Joint snake-like mobile robot û Genbu ü", Proc. IEEE International Conference on Robotics and Automation, 2004.

[8] S. Kobayasi| T. Takamori| H. Fukumoto| S. Takashima| N. Nakagawa| Nguyen Huu Minh| S. Hayashi| M. Yamada: "Basic characteristic of getting over obstacle of rescue crawler UMRS"| Proc. JSME Conference on Robotics and Mechatronics, 2005. (in Japanese)

[9] Jinguo Liu, Yuechao Wang, Shugen Ma, Bin Li: "Analysis of Stairs-Climbing Ability for a Tracked Reconfigurable Modular Robot"| Proc. IEEE International Workshop on Safety, Security and Rescue Robotics, 2005.