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A Novel Modular Mobile Robot Prototype for Urban Search and Rescue

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1. Introduction

The last few years have witnessed an increasing interest in reconfigurable mobile robotic technologies (Yim, M.; et al., 2000). The applications include the following areas: industrial inspection (Granosik, G.; Hansen, M. G.; Borenstein, J. 2005), conducting surveillance, urban search and rescue, military reconnaissance and space exploration (Yim, M.; et al., 2003). Reconfigurable robots consist of several modules which are able to change the way they are connected. The modular approach enables mobile robots to reconfigure, which is essential for tasks that are difficult for a fixed-shape robot (Kamimura, A.; et al.; 2001). During movement the robot confronts an unstructured environment and handles the uncertainties by reconfiguring its structure (Castano, A.; et al., 2000). The basic requirement for this kind of robotic system moving on rough terrains is extraordinary motion capabilities.

The emphasis for discussion of this chapter is on the field of urban search and rescue (Miller, P.G. 2002) (Takayama, T.; Hirose, S. 2000). The history of human development has always been a struggle with natural disasters such as earthquakes, storms and floods. Recently the number of disasters by accidents or terrorism has evidently been increasing too (Casper, J.; 2002). Urban search and rescue is a domain that involves a great amount of manpower; and it is quite dangerous and laborious in a hostile environment (Matsuno, F.; Tadokoro, S. 2004). The development of mobile robots offers an intelligent alternative solution to the above-mentioned problems. The application of the robotic system can relieve people of this challenging work and provide an opportunity for robots to play a pivotal support role, realize automatic manipulation in a complex environment and improve the level of civil and military technology.

In this chapter, a novel modular reconfigurable mobile robot named JL-I is presented, which to date consists of three identical modules. After a short survey, the basic functions of a reconfigurable mobile robot are summarized systematically based on research into work targets. JL-I features active joints formed by serial and parallel mechanisms which endow the robot with the ability of changing shapes in three dimensions. With the docking mechanisms, the modules can connect or disconnect flexibly and automatically. After that the discussion focuses on the various locomotion capabilities, such as crossing high vertical

obstacles and getting self-recovery when the robot is upside-down. The results of a series of successful on-site tests are given to confirm the principles described above and the robot's ability.

2. Reconfigurable robots in literature

In recent years considerable progress has been made in the field of reconfigurable modular robotic systems, which usually comprise three or more rigid segments that are connected by special joints (Rus, D.; Vona, M.; 2000) (Suzuki, Y.; et al. 2006). The common kinematics modes include multiple legs, wheeled and chain-track vehicles. However, the robots with multiple-legs kinematics are too complex due to a structure with many degrees of freedom (Zhang, H.; et al., 2004). These robots do not meet the requirements of miniaturization, flexible and quick movement, so that multi-legs kinematics is rarely adapted.

The common characteristics of reconfigurable robotic systems lie in two points. Firstly, the robotics system comprises several similar modules which are independent units with full locomotion functions (Shen, W.; et al. 2006). Secondly, specially designed joints connect individual units to form a more flexible prototype. The first prototype (Hirose et al. 1990) with powered wheels was designed by Hirose and Morishima in 1990, which consists of several vertical cylindrical segments. Another robot with wheels on each module to provide the driving force was developed by Klaassen for the inspection of sewage pipes (Klaassen et al. 1999). A serpentine robot from Takayama and Hirose consists of three segments. Each segment is driven by a pair of tracks, but all tracks are powered simultaneously by a single motor located in the centre segment (Takayama, T.; Hirose, S.; 2000). The special ability of adapting to irregular terrain is passive and provided by springs. KOHGA (Kamegawa, T.; et al. 2004) has recently been developed by IRS in Japan. It consists of eight serially interconnected individual units with two tracks except the first and last modules.

Another group of reconfigurable robots features passive modules (Yim, M.; et al. 2001) (Murata, S.; et al. 2002) (Shen. W.; et al. 2002) (Kurokawa, H.; et al. 2003). It can only move after the modules are assembled (Moechel, R.; et al, 2005) (Gonzalez-Gomez, J.; et al. 2005) (Gonzalez-Gomez, J.; et al. 2004). In (Gonzalez-Gomez, J.; et al. 2007), 1D, 2D and 3D chain robots are classified according to their topology. As an example, PolyBot is able to optimize its parts to fit the specific task. Generally, this kind of reconfigurable robots is relatively simple so that the locomotion capability is not as efficient as the above-mentioned kind with powered tracks.

However, for urban rescue and search, the fact that the known reconfigurable robots can only assume few configurations due to relatively simple connecting and pose-adjusting mechanisms is a ubiquitous deficiency. For example, the Millibot Train robot from Carnegie Mellon University consists of seven compact segments, which can connect by couplers with one DOF (Brown, H.B.; et al., 2002). A reconfigurable mobile robot designed by M. Park is not able to change its configuration actively (Park, M.; et al., 2004). Another recent module robot (Wang, T.M.; et al., 2005) has only one DOF in its pose-adjusting mechanism. The robot from Université Libre de Bruxelles (Sahin, E.; et al., 2002) has a one-DOF pose-adjusting mechanism and one coupler to change the configuration between the neighboring modules as well.

Since 1999 our group has been focusing on the design and development of mobile robots for urban search and rescue purposes. A smart mobile robot was proposed as a flexible mobile

platform carrying a CCD camera and other sensors. A more flexible structure with two linked-track vehicles was proposed (Wang, W.; et al. 1999). The structure can be reconfigured so that the robot can move between surfaces standing at an angle of 0 - 90 degrees due to the pitching DOF actuated by the joint to increase the flexibility. The project presented here has the aim of developing an automatic field robot to meet the requirements of high flexibility, robustness.

3. System design and realization

3.1 Design considerations

Urban search and rescue is one important application for mobile robots in a complex environment. The basic functions of urban search and rescue robots include five aspects. (Zhang, H.; et al. 2006a)

1) Locomotion capability is the lowest basic functionality of the robotic system, which includes the following details.

The robot works not only indoors but outdoors as well. It should have a flexible mobility in rugged terrain to get to every point in the work space. In order to finish a task in an unstructured environment, the ability to cross high obstacles and span large gaps is indispensable. Sometimes the working environment is very complicated, including not only high steps and deep ditches but also narrow fences and floors cluttered with debris. As a result, the robot should have the capability of adopting different configurations to match various tasks and suit complex environments.

2) Enough intelligence for the discrimination of a variety of obstacle situations: Multiple sensing and control systems are incorporated to handle the uncertainties in a complex environment. Software should be dexterous enough to identify the various geometries and intelligent enough to autonomously reconstruct the environment. Sensor fusion is an important capability since no single sensor can identify all aspects of the environment.

3) Working autonomously with the corresponding effective treatment: As a rescue robot, it should move as fast as possible in order to get real-time information. Once the global task commands are entered by the user, the robot should move while accomplishing the rescue task. Path planning and behavior organization is built on global prior knowledge and local sensory information.

4) No connection with the environment: In order to move freely, it is important for the mobile field robot not to be wired or otherwise connected to the environment. The robot should carry all it needs: onboard power, the controller, and wireless communication.

5) Cooperation ability: The rescue robot is designed to operate with humans. The level of interaction may vary significantly, depending on the robot's design and on the circumstances. The controlling and monitoring of the robot is achieved through a GUI to allow an effective and user-friendly operation.

Usually urban searching and rescuing is based on the cooperation in a team. The given targets will be assigned separately. Every robot should communicate with the others and perform distributed activities.

3.2 Prototype design and realization

The proposed mobile system should have various moving modes. The JL-I system consists of three connected, identical modules for crossing grooves, steps, obstacles and traveling in complex environments. Design of the robot includes five parts:

1) Design of the independent mobile module which includes movement mechanisms and driving systems;
2) Development of the docking system and the reconfigurable driving mechanisms;
3) Development of the control system;
4) Kinematics analysis;
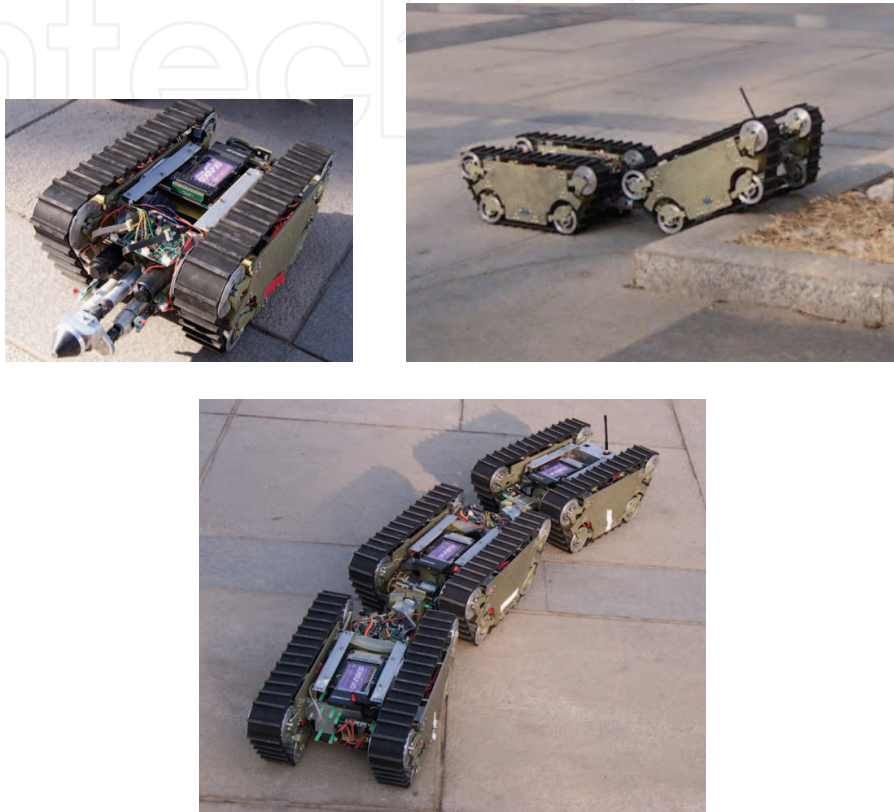5) Experimental testing.

Fig. 1. A photo of JL-I

The mechanical structure of JL-I is flexible due to its identical modules and special connection joints (Fig. 1). Actually, each module is an entire robot system that can perform distributed activities (Fig. 2). Three DOF active spherical joints between two modules and the docking mechanism enable the adjacent modules to adopt optimized configurations to negotiate difficult terrain or to split into three small units to perform tasks simultaneously.

Fig. 2. Performing distributed activities

By combining such locomotion capabilities, JL-I will move in almost all kinds of rough environments. The principle of terrain adaptability is shown in Fig. 3. The robot can change its posture by pitching around the Y axis, yawing around the X axis and rotating around the Z axis. The yawing and pitching movements are achieved by the parallel mechanism. The third rotation DOF around the joint's Z axis is achieved by the serial mechanism.
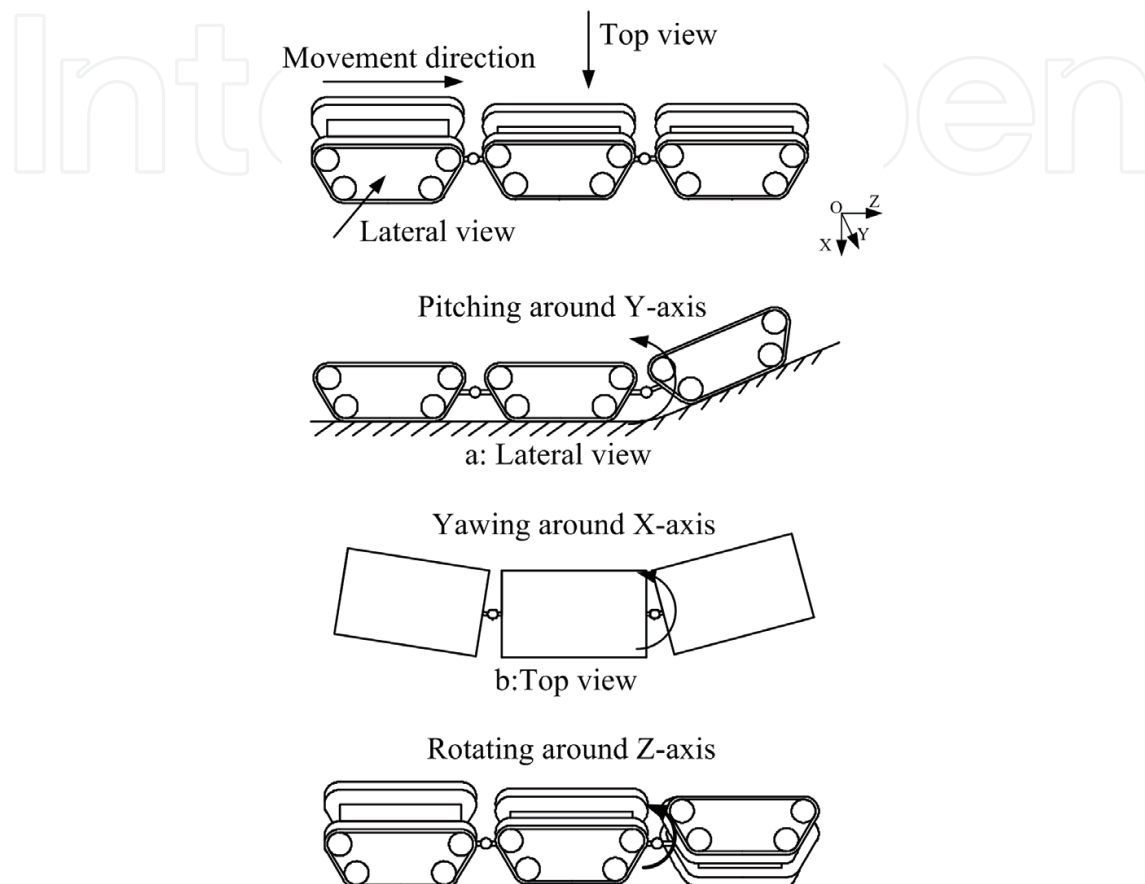

Fig. 3. Adapting to terrains

In contrast to the results of previous research, this robot includes the following innovative aspects (Zhang, H.; et al. 2006b):

1. Smooth movement: It is known that a common mobile robot will lose its moving ability if it is not able to keep its balance. However, the JL-I with its many active spherical joints can smooth the undulating motion of the gravity centre of the whole system.

2. High adaptability: Identical modules in the JL-I robot have a large variety of configurations owing to the pose-adjusting joints and the docking mechanisms. Therefore, the robot can adopt many shapes which make the JL-I system able to carry out various different tasks and move in diverse environments.

3. Self recovering ability: Furthermore, JL-I has the ability to implement self-recovery. By disconnecting the malfunctioning module, the system can repair itself if one module does not work normally. In this way, working safety and efficiency are increased when the robot moves in a complex environment.

The single module is about 35 centimetres long, 25 centimetres wide and 15 centimetres high. Fig. 4 shows the mechanical structure of the module which comprises two powered

tracks, a serial mechanism, a parallel mechanism, and a docking mechanism. Two DC motors drive the tracks providing skid-steering ability in order to realize flexible movement.
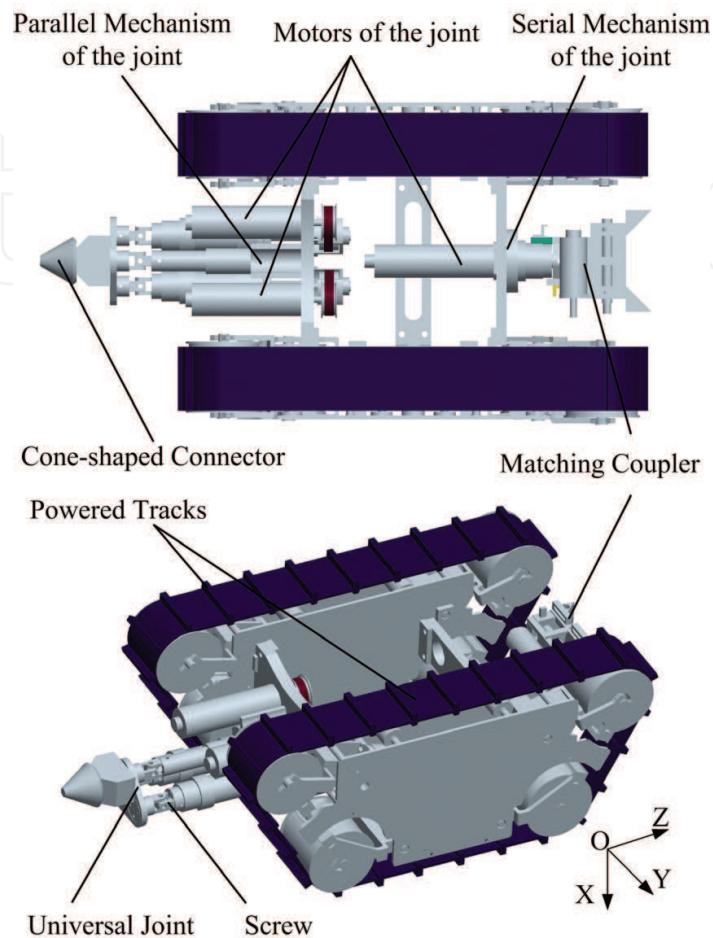

Fig. 4. The mechanical structure of the module

The docking mechanism consists of two parts: a cone-shaped connector at the front and a matching coupler at the back of the module, as shown in Fig. 5. The coupler is composed of two sliders propelled by a motor-driven screw. The sliders form a matching funnel which guides the connector to mate with the cavity and enables the modules to self-align with certain lateral offsets and directional offsets. After that, two mating planes between the sliders and the cone-shaped connector constrain the movement, thus locking the two modules. This mechanism enables any two adjacent modules to link, forming a train-like configuration. Therefore the independent module has to be rather long in order to realize the necessary docking function. In designing this mechanism and its controls, an equilibrium between flexibility and size has to be reached (Wang, W.; et al. 2006) (Zong, G.; et al. 2006).

The robot features the serial and parallel mechanisms which form a three-DOF active spherical joint. There are two reasons for using serial and parallel mechanisms for our mobile robot. Firstly, the JL-I robot can be made lightweight and dexterous while allowing for a larger payload. Secondly, the advantages of the high rigidity of a parallel mechanism, as shown in Fig. 6, and the extended workspace of a serial mechanism can be combined, thus improving the flexibility of the system.
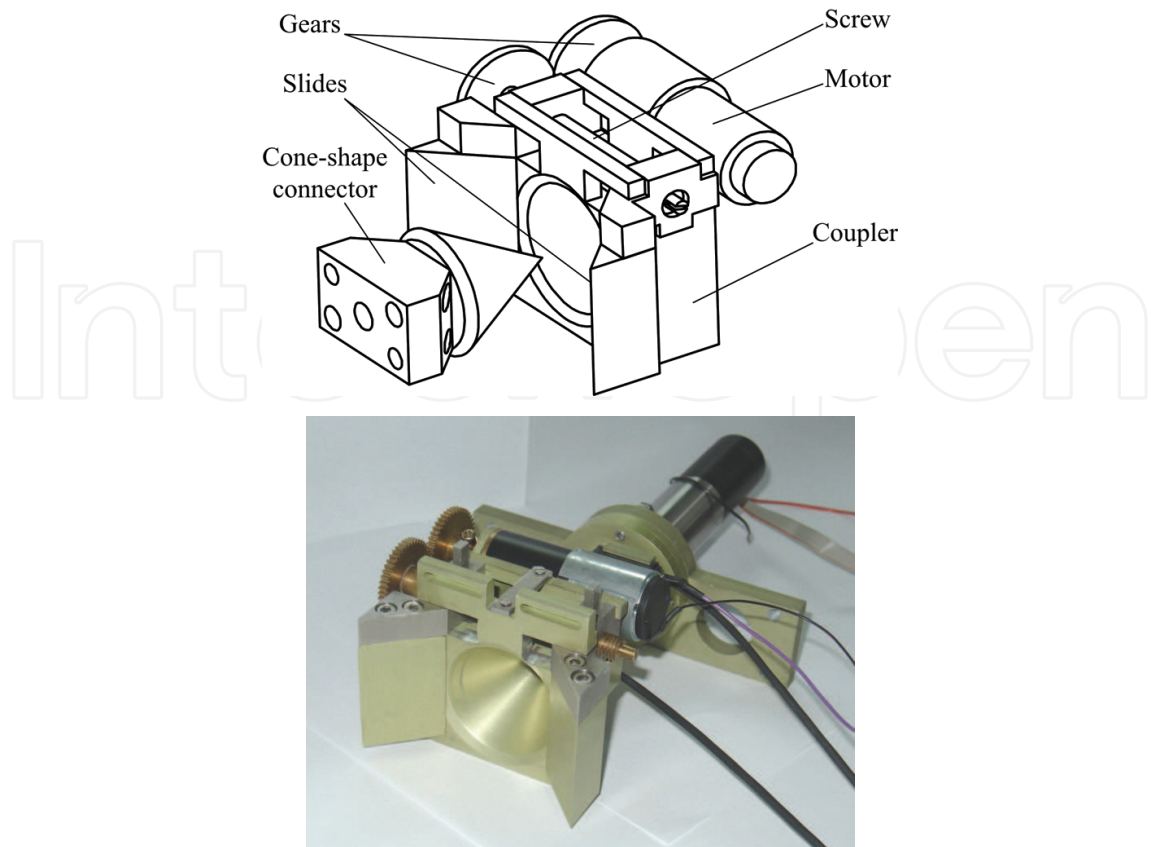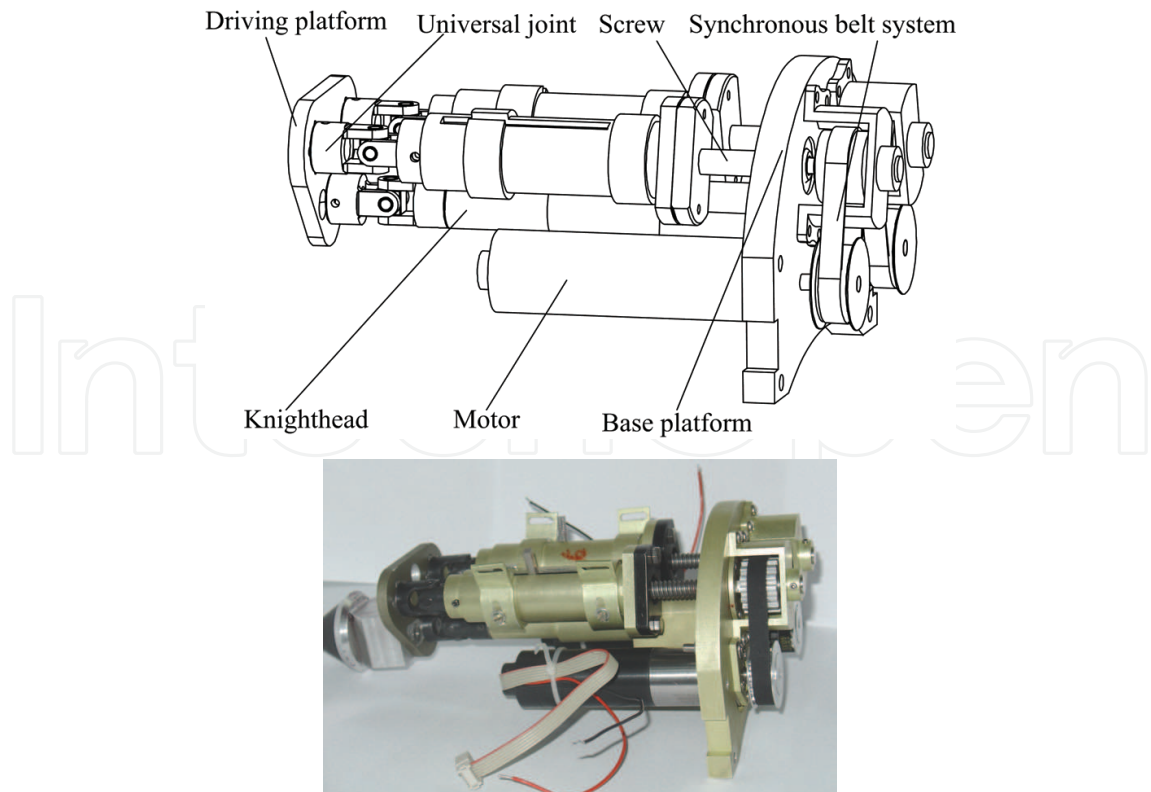
Fig. 5. The docking mechanism

Fig. 6. The parallel mechanisms

The serial mechanism can rotate 360° around the Z axis. This joint is actuated by a geared minimotor which provides a continuous torque of 3.5 Nm at a speed of 30 rpm. The parallel mechanism can pitch around the Y axis and yaw according to the X axis. Each leg of this parallel joint consists of a driving platform, a universal joint, a screw, a synchronous belt system, a DC motor and a base platform. The universal joint connects the driving platform and the knighthead. The other end of the knighthead is fixed to the base platform. By revolving the screw, the driving platform can be manipulated relatively to the base platform. By controlling the active joints and the docking mechanisms, the JL-I can change its shape in three dimensions.

To ensure its ability of performing tasks individually, there is enough space in each module for sensors, the onboard controller, and batteries. Considerable stress is laid on weight reduction as well as on construction stiffness to achieve a dexterous movement mechanism. Most of the mechanical parts are designed specifically and mainly manufactured from aluminium. A module weighs approximately 7 kg including the batteries.

4. Required locomotion capability

Due to the uncertainty of the practical environment, it is important for a robot to be able to carry out various complicated locomotion processes for performing urban search and rescue tasks. The JL-I is capable of almost all necessary actions that can be required in real situations, e.g. crossing obstacles such as steps and roadblocks, self-recovery (Zhang, H.; et al. 2007).

4.1 Crossing a step

Fig. 7 shows the process of crossing a step from a view in the Y direction. Here the step is almost twice as high as the robot.
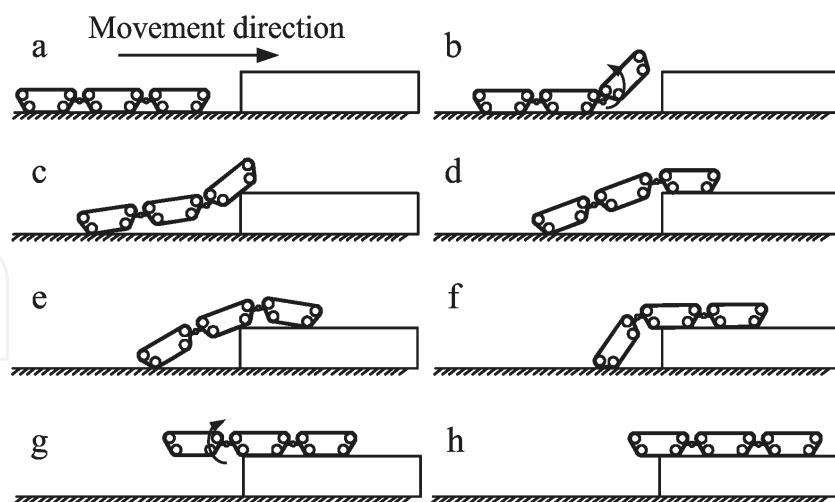

Fig. 7. The sequence of crossing a step

(a) The robot is in its home state, and the sensor detects the step in the movement direction.
(b) The first module is pitching up around the Y axis while the robot is moving forward.
(c) The approaching movement does not stop until the first module touches the step.
(d) The first module pitches down to attach to the top of the step.
(e) The robot is moving forward continuously.

(f) The robot is moving until the first two modules are attached to the step.

(g) The last module is pitching up around the Y axis while the robot is moving forward.

(h) The robot is now in its home state again, and the process of crossing the step is over.

4.2 90° self-recovery

It is possible for the robot to implement a 90° recovering movement by adopting the proper configuration sequence as shown in Fig. 8.
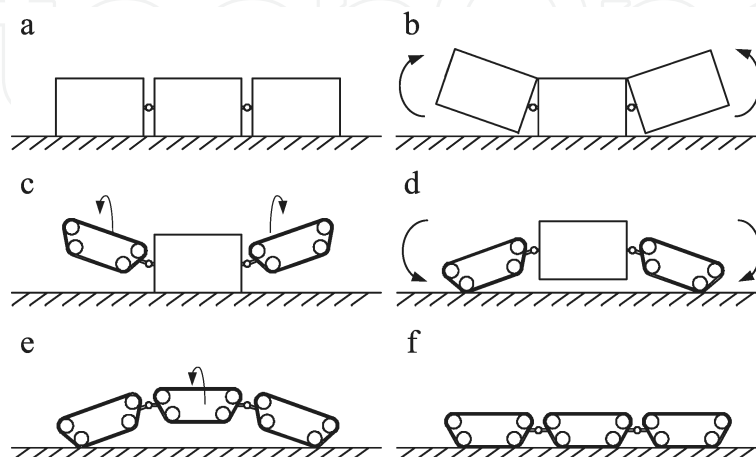

Fig. 8. The 90° recovering movement

(a) The robot is lying on its side.

(b) The first module and the last module are yawing up around the X axes of the active joints.

(c) Then the first module and the last module rotate 90° around the Z axes.

(d) After that, they are pitching down around the Y axes of the active joints until they attach to the ground in order to raise the middle module up.

(e) The middle module rotates around the Z axis until it is parallel to the ground.

(f) In the end, the module is pitching down around the Y axes of the active joints until all three modules attach to the ground together. The robot is now in its home state again, and the process of 90° self-recovery is over.

4.3 180° self-recovery

It is also possible for the robot to tip over and realize the 180° recovery movement as shown in Fig. 9.

(a) The robot is in its home state.

(b) The first and the last modules are pitching down around the Y axes of the active joints until the middle module is in the air.

(c) The middle module rotates 180° according to the Z axis.

(d) The first module and the last module are pitching down around the Y axes of the active joints until the middle module attaches to the ground.

(e) The first module and the last module are pitching up around the Y axes of the active joints again.

(f) The first module and the last module are rotating 180° around the Z axes of the active joints.

(g) Then the first module and the last module are pitching down around the Y axes of the active joints again until all three modules attach to the ground.
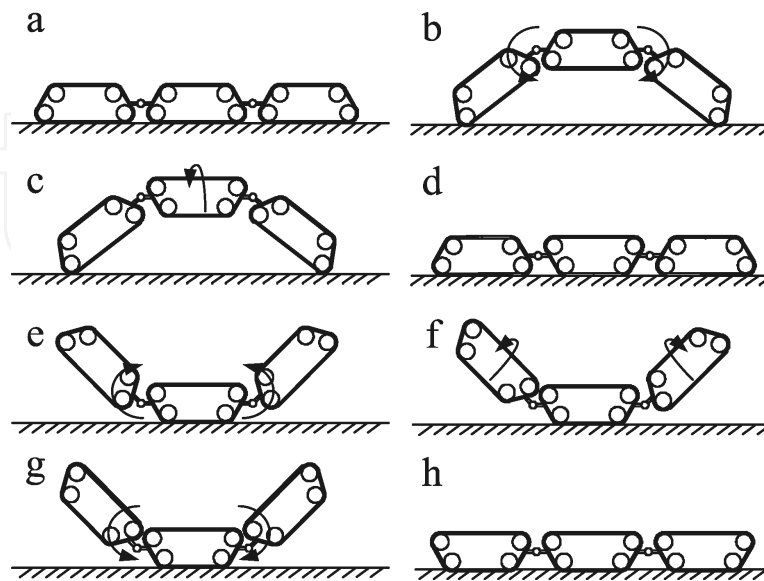(h) The process of 180° self-recovery is over.

Fig. 9. The 180° recovering movement

4.4 Crossing a narrow fence
As shown in Fig. 10, the train configuration robot is able to cross a fence narrower than the width of its modules.
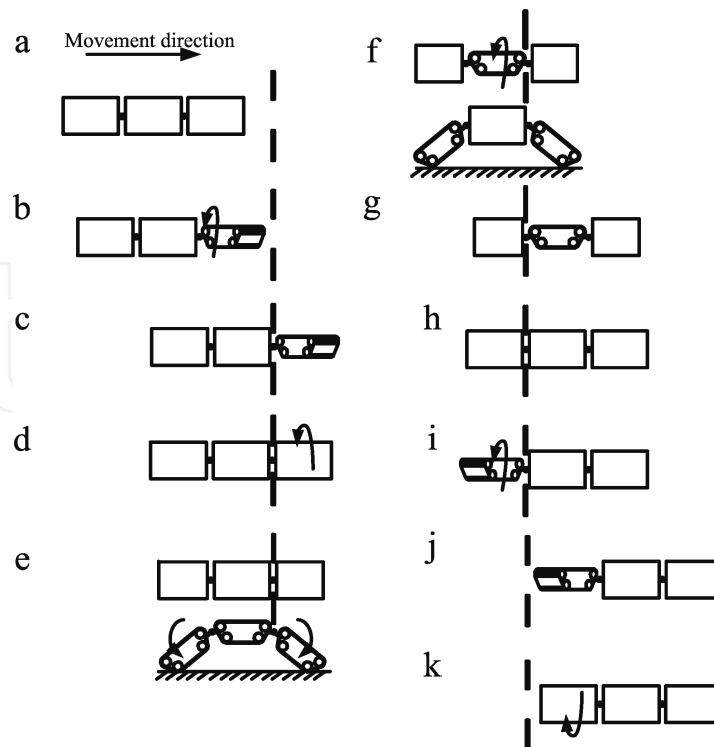

Fig. 10. The sequence of crossing a fence

(a) The robot is in its home state, and the sensor detects the fence in the moving direction.

(b) The robot stops before the fence, and then the first module pitches up around the Y axis and then rotates 90° according to the Z axis.

(c) The crossing movement does not stop until the first module passes through the fence.

(d) The first module rotates and pitches to get back into the home state, and then the three modules attach to the ground together again.

The following steps (e) to (k) of the second and third modules are similar to those of the first one. The process will be achieved until the robot crosses the fence entirely. In order to show the principle clearly, the lateral views of steps (e) and (f) are also given.

5. Kinematics analysis

5.1 The DOF of the active joint

To demonstrate the reconfiguring capability, the kinematics analysis of two connected modules should be studied. Fig. 11 shows the kinematics model of the joint between two modules. Where $OXYZ$ is the world coordinate fixed at the plane QEF which represents the front unmovable module during the reconfiguration. The origin is located at the universal joint O, the Z-axis coincides with the axis of the serial mechanism and the X-axis points to the middle point of line AB. Another reference coordinate $O'X'Y'Z'$ is fixed at triangular prism $OABPCD$ which represents the back moveable module. The $O'X'Y'Z'$ is coincident with the $OXYZ$ when the spherical joint is in its home state.

The required orientation for the reference frame $O'X'Y'Z'$ on the back module is achieved by a rotation of θ_z, a pitching angle θ_y and a yawing angle θ_x according to the relative axes. From the mechanical point of view, actually the pitching and yawing motions are implemented by the outstretching and returning movement of the L_1, L_2 of the parallel mechanism, and the rotation of θ_z is actuated by the serial mechanism. The freedom of the reconfiguring movement is three and can be described with the generalized coordinate θ (1). The joint variants of the movement are named q, described as (2).

$$\theta = [\theta_x, \theta_y, \theta_z]^T \tag{1}$$

$$q = [L_1, L_2, \theta_z]^T \tag{2}$$

According to the mechanical principle, the DOF can be concluded first, which will lay the foundation for later discussions. As shown in Fig. 11, there are altogether 8 joints, out of which 3 joints are active and actuated by respective DC motors. In this figure, there are three Hooker joints at points O, A, and B; two linear movement joints at links AC and BD; one rotating joint along the axis Z_1Z_2 and two spherical joints at C and D. According to (3), the DOF can be concluded. Where m means the DOF; n means the movable links of the active joint, there are seven links totally; g means the total number of the joints

Where f_i is the DOF of the relative joints. It is noted that the DOF of a rotating joint and a linear movement joint is one; the DOF of the Hooker joint is two while the spherical joint has three DOF. All these results are inserted into (3) to get the DOF.

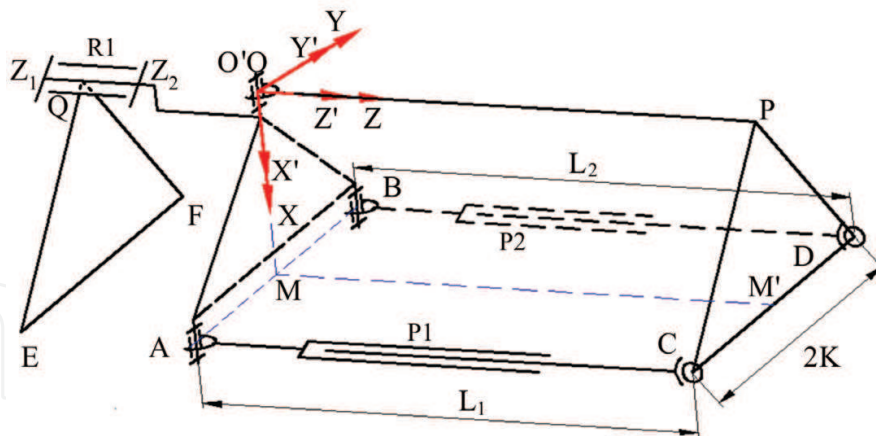$$m = 6(n - g - 1) + \sum_{i=1}^{g} f_i = 3 \tag{3}$$

Fig. 11 The kinematics mode of the active spherical joint.

5.2 Preliminary analysis of working space

The next question is the working space analysis in the world coordinate in order to implement all locomotion capabilities since there are three general DOFs. As discussed in the former section, the angle θ_z is required to have 360° rotation around the Z axis. It is noted that θ_z is an independent DOF actuated by the serial mechanism and it normally occurs after the pitching movement or yawing movement. So we only need to focus on the working spaces of θ_x and θ_y since both pitching and yawing movements are dependent on the extending or contacting cooperation of L_1 and L_2 in the parallel mechanism. All these are important for designing the system structure and the parallel mechanism.

For a general movement, the JL-I robot only needs to pitch up at a tiny angle in order to cross a low step or some small obstacles; it should also only yaw at a small angle to turn left or right during the movement. In practice the maximum positions should be calculated considering the mechanical constraints and collision avoidance.

Fig. 12 shows the analytic draft of the working space for the pitching movement, in which the collision and structure constants are taken into account. Here three rectangles represent the modules to simplify the discussion in the lateral view. The left module is fixed and the right one is moveable. Situation a_1 in black is the same home state as that shown in Fig. 9(h); b_1 in blue is the maximum pitching position taking the mechanical constraints into account in order to avoid collision, similarly as in Fig. 9(g).

From Fig. 12, the maximum pitching angle θ_{ymax} can be found as in (4).

$$\theta_{y\max} = 180 - 2arctg\frac{y}{l} \tag{4}$$

Where y is the half vertical height when the module stands on flat ground; l is the length of the equivalent connecting joint of JL-I; x is the half width of the largest rotating section. Taking the example parameters of the robot implemented in practice, i.e. y is 75 mm and l is 35 mm, finally the general working space of the pitching movement can be concluded to be

$$\theta_{y\max} = 50.0° \tag{5}$$

This result comes from the designing point of view. However, in order to implement a 90-180° recovering movement, the JL-I robot has to adopt a proper configuration sequence as

shown in the previous section. In Fig.12, c_1 in red is the minimum pitching position in order to implement the DOF of θ_z. This minimum angle limitation is nevertheless very important for the practical implementation of the robot's reconfiguration.
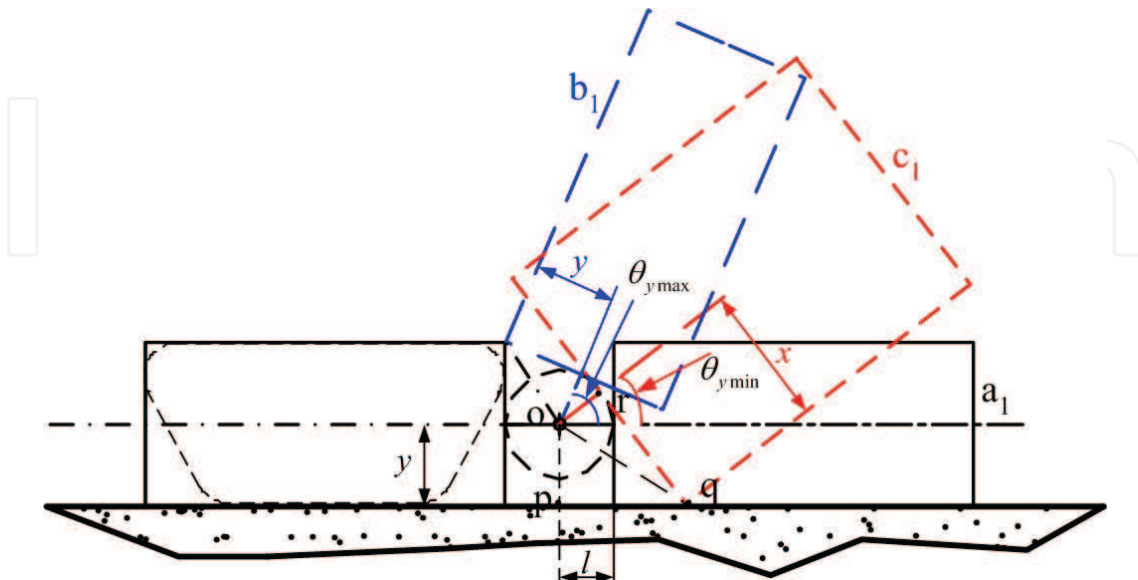

Fig. 12. The working space of the pitching movement.

Furthermore, as shown in Fig.9 (f), in order to actuate one module to rotate 90-180° around the Z axes of the active joints, it can only operate without any collision. The largest rotating section is illustrated in Fig. 13 in red, which is the same red rectangle in Fig. 12.
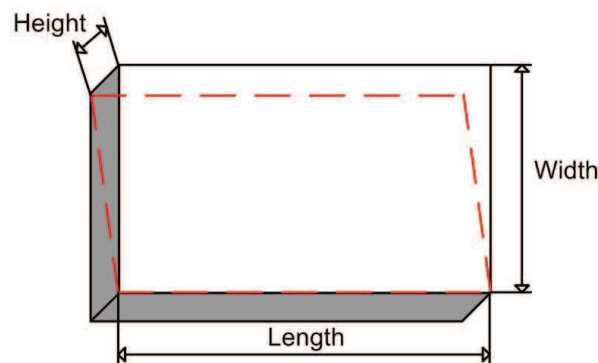
Fig. 13. The maximum rotating section during pitching movement.

Fig. 14 illustrates the analytic quadrangle of the robot working space of Fig. 12 at a large scale. According to the geometric analysis, we have

$$\begin{cases} \theta_1 = \arccos \dfrac{y}{\sqrt{l^2 + x^2}} \\ \theta_2 = \theta_3 = 90 - \theta_1 \\ \theta_4 = \arccos \dfrac{x}{\sqrt{l^2 + x^2}} \end{cases} \qquad (6)$$

$$\theta_{\min} = 90 - \theta_4 - \theta_3 = 90 - \theta_4 - (90 - \theta_1)$$

$$= \theta_1 - \theta_4 = \arccos\frac{y}{\sqrt{l^2 + x^2}} - \arccos\frac{x}{\sqrt{l^2 + x^2}} \tag{7}$$

$$\begin{cases} x = \sqrt{Height^2 + Width^2} \\ y = Height / 2 \end{cases} \tag{8}$$
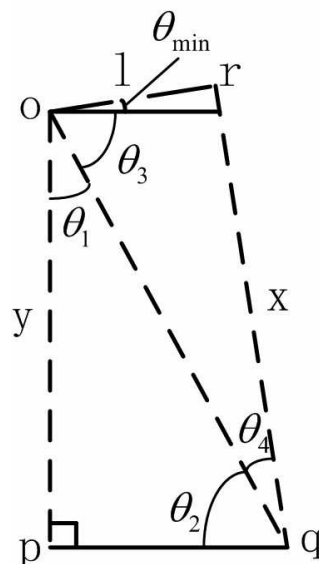

Fig. 14. The analytic quadrangle of the working space.

Given the height and width of the module, putting (8) into (7) we can get the minimum working space of the pitching DOF for robotic runtime reconfiguration in order to avoid collisions. Finally the working space for θ_y is as in (9).

$$\theta_y \in [-(180 - 2arctg\frac{y}{l}), -(\arccos\frac{y}{\sqrt{l^2 + x^2}} - \arccos\frac{x}{\sqrt{l^2 + x^2}})] \cup$$
$$+(\arccos\frac{y}{\sqrt{l^2 + x^2}} - \arccos\frac{x}{\sqrt{l^2 + x^2}}), +(180 - 2arctg\frac{y}{l})] \tag{9}$$

Similarly for the working space of the yawing movement, θ_x can be also described like θ_y (9) while y is the half width of the module at the moment. According to the prototype structure, the pitching and yawing working spaces are obtained. As in our implementation, when the module width is 250 mm, the height is 150 mm and l is 35 mm, the general working space is described in (10); while the restricted working space for avoiding collision is (11)

$$\begin{cases} \theta_x \in [-32.0°, +32°] \\ \theta_y \in [-50.0°, +50.0°] \end{cases} \tag{10}$$

$$\begin{cases} \theta_x \in [-32.0°, \quad -8.0°] \bigcup [+8.0°, \quad +32.0°] \\ \theta_y \in [-50.0°, \quad -24.0°] \bigcup [+24.0°, \quad +50.0°] \end{cases} \tag{11}$$

In order to simplify the mechanical structure, we can design the working space of θ_x, θ_y to be the same, e.g. both within -50 to 50 degrees, which not only reduces the implementation cost but also slightly increases redundancy for practical operation (Zhang, H.; et al. 2007).

6. On-site experiments

Relevant successful on-site experiments with the JL-I were carried out recently, confirming the principles described above and the robot's ability.

| (a) | (b) | (c) | (d) |
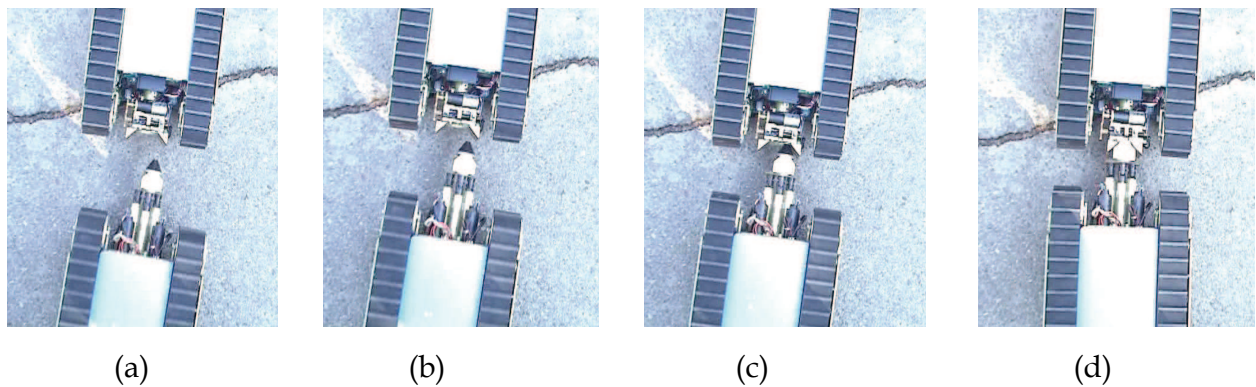
Fig. 15. The docking process

Fig. 15 shows the docking process of the connection mechanism whose most distinctive features are its ability of self aligning and its great driving force. With the help of the powered tracks, the cone-shaped connector and the matching coupler can match well within ±30mm lateral offsets and ±45°directional offsets.

Compared with many configurable mobile robots, the JL-I improves its flexibility and adaptability by using novel active spherical joints between modules. The following figures 16, 17, 18, 19 show the typical motion functionalities of the robot one by one, whose principles are discussed above.
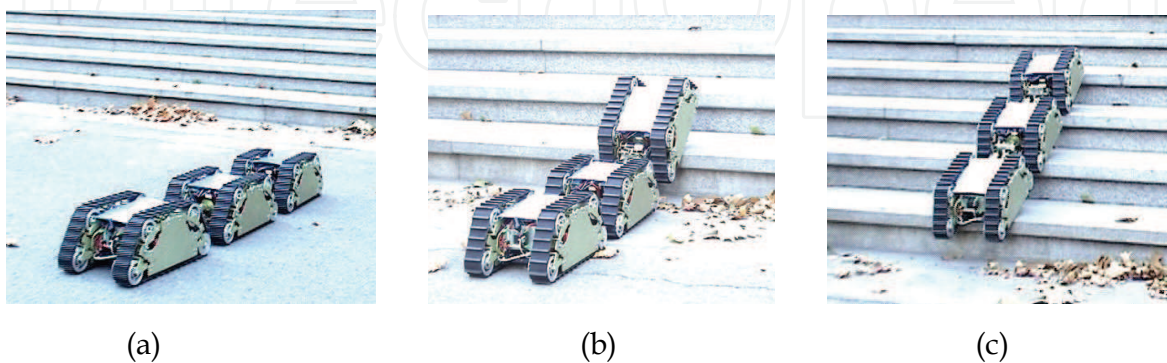

| (a) | (b) | (c) |

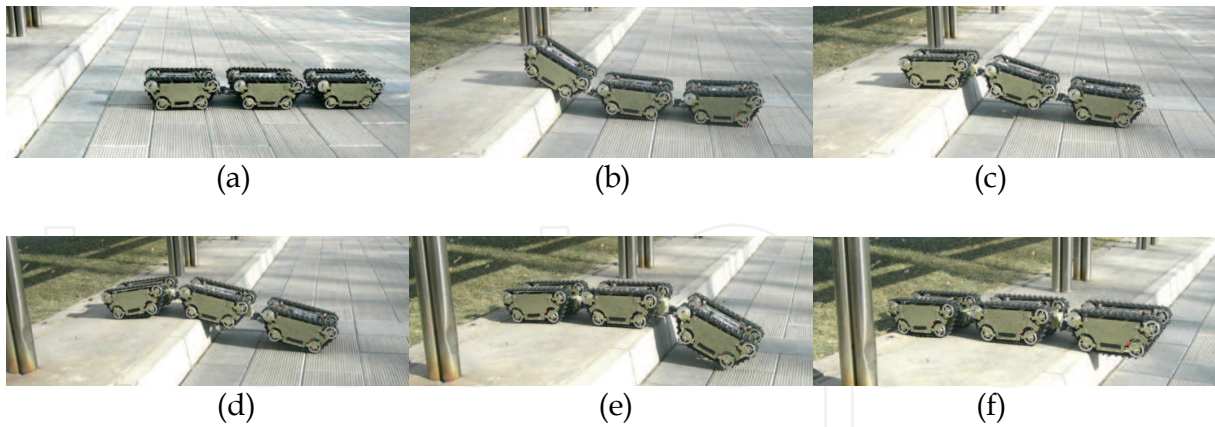Fig. 16. Climbing stairs

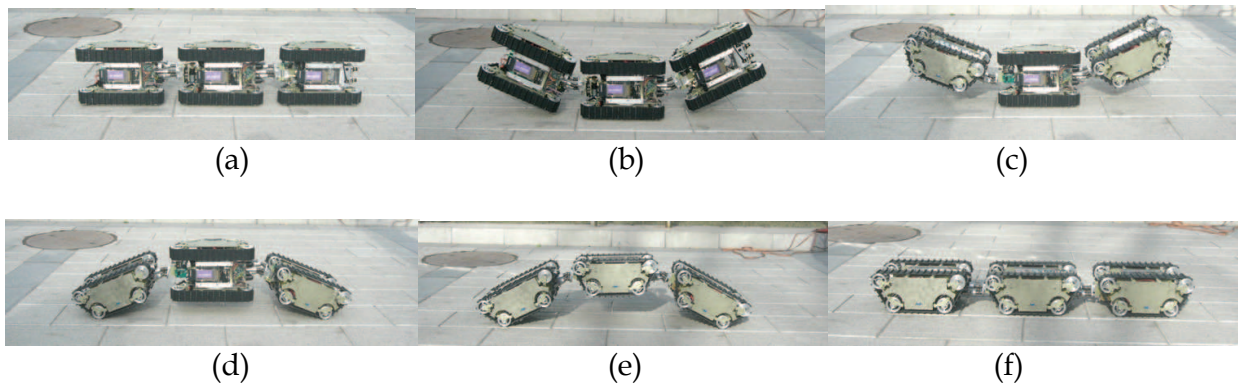Fig. 17. Snapshots of crossing a step
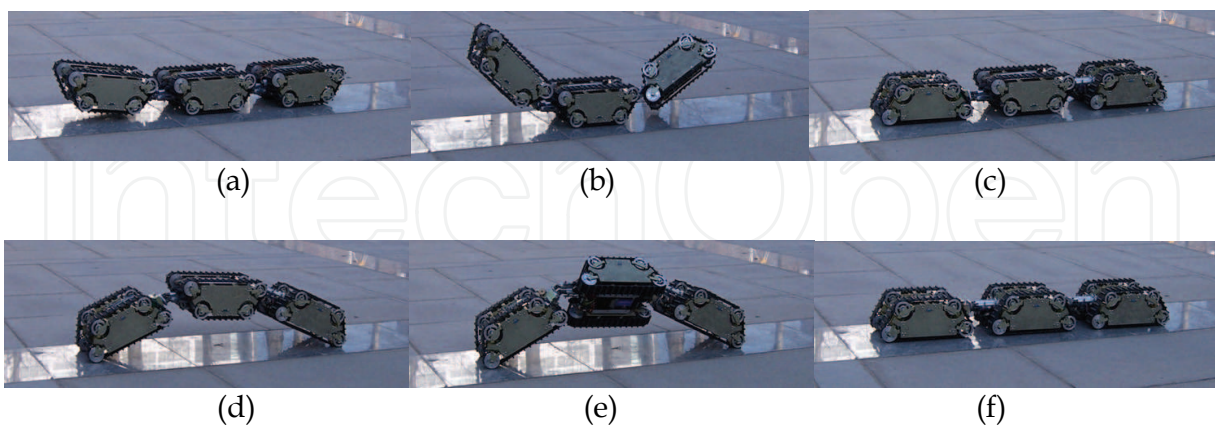

Fig. 18. Snapshots of the 90° self-recovery

Fig. 19. Snapshots of the 180° self-recovery

The experimental results show that the 3 DOF active joints with serial and parallel mechanisms have the ability to achieve all the desired configurations. The performance specifications of JL-I are given in Table 1.

Parameters	Values
Posture adjustment angle around X-axis	±45°
Posture adjustment angle around Y-axis	±45°
Posture adjustment angle around Z-axis	0~360°
Maximum lateral docking offset	±30 mm
Maximum directional docking offset	±45°
Maximum height of steps	280 mm
Maximum length of ditches	500 mm
Minimum width of the fence	200 mm
Maximum slope angle	40°
Self-recovering ability	0~180°
Maximum climbing velocity	180 mm/s
Maximum unchangeable working time	4 hours

Table 1. Performance specifications

8. Conclusions

In contrast to conventional theoretical research, the project introduced in this project successfully completes the following innovative work:

1. It proposes a robot named JL-I which is based on a module reconfiguration concept. The robot features a docking mechanism with which the modules can connect or disconnect flexibly. The active spherical joints formed by serial and parallel mechanisms endow the robot with the ability of changing shapes in three dimensions.

2. The DOF and working space of reconfiguration between two modules is given. Related experimental tests have shown that the JL-I can implement a series of various reconfigurations. This implies the mechanical feasibility, the rationality of the analysis and the outstanding movement adaptability of the robot.

Actually all of the locomotion capabilities are pre-programmed at the moment. In future, our research will focus on the realization of real autonomy. At the same time, the dynamic analysis of the movement functions is another important issue in this project.

9. Acknowledgement

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Service Robot Applications

Edited by Yoshihiko Takahashi

ISBN 978-953-7619-00-8

Hard cover, 400 pages

Publisher InTech

Published online 01, August, 2008

Published in print edition August, 2008

The aim of this book is to provide new ideas, original results and practical experiences regarding service robotics. This book provides only a small example of this research activity, but it covers a great deal of what has been done in the field recently. Furthermore, it works as a valuable resource for researchers interested in this field.

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