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A Reconfigurable Mobile Robots System Based on Parallel Mechanism

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1. Introduction

Reconfigurable robots consist of many modules which are able to change the way they are connected. As a result, these robots have the capability of adopting different configurations to match various tasks and suit complex environments. For mobile robots, the reconfiguration is a very powerful ability in some tasks which are difficult for a fixed-shape robot and during which robots have to confront unstructured environments (Granosik et al. 2005; Castano et al. 2000), e.g. navigation in rugged terrain. The basic requirement for this kind of robotic system is the extraordinary motion capabilities.

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. and Vona, M. 2000). One group of the reconfigurable robots featuring in interconnected joint modules realizes the locomotion by virtue of the structure transform performed by the cooperative movements and docking/undocking actions of the modules (Suzuki et al. 2007; Kamimura et al. 2005; Shen et al. 2002; Suzuki et al. 2006; Vassilvitskii et al. 2002). Because the modules in these robots are not able to move independently and the possible structures of the robot are limited, these kinds of robots are not suitable for the field tasks.

The other kind of reconfigurable robots being composed of independently movable modules is more suitable for the field environment. The first prototype (Hirose et al. 1990) with powered wheels was designed by Hirose and Morishima in 1990, which consists several vertical cylindrical segments. The robot looks like a train, however with a weight over 300 kg it is too heavy. Klaassen developed a mobile robot with six active segments and a head for the inspection of sewage pipes (Klaassen et al. 1999). There are twelve wheels on each module to provide the driving force. Mark Yim proposed another reconfigurable robot PolyBot which is able to optimize the way its parts are connected to fit the specific task (Yim et al. 2000). PolyBot adopts its shape to become a rolling type for passing over flat terrain, an earthworm type to move in a narrow space and a spider type to stride over uncertain hilly terrain.

The application of powered tracks to field robots enriches their configurations and improves the adaptability to the environments. 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 et al., 2000). The special ability of adapting to irregular terrain is passive and provided by springs. The OmniTread serpentine robot (Granosik et al. 2005) for industrial inspection and surveillance was developed by Grzegorz Granosik in 2004. Optimal active joints are actuated by pneumatic cylinders in order to compromise the strength and compliance. However, the known robots usually have few configurations due to relatively simple docking and pose-adjusting mechanisms. For example, the Millibot Train robot consists of seven compact segments, which can connect by couplers with one DOF (Brown et al. 2002). A reconfigurable mobile robot designed by M. Park is not able to change its configuration actively at all (Park et al. 2004). The robot from Université Libre de Bruxelles has a one-DOF pose-adjusting mechanism and one coupler to change the configuration between the neighboring modules as well (Sahin et al. 2002).

From the mechanical point of view, the reconfiguration mechanism applied to mobile robot is composed of the posture-adjusting and connecting mechanism, and the most important technology is how to construct a posture-adjusting mechanism with large workspace and high driving ability in a limited robot body. However, in complex field terrain, the fact that the existing reconfigurable mobile robots can only assume limited configurations due to relatively simple posture-adjusting is a ubiquitous deficiency.

The project presented in this chapter aims at developing a reconfigurable mobile multi-robot platform made highly flexible and robust by its three-DOF posture-adjusting ability. The key object of the project is to develop a new posture-adjusting mechanism featuring in compact structure, large workspace and powerful driving ability. As a secondary object, the project has developed an effective connecting mechanism aligned to flat terrain and synthesized it with the posture-adjusting mechanism. The locomotion abilities of the system are expected to be as follows.

1. The single robots in the system have an independent omni-directional locomotion ability equivalent to that of a normal outdoor mobile robot.
2. Due to the posture-adjusting mechanism, which enables the robots to drive very well and to operate in a large workspace, the robots can adjust the posture of their partners.
3. The connecting mechanism tolerating large posture deviation in flat terrain can link two robots in a locked connection and transit large forces and torques between them.
4. Compared with a single robot, the connected robots are able to perform more demanding locomotion activities, such as stepping over high obstacles, crossing wide grooves, passing through narrow barriers and self-recovering from invalid postures and other actions which are impossible for a single robot.

To reach the above targets, a novel reconfigurable mobile robot system JL-1 based on a serial and parallel active spherical mechanism and a conic self-aligning connecting mechanism has been developed. This system is composed of three robot modules which are able to not only move independently, but also to connect to form a chain-structured group capable of reconfiguration. On flat terrain, each module of JL-1 can corporate with each other by exchanging information to keep up its high efficiency; while on rugged terrain, the modules can actively adopt a reconfigurable chain structure to cope with the cragged landforms which will be a nightmare for a single robot (Zhang et al. 2006; Wang et al. 2006).

In the chapter, after giving an overview of JL-1, the discussion focuses on some special locomotion capabilities of it. Then the related kinematics analysis of the serial and parallel
mechanism is discussed thoroughly as well as the theory of the connecting mechanism. Based on the discussion, the mechanical realization of JL-1 is introduced in detail. The prototype shows the advantage of the parallel mechanism in realizing powerful driving force in a relative small size. In the end, a series of successful on-site tests, such as crossing high vertical obstacles, connecting action and getting self-recovery when the robot is upside-down, is presented to confirm the above principles and the locomotion abilities of JL-1.

2. Overview of the reconfigurable JL-1

2.1 Mechanical model of JL-1

By virtue of three uniform modules being capable of docking with each other, JL-1 has various moving modes which enable JL-1 to move in almost all kinds of rough terrains. The principle of terrain adaptability is shown in Fig. 1. In connected state, JL-1 can change its posture by pitching around the Y axis, yawing around the X axis and rotating around the Z axis. JL-1 is endowed with the abilities of adopting optimized configurations to negotiate difficult terrains or splitting into several small units to perform tasks simultaneously, by the three DOF active spherical joints between the modules and the docking mechanism being capable of self-aligning within certain lateral and directional offsets. In JL-1, the yawing and pitching movements are achieved by a parallel mechanism. The third rotation DOF around the joint’s Z axis is achieved by a serial mechanism. There are two reasons for using the serial and parallel mechanisms for JL-1. 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 and the extended workspace of a serial mechanism can be combined, thus improving the flexibility of the robotic system.

2.2 Locomotion capabilities

It can be easily imagined that the locomotion abilities of JL-1 will be enhanced when it is in connected state, such as climbing up higher steps, spanning wider ditch and stepping up stairs. Furthermore, JL-1 is capable of some novel actions, which will be required in outdoor environment, e.g. self-recovery and passing through a narrow fence.
2.2.1 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. 2.

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.

Fig. 2. 90° recovering movement

2.2.2 180° Self-recovery
It is also possible for the robot to tip over and realize the 180° recovery movement as shown in Fig. 3.

Fig. 3. 180° recovering movement
2.2.3 Crossing a narrow fence

As shown in Fig. 4, the train configuration robot is able to cross a fence narrower than the width of its modules.

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.

Fig. 4. The sequence of crossing a narrow fence
3. Kinematics analysis of the active spherical joint

As described above, the robot’s reconfiguring abilities are achieved by the motion of the 3 DOF active spherical joints. Two of the DOF achieved by the parallel mechanism are yawing and pitching around the joint’s X and Y axes respectively. The third rotation DOF around the joint’s Z axis is achieved by the serial mechanism.

![Kinematics model of the active spherical joint](image_url)

To demonstrate the reconfiguring possibility, the kinematics analysis of two connected modules should be studied first. Fig. 5 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. Equations (1) and (2) are satisfied due to the mechanical constraints. QF is perpendicular and equal to QE.

\[ QEF // OAB // PCD \]  
\[ QEF = OAB = PCD \]

The required orientation for the reference frame O’X’Y’Z’ on the back module is achieved by a rotation of \( \theta_x \), a pitching angle \( \theta_y \) and a yawing angle \( \theta_z \) according to the relative axes. From the mechanical point of view, actually the pitching and yawing motions are realized by the outstretching and returning movement of the \( L_1, L_2 \) of the parallel mechanism, and the rotation of \( \theta_z \) is actuated by the serial mechanism. The freedom of the reconfiguring movement is three and can be described with the generalized coordinate \( \boldsymbol{\theta} \) (3). The joint variants of the movement are named \( \boldsymbol{q} \), described as (4).

\[ \boldsymbol{\theta} = [\theta_x, \theta_y, \theta_z]^T \]  
\[ \boldsymbol{q} = [L_1, L_2, \theta_z]^T \]

The purpose of the kinematics analysis is to deduce the relationship between \( \boldsymbol{q} \) and \( \boldsymbol{\theta} \). In Fig. 10, the points A, B, C, D are described as (5) in the OXYZ coordinate.

\[ A = \begin{bmatrix} K & -K \\ 0 & K \end{bmatrix} \quad B = \begin{bmatrix} K \\ K \end{bmatrix} \quad C = \begin{bmatrix} K \\ -K \end{bmatrix} \quad D = \begin{bmatrix} K \\ K \end{bmatrix} \]

(5)
The homogeneous transformation matrix $[T]$ from the world coordinate $OXYZ$ to the coordinate $O'X'Y'Z'$ is described as (6).

$$T = \text{Rot}(Y)\text{Rot}(X)\text{Rot}(Z) = \begin{bmatrix}
  c\theta_y & 0 & s\theta_y \\
  0 & 1 & 0 \\
  -s\theta_y & 0 & c\theta_y
\end{bmatrix} \begin{bmatrix}
  1 & 0 & 0 \\
  0 & c\theta_x & -s\theta_x \\
  0 & s\theta_x & c\theta_x
\end{bmatrix} \begin{bmatrix}
  c\theta_z & -s\theta_z & 0 \\
  s\theta_z & c\theta_z & 0 \\
  0 & 0 & 1
\end{bmatrix}$$  

(6)

After the reconfiguring movement, $A$, $B$, $C$, and $D$ are changed to new positions described as $A_1$, $B_1$, $C_1$, and $D_1$. The Cartesian coordinates of the new points can be expressed as (7) and (8).

$$[A_1 \quad B_1] = \text{Rot}(Z)[A \quad B]$$  

(7)

$$[C_1 \quad D_1] = [T][C \quad D]$$  

(8)

There are some constraints to the mechanical structure, as shown in (9) and (10). The lengths of the link $L_1$ and $L_2$ are equal to the distance between $C_1A_1$ and $D_1B_1$ respectively.

$$L_1 = C_1 - A_1$$  

(9)

$$L_2 = D_1 - B_1$$  

(10)

All these results are inserted into (9) and (10), then the kinematics expression results from them.

$$L_1^2 = (K(c\theta_c c\theta_z + s\theta_s s\theta_c s\theta_z) -$$

$$K(-s\theta_s c\theta_y + s\theta_s s\theta_c c\theta_y) +$$

$$Lc\theta_z s\theta_y - Kc\theta_z + Ks\theta_y)^2 +$$

$$(K(c\theta_x s\theta_z) - K(c\theta_x c\theta_y) - Ls\theta_z + Ks\theta_y + Kc\theta_y)^2$$

$$+ (K(-s\theta_z c\theta_z + s\theta_z s\theta_c s\theta_z) -$$

$$K(s\theta_y s\theta_z + s\theta_z c\theta_y c\theta_z) + Lc\theta_z c\theta_y)^2$$

(11)

$$L_2^2 = (K(c\theta_x c\theta_z + s\theta_z s\theta_c s\theta_z) +$$

$$K(-s\theta_z c\theta_y + s\theta_z s\theta_c c\theta_y) +$$

$$Lc\theta_z s\theta_y - Kc\theta_z + Ks\theta_y)^2 +$$

$$(K(c\theta_y s\theta_z) + K(c\theta_y c\theta_y) - Ls\theta_z + Ks\theta_y - Kc\theta_y)^2$$

$$+ (K(-s\theta_z c\theta_z + s\theta_z s\theta_c s\theta_z) +$$

$$K(s\theta_y s\theta_z + s\theta_z c\theta_y c\theta_z) + Lc\theta_z c\theta_y)^2$$

(12)

Named $T_{11}=L_1^{1/2}$, $T_{12}=L_2^{1/2}$, then the relation between $q$ and $\theta$ can be concluded as (13).

$$q = [T_{11}^{1/2}, T_{12}^{1/2}, \theta_2]^{\top}$$  

(13)

The relationship of the world coordinate and the reference joint coordinate can be concluded. Furthermore the movements can be anticipated according to the joints’ driving outputs.
4. System realization

4.1 Mechanical realization

The JL-I system consists of three connected, identical modules for crossing grooves, steps, obstacles and traveling in complex environment. The mechanical structure is flexible due to its uniform modules and special connection joints (Fig. 6a). Actually each module is an entire robot system that can perform distributed activities (Fig. 6b).

Fig. 6. The robotics system of JL-I

Fig. 7. An artistic impression of the module
The single module is about 35 centimeters long, 25 centimeters wide and 15 centimeters high. Fig. 7 shows the mechanical structure of the module which has 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 the flexible omni-directional movement. The docking mechanism consists of two parts: a cone-shaped connector at the front and a matching coupler at the back of the module. It enables any two adjacent modules to link, forming a train configuration.

4.1.1 Realizing the parallel mechanism
The realization of the parallel mechanism is also shown in Fig. 8. Each branch of it consists of a driving platform, a Hooker joint, a lead screw, a nut slider, a ball bearing, a synchronous belt system, a DC motor and a base platform. The Hooker joint connects the driving platform and the nut slider. The lead screw is supported by a ball bearing in the base platform. The cone-shaped connector fixed on the driving platform is called a buffer head, because its rubber is used to buffer the wallop during the docking process. Besides the two branches, there is a knighthead fixed on the base platform and connected to the driving platform by another Hooker joint. By revolving the two lead screws, the driving platform can be manipulated relative to the Hooker joint on the knighthead.

Fig. 8 The parallel mechanism

There are two advantages in applying the synchronous belt system.

a) When the screw revolves, it rocks around the ball bearing. By using the synchronous belt system and an elastic connector, the rock motion of the screw is isolated from the motor.

b) The motor and the lead screw can be installed on the same side of the base platform, and that decreases the dimension of the structure.

4.1.2 Realizing the serial and docking mechanism
The docking mechanism consists of two parts: a cone-shaped connector at the front (shown in Fig. 8) and a matching coupler at the back of the module, as shown in Fig. 9. 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 configuration. Therefore the independent module has to be rather long in order to realize all necessary docking functions. In designing this mechanism and its controls, the equilibrium between flexibility and size has to be reached. A DC motor is connected to the coupler with its motor shaft aligned with the module’s Z axis, which also passes through the center of the Hooker joint on the knighthead of the parallel mechanism. Therefore a full active spherical joint is formed when two modules are linked.

Fig. 9. The serial and docking mechanism

This docking mechanism can compensate a position deviation within ±30mm and a posture deviation within ±45° between two modules. The self-locking characteristic of the screw-nut mechanism ensures a reliable connection between two modules to endure the vibration in motion.

4.2 Control system

The control system of the robot based on an industrial PC (IPC) and a master-slave structure meets the requirements of functionality, extensibility, and easy handling (Fig. 10). Multiple processes programming capability is guaranteed by the principle of the control structure. The hardware consists of an SBC-X255, an independent image processing unit and a low-level driving unit (SBC 2).

The SBC-X255 is the core part of the control system. It is a standard PC/104+ compliant, single-board computer with an embedded low power Intel Xscale PXA255 (400 MHz). This board operates without a fan at temperatures from -40° C up to 85° C and typically consumes fewer than 4.5 Watts while supporting numerous peripherals. The Ethernet port is used as a communication interface between the IPC and the image processing unit which is in charge of searching and monitoring. The IPC is a higher-level controller and does not take part in joint motion control. Its responsibilities include receiving orders from the remote controller, planning operational processes, receiving feedback information.

The SBC 2 is in charge of driving five DC motors and receives and processes all related sensor signals. It can directly count the pulse signals from the encoder, deal with the signals
from other magnetic sensors, and directly drive the DC motors forward and backward at different velocities. Meanwhile it sends all information to the IPC through another Ethernet port.

![Diagram of JL-1's module control system](image)

Fig. 10. The control system of JL-1’s module

There are two kinds of external sensors on the robot: a CCD camera and touchable sensors, which are responsible for collecting information about the operational environment. The internal sensors such as GPS, digital compass, gyro sensors are used to reflect the self-status of the robot. The gesture sensor will send the global locomotion information of the robot $\theta_x$, $\theta_y$, and $\theta_z$ to the controller, which are essential to inverse kinematics. Meanwhile there are limit switches to give the controller the position of the joint. On the joint where the accurate position is needed, the optical encoder is used.

5. On-site tests

Relevant successful on-site tests with the mobile robot were carried out recently, confirming the principles described above and the robot’s ability. Fig. 11 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 $\pm 30$ mm lateral offsets and $\pm 45^\circ$ 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 show the typical motion functionalities one by one, whose principles are discussed above.

Fig. 12. Climbing stairs

Fig. 13. Snapshots of crossing a step

Fig. 14. Snapshots of the 90° 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.

Table 1. Performance specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Posture adjustment angle around X-axis</td>
<td>±45°</td>
</tr>
<tr>
<td>Posture adjustment angle around Y-axis</td>
<td>±45°</td>
</tr>
<tr>
<td>Posture adjustment angle around Z-axis</td>
<td>0~360°</td>
</tr>
<tr>
<td>Maximum lateral docking offset</td>
<td>±30 mm</td>
</tr>
<tr>
<td>Maximum directional docking offset</td>
<td>±45°</td>
</tr>
<tr>
<td>Maximum height of steps</td>
<td>280 mm</td>
</tr>
<tr>
<td>Maximum length of ditches</td>
<td>500 mm</td>
</tr>
<tr>
<td>Minimum width of the fence</td>
<td>200 mm</td>
</tr>
<tr>
<td>Maximum slope angle</td>
<td>40°</td>
</tr>
<tr>
<td>Self-recovering ability</td>
<td>0~180°</td>
</tr>
<tr>
<td>Maximum climbing velocity</td>
<td>180 mm/s</td>
</tr>
<tr>
<td>Maximum unchangable working time</td>
<td>4 hours</td>
</tr>
</tbody>
</table>
6. Conclusions

The modular reconfiguration robot has the ability of changing its configuration which makes it more suitable for complex environments. In contrast to conventional theoretical research, the project introduced in this paper successfully completes the following innovative work.

a) It proposes a robot named JL-I which is based on a modular reconfiguration concept. The advantages and the characteristics of the mechanism are analysed. 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.

b) A kinematics model of reconfiguration between two modules is given. The relationship of the world coordinate and the reference joint coordinate is concluded. Furthermore, the movements can be anticipated according to the joints’ driving outputs. The analysed results are important for system design and the design of the controlling mechanism for the robot.

c) Experimental tests have shown that the JL-I can implement a series of various locomotion capabilities such as 90° recovery, 180° recovery, and crossing steps. This implies the mechanical feasibility, the rationality of the analysis and the outstanding movement adaptability of the robot.

The future research will focus on the following aspects.

a) Developing a new docking mechanism which tolerates larger offset in rugged terrain and can be used as a simple manipulator;

b) Developing a more reliable track modules with shock absorption function;

c) Developing a new mechanism which can actively undock a disable robot module.

7. Acknowledgement

The work in this chapter is proposed by National High-tech R&D Program (863 Program) of China (No. 2006AA04Z241).

8. Reference


In recent years, parallel kinematics mechanisms have attracted a lot of attention from the academic and industrial communities due to potential applications not only as robot manipulators but also as machine tools. Generally, the criteria used to compare the performance of traditional serial robots and parallel robots are the workspace, the ratio between the payload and the robot mass, accuracy, and dynamic behaviour. In addition to the reduced coupling effect between joints, parallel robots bring the benefits of much higher payload-robot mass ratios, superior accuracy and greater stiffness; qualities which lead to better dynamic performance. The main drawback with parallel robots is the relatively small workspace. A great deal of research on parallel robots has been carried out worldwide, and a large number of parallel mechanism systems have been built for various applications, such as remote handling, machine tools, medical robots, simulators, micro-robots, and humanoid robots. This book opens a window to exceptional research and development work on parallel mechanisms contributed by authors from around the world. Through this window the reader can get a good view of current parallel robot research and applications.

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