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Docking Manipulator for a Reconfigurable Mobile Robot System

Wei Wang, Houxiang Zhang, Wenpeng Yu, Jianwei Zhang

***Abstract*—JL-2, as a new version of the JL reconfigurable mobile robot system, features not only a docking and 3D posture adjusting capability between its robots, but also a multi-functional docking gripper. The basic concept of JL is that the robots in the system can simultaneously perform basic tasks in flat terrains, and in the case of rugged terrains, the robots can interconnect to enhance their locomotion capabilities. This paper introduces new designs for JL-2 by which the docking mechanism can be used as a simple gripper with 3 DOFs. Then the technologies of the docking mechanism are discussed in detail, including the workspace of the docking gripper, the docking procedure and analyses of the self-aligning ability. Then the workspaces of the posture adjusting mechanisms between two docked robots are analyzed to clarify the reconfiguration ability of JL-2. At last, a series of real experiments are proposed to test the designs and analyses and the basic performance of JL-2.**

I. INTRODUCTION

Self-reconfiguration technology is expected to be one of the key answers to the question of how to combine flexibility, robustness, ability to self-repair and all-terrain navigation in one mobile robot system [1], which will serve for applications like space explorations [2], rescue [3] or civil exploration [4]. From the mechanical point of view, the docking mechanism and posture adjusting mechanism are two main aspects of the self-reconfiguration technology [5] which play different roles in various reconfigurable robotic systems.

For modular reconfigurable robots, the docking mechanism is indispensable to construct a movable configuration, since one module of such robots, which has only 1 or 2 actuated joints, possesses limited or no navigation ability in the field. When the modules interconnect, their postures are adjustable by virtue of the modules' joints, therefore no special posture adjusting mechanisms are needed [6][7][8].

Another kind of reconfigurable robot, which is also the research interest of this paper, is composed of independent mobile robots integrated with docking and posture adjusting mechanisms [9]. In these systems, each robot is mobile with full navigation ability. The reconfiguration technology is just an assistant tool to enhance the robot's adaptability to rugged terrains. For example, the following two typical reconfigurable mobile robot systems, the Millibot [10] and SWARM-Bot [11], are all composed of mobile units with powered tracks or wheels, which can navigate simultaneously in flat terrains. When the robots try to pass through rugged terrains, they will actively interconnect to form a chain structure, thus enhancing their mobility. Most existing reconfigurable mobile robots suffer the limited DOFs of the posture adjusting mechanism as well as the strict docking conditions. Because of their simple docking mechanism, Millibot and SWARM-Bot can only perform docking actions in flat terrains. When docked, the Millibot robots can only lift or lower each other, but the rotation and yawing are not possible for them. With SWARM-BOT, the situation is similar, except that the distance between two docked robots can be adjusted by the reconfiguration mechanism.

JL-1 is a reconfigurable mobile robot system in which the robots can dock or undock, as well as actively adjust each other's posture in 3 dimensions [12]. It is highly adaptable to rugged terrains by virtue of its powerful serial and parallel posture adjusting mechanism. However, it can only complete the docking action in flat terrains because of its simple cone-shaped docking mechanism [13]. Another shortcoming of JL-1 is that it cannot manipulate any objects.

In this paper, JL-2, a new version of the JL system, is developed to improve the performance in two aspects.

- The docking ability tolerating the aligning errors in five dimensions;
- A docking manipulator integrating the docking mechanism and manipulability.

This paper focuses on the new mechanical design and performance of JL-2 and is organized as follows. Section two describes the new designs in detail. Then the grasping and docking abilities of JL-2 are analyzed in section three. Section four discusses the possible workspace of the posture adjusting

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W. Wang works with the Robotics Institute, School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, 37 Xueyuan Road, 100083, Beijing, China. He is currently a guest researcher at the Dept of Informatics, University of Hamburg, Germany (as the corresponding author, e-mail: wangweilab@buaa.edu.cn, wang@informatik.uni-hamburg.de).

H. X. Zhang works with the Institute of Technical Aspects of Multimodal Systems, Department of Computer Science, University of Hamburg, Vogt-Koelln-Strasse 30, 22527, Hamburg, Germany (e-mail: hzhang@informatik.uni-hamburg.de, hxzhang@ieee.org).

W. P. Yu works with the Robotics Institute, School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, 37 Xueyuan Road, 100083, Beijing, China. (e-mail: w_p_yu@163.com).

J. W. Zhang works with the Institute of Technical Aspects of Multimodal Systems, Department of Computer Science, University of Hamburg, Hamburg, Germany(e-mail: zhang@informatik.uni-hamburg.de).

mechanism, which represents the adaptability of JL-2 to rugged terrains in the docked state. To demonstrate the analyses above, a series of tests are presented in section five. At last, the conclusions are summarized.

II. New Designs in JL-2

A. Overview of JL-2

Just like JL-1, JL-2 is composed of three independent robots with full navigation abilities in the field. These robots are called the Back Robot, the Middle Robot, and the Front Robot respectively. If the robots connect with each other by the docking mechanism, they will form a chain structure in which one robot is able to actively adjust the posture of the adjacent one in 3 dimensions, namely pitching, yawing and rotating.

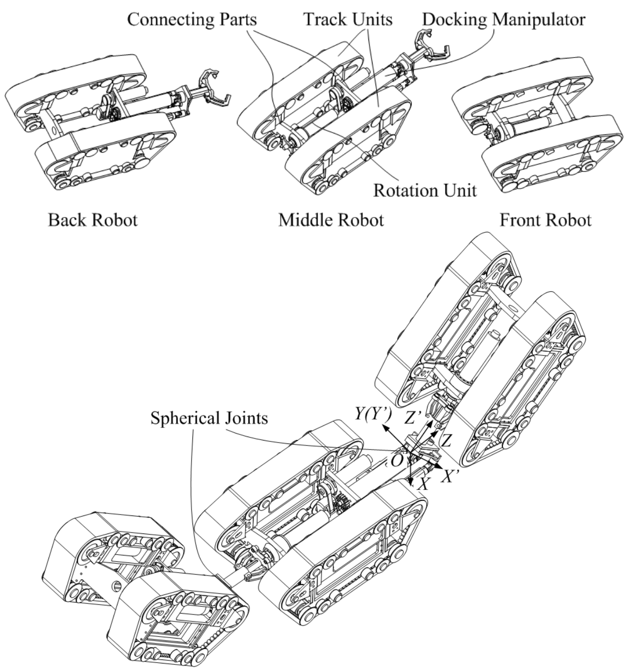


Fig. 1 Mechanical structures of the robots in JL-2

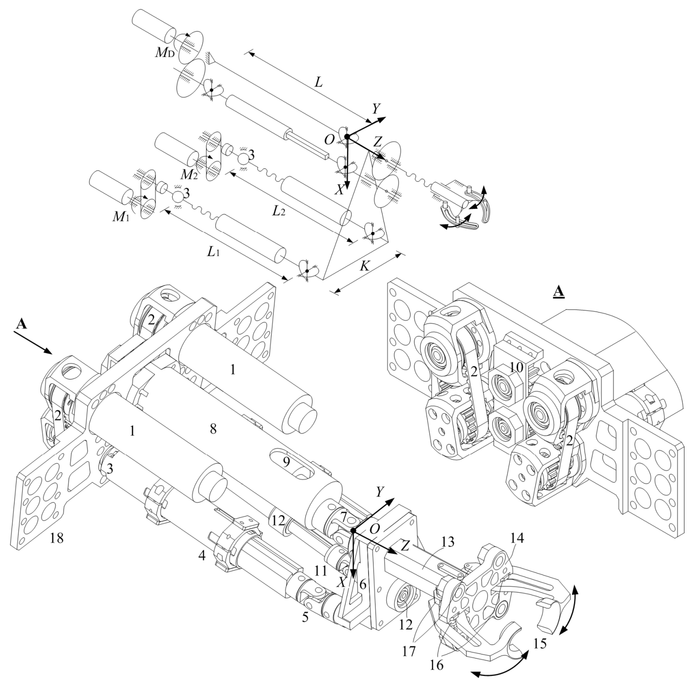
Fig. 1 shows the mechanical structures of the three robots in JL-2. One robot in JL-2 may consist of three types of units: two track units, a rotation unit and a docking manipulator, which can be assembled by two connecting parts. In fact, for economical reasons only the Middle Robot contains all of these units. Though it is ideal to construct all of the robots with a uniform structure, currently a simplified version is sufficient for testing the basic functions of JL-2.

B. Docking Manipulator and Rotation Unit

The docking manipulator and the rotation unit, which enable JL-2 to perform the docking/undocking action, grasping tasks, and posture adjusting functions when docked, are the new designs distinguishing JL-2 from JL-1 and other reconfigurable mobile robot systems.

It has already been proven that the serial and parallel mechanism in JL-1 is compact and efficient enough to form a motorized spherical joint [13]. Therefore, this design is inherited by JL-2, which means a parallel mechanism will be installed on one robot to drive the yawing and pitching motions (around X and Y axes respectively in Fig. 1), while a rotation unit on another robot will drive the rotation motion (around Z axis in Fig. 1). To enable grasping and robust docking, these two mechanisms are improved in JL-2.

A gripper is integrated at the end of the parallel mechanism to form a docking manipulator, as shown in Fig. 2.



1.Manipulator motors 2.Synchronal belts 3.Ball bearings 4.Ball screws 5.Hooker joints 6.Gripper base 7.Main hooker joint 8.Supporting pole 9.Docking motor 10.Gears 11.Hooker joints 12.Sliding key 13.Docking screw 14.Docking base 15.Cam fingers 16.Guiding pins 17.Gripper shafts 18.Connecting part-1

Fig. 2 Diagram of docking manipulator

The docking manipulator is installed on connecting part-1, making the manipulator part of one robot. A supporting pole inserted into connecting part-1 supports the gripper base through the main hooker joint, which permits the gripper to yaw and pitch around the X and Y axes. These two turning motions are driven by two parallel ball screw sub-units, each of them connected with the gripper base by a hooker joint and supported on connecting part-1 by a ball bearing. Two manipulator motors, whose rating output torques are M_1 and M_2 and all equal to 4.5 Nm, will drive the ball screws through the synchronal belts. If the parallel motors run, the lengths of the ball screws,

L_1 and L_2, will change, which will cause the yawing and pitching motion of the gripper. Equations (1) and (2) show the relations between L_1, L_2 and the yawing and pitching angles θ_x, θ_y.

$$\boldsymbol{L}_1 = (\boldsymbol{L}^2 + 4\boldsymbol{K}^2 + 2\boldsymbol{KL}\mathrm{s}\theta_y + -2\boldsymbol{K}^2\mathrm{c}\theta_x - 2\boldsymbol{K}^2\mathrm{c}\theta_y + 2\boldsymbol{KL}\mathrm{s}\theta_x\mathrm{c}\theta_y + 2\boldsymbol{K}^2\mathrm{s}\theta_x\mathrm{s}\theta_y)^{1/2} \quad (1)$$

$$\boldsymbol{L}_2 = (\boldsymbol{L}^2 + 4\boldsymbol{K}^2 + 2\boldsymbol{KL}\mathrm{s}\theta_y - 2\boldsymbol{K}^2\mathrm{c}\theta_x - 2\boldsymbol{K}^2\mathrm{c}\theta_y - 2\boldsymbol{KL}\mathrm{s}\theta_x\mathrm{c}\theta_y - 2\boldsymbol{K}^2\mathrm{s}\theta_x\mathrm{s}\theta_y)^{1/2} \quad (2)$$

Where,

L is the distance between the main hooker joint and the center of the ball bearing along the Z axis;

K is the distance between the two hooker joints supporting the ball screws;

s and *c* are the abbreviations of *sin* and *cos* respectively.

We have already constructed a parallel mechanism which features a compact structure as well as powerful output torques M_x and M_y, whose values are 20.5 Nm and 24.5 Nm respectively, to drive one robot to turn around *X* and *Y* axes.

Two problems should be taken into consideration when a docking mechanism is designed. One is how to compensate the possible position and orientation errors between two robots. The other is how to realize a solid connection to bear those loads which are normally introduced by the weight of the robots in six dimensions.

In addition to the parallel mechanism, a docking gripper is also integrated on this 2-DOF manipulator to resolve the above problems. Two advantages result from installing the docking gripper at the end of the parallel mechanism. The one is that the gripper now features 2 DOFs in a spherical workspace. The other is that the docking process now tolerates more aligning errors between two robots.

A cam guidance principle and a gear-screw mechanism are applied in the gripper to realize gradual aligning, as well as aligning with high contact forces between two robots during and after the docking procedure. In Fig. 2, two guiding pins are embedded in the cam grooves of the gripper's fingers. When the docking base is driven forward or backward by the docking screw, it will further drive two fingers to revolve around two gripper shafts, and further close or open the gripper by virtue of the guiding pins. The shapes of the cam groove and the fingers are deliberately designed to permit a gradual aligning procedure, which will be analyzed in the next section. The docking screw is driven by a docking motor through two pairs of gears, a sliding key, and two hooker joints. The function of the sliding key and hooker joints is to adapt to the relative motion between the gripper base and connecting part-1. To save space, the docking motor is embodied in the supporting pole.

Fig. 3 shows the rotation unit and the details of the docking base. A docking disk is installed on the shaft of the rotation motor which is responsible for driving the rotation around the *Z* axis after docked, as well as diminishing the angular error around the *Z* axis between two robots when docking. The main cone and the four sub-cones on the docking disk will fit the main hole and the four sub-holes in the docking base respectively. The function of the main cone and hole is to guarantee the final aligning, and that of the sub-cones and holes is to overcome the rotation load around the *Z* axis when docked. Two sides of the docking disk are designed in a curve shape to permit the gripper to encompass the disk easily.

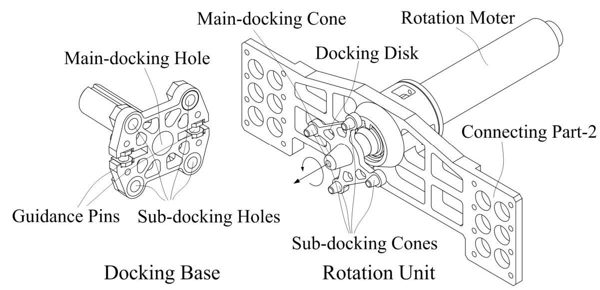


Fig. 3 Rotation unit and docking base

III. GRASPING AND DOCKING ABILITIES

A. Grasping Workspace and Modes

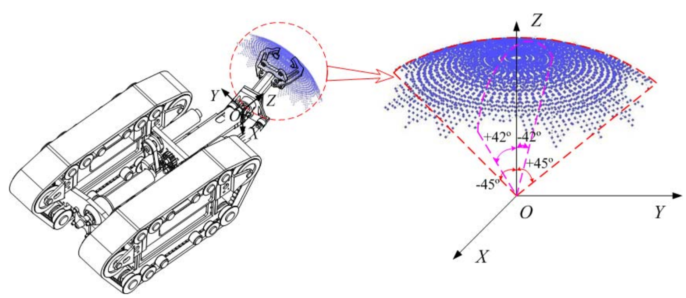


Fig. 4 Grasping workspace

After installing the docking manipulator on the robot, we can calculate the valid workspace of the gripper, according to equations (1), (2) and the structure constraints introduced by the size of the parts and the limited space between two track units. The result is shown in Fig. 4, in which the spherical surface is composed of the points that can be reached by the tip of the gripper. The center of the spherical surface is the center point (*O*) of the main hooker joint. In theory, the pitching angle of the gripper θ_x lies between -45º and +45º, and the yawing angle θ_y lies between -42º and +42º, but the structure constrains prevent the gripper from reaching these angle limits in all directions. This phenomenon is shown by the ragged edge of the spherical surface in Fig. 4.

The cam groove in each finger is divided into two segments: a nipping segment and a holding segment, as shown in Fig. 5. When the guiding pins are in the nipping segments, it will enforce the gripper to open or close as long as the docking base moves backward or forward. In this period, the gripper may perform a grasping mode called nipping. The fingers revolving around the gripper shafts from 0º - 24º will result in a fluctuating distance between two tips from 2mm - 43mm, which are also the width limits of the object to be nipped. The nipping force F_N is introduced by the pushing force of the docking base F_D, whose value can be calculated from equation (3).

$$\boldsymbol{F_D} = 2\pi \cdot \boldsymbol{M_D} \boldsymbol{n} \eta / \boldsymbol{l} \qquad (3)$$

Where,

M_D is the rating output of the docking motor;

n is the gear ratio from the docking motor to the docking screw;

η and l are the efficiency and the pitch of the docking screw respectively.

The rating value of F_D is 10.1 kN, by which the value of F_N can be calculated. The value of F_N changes from 0.56 kN to 0.88 kN when the object width changes from 43mm to 2mm.

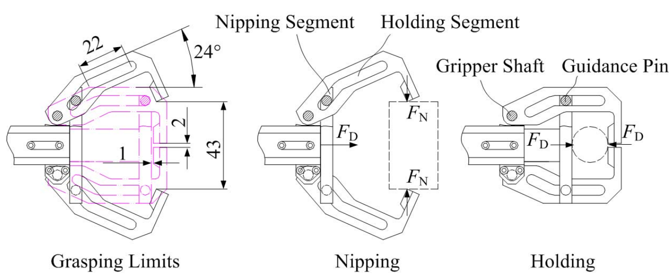


Fig. 5 Grasping modes

When the guiding pins enter the holding segments, a holding mode will be performed by the gripper, as shown in the right of Fig. 5. The available thickness of the objects that can be held is between 1mm to 22mm in theory. Obviously, the holding force equals F_D.

When grasping, the robots in JL-2 will perform a nipping action for an object with flat surfaces and a holding action for a round object. When docking, these two modes will result in a gradually aligning procedure to diminish the position and orientation errors between two robots sequentially. It seems that the rating contact forces between the gripper and objects are too large, but those are necessary to ensure a reliable docking action. Actually, during the grasping period, the contacting forces will be limited by monitoring the current in the docking motor to protect the object from being damaged.

B. Principle of Docking

When two robots try to connect with each other, there are usually five aligning errors between them due to the limited accuracy of sensors and control, as well as the rugged terrains, if this is performed in an outdoor environment. For JL-2 in Fig. 1, these errors are two position errors d_x and d_y along the X and Y axes, and three orientation errors ε_x, ε_y and ε_z around the X, Y and Z axes respectively. Fig. 6 shows how the Middle Robot (the top and left one) and the Front Robot (the bottom and right one) overcome the aligning errors and realize the final solid connection.

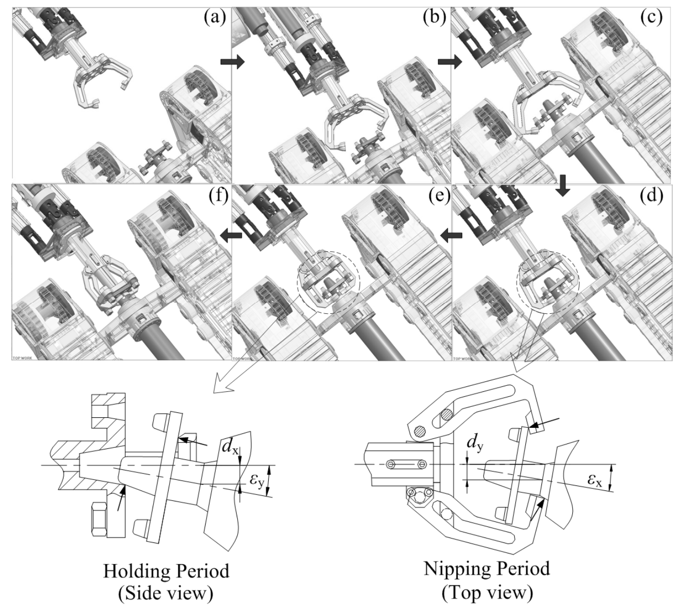


Fig. 6 Docking procedure

In Fig. 6, six typical steps are illustrated, in which (a) and (b) are called the accessing period, (c) and (d) belong to the nipping period, (e) and (f) are the holding period. During the accessing period, the Front Robot stops, but rotates the docking disk to align with the gripper around the Z axis. The Middle Robot opens the gripper completely, then keeps moving forward and adjusting the postures of the gripper simultaneously, until the gripper encompasses the docking disk.

Then the nipping period begins, during which the gripper closes to diminish the errors in the horizontal plane, namely d_y and ε_x. This function is ensured by the contacting forces between the gripper and the docking disk, whose alignments are shown in a top view of the nipping period in Fig.6. Although the contacting forces are changed during this period, the results of the previous section indicate that they are powerful enough to overcome the friction force between the tracks and the ground, and will align two robots in the horizontal plane.

When the gripper is closed completely, the holding period will be triggered. Along with the outstretching of the docking base, the main cone will be embedded into the main hole, which is ensured by their dimensions. As soon as they make contact with each other, the contacting forces will diminish the aligning errors in the vertical plane, namely d_x and ε_y, as shown in the side view in Fig. 6. At the end of this period, the sub-cones will fit the sub-holes to eliminate the error ε_z at last.

After the docking procedure, all of the six DOFs between two robots are constrained, and the docking disk is held forcefully between the docking base and the gripper by the resident pressure. Since the driving chain from the docking motor to the gripper and the docking disk is self-locked, there is no possibility to disconnect the two robots, unless the docking motor is controlled to do it.

IV. Real Experiments

Based on the above analyses and designs, we have developed a JL-2 prototype. A series of experiments have been completed to test some basic functions of the prototype. The control system of JL-2 is similar to that of JL-1, but this is beyond the scope of this paper. To date, most of the motions are under the control of an operator, except those requiring cooperative actions between robots, e.g. posture adjusting actions.

A. Grasping Experiments

Two grasping modes have been tested on the Middle Robot and the Back Robot. In our experiments, the gripper successfully nipped several wood blocks, whose widths were 5mm, 10mm, 20mm and 30mm, as shown in Fig. 7.

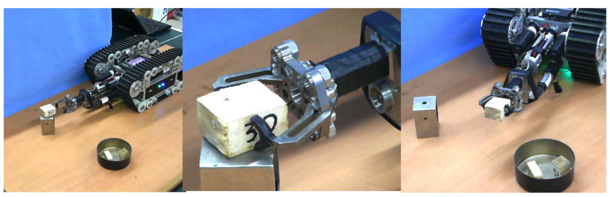


Fig. 7 Nipping a wood block

To grasp an object with a cylinder shape, the holding mode was applied. The diameters of the metal shafts were selected between 5mm, 10mm and 20mm. Fig. 8 shows the procedure of holding a 20mm metal shaft.

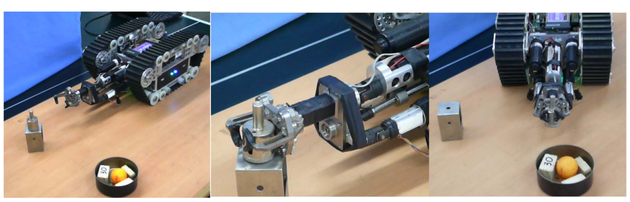


Fig. 8 Holding a metal shaft

The current of the docking motor is monitored by the onboard controller during the grasping experiments in time. If a preset current value is reached, the docking motor will be stopped. For objects of different material, different maximum values of the current are selected to protect the objects and the gripper from damage.

B. Docking Experiments

To test the self-aligning abilities of the docking mechanism, the five posture errors, d_x, d_y, ε_x, ε_y, and ε_z, were preset individually in several experiments.

Fig. 9 shows how the docking mechanism compensates the orientation error ε_x in the horizontal plane. Two robots are set on one plane with a preset orientation error ε_x, and the docking gripper has already encompassed the docking disk. Then the docking gripper performs the docking process to align two robots.

Fig. 10 shows the procedure of overcoming the vertical position error d_x. Two robots are set on two different planes, at a vertical distance d_x. The gripper is adjusted to encompass the disk. Then the gripper closes to grasp the disk. When the docking procedure is completed, the Middle Robot lifts the Front Robot to check the final result of docking.

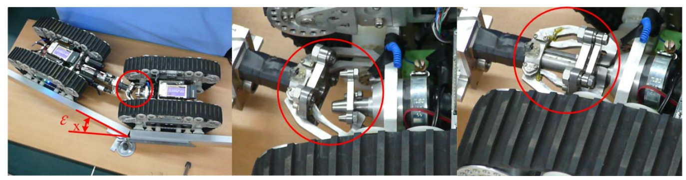


Fig. 9 Docking with horizontal orientation error ε_x

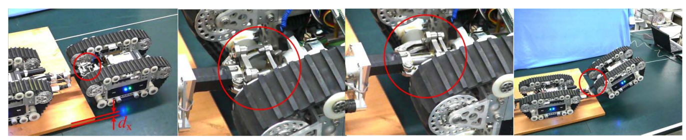


Fig. 10 Docking with vertical position error d_x

From these experiments, we can find that the self-aligning abilities in the horizontal plane are better than those in the vertical plane. This is due to the difficulty of grasping the neck behind the docking disk and the influence of the robot weight.

The self-aligning ability around the *Z* axis is the poorest one, because the multi sub-cones can cause over-constraint, although they will help to realize a solid connection. It is not a serious problem in actual docking actions, as the rotation angle of the docking disk can be accurately adjusted by the rotation motor.

When docked, a very solid connection is ensured by the high pressure between the docking base and disk, as well as the multi-point mating structure. Such a connection without clearance enables the following posture adjusting experiments.

C. Posture Adjusting Experiments

In indoor environments, JL-2 performed similar posture adjusting experiments to JL-1, such as self recovery, lateral motion, passing through a narrow fence, etc. Fig. 11 shows the 90º self recovery experiment. These experiments prove that even applying a more complex docking mechanism, JL-2 still retains its marvelous posture adjusting abilities. That encourages us to test JL-2 in the field in the future.

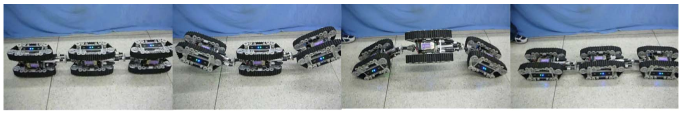


Fig. 11 90º self recovery

The results of our experiments are listed in Table I.

TABLE I
BASIC PERFORMANCE SPECIFICATIONS

Item		Values
Physical parameters of single robot		
Weight	Front robot	7.2kg
	Middle robot	9.1kg
	Back robot	8.5kg
Dimensions	Front robot	$370*252*172mm^3$
	Middle robot	$569*252*172mm^3$
	Back robot	$569*252*172mm^3$
Maximum moving velocity		200 mm/s
Maximum endurance time		2 hour
Grasping ability		
Pitching angle		-45°-+45º
Yawing angle		-42°-+42º
Object width in nipping mode		5-30mm
Object diameter in holding mode		5-20mm
Rating nipping force		0.65-0.88kN
Rating holding force		10.1kN
Docking ability (Maximum permitted errors)		
Horizontal position error d_y		-30-+30mm
Horizontal orientation error ε_x		-35-+35º
Vertical position error d_x		-15-+15mm
Vertical orientation error ε_y		-20-+20º
Rotation error ε_z		-8-+8º
Posture adjusting ability		
Turning angle around X-axis θ_x		-45-+45º
Turning angle around Y-axis θ_y		-42-+42º
Turning angle around Y-axis θ_z		-180-+180°
Maximum torque around X-axis M_x		20.5Nm
Maximum torque around Y-axis M_y		24.5Nm
Maximum torque around Z-axis M_z		4.5Nm

V. CONCLUSION

This paper presents the new reconfigurable mobile robot system JL-2, which is distinguished from its predecessor JL-1 by a novel docking manipulator and a 3D docking ability. The analyses and tests yield the following conclusions.

1) Integrating a simple gripper at the end of the parallel mechanism is a feasible solution to combine the grasping and docking function on reconfigurable mobile robots.
2) The docking ability of JL-2 is enhanced by a 3 DOFs docking gripper and the high docking forces arising from a cam guidance mechanism. It is possible for JL-2 to realize the docking action in rugged terrains in the future.
3) Although the multi-point mating structure ensures a solid connection, it may introduce an over-constraints problem which results in a poor self-aligning ability around the rotation axis.

In the future, the structure of the gripper and the docking disk will be improved to extend the permitted errors in the vertical plane and around the rotation axis. Automatic docking will be further topic for the research on JL-2. Covers will be added on the JL-2 robots to prevent them from dust and splash water. Then a series of outdoor experiments will be performed.

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REFERENCES

[1] F. Mondada, A. Guignard, M. Bonani, D. Bar, M. Lauria and D. Floreano, “SWARM-BOT: from concept to implementation”, in *Proc. of the 2003 IEEE/RSJ International Conference on Intelligent Robotics and Systems*, Las Vegas, Nevada, USA, 27 - 31, Oct. 2003, pp. 1626-1631.

[2] G. Visentin, M. Van Winnendael, and P. Putz. “Advanced mechatronics in ESA space robotics developments”, in *Proc. of the 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Maui, Hawaii, USA, October 29 - November 3, 2001, pp. 1261–1266.

[3] J. Casper and R. R. Murphy, “Issues in intelligent robots for search and rescue”, *SPIE Ground Vehicle Technology II*, 2000

[4] S. Hirose and A. Morishima, “Design and control of a mobile robot with an articulated body”, *International Journal of Robotics Research*, 9(2), pp. 99-113, April, 1990

[5] M. Nilsson, “Heavy duty connectors for self-reconfiguring robots”, in *Proc. of the IEEE International Conference on Robotics & Automation*, Washington, DC, USA, 2002, pp. 4071-4076

[6] A. Kamimura, H. Kurokawa, E. Yoshida, S. Murata, K. Tomita and S. Kokaji, “Automatic locomotion design and experiments for a module robotic system”, *IEEE/ASME Transactions on Mechatronics*, 10(9), pp: 314-325, 2005.

[7] M. Yim, B. Shirmohammadi, J. Sastra, M. Park, M. Dugan and C.J. Taylor, “Towards robotic self-reassembly after explosion” in *Proc. of the IEEE International Conference on Robotics and Automation*, Roma, Italy, 2007, pp: 2767-2772.

[8] W.M. Shen, and P. Will, (2001, May). “Docking in self-reconfigurable robots”, in *Proc. of the IEEE International Conference on Robotics and Automation*, Seoul, Korea, 2001, pp: 1049-1054.

[9] S. Hirose, “Super-Mechano-Colony and SMC Rover with detachable wheel units”, *in Proc. of the TITech COE/Super Mechano-Systems workshop '99*, 1999, October, Tokyo, Japan.

[10] H.B. Brown, J.M.V. Weghe, C.A. Bererton and P.K. Khosla, “Millibot trains for enhanced mobility”, *IEEE/ASME Transactions on Mechantronics*, 7(2), pp. 452-461, 2002

[11] F. Mondada, G. C. Pettinaro, A. Guignard, I. W. Kwee, D. Floreano, J. Deneubourg, S. Nolfi, L. M. Gambardella and M. Dorigo, “Swarm-Bot: a New Distributed Robotic Concept”, *Journal of Autonomous Robots*, vol.17, No.2-3, pp. 193-221, September, 2004

[12] H.X. Zhang, S.Y. Chen, W. Wang, J.W. Zhang and G.H. Zong, “Runtime reconfiguration of a modular mobile robot with serial and parallel mechanisms”, in *Proc. of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, San Diego, U.S.A, Oct.29-Nov.02, 2007, pp: 2999-3004

[13] W. Wang, H.X. Zhang, J.W. Zhang and G.H. Zong, “Force cooperation in a reconfigurable field multi-robot system”, *Journal of Field Robotics*, Vol. 25, Issue 11–12, pp 922–938, Nov./Dec., 2008