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Mobile Robot Manipulation System with a Reconfigurable Robotic Arm: Design and Experiment*

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***Abstract* -Working in unknown environment has become a fundamental requirement of mobile robot manipulation system. This application scenarios require robots to have some basic capabilities, such as the fast and flexible locomotion, dexterous manipulation, and environmental interaction. However, most studies have only focus on just one of the aspects, which restricts the actual applications. This paper attempts to show a novel design of the mobile robot manipulation system with all above capabilities. The system consists of a mobile platform and a reconfigurable 7 degrees of freedom (DOF) robotic arm. The quadruped and wheeled locomotion is realized on the mobile platform. Different from traditional mobile robot manipulation system, a new type of reconfigurable connecting mechanism (RCM) is developed to realize the quick change the configurations and modules. Due to these designs, the system can adapt for different tasks. Besides, the hardware and software of the control system are introduced. Finally, the performances of the developed mobile robot manipulation system are validated by a series of experiments.**

Index Terms - mobile manipulation system, hybrid mobile platform, dexterous manipulation, reconfigurable connecting mechanism.

I. INTRODUCTION

The fast and flexible moving, dexterous manipulation, environmental interaction and heavy payload, are the fundamental properties of robots. Any of them has been received considerable attentions. But robot with single capability cannot satisfy the actual applications, such as the detection and rescue of dangerous environments. These application scenarios require the robot can walk in rugged environment, detect and even manipulate the obstacles. Compared with the single capability robots, mobile robot manipulation system, which integrates all above capabilities, is more adaptable and has potentials in these scenarios. So there is an increasing research prospect in mobile robot manipulation system.

The mobile robot manipulation system can be divided into mobile platform, manipulator and control system. The mobile platform has three working modes, legged robot, wheeled robot and crawler robot. Especially in recent years, legged robot has been greatly developed for its advantages in complex scenarios. It can be divided into bipedal robot, quadruped robot and multi-legged robot. For bipedal robots, which are driven by motors, the payload and locomotion velocity are strictly restricted, such as the Walkman[1], HPR series[2], TORO[3]. The payload and locomotion velocity are strictly restricted. To improve the load capacities, researchers about the hydraulic driven bipedal robots, ATLAS, PETMAN are published. It brings much noise and energy consumption. In addition, bipedal robots are difficult to achieve dynamic stability. Compared with the bipedal robots, quadruped robots and multi-legged robots have a better performance in stable walking and heavy payload capability, even though some of them are driven by motors, such as Cheetah[4], BigDog[5], ANYmal[6], RHex[7] and Weaver[8]. Multi-legged robots have a more complex structure, which will bring more cost. So quadruped robot is our first choice for the mobile platform. To combine the advantages of the multi-legged robots for obstacles avoidance and the wheeled robots for fast moving, the legged/wheeled hybrid robots have been developed, such as Work-Partner[9] and Centauro[10]. They can move in the rugged terrain by legged mode and flat terrain by wheeled mode.

The manipulator is also a key characteristic of the mobile robot manipulation system. It has the dexterous manipulation ability to execute various missions, such as turning valves, pushing buttons or removing obstacles. However, most of the quadruped robots lack manipulation ability about the environment, such as Cheetah[4] and ANYmal[6]. With the urgent need for the mobile manipulation, little researchers have paid attention to the dexterous manipulation ability recently. The SpotMini[11], a quadruped robot developed by the Boston Dynamic, uses a single 5-DOFs robotic arm to realize the manipulation ability. Integrating the arm with an end effector, SpotMini can complete the fundamental missions, for example grasp a cup. Another multifunctional robot is the Centauro[10], developed by IIT, which has a wheeled/legged hybrid mobile platform and two cooperative manipulation arms. It can complete much more difficult operations, such as collision detection and bi-manipulation.

In order to further improve the adaptability for different tasks, the 7-DOFs reconfigurable robotic arm is installed for the mobile robot manipulation system. A new type of electric

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connection RCM is developed for the arm to change configuration and replace end effectors for different missions. Multiple RCMS are compared and reviewed in [12]. The drive methods of RCMs mainly include magnetic, mechanical, pneumatic and hydraulic. The magnetic driven RCMS are widely used because of the simple structure and high reliability to reconfigure robots, such as HexBot[13], the M-Blocks[14] and UBot[15]. However, these RCMs are designed for cell robots which are not suitable for the load operation of the robotic arm.

Based on these fundamental requirements, the legged/wheeled hybrid mobile robot manipulation system with a reconfigurable robotic arm is developed in this paper. Compared with the traditional mobile manipulation robot, it has many benefits.

(1) With two flexible locomotion modes which can be converted to each other quickly, the robot can adapt to different walking environments.

(2) With RCMs, the manipulator can change to configurations to adapt the environment, especially for replacing joints and end effectors.

(3) With the remote control and visual control algorithms, the robot can work semi-autonomously.

The remainder of the paper is organized as follows. Section II introduces the mechanical design, including the technical requirements, the structure of robot, actuator, and RCM. Section III shows the architecture of the control system to explain the control strategy. Section IV exhibits the prototype and a series of experiments to verify the reconfiguration, heavy load, locomotion, and dexterous manipulation performances of the robot. Finally, the conclusions give a brief summary.

II. MECHANICAL SYSTEM DESIGN

A. *The Overall Mechanical System Design*

The mobile robot manipulation system works in the unstructured environment should have the following technical requirements:

(1) Effective locomotion ability
(2) Dexterous manipulation ability
(3) Environment interaction
(4) Load capability

Based on these requirements, we developed a mobile robot manipulation system with a 7-DOFs reconfigurable robotic arm, shown in Fig. 1. The design of the mobile platform considers legged/wheeled hybrid mode locomotion. The legged mode is used to work in the rugged environment. It has four 4-DOFs legs, with the yaw-roll-pitch-pitch configuration. Besides, four 3-axis force sensors are fixed at the end of each leg to measure the contact forces for dynamic control. The stall torque of the yaw and roll joint is 25Nm and for the pitch joint is 80Nm. The platform has a height of 420mm, a width of 570mm and a length of 500mm.

In the wheeled mode, four McNamm wheels, driven by the DC brushless motors (RoboMaster 3510), are used to realize the omnidirectional movement. To decrease the shaking of the robot in rugged ground due to its big inertia and high centroid, two passive spring damper systems are added at the rear wheels. The key dimensions of the robot is shown in Fig. 2.

The reconfigurable robotic arm with two RCMs is fixed on the platform. The first RCM is installed between the fourth joint and the fifth joint. Besides, another RCM is used to connect the end effector, mounted at the output of the 7th joint. We can change the configuration and the end effectors of the arm by the RCMs based on different missions' requirements. The total length of the arm, including the end effector, is about 150mm. The maximum required torque of the first four joints is 63Nm and the last three joints 14 Nm. The end effector is a compliant adaptive grasper and introduce in reference [16].

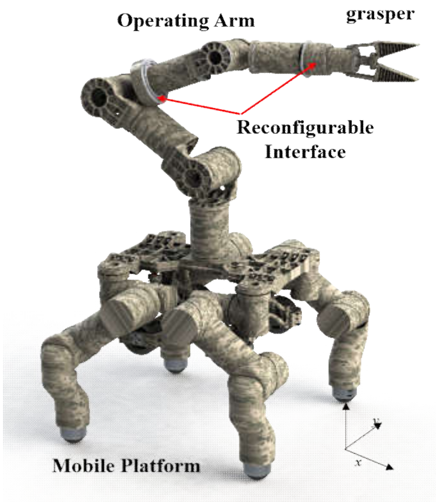


Figure 1. The 3D model of the reconfigurable multifunctional dexterous manipulation robot

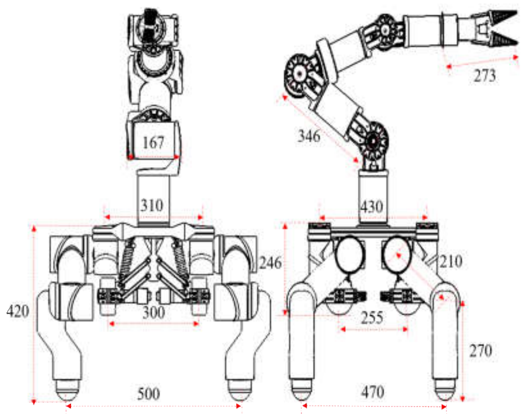


Figure 2. The key dimensions (in mm) of the robot and limbs

B. *Modular Actuator Design*

As Fig. 1 shows, there are total 16 joints in the locomotion platform and 7 joints in the manipulator. Compared with the required torques of the joints in the legs and arm, the 23 joints can be divided into 2 types. We take the modular design method to design the 2 type actuators, named 17-type joint and 25-type joint. 17-type joint can provide rated torque 25Nm, and 25-type joint can provide 113.6Nm rated torque. Take the 25-type joint as an example, the mechanical design is shown in Fig. 3.

The actuator is designed compactly referred to the typical joints. It mainly consists of four components, including the motor, reducer, joint sensor and the drive board. The motor is a brushless DC motor, integrated with hall position sensors. In order to control the weight and size of actuator, a harmonic reducer with a specific reduction ratio is connected with the motor by a hollow shaft. Except the hall sensors in the motor, the actuator is also equipped with rich sensors to achieve good performances. The multi-turns incremental encoder is assembled in the motor part for the speed control. The single-turn absolute encoder is fixed on the output flange for the position control. The current(A) sensors are integrated in the motor driver board for the current(A) control. The output flange is fixed to the flexible wheel of the harmonic reducer as the output part. The parameters of the two type actuators are shown in Table 1.

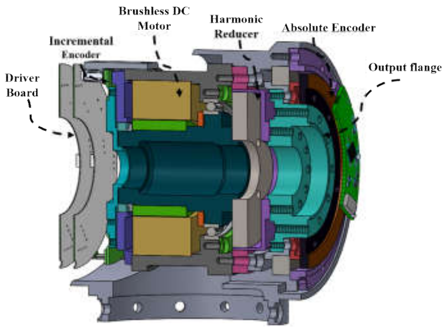


Figure 3. The 3D model of 25-type actuator

Table 1. Actuator parameters of 17 type and 25 type

Item	Actuator Values	
	17-type	**25-type**
Peak torque(Nm)	40	150
Rated torque(Nm)	25	113.6
Maximum Velocity (rad/s)	2.51	1.57
Reduction ratio	1:100	1:160
Weight(kg)	1.2	2
Overall dimensions(mm)	Φ80×130mm	Φ100×143mm

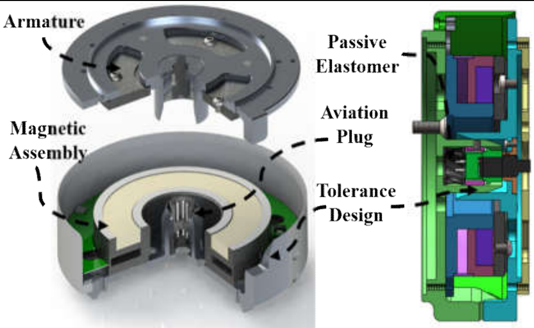


Figure 4. The 3D model of the RCM

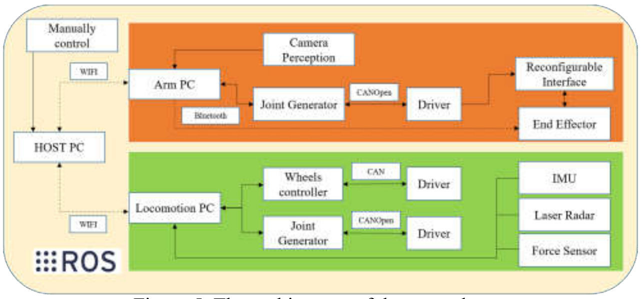


Figure 5. The architecture of the control system

C. The Reconfigurable Connecting Mechanism Design

Two RCMs are used in this robot. The first RCM is used to reconfigure the manipulation arm, mounted after the fourth joint. Another small RCM is used to connect the grasper with the arm. Fig. 4 exhibits the 3D model of the first RCM.

To ensure the reliability of the RCMs, the structure of the RCM is designed very simple with the magnetic assembly and armature. The magnetic assembly includes a permanent magnet and a coil. It is fixed with the former 4 DOFs arm. The armature is installed with the latter 3 DOFs arm by screws. The working principle of the RCM is as following. When the coil is in power, it generates an anti-magnetic field to counteract the permanent magnetic forces. During this process, the RCM is unlocked. When the coil loses power, the RCM is locked. Besides, the key connections are designed to withstand torque. Another optional connection choice is the latching connection mechanism. But the magnetic RCM can provide enough connection force with a simple mechanism. The tolerance structure design is used to guarantee the success rate of the connection. The maximum radial tolerance is up to ±10mm and the radial angular tolerance is up to ±7°. A four-pin electrical connector is fixed on the center of the RCM for power and communication connections. The dimension of RCM is about Φ128×44.6mm, weight 1.2kg. It can provide 500N maximum locking force. The locking force per weight is 41. The bigger tolerance and locking force ensure the reliability of the connection.

Another RCM is used to connect the end effector. It has the same structure as the first RCM but with a relative small dimensions and locking force, about 200N and 25Nm.

III. CONTROL SYSTEM DESIGN

A distributed multi-layers control system is designed for mobile robot manipulation system. In order to clearly assign the tasks of the control system, we divide the control system into three layers.

(1) The top layer is the Input layer to receive tasks, decide the missions' priority, and perceive the sensors' information to analyze the robot's state.

(2) The middle layer is the planned layer to receive the specific missions and make some calculations to get the footholds, joints angles, velocities and torques for the different missions.

(3) The bottom layer is the actuated layer to control the

joints according to the desired parameters sent from the middle layer. The interpolations are also completed in this level.

Except the sensors integrated in the actuation, the mobile robot manipulation system also contains some externals sensors. The three-axis force sensor is mounted at the end of each leg. The laser radar and inertial measurement unit are installed on the system. The monocular camera is integrated to detect the environment. The control system is displayed in Fig. 5.

The whole system is running under the ROS with three microcomputers. The host computer is responsible for the organized layer. It sends commands to the arm computer and locomotion computer based on the missions' priority by WIFI. The arm computer and locomotion computer obtain the required data by the specific algorithms and send them to the joints' driver by the CANOpen communication bus. Finally, the drivers deal with the receiving data and control the movement of the motor. The robot can works in semi-automatic mode or remote control mode to execute some tasks, for example the reconfiguration of the manipulator.

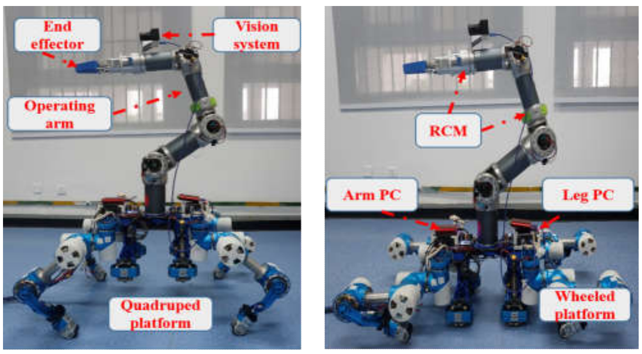
IV. PROTOTYPE AND EXPERIMENTS

A. *Prototype*

To verify the performances of the mobile robot manipulation system, we built the prototype and carried out several experiments. The prototype is shown in Fig. 6. Fig. 6.*a* is the robot in the quadruped mode and Fig. 6.*b* is the robot in wheeled mode. The prototype includes the quadruped moving subsystem, wheeled moving subsystem, 7-DOFs arm, vision subsystem, end effector, RCMs and the control system. The total mass of the robot is about 52kg.

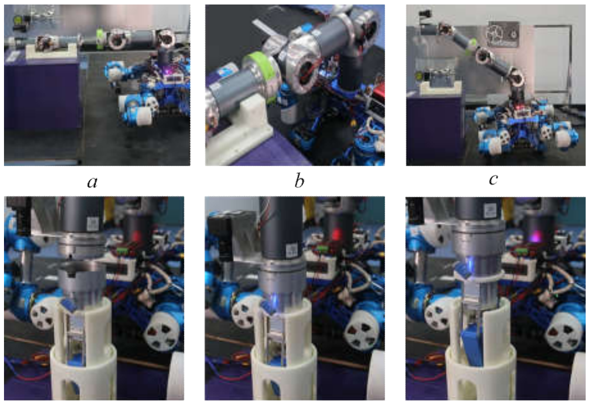
B. *Reconfigurable Experiments*

There are two RCMs integrated with the manipulator. The first one locates between the fourth and fifth joint to extend the structure of the manipulator. The end effector used in the experiments is a compliant adaptive grasper. It has a reliable capture for different objects with various shapes and sizes. The detailed parameters shows in reference [16]. The second one is at the end of the arm to connect the end effector. The reconfigurable experiment is exhibited in Fig. 7.



a *b*

Figure 6. The prototype of the robot



a *b* *c*

d *e* *f*

Figure 7. The reconfigurable experiment

The reconfigurable experiment is carried out in remote control mode. Fig. 7.*a* to *c* show the reconfigurable experiment by the first RCM. The former 4-DOFs manipulator is assembled with the locomotion platform. The latter 3-DOFs arm is placed with a specific fixture to prevent it moving during the reconfigurable process. The two parts of the RCM are fixed respectively. After the preparation, we adjust the angles of the former four joints, ensuring the two parts of the RCM are approximately on the same line within the tolerance, shown in Fig. 7.a. Then we control the locomotion platform moving in the direction of the line. With the magnetic force, the two parts of the RCM connect with each other easily, shown in Fig. 7.b. Finally, we control the new manipulator to an arbitrary configuration to verify the success of the reconfigurable experiment as Fig. 7.c shows.

Fig. 7.*d* to *e* show the reconfigurable process of the end effector and manipulator, which is similar to the reconfigurable process mentioned above. When the end effector is successfully connected with the manipulator, the blue light is flickering as Fig. 7.*e* shows. Then we can manipulate the end effector to complete the required tasks.

The reconfigurable experiments verify the feasibility and reliability of the RCMs used in the manipulator. It can not only complete the mechanical connection, but also the power and communication connections.

Figure 8. The repeat positioning accuracy experiment

Table 2. Coordinates of the target ball

Group number	Coordinates
1	(684.1747,-3752.4972,10.7697)
2	(683.9452,-3752.5406,10.3196)
3	(684.2269,-3752.6686,10.9407)
4	(684.0575,-3752.4736,10.5073)
5	(684.2225,-3752.5349,10.8661)

C. The Repeat Positioning Accuracy Experiment

One of the main technical index of a manipulator is the repeat positioning accuracy. It decides the possibility of the reconfigurable manipulator to complete the fine operations. The repeat positioning accuracy experiment process is shown in Fig. 8. A target ball is fixed at the end of the manipulation arm. We control the first joint moving between angles, such as from 0 to -60 degrees. We record the target ball's coordinates from the laser tracker. Finally, all joints return to their initial angles. We repeat the above process five times and five group data are record, shown in Table 2.

We calculate the repeat positioning accuracy with the following algorithm. Firstly, we get the average number of the three coordinates, named x, y, z. Then calculate the distance between the *j-th* data and the average number:

$$l_j = \sqrt{(x - x_j)^2 + (y - y_j)^2 + (z - z_j)^2} \qquad (1)$$

Use (2) to calculate the average distance of l_j:

$$\bar{l} = \frac{1}{n}\sum_{j=1}^{5} l_j \qquad (2)$$

So the repeat position accuracy s is equal to:

$$s = \max(|l_j - \bar{l}|) \qquad (3)$$

The repeat positioning accuracy is 0.3611mm. The manipulator has a high repeat positioning accuracy, which also implies the RCM also has a high connection accuracy.

D. Load Capability Experiment

Load capability is an important index for the arm to work. In this experiment, 3.5kg objects is placed at the end of manipulation arm, shown in Fig. 9. The maximum torque of

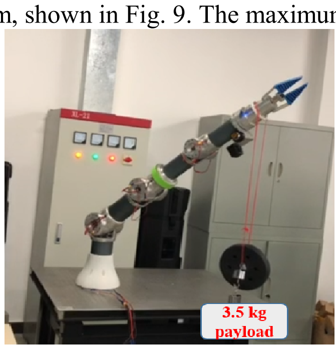


Figure 9. Arm load experiment

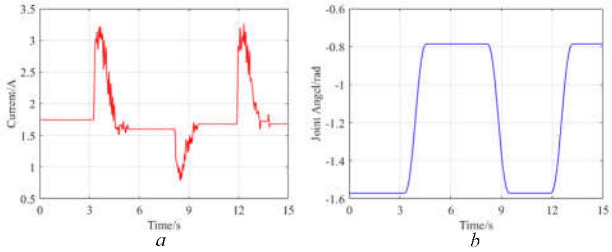


Figure 10. The current and angle of joint 2

the manipulator is the second joint. We control the second joint moving from the $-pi/2$ rad to $-pi/4$ rad and return back. The recorded currents and angles are shown in Fig. 10.

Fig. 10.a is the current curve of joint 2. The load capability of the manipulation arm is above 3.5kg. Besides, this experiment also validates the good performance of the RCM, which can bear more than 3.5kg objects. Fig. 10.b is the joint position curves.

E. Locomotion Experiment

This experiment is to validate the locomotion ability in quadruped mode. The robot walks in the static gait. It is supported by three legs at any moment of walking time. The trajectory of the foothold is planned by the fifth order polynomial equation. The robot moves 0.2m in six seconds. The phase-sequence diagram of the static gait is shown in Fig. 11. The white block means the swing phase and black block means the stance phase of the leg. By the kinematic algorithm, we record the two 25-type joints' parameters of the left-front (LF) leg, shown in Fig. 12. The red line is the actual angular velocity of the joint, the green line is the actual joint's angle and the blue line stands for the planning angle sending from the controller to the driver. We can see that the motion of the joint can track the sending data with a quick speed. This means the good performance of the robot system. The maximum angular velocity of the 25-type joint is the 1 rad/s, and the maximum theory angular velocity is 1.57 rad/s. So the maximum speed of the robot can be up to 5cm/s by the static gait. Besides, we also test the locomotion speed in the wheeled mode. The maximum speed is about 10km/h.

This experiment validates the hybrid locomotion ability of the system. Even though the total mass is 52kg, the system can walk in static gait stably.

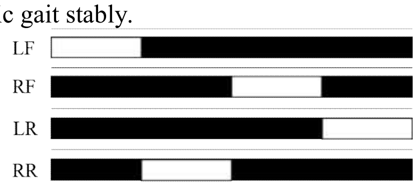


Figure 11. The phase-sequence diagram of static gait

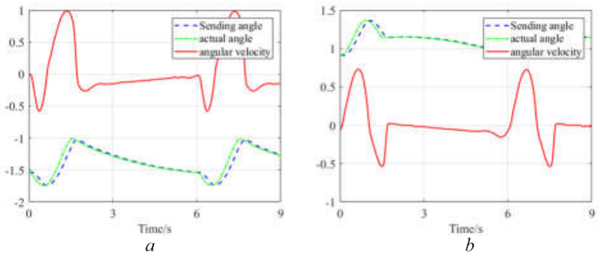


Figure 12. The joints angle data of 25-type

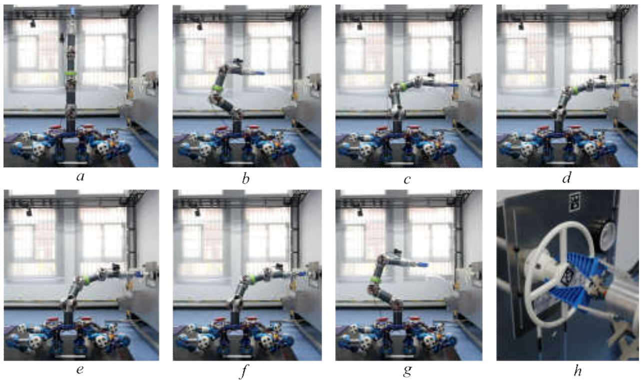


Figure 13. The dexterous manipulation experiment

F. Manipulation Experiment

This experiment is to validate the dexterous manipulation ability of the robot. The experiment scenario is to rotate a valve by the end-effector in the visual control mode, shown in Fig. 13. A monocular camera is fixed at the end of manipulation arm and the relative relationship between this camera and end effector is calibrated firstly.

We adjust the attitudes of the camera by the remote control from the initial position (Fig. 13.a). Fig. 13.b shows the camera detects the QR code on the valve. Then the arm works in the visual servo control mode. It gets closer to the center of the valve. During this process, the grasper opens and holds the valve to rotate a specific angle (Fig. 13.c to f). Fig. 13.h is the close-up picture of Fig. 13.d, which shows the grasper holding the valve. Finally, the grasper releases the valve and the manipulation arm returns to an arbitrary stable configuration.

This experiment shows the high performance of the system. Through the coordinated control of each subsystem, the mobile robot manipulation system can complete given tasks.

V. CONCLUSION

In this paper, a mobile robot manipulation system with multi-functions is exhibited. The system is divided into three parts. The locomotion is realized by a hybrid legged/wheel platform. It not only can walk in rugged environments in quadruped mode, but also can move in flat ground by wheels. Different from other manipulators, the system has a 7-DOFs reconfigurable robotic arm. It can change the DOF and end effector of the manipulator by different tasks requirements. The modularly designed actuator and the RCM are introduced in detail. What's more, the distributed control system is analysed. Finally, we build the prototype and validate the performances of the robot by a series of experiments. The reconfigurable experiment shows the feasible and flexible of the RCM. The repeat positioning accuracy experiment and load experiment exhibit the good performances of the manipulator and RCMs. The locomotion experiment validates the hybrid locomotion mode of the platform. The last manipulation experiment shows the ability for task operation.

However, there are still some insufficiencies in this paper, such as the low locomotion speed and the unintelligent control algorithm. In the future, we will focus on these problems to perfect our robot.

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