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ORIGINAL RESEARCH

HeterBot: A heterogeneous mobile manipulation robot for versatile operation

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Abstract

This study presents the overall architecture of HeterBot, a heterogeneous mobile manipulation robot developed in our lab, which is designed for versatile operation in hazardous environments. The most significant feature of HeterBot is the heterogeneous design created by adopting the idea of 'big arm + small arm' and 'big car + mini car'. This combination has the advantage of functional complementation, which achieves performance promotion in both locomotion and manipulation capabilities, making HeterBot distinguished from other mobile manipulation robots. Besides, multiple novel technologies are integrated into HeterBot to expand its versatility and ease of use, including Virtual Robot Experimentation Platform-based teleoperation, reconfigurable end effectors, laser-aided grasping, and manipulation with customised tools. Experimental results validate the effectiveness of HeterBot in various locomotion and manipulation tasks. HeterBot displays huge potential in future applications, such as searching and rescue.

KEYWORDS

rescue robots, telerobotics

1 | INTRODUCTION

Mobile manipulation robots have received more and more attention in recent years due to the increasing application demands. Mobile manipulation robots can be used for industrial applications [1], can be deployed in restaurants, hospitals, and homes as service robots [2], and can also work outdoors to do constructions [3]. More importantly, they can be sent to hazardous environments to execute dangerous missions, such as disaster relief [4], bomb disposal [5], planetary exploration [6], and so on. Recently, several contests on mobile manipulation robots have been launched, such as the Defense Advanced Research Projects Agency Robotics Challenge [7] and the Subterranean Challenge [8], which represent the highest level of current mobile manipulation technology. However, it can be seen from the contests that the overall performance of mobile manipulation robots is still far from humans. The adaptability, versatility, and reliability of mobile manipulation robots still need to be improved to cope with the uncertainty, diversity, and complexity of real-world applications.

Mobility is an important aspect of mobile manipulation robots. The basic mobile form includes wheeled, legged, and tracked types, where each has different advantages. Recently, some new designs have attempted to merge two of them into one system, which can greatly improve the locomotion capability. For example, the wheeled-legged system [9] has wheels attached to each leg, which allows moving fast on flat ground by wheels as well as traversing rough terrains by legs. Another one is the tracked car with mobile flippers [10], which has subtracks connected to the end of the main tracks. The flippers can rotate to different positions just like legs, which can greatly enhance the obstacle surmounting capability of the tracked car. Manipulation is another important aspect of mobile manipulation robots. The most widely seen are single-arm [5, 11] and anthropomorphic dual-arm design [12, 13], and a few have been equipped with more robotic arms [14].

While one robot might be very good at some specific tasks, it is impossible to fulfil all the requirements. Therefore, the multi-robot system has become a hot research area. The heterogeneous multi-robot system has gathered robots of different types, which can take full advantage of their own merits and maximise the system capability. In the TransTerrA [6] project, a heterogeneous multi-robot system is designed for lunar exploration, which consists of a large rover and a small shuttle with robotic arms. In the Subterranean Challenge, a couple of heterogeneous multi-robot systems have been created to execute underground search and rescue missions. For example, team CSIRO Data61 [15] and team CTU-CRAS [8] both deployed a set of heterogeneous ground and aerial robots.

Although much progress has been made during the last decades, most of them are focussed on a specific technique of mobile manipulation. Very few teams can finally make a versatile mobile manipulation robot, which requires not only innovative ideas but also engineering ability to integrate lots of techniques together. Therefore, we aim to make a small step towards making a versatile mobile manipulation robot. To achieve this goal, we build the HeterBot robot in our lab, which has integrated several advanced techniques and is very different from other mobile manipulation robots. We hope HeterBot can promote the development of future unmanned system technology.

The main contributions of this paper are as follows. First, the overall design of HeterBot is novel. On the one hand, we adopted the heterogeneous dual-arm design with a big arm and a small arm rather than the traditional anthropomorphic design with two equal arms. Our design allows wide-range operation as well as dexterous operation and dual-arm cooperation. On the other hand, we adopted a mini car to establish a compact multi-robot system. The mini car is carried on the robot and can be released to the ground by the robotic arm. Second, multiple useful techniques have been integrated into HeterBot and tested, including V-REP (Virtual Robot Experimentation Platform)-based teleoperation, reconfigurable end effectors, laser-aided grasping, and manipulation with customised tools, which form solid technic foundations for future mobile manipulation technology.

The rest of the paper is organised as follows. Section 2 gives an overview of the hardware details. Section 3 introduces the software architecture. Section 4 presents the experimental results, and Section 5 concludes this paper.

2 | SYSTEM OVERVIEW

The main hardware components of HeterBot are shown in Figure 1. As can be seen, the system is composed of several parts, including a tracked car, two robotic arms, a mini car, a reconfiguration platform, a control cabinet, and so on. The biggest feature of this system is the heterogeneous design created by using a big car with a mini car, and a big arm with a small arm. This design combines the advantages of big/small car and big/small arm as listed in Table 1.

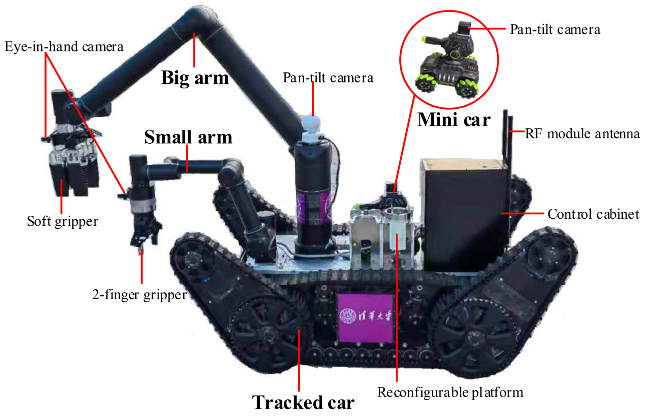


FIGURE 1 An overview of the HeterBot system

TABLE 1 Advantages analysis

Hardware	Advantages
Big car	High payload and cross large obstacles
Mini car	Agile and enters narrow spaces
Big arm	High payload and wide operation range
Small arm	Accurate and dexterous

Although the design idea is simple, selecting the approximate components and integrating them is a challenging task. To achieve this, we have relied heavily on the V-REP [16] (Coppelia Robotics, Zurich, Switzerland) software to build rough models, run simulations, and evaluate the feasibility of the design. As a result, we can go through rapid design iterations and finally determine an optimised design in a short time. It can be seen from Figure 1 that the system is compact and meanwhile guarantees enough workspace for both arms. The details of each part are introduced as follows.

2.1 | Mobile platform

As shown in Figure 2, the tracked car has two main tracks and four articulated flippers with tracks. There are four motors in all. Two big motors in the back are applied to drive the left and right tracks. The three tracks on the same side (including a main track and two flipper tracks) are driven by the same motor and move synchronously. The tracks on the left and right side can move with different speeds or move in opposite directions, which causes turning. In addition, two smaller motors are used to control the rotation of the flippers: one in the front, which controls the rotation of the front flippers, and one in the back, which controls the rotation of the back flippers. The flippers can rotate 360°, which can greatly enhance the obstacle negotiation capability of the tracked car. As we have tested, the tracked car can climb stairs and slopes, cross high steps up to 50 cm, and can move rapidly up to 2.5 m/s. The maximum payload is 200 kg.

A mini car is carried on HeterBot, which can be released to the ground by the robotic arm to execute tasks. To release the

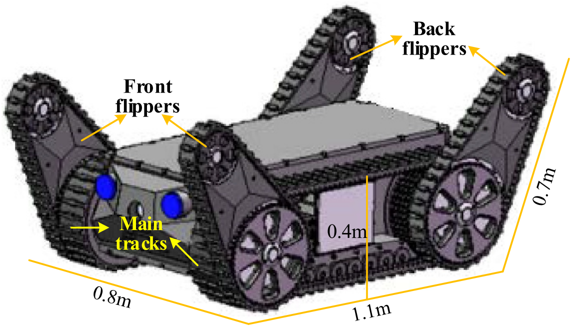


FIGURE 2 The tracked car

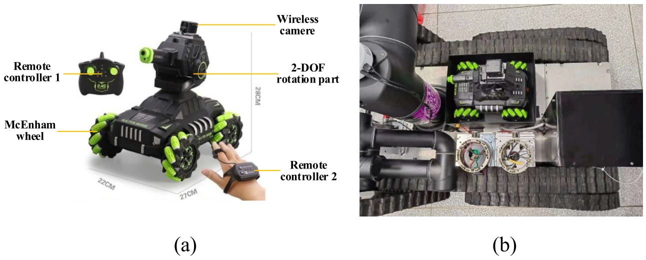


FIGURE 3 The mini car. (a) Mini car structure and (b) Mini car mounted on big car.

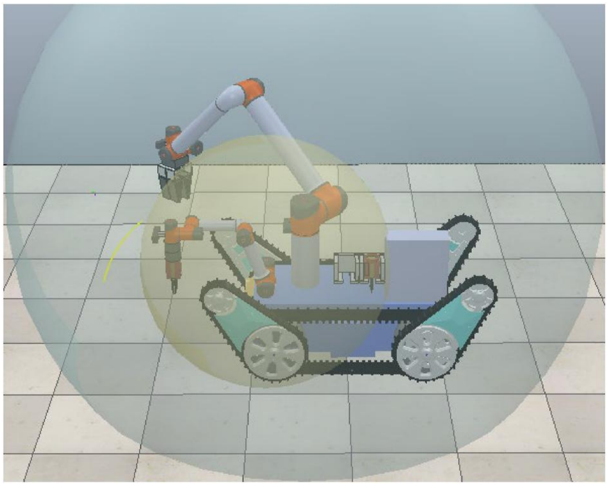


FIGURE 4 Workspace of the two robotic arms

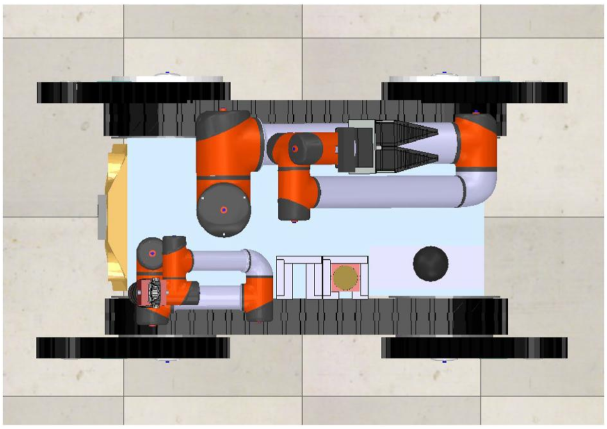


FIGURE 5 Arrangement of the two robotic arms

mini car, we can control the big arm to a predefined configuration where the soft gripper is just over the mini car. Then, we let the soft gripper move down to grasp the mini car and transfer it to the ground (see attached video S1).

As shown in Figure 3, the mini car is an omnidirectional car with mecanum wheels. The car has a 2-DOF rotation part on the top, where we have put a wireless camera on it. The mini car is small and agile, which can be used for rapid reconnaissance and enables us to see the external global view of the robot system, which is quite useful for teleoperation of both locomotion and manipulation tasks. For example, when crossing a high step, the cameras on the robot can hardly see the area below the car, while the mini car can stay beside it and monitor the whole robot. Besides, when performing manipulation tasks, especially tasks that require dual-arm cooperation, having an external view will be much more convenient.

2.2 | Robotic arms

Heterbot is equipped with two 6-DOF robotic arms. Unlike the traditional dual-arm setup which mimics humans, we adopt a heterogeneous design by using a big arm and a small arm. The big arm is 1.5 m with a 10 kg payload capacity, and the small arm is about 0.67 m with a 5 kg payload capacity. Due to the hollow in the centre of the motors, all the wires can run inside the robotic arm. The design purpose is to achieve functional complementation, where the big arm can achieve a 360° wide-range manipulation around the tracked car and the small arm can handle more dexterous manipulation in front of the base, as shown in Figure 4. Besides, this design also allows dual-arm cooperation to accomplish some specific tasks.

To make full use of the limited space on the top of the tracked car, we assemble both arms in the front position of the car with a small displacement between them, as shown in Figure 5. In this way, the two arms can be folded compactly on the car and can also have a good operation space when unfolded, as shown in Figure 6.

2.3 | End effectors

For the selection of the end effector, our principle is to match its function with the capability and role of each arm. For the big arm, we hope the end effector can grab big and heavy objects. For the small arm, the end effector is expected to be able to handle delicate and high-precision tasks. Moreover, we also hope the end effector will be versatile to handle multiple tasks if possible. To this end, we select the end effectors as follows.

First, for the big arm, a soft gripper with four fin-ray fingers is adopted, as shown in Figure 7. This gripper is compliant and can fit to the objects' shape adaptively during


(a) (b)

FIGURE 6 Folded and unfolded configurations of the two robotic arms. (a) Folded configuration, and (b) Unfolded configuration.

grasping. The opening and closing of the fingers are controlled by a ball screw mechanism, which allows the gripper to open up to 20 cm. Although the soft gripper can grasp objects with different shapes and relatively big size, it can hardly hold heavy objects firmly since the fin-ray fingers can only provide limited contact force. To solve this problem, we add a hook to the flange of the big arm. The hook has three claws, which enables it to catch the object from different directions. The strength of the hook is enough to lift the maximum payload of the big arm.

Next, for the small arm, we attach the flange with a quick changer to enable reconfiguration of the end effector. Currently, we have provided it with two end effectors, including a 2-finger adaptive gripper and a pair of electrical scissors, as shown in Figure 8. The two fingers of the adaptive gripper always remain parallel and have a stroke of 106 mm. The electrical scissors can cut wires in explosive ordnance disposal tasks. In particular, we have modified the 2-finger gripper by adding three laser pointers to it: two attached to the fingers and one placed in the middle of the palm. The purpose is to help the human operator identify the relative position of the gripper with the environment or target object, which is difficult when we can only see the 2D images.

2.4 | Reconfiguration module

The quick changer is shown in Figure 9. Unlike most commercial quick changers that are pneumatic, this one here is self-made and electrically powered. It can withstand minor position errors, and the strength of connection is high.

Two holders are designed for each end effector, which is located just behind the small arm, as shown in Figure 10. During operation, the small arm can change the end effector easily to handle different tasks.

2.5 | Cameras

Despite the camera on the mini car, there are three other cameras attached at different positions of the robot, including two eye-in-hand cameras attached to the end of the robotic arms and a pan-tilt camera attached to the first joint of the big

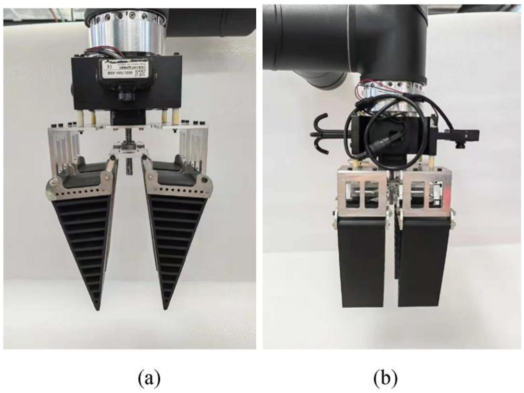
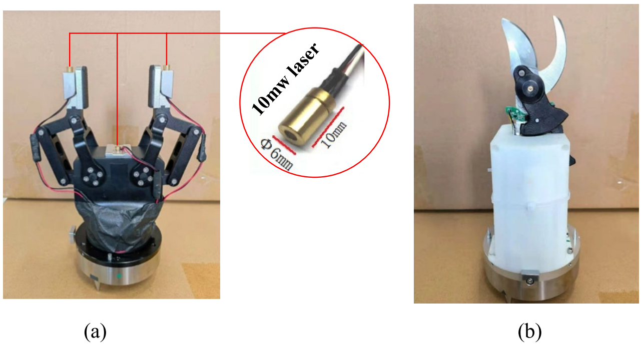

(a) (b)

FIGURE 7 The soft gripper and the hook. (a) Front view. (b) Side view.



(a) (b)

FIGURE 8 2-finger adaptive gripper and electrical scissors. (a) 2-finger adaptive gripper. (b) Electrical scissors.

FIGURE 9 The electrical quick changer

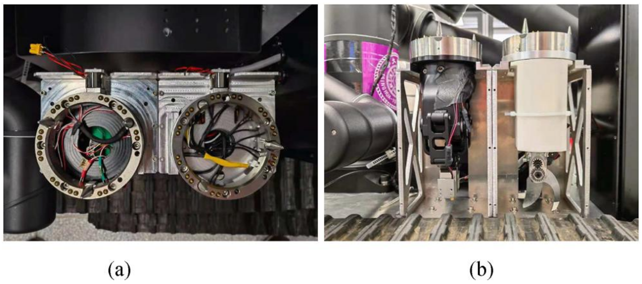

(a) (b)

FIGURE 10 Holder of the reconfigurable end effectors. (a) Top view. (b) Side view.

arm (see Figure 1 for details). The eye-in-hand camera is a Power over Ethernet camera with 500 mega pixels. The pan-tilt camera has 300 mega pixels and can perform 360° horizontal rotation and 163° vertical rotation (see Figure 11). The eye-in-hand camera is mainly used for manipulation, and the pan-tilt camera is mainly used for navigation and searching.

2.6 | Other devices

Some other devices are shown in Figures 12 and 13, including the RF (radio-frequency) modules, which enable the user to operate the robot remotely; an IPC (Industrial Personal Computer) running real time Ubuntu, which controls all the devices in the robot; and gamepads, which are used to control the tracked car and the robotic arms.

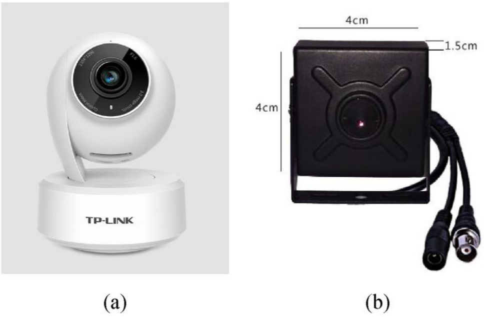


FIGURE 11 Cameras. (a) Pan-tilt camera. (b) Eye-in-hand camera.

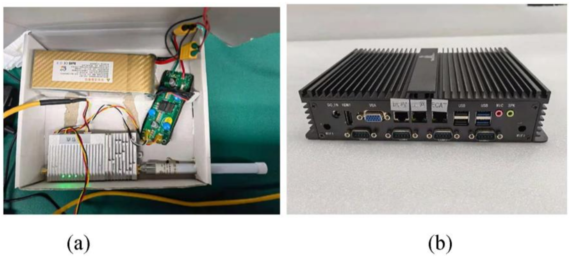


FIGURE 12 Other devices. (a) Radio-frequency (RF) module. (b) Industrial Personal Computer (IPC).

FIGURE 13 The wireless gamepad. (a) Car controller. (b) Arm controller.

3 | SOFTWARE ARCHITECTURE

The overall software architecture is shown in Figure 14. On the user side, there is a laptop and several input devices. The laptop runs on Windows and involves three software programmes, including V-REP, Qt, and VNC, whose functions are described as follows.

1) In V-REP, we build a simulated model of HeterBot and write all the high-level control algorithms. The simulation is responsible for sending all user commands and joint angles to the robot.
2) In Qt, we write a programme to display the real-time image stream from the cameras, which helps the user to obtain information about the robot and the surrounding environments.
3) VNC (Virtual Network Console) is applied to allow the user to inspect and operate the IPC remotely (connected through the RF module).

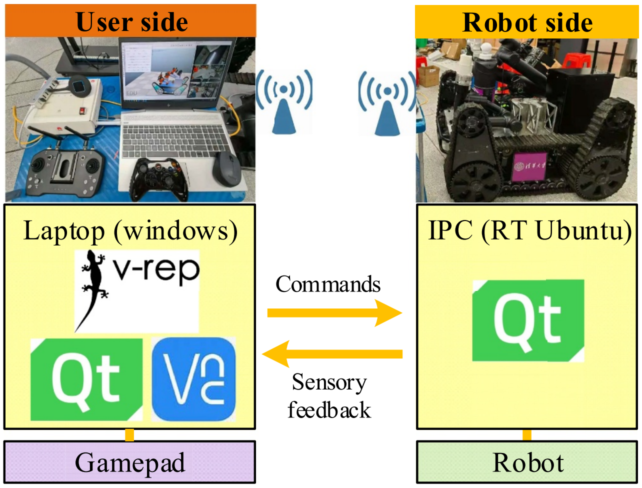


FIGURE 14 Overall software architecture

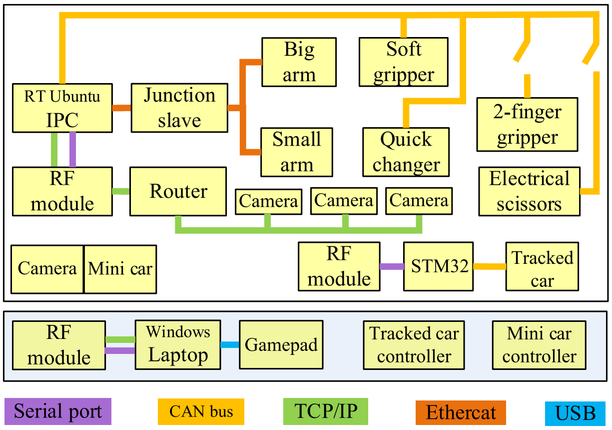


FIGURE 15 The communication architecture of HeterBot

The overall communication architecture of HeterBot is shown in Figure 15. The robotic arms are controlled through Ethercat. The camera signals are transmitted through TCP/IP, and most of the other devices are controlled through a CAN (Controller Area Network) bus. Besides, the robotic arms, the tracked car and the mini car are controlled separately.

The entire user interface, which can be seen by the human operator, is shown in Figure 16. The left is the V-REP panel, which shows the view of the robot and provides buttons as a supplement for the gamepad to operate the robot. The right of Figure 16 shows the real-time surveillance images from the cameras.

Teleoperation is an important way to control the mobile platform and the robotic arm [17, 18]. In this paper, a teleoperation framework is developed based on V-REP. There are two basic operation modes for the robotic arm, including the Cartesian-space and joint-space modes. In the Cartesian-space mode, the end effector can move or rotate along the three axes in the reference frame. This can be easily achieved by using the inverse kinematics in V-REP. We have applied damped least-squares algorithm with a damp of 0.01 to guarantee stability as well as accuracy. To make it more convenient for the operator, two reference frames are provided. One is the base coordinate, and the other is the end effector coordinate. We can switch between them through the button in the V-REP interface. In the joint-space modes, we have predefined several well-designed configurations for the two arms so that the arm can switch to different configurations conveniently. For the big arm, three configurations are defined, including a folded configuration, an operation configuration, and a mini-car grasp configuration. For the small arm, eight configurations are defined, including a folded configuration, an operation configuration, one tool-grasp configuration, and five reconfiguration-related configurations. Besides, we also add buttons for each joint to enable a single-joint movement.

During teleoperation, safety is the most important requirement. Several strategies have been adopted to ensure safety. First, several ways to avoid self-collision have been incorporated into the V-REP programme. For example, joint angle constraints have been set, and Cartesian-space operation is forbidden in folded status. Second, position and force protection mechanisms. The arm will be automatically disabled if the force exceeds the limit or the desired position is largely deviated from the current angle. Third, a synchronisation mechanism is proposed. The wireless transmission might be interrupted during operation, for example, when the distance is too far or too many barriers block the RF signals. In this case, the real robot cannot receive the command and will stop moving. However, the simulation will continue moving if the user operates, which will cause significant deviation between the real and simulated robot. Besides, when the simulation just starts, the status of the real and simulated robot may also have large deviations. To deal with this problem, we let the simulation turn into synchronisation mode when no human operation is detected, as shown in Figure 17. In this mode, the simulation receives the joint angles from the real robot and resets the joint angles to the true values accordingly. Finally, a key release stop mechanism is added. For both Cartesian-space and joint-space operation, the operator needs to hold on to the key to keep moving. Once the operator releases the key, the robot will stop. In this way, it enables the robot to stop during an emergency and thus ensures safety.

This teleoperation framework takes advantage of the powerful robotic simulation software V-REP, which greatly simplifies the software development process. Therefore, we can share the benefits of the physics engine, the rendering engine, and the motion planning algorithms provided by V-REP, which is very user-friendly. In other words, it enables direct transfer from simulation to the real robot. Besides, the system is easy to use. The user can use their own laptop by connecting the RF module and run the V-REP programme.

4 | EXPERIMENTAL RESULTS

The experimental results of HeterBot are introduced in the following. It is highly recommended for the reader to watch the attached video S1 for more information.

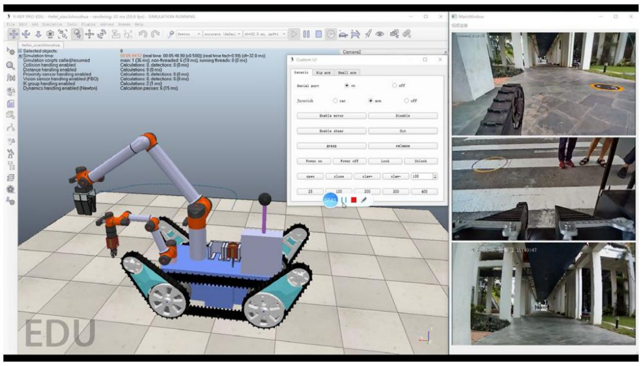


FIGURE 16 Entire view on the operator laptop

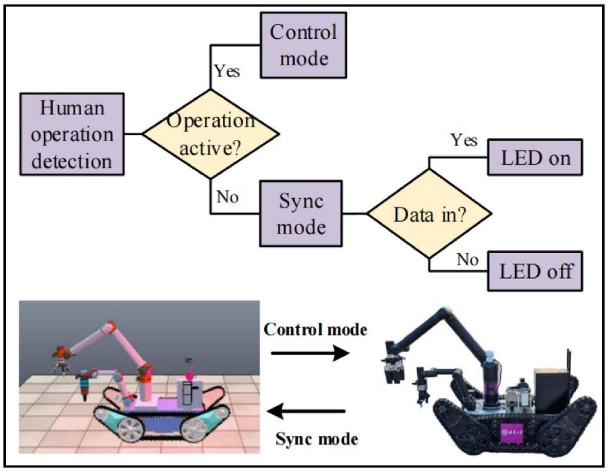


FIGURE 17 Two kinds of operation modes

4.1 | Mobility test

As we have tested, the tracked car can climb regular stairs and cross high steps of about 50 cm (see Figure 18 and the Video S1).

4.2 | Teleoperation

As seen from the video S1, teleoperation using V-REP is feasible and reliable. When the simulation starts, the simulation enters the synchronisation mode, and the simulated robot adjusts its configuration quickly to maintain the same as the real robot. When the user operates, the real robot follows the simulation very well with no obvious delays. We also test the situation when the communication is cut-off, which can happen when the RF connection is lost due to a long distance or barriers. In this case, the real robot does not follow the simulation when the user continues operating. Therefore, the configuration of the simulated robot differs from that of the real robot. However, once the communication recovers, the simulation will synchronise with the real robot soon, which validates the reliability of the teleoperation framework.

4.3 | Big arm grasp

We have conducted three experiments to test the grasping capability of the big arm, as shown in Figure 19. First, the big arm grasps objects with different shapes. The left figure shows the camera view from the mini car, which is very helpful during teleoperation. The soft gripper deforms when contacting the ground, which protects the arm from damage. Second, we put 10 kg weight into a bag, and the big arm lifts the bag with the hook. This verifies the payload capability of the big arm. Third, we transfer the mini car from the storage box on the car to the ground. This is achieved by using configuration control of the big arm. This verifies the mini car releasing capability of the robot.


(a) (b)

FIGURE 18 HeterBot crossing stairs and high steps. (a) HeterBot crossing stairs. (b) HeterBot crossing high steps.

(a) (b) (c)

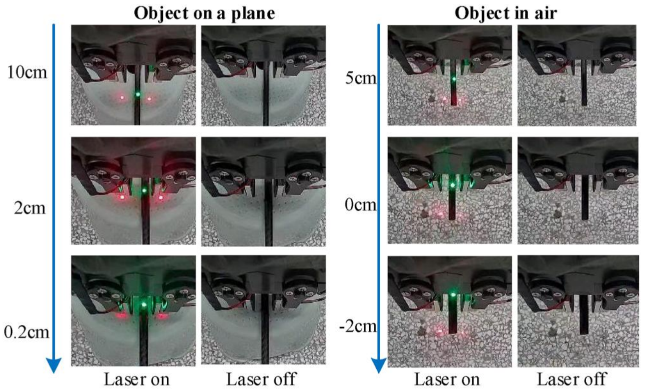
FIGURE 19 Big arm grasping experiments. (a) Camera view from the mini car. (b) Weight and bag. (c) Mini car grasping.

4.4 | Small arm grasp

The two-finger gripper attached to the small arm is suitable for grasping a small object and performing dexterous manipulation. However, one problem is, the user can hardly tell the distance between the gripper and environments from the 2D images. Collision can easily happen if it is not operating properly. The proposed laser-aided strategy can solve this problem. Figure 20 shows the images from the eye-in-hand camera of the small arm when the gripper is approaching the object. Two circumstances are considered here. The first is shown on the left, where the object is placed on a plane. In this case, we should avoid the fingers colliding with the plane. As can be seen, the laser spot on the plane approaches the finger as the distance decreases. When the finger is about to hit the plane, the red spot is just hidden under the finger, which indicates that it is time to grasp. As a comparison, when the laser is turned off, it is difficult to estimate the relative distance. The second one shown on the right is an object in the air. In this case, we rely on the middle laser for judgement. When the green spot is about to disappear, the distance is about -2 cm. Overall, the laser is very useful in teleoperated grasping, which can greatly improve the grasping efficiency in certain applications.

4.5 | Manipulation using tools

Although the 2-finger gripper is good at small object manipulation, it still has limitations in more dexterous operations, such as opening the zipper. People can easily use tools



(a) (b)

FIGURE 20 Images from the eye-in-hand camera. (a) Object on a plane. (b) Object in air.

to accomplish complicated tasks, for example, we use tweezers to clamp tiny objects. Inspired by this, we designed a customised tool for the 2-finger gripper to perform more dexterous operations. As shown in Figures 21–24, the tool has four tiny hooks, which can close or open as it moves in or out of a spring pipe. As seen from the video S1, the tool can easily grasp various tiny objects. We use a steering gear to actuate the tool and remotely control it through V-REP buttons. The tool can be attached to the front right part of the tracked car through hook and loop fasteners. The small arm can reach it, then pinch it using the 2-finger gripper and then use the tool for operation. In this way, we can successfully open the zipper. This provides much more possibilities for manipulation.

4.6 | Dual-arm cooperation

A big arm following mode is developed to allow dual-arm cooperation, as shown in Figure 22. In this mode, the camera on the big arm will maintain a fixed relative position and orientation to the end of the small arm. Therefore, the big arm will follow the movement of the small arm and therefore provide a stable external view of the small arm, which can facilitate the small arm manipulation. By using this mode, we accomplish a delicate task by putting a metal ring in the neck of a bottle and then throwing them together into a circular hole.

4.7 | End effector reconfiguration

The small arm can be reconfigured to different end effectors, as shown in Figure 23. To fulfil the reconfiguration task, we have defined a couple of predefined configurations. During reconfiguration, the end of the small arm first moves to a position beside the end effector holder, then it moves to the next position just above the end effector, then moves down to connect to the end effector, and finally moves away from the holder when connected. The detach process is similar.

4.8 | Bomb disposal task demonstration

To validate the overall performance of HeterBot, a bomb disposal task is conducted, as shown in Figure 24. We hide an assumed explosive in a big wooden box. During the mission, the robot drives into the target position, pushes aside the cover board of the wooden box and grabs the bomb out. Then, it transfers the bomb to a certain place and cuts the wire of the bomb.

5 | CONCLUSIONS

This paper investigates the novel design and technical validation of a versatile mobile manipulation robot named HeterBot. The heterogeneous feature of 'big arm + small arm' and 'big car + mini car' distinguishes HeterBot from other robots and multiple-integrated techniques have greatly improved its versatility and ease of use. More importantly, Heterbot has shown huge possibilities for future extension. For example, despite the mini car, we can also add small aerial vehicles as part of the multi-robot system to enhance its searching capability. For the reconfigurable end effectors, although we selected 2-finger gripper and scissors, other end effectors may also be added to further improve its manipulation capability. In addition, the use of more customised tools also provides a promising way to extend its manipulation capability. Besides,

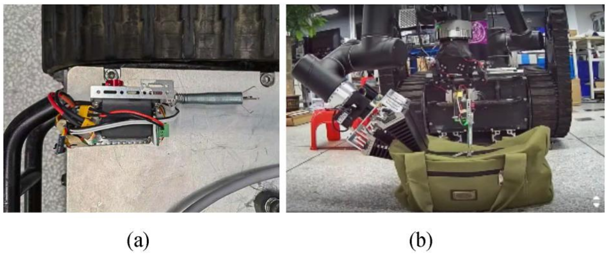

(a) (b)

FIGURE 21 Manipulation with customised tool. (a) Customised tool on the car. (b) Zipper Opening using tool.

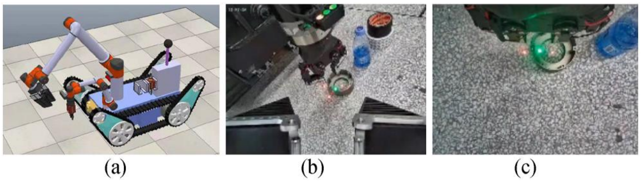

(a) (b) (c)

FIGURE 22 Small arm manipulation in big arm following mode. (a) Big arm camera aimed at small arm gripper. (b) View from big arm camera. (c) View from small arm camera.

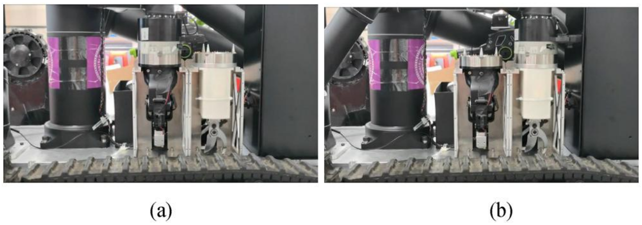

(a) (b)

FIGURE 23 Small arm reconfiguration with different end efffectors. (a) Connected with 2-finger gripper. (b) Connected with electrical scissors.

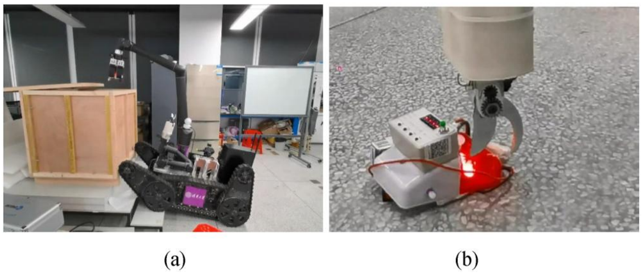

(a) (b)

FIGURE 24 Bomb disposal task. (a) Robot opens box and looks for the bomb. (b) Cut the bomb wire with scissors.

the techniques developed for HeterBot may also be helpful for other applications. For example, the V-REP-based control framework for HeterBot provides a rapid method for robot control design. Laser-aided grasping has also been proven to be very effective in teleoperation, and is worth further study. Currently, the whole system of HeterBot is purely teleoperated, and we will focus on improving its autonomy in the future.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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REFERENCES

1. Bischoff, R., Huggenberger, U., Prassler, E.: Kuka youbot-a mobile manipulator for research and education. In: IEEE International Conference on Robotics and Automation, pp. 1–4 (2011)
2. Vogel, J., et al.: An ecosystem for heterogeneous robotic assistants in caregiving. IEEE Robot. Autom. Mag. 28(3), 12–28 (2020). https://doi.org/10.1109/MRA.2020.3032142
3. Zhang, L., et al.: An autonomous excavator system for material loading tasks. Sci. Robot. 6(55), 1–12 (2021). https://doi.org/10.1126/scirobotics.abc3164
4. Kawatsuma, S., Fukushima, M., Okada, T.: Emergency response by robots to Fukushima-Daiichi accident: summary and lessons learned. Ind. Robot. 39(5), 428–435 (2012). https://doi.org/10.1108/01439911211249715
5. Grigore, L.Ş., et al.: Development and evaluation of the traction characteristics of a crawler EOD robot. Appl. Sci. 11(9), 3757 (2021). https://doi.org/10.3390/app11093757
6. Wenzel, W., Cordes, F., Kirchner, F.: A robust electro-mechanical interface for cooperating heterogeneous multi-robot teams. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 1732–1737 (2015)
7. Krotkov, E., et al.: The darpa robotics challenge finals: results and perspectives. J. Field Robot. 34(2), 229–240 (2017). https://doi.org/10.1002/rob.21683
8. Rouček, T., et al.: Darpa subterranean challenge: multi-robotic exploration of underground environments. In: International Conference on Modelling and Simulation for Autonomous Systems, pp. 274–290 (2019)
9. Bjelonic, M., et al.: Whole-body mpc and online gait sequence generation for wheeled-legged robots. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 8388–8395 (2021)
10. Gianni, M., et al.: Adaptive robust three-dimensional trajectory tracking for actively articulated tracked vehicles. J. Field Robot. 33(7), 901–930 (2016). https://doi.org/10.1002/rob.21584
11. Takemori, T., et al.: Development of the multifunctional rescue robot FUHGA2 and evaluation at the world robot summit 2018. Adv. Robot. 34(2), 119–131 (2020). https://doi.org/10.1080/01691864.2019.1697751
12. Mehling, J.S., et al.: Centaur: NASA's mobile humanoid designed for field work. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 2928–2933 (2007)
13. Kashiri, N., et al.: CENTAURO: a hybrid locomotion and high power resilient manipulation platform. IEEE Rob. Autom. Lett. 4(2), 1595–1602 (2019). https://doi.org/10.1109/lra.2019.2896758
14. Kamezaki, M., et al.: Development of a prototype electrically-driven four-arm four-flipper disaster response robot OCTOPUS. In: IEEE Conference on Control Technology and Applications (CCTA), pp. 1019–1024 (2017)
15. Hudson, N., et al.: Heterogeneous ground and air platforms, homogeneous sensing: team CSIRO Data61's approach to the DARPA subterranean challenge. J. Field Robot. 2(1), 595–636 (2021). https://doi.org/10.55417/fr.2022021
16. Rohmer, E., Singh, S.P., Freese, M.: V-REP: a versatile and scalable robot simulation framework. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 1321–1326 (2013)
17. Dong, P., et al.: Design and control of a tracked robot for search and rescue in nuclear power plant. In: International Conference on Advanced Robotics and Mechatronics (ICARM), pp. 330–335 (2016)
18. Xing, H., et al.: Dual-user haptic teleoperation of complementary motions of a redundant wheeled mobile manipulator considering task priority. IEEE Trans. Syst. Man Cybern. Syst. 52(10), 6283–6295 (2022). https://doi.org/10.1109/TSMC.2022.3144009

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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