Safety-Oriented Teleoperation of a Dual-Arm Mobile Manipulation Robot

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Abstract. Mobile manipulation robots can be deployed to handle various hazardous tasks such as fire fighting, disaster relief, and bomb disposal. Currently, the high-level control of mobile manipulation systems mostly relies on human teleoperation. This paper designs a novel dual-arm mobile manipulation robot and proposes a safety-oriented teleoperation strategy for it. Unlike traditional dual-arm setup which mimics humans, a functional complementary design is adopted by using a longer arm and a shorter arm. The longer arm can achieve a 360° wide-range manipulation around the base, while the shorter arm is aimed at more dexterous manipulation in the front of the base. Then a teleoperation system is designed based on the V-REP software. Three aspects are taken into account to guarantee safety during operation, including the workspace protection based on virtual walls, the self-collision protection based on minimal distance calculation, and the configuration-switch protection based on open motion planning library (OMPL). The effectiveness of the proposed method is verified through simulations and experiments.

Keywords: Dual-arm mobile robot · Teleoperation · Safety-oriented

1 Introduction

In the post-disaster rescue scene and the implementation of specific explosive disposal tasks, mobile robots are put to great use, which can reduce losses and save manpower. But in this situation, the requirement of the robot is very high, it needs to have the capability to cross unstructured terrain, and can respond quickly, stably and safely. At present, the mobile robot is mainly controlled by teleoperation, which allows humans to operate the robot to complete the task without entering a dangerous place. To better complete the task in various scenes, we need to take careful consideration for the structure of each module and the design of the robot control algorithm. The structure of a mobile manipulation robot mainly includes a mobile base and a manipulation system.

According to the structure of the mobile base, the categories of ground mobile robots can be divided into wheeled, tracked, and legged robots. One of the main challenges for

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ground mobile robots is the movement in complicated environments [1]. Wheeled robots have advantages in moving on smooth ground, which can move at high speed and has good steering flexibility [2]. The control of wheeled robots is simple and the energy consumption is lower than that of tracked and legged robots. However, the wheels need to be designed very large to pass through an uneven road. Legged robots such as Atlas and Spot from Boston Dynamics and MIT cheetah [3] are very famous. Legged robots have a strong capability to deal with unstructured terrains, but the control of the robot is complex [4]. The wheeled-legged hybrid mobile robot combines the advantages of wheeled robots and legged robots, but the cost is very high [5]. Tracked mobile robots have good adaptability to unstructured terrain and are easy to control. There are many excellent tracked mobile robots as can be seen from the RoboCup-Rescue competition, which aims to create rescue robots that can be used after a disaster. In the RoboCup competition of 2013, new tracked mobility apparatuses overcome the alternative version of the stepfield built of concrete blocks [6]. And a tracked robot VIKINGS is introduced in [7], which has mobile flippers that can help the main track to cross more difficult terrains. To sum up, tracked robots (especially when equipped with mobile flippers) can cross large obstacles and is easy to control, which has great potential to be used in complicated environments.

In terms of the manipulation system, a mobile manipulation robot can have single or multiple manipulators. In the 2014 World Cup in Brazil, a mobile robot named "Pack-bots" [8] with a retractable arm and a tactile claw helped deal with security problems. But the range of motion of a mobile robot with one manipulator is usually limited. For the design of multiple manipulators, most of them are in the form of a dual-arm setup that mimics humans. For example, Centauro [9] has a design with wheels at the bottom of its four legs (like a quadruped with wheels), and its head and humanoid arms are connected to the upper torso in a human form. Robots with humanoid arms can achieve coordinated control, but the workspace is still limited, especially for ground objects. It is of great significance to design new types of multi-arm systems that can achieve wide-range operation (like an excavator) as well as coordinated control.

Motivated by the above work, we design a novel dual-arm mobile manipulation robot. The main advantages of our robot are as follows. First, for the mobile base, we adopt tracks along with the front and rear flippers, which allows the robot to have excellent mobility to cross large obstacles and unstructured terrains. Second, for the manipulation system, we adopt a novel dual-arm design with a longer arm and a shorter arm, so it not only has a large workspace but also can perform fine operations. The longer manipulator can grasp objects in a wide range like an excavator, while the short manipulator can perform more precise operations in a close range. Third, we take advantage of the powerful robot simulator V-REP [10] along with a joystick to control the robot. We can use the joystick to control the simulated robot in V-REP and the real robot at the same time, which is more intuitive and effective. We also designed several algorithms including the workspace protection based on virtual walls, the self-collision protection based on minimal distance calculation, and the configuration-switch protection based on the open motion planning library (OMPL) to ensure safety. Simulation and experimental results demonstrate that the proposed methods can guarantee safety effectively during teleoperation.

The rest of this paper is organized as follows. Section 2 introduces related work on robot teleoperation. The overview of the robot design is described in Sect. 3, followed by the teleoperation strategy in Sect. 4. Section 5 describes the simulation and experimental results. Conclusions are given in Sect. 6.

2 Related Work

2.1 Teleoperation Forms

At present, the forms of teleoperation mainly include visual teleoperation, tactile teleoperation, teleoperation by control interface and so on. Reference [11] introduces visual teleoperation based on gesture recognition which explored the similarity of the human arm and robot arm in appearance and anatomy, then enriched the local features of the reconstructed image. But visual teleoperation is based on gesture recognition, the operator may feel uncomfortable in long-time teleoperation, and it is difficult for high-precision tasks. In [12], a telerobot system Rokviss was designed, which provides tactile feedback for ground operators. It has force feedback and can provide more detailed information, but it has a complex structure and high cost. In [13], to control the UR manipulator, an appropriate control interface is designed to have a comprehensive grasp of the task.

In this paper, we take advantage of the powerful robot simulator V-REP and a joystick BTP-2185T2 (Fig. 1) to control the robot, which is convenient and intuitive. We can control the movement of the manipulator in Cartesian space mode with two vertical control rods, control the movement of the tracked vehicle with the left button, and perform special functions and joint space moving through the right and upper buttons.

Fig. 1. Function assignment for the joystick.

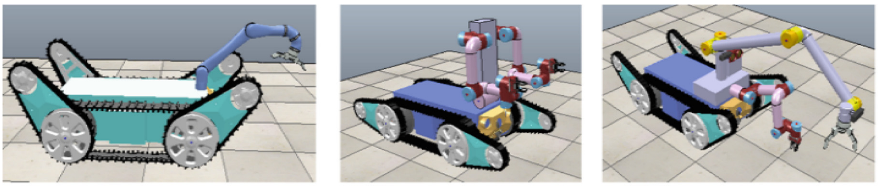
2.2 Teleoperation Algorithms

Mobile robots need to have optimized algorithms to better meet the task requirements. Reference [14] considers the trajectory planning to avoid collision. They used a 3D model of the environment based on the OctoMap library. Using the method of reachability planning, the observation configuration of the given target configuration is generated automatically. This method improves the robustness of the robots, but when there are multiple manipulators, we need to further consider the interaction between the manipulators. In [15], Niklas Litzenberger's mobile robots have nuclear sensors, cameras and a mechanical claw. The robot can operate remotely and autopilot to return. It is improved in shape design to prevent the collision, and the arm can ensure safety when disconnected. In [16], there are two control modes for the manipulator of a mobile robot, one is the operation of the twist position based on the cellular coordinate system, the other is an operation based on the hand coordinate system. This design is more convenient for operation.

In this paper, the teleoperation algorithm is designed in the V-REP environment. The teleoperation includes two basic modes. One is the Cartesian space control, which allows the end effector of the manipulator to move in the three axes in 3D space. The other is joint space control, which allows the manipulator to switch between different configurations conveniently. Besides, we also design three algorithms to ensure safety during teleoperation, including workspace protection, self-collision avoidance, and autonomous trajectory planning. The proposed framework offers some advantages compared to other teleoperation algorithms. On one hand, we take advantage of the powerful tools in V-REP, such as inverse kinematics solver and minimum distance calculator, which is easy to implement. On the other hand, the additional protection algorithms can guarantee safety for dual-arm manipulation, so damages can be prevented due to inappropriate operations of the operator.

3 Overview of the Robot Design

As can be seen from Fig. 2, there are several options for the arm design. The first is the single-arm design. For a short arm, the operation range is small and the task it can accomplish is limited. For a long arm, although the operation range is large, it is difficult to perform fine operations near the base. The humanoid dual-arm design can perform some fine tasks and has more flexibility than single-arm design, but its operating range is still small and it is not convenient to operate near the ground. Therefore, we proposed a new dual-arm design (see Fig. 2c), which uses complementary long and short arms. It combines the advantages of the big arm and the small arm. The long arm can achieve a 360° wide-range manipulation around the base, while the short arm is in charge of more dexterous manipulation in the front of the base. A detailed comparison of the three manipulator designs is listed in Table 1.



(a) Single-arm design (b) Humanoid dual-arm (c) Design with long and short arms

Fig. 2. Comparison of three kinds of manipulator design

The main structure of the proposed robot is shown in Fig. 3. The main track and flippers can have configuration combinations to deal with various complex terrain. The designed robot can be applied to find explosives, extract explosives and carry out bomb removal tasks. Besides, it can help search and rescue in disaster areas. Several cameras are installed on the robot to facilitate teleoperation.

Table 1. Comparison of manipulator design

Type of manipulator	Operation range	Fine operation	Cooperative operation
Single long arm	Wide	Limited	Unavailable
Single short arm	Limited	Fine	Unavailable
Humanoid arms	Limited	Fine	Fine
A longer arm and a shorter arm	Wide	Fine	Moderate

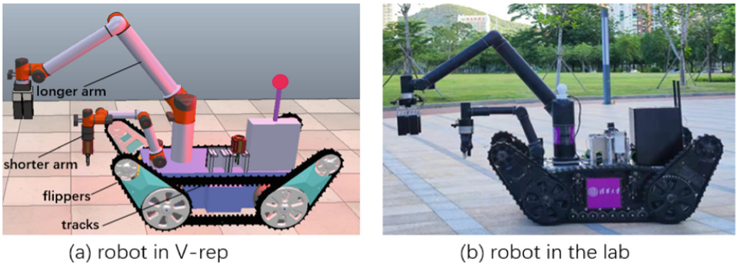


Fig. 3. The main structure of the proposed robot

4 Teleoperation Strategy

To make mobile robots perform tasks more safely, we designed the workspace protection based on virtual walls, the self-collision protection based on minimal distance calculation, and the configuration-switch protection based on open motion planning library (OMPL).

4.1 Teleoperation Framework

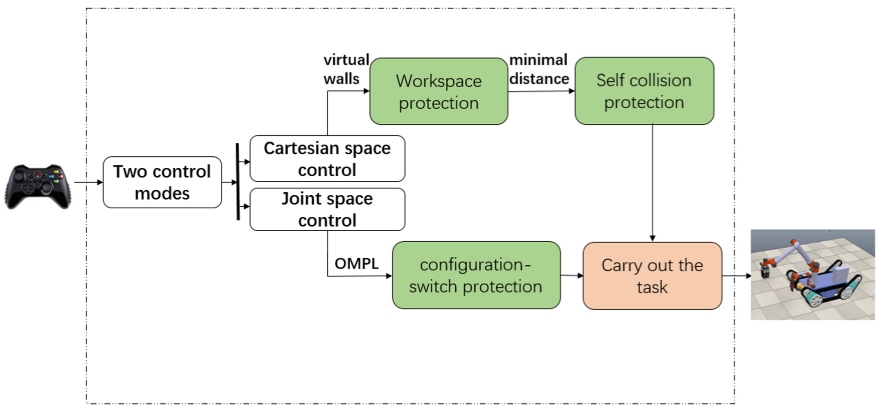


Fig. 4. Control mode and protection measures.

There are two kinds of control modes for the manipulator of the mobile robot. One is Cartesian space mode, the other is joint space mode. Our joystick can control the movement of the mobile robot, the movement of the long and short manipulator, and the switch of the control modes of the manipulator (Fig. 4).

Mode 1: Cartesian Space Mode
In Cartesian space mode, the end of the manipulator can move in a straight line. The space increment of x, y and z directions of the manipulator end is given by the joystick. The manipulator can move by using the inverse kinematics solver in V-REP.

Mode 2: Joint Space Mode
The angle of each joint angle is controlled, the expected value of each joint angle is set in advance, and the value of the current joint angle is obtained. The movement of the manipulator is completed by continuously reducing the difference between the current angle value and the expected angle value of each joint. The start and end of the movement can be controlled by the joystick. The changes of joint angle are as follows:

$$cq[i] = cq[i] + 0.1\tanh\left[2(cf[i] - cq[i])\right] \tag{1}$$

where is $cq[i]$ the i-th joint angle, $cf[i]$ is the expected value of the i-th joint angle. Through the above formula, the error between the current angle and the desired angle can be continuously reduced to achieve the desired configuration.

4.2 Workspace Protection

In teleoperation, it is found that when the end of the manipulator approaches the boundary of the workspace, it will not only affect the work task, but also bring potential safety hazards. Therefore, this situation must be avoided (Fig. 5).

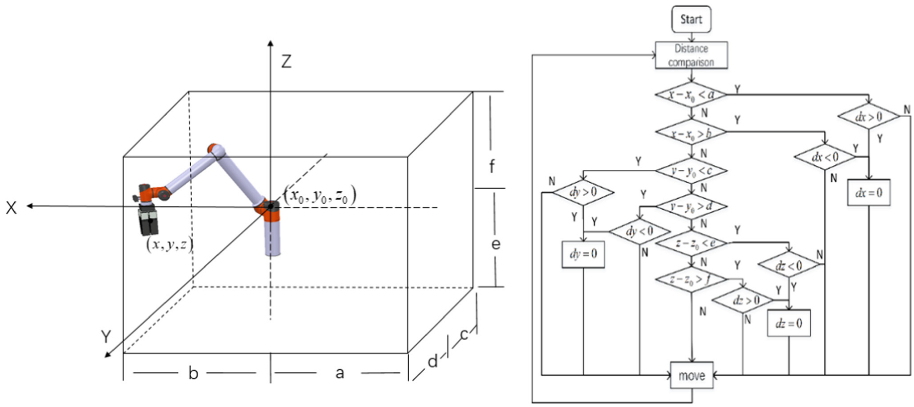


Fig. 5. Workspace protection.

We set a workspace limit. Taking the base of the manipulator as the origin, the distance from the workspace boundary to the origin is set:

$$\begin{aligned} a \le x - x_0 \le b \\ c \le y - y_0 \le d \\ e \le z - z_0 \le f \end{aligned} \tag{2}$$

$$a,\ b,\ c,\ d,\ e,\ f \in R \tag{3}$$

where $(x_0,\ y_0,\ z_0)$ is the coordinate of the origin, and $(x,\ y,\ z)$ is the coordinate of the end of the manipulator. Because the base of the manipulator is taken as the center origin, the point most likely to exceed the workspace is at the vertex of the cube:

$$\begin{aligned} |\vec{\alpha}|^2 \le \max\Big\{ & b^2 + d^2 + e^2, b^2 + d^2 + f^2, \\ & a^2 + c^2 + e^2, a^2 + c^2 + f^2 \Big\} \end{aligned} \tag{4}$$

where $\vec{\alpha}$ is the vector from the base to the end of the manipulator. Because of the symmetry, we only need to compare the maximum of the four distances.

The six sides of the cube workspace protection are like virtual walls. When the end of the manipulator is in the workspace, it can move freely. Only when the end of the manipulator moves to the boundary of the virtual wall and moves away from the base, the increment of Cartesian space operation will be cleared, which completes the protection of the workspace. The length, width and height of the cube are set according to the task and the workspace of the manipulator.

4.3 Self-collision Protection

When we remotely operate a mobile robot, we don't want the robot arm to touch the robot itself in the process of moving. But in practice, although there is a camera that can detect the movement of the manipulator in real-time, the manipulator may still encounter obstacles in the process of Cartesian space control. We hope to use a simple algorithm to avoid self-collision. When the distance between the manipulator and the obstacle is less than the threshold, the movement of the manipulator is forbidden, so the collision can be avoided. The algorithm flow chart of this design is shown in Fig. 6.

We set three states to complete this function. Firstly, the safety distance is set as the threshold, and the shortest distance between the manipulator and the other parts of the robot is obtained by using the minimal distance calculator in V-REP. When the shortest distance reaches the threshold, it switches to intermediate state 1, and the motion of the manipulator is limited. When the teleoperation signal is detected, it will switch to state 2. According to the shortest distance, it will judge whether it is slightly adjusted under the limit of state 1 or normal operation in state 0. The constant d0 is a value slightly smaller than the threshold value, which is convenient for a slight adjustment in state 1. We confirm that there is no collision when the shortest distance is close to d0.

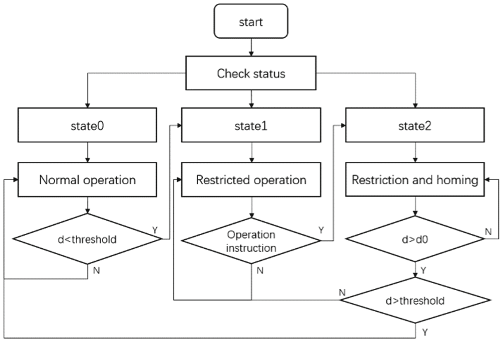


Fig. 6. Self-collision protection flow chart

4.4 Configuration-Switch Protection

As shown in Fig. 7, to make the mobile robot complete the task better through teleoperation, we designed several configurations for the robot arm in advance. One configuration is that the mobile robot is easy to move. At this time, the manipulator folds up. The other is the configuration that is convenient to operate the objects on the ground. At this time, the manipulator is extended. Because our mobile robot has two robotic arms, they all have complex postures. Therefore, in the process of configuration switching, it is necessary to ensure that there is no collision between the manipulators.

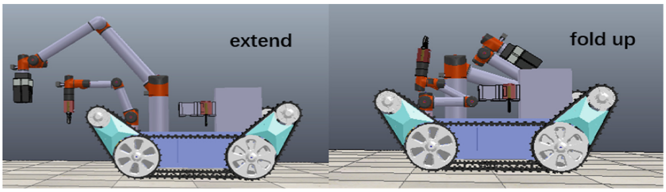


Fig. 7. The configurations of the arms.

To avoid collision, we use the OMPL library, call the RRT-connect algorithm to optimize the path between different configurations: RRT algorithm generates multiple random points according to the step size L at the same time, then selects the best point considering the index of avoiding obstacles and the closest target point. Every step L, we select the best point of a path and then connect them in turn. So we get a collision-free path from the starting point to the endpoint. As an improvement, RRT-connect can generate paths from both sides at the same time, which improves efficiency.

The basic ideas of RRT are shown in Fig. 8. Denote C as the reachable Cartesian space of the robot arm, and (x, y, z) can be used to represent the end position coordinates of the robot space. Let G_k be the workspace random tree of the manipulator with k nodes, x_{start} be the initial state and x_{goal} be the target state. x_{randm} is a random point in C space. Traverse the random tree G_k. L is the search step length, $p, \ q \in C, \ d(p, \ q)$ is the geometric distance between two pose in space, if $L \leq d(x_{near}, \ x_{randm})$, then find

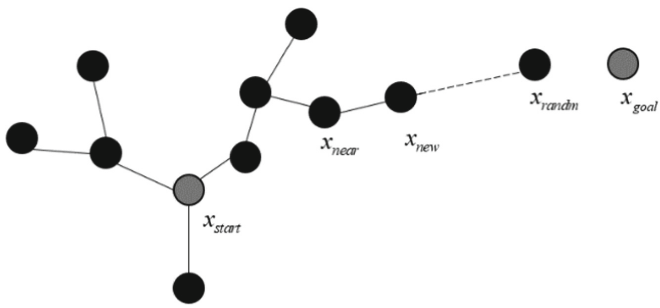


Fig. 8. Basic ideas of RRT.

x_{new} on the line between x_{near} and x_{random}, make $L = d(x_{near},\ x_{new})$. If x_{new} exists and there is no collision with obstacles at any point of the connecting line between x_{near} and x_{new}, a new node is added to the random tree. Otherwise, a new set x_{random} is selected and the above process is repeated until the target point is reached. We use RRT connect, which is expanded from both ends of the starting point and the target point [17]. The expansion formula is as follows:

$$x_{new} = x_{near} + L * \frac{(x_{randm} - x_{near})}{\|x_{randm} - x_{near}\|} \tag{5}$$

Based on RRT connect, the obstacle avoidance motion planning algorithm of the manipulator is applied to plan a collision-free path from the start configuration to the target configuration.

5 Simulation and Experimental Results

The effectiveness of the designed algorithm is verified through simulation environment V-REP and experiments. The video of experiments can be found in:

https://www.bilibili.com/video/BV1DY411M7Zp?share_source=copy_web.

5.1 Workspace Constraints

We set up a simple cube as the workspace of the manipulator. The limit length, width, and height of the cube workspace are 2.4 m, 1.3 m, and 1 m respectively.

Make the manipulator move away from the origin. When the end of the manipulator exceeds the workspace, vibration may occur, which may bring danger to the robot and affect the work task. By comparing the situation with and without space protection, as shown in the Fig. 9, the situation with protection can effectively ensure safety.

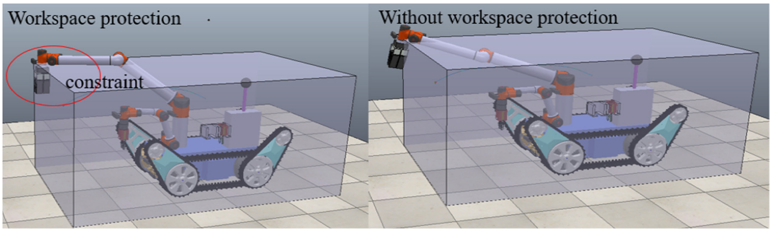


Fig. 9. Space limitation of a manipulator.

5.2 Self-collision Protection

To verify the effectiveness of the algorithm, we control the longer arm in Cartesian space to move towards some objects that are easy to collide, such as the shorter arm, flippers. In Fig. 10, the red circle marks the place where self-collision is likely to occur.

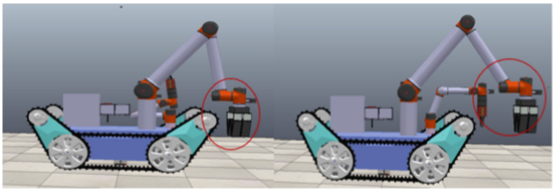


Fig. 10. The most likely part to collide with the longer arm (the flippers, and the shorter arm). (Color figure online)

We set the threshold of the shortest distance to 0.05 m. During the experiment, we move the long arm in the direction of the short arm through the joystick (see Fig. 11). The red arrow is the movement direction of the longer arm. The lower part of the picture corresponds to the state of the joystick of each process. When the manipulator is very close to the easily colliding object, it will stop moving though the joystick continues to output commands. Next, we can make the longer arm move away from it by teleoperation.

Similarly, when the longer arm moves near the flippers, it will stop when it approaches the minimum distance threshold, which proves the effectiveness of the algorithm.

5.3 Configuration Switch

When the robot is performing a task, the manipulator can switch between different configurations. By optimizing the trajectory, we can avoid collisions and interference between the two arms.

We make the manipulator move from a preset configuration to a random configuration and then move to another preset configuration. We design a random value for the joint angle of the longer manipulator and determine whether this configuration is safe so that this configuration is random. This method is repeated many times to verify the effectiveness of the algorithm.

Fig. 11. The process of the longer arm approaching the object easy to collide (Color figure online)

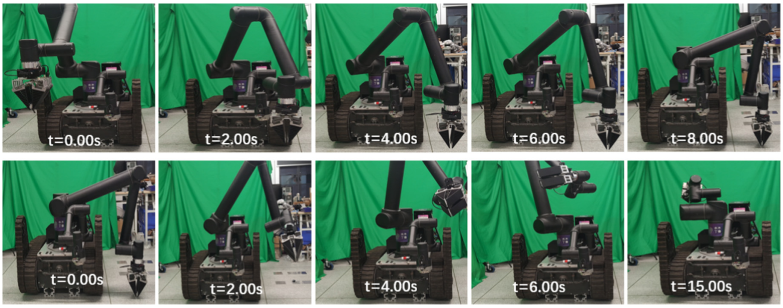


Fig. 12. Trajectory planning with no collision between the two arms

In the experiment, we did a lot of tests. The longer arm switches between the two kinds of pre-designed configurations and random configuration arbitrarily, and there was no collision. One case is listed in Fig. 12, t is the time of the each movement. The first row is the motion planning from extended configuration to random configuration, and the second row is the planning from random configuration to folded configuration.

6 Conclusion

We have designed a dual-arm mobile manipulation robot that can demolish explosives and rescue in a dangerous environment. By using V-REP along with a joystick, an intuitive and effective teleoperation interface is designed. At the same time, the workspace protection based on virtual walls, the self-collision protection based on minimal distance calculation, and the configuration-switch protection based on OMPL can guarantee safety during operation. Through simulations and experiments, it is found that the robot has accomplished the task excellently. We have also applied our algorithms in the A-TEC Advanced Technology & Engineering Challenge (https://atec.leaguer.com.cn/), which has won the second place. Mobile manipulation robots can play a huge role in disaster relief and explosive disposal tasks. The robot we designed has strong locomotion ability and effective algorithms to ensure safety, which makes it promising to be used in real task scenes. In the future, we will optimize the configuration-switch protection, such as the shortest time or the most energy-saving.

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