Two multi-linked rescue robots: design, construction and field tests

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Received 11 March 2016

Abstract
Rescue robots that can penetrate into narrow gaps in the rubble, create and maintain spaces for rescuers after earthquakes are urgently needed in search and rescue missions. This paper proposes two novel rescue robots, including a cutting robot and a jack robot, which are used to cut obstacles and jack up heavy debris in hazardous locations and in narrow spaces, where rescuers cannot work or approach. Firstly, a multi-linked tracked, or snake-like rescue robot platform is designed, which is composed of modular crawler vehicles connected by active and passive joints with three degrees of freedom. This rescue robot platform has high mobility on irregular terrains and the ability to move into narrow collapsed structures. Then, portable rescue tools including an electric cutter and a novel electric screw jack are designed. In order to perform operations to the tools, manipulators with multi degrees of freedom are also developed. Consequently, the cutting robot and jack robot are realized by equipping the corresponding rescue tool and manipulator in the rescue robot platform. Finally, field tests of the two rescue robots operating on different terrains and performing rescue missions are carried out in the national training base for urban search and rescue. The results validated the mobility, cutting and lift-up capacity of the two rescue robots. The experiments show that they might play some role in rescue operations.

Key words: Rescue robot, Multi-linked robot, Field test, Jack robot, Cutting robot

1. Introduction

Natural disasters such as earthquakes occur regularly, and cause heavy losses to the lives and property of the people in disaster-hit areas. It is proved in practice that victims are much more likely to survive during the window period of 72 hours for relief efforts after earthquakes; once over 72 hours, the chances of survivals are getting much smaller due to body injuries and lack of food and water. Fast and effective rescue plays a significant role after such disasters. Therefore, quite a variety of rescue robots which can increase the efficiency of rescue operations have been developed.

Depending on the tasks to be completed, rescue robots can be roughly divided into two categories. The first category of rescue robots, mostly equipped with gas detectors, radiation sensors and infrared cameras, are used to search victims and collect information in unknown dangerous environment (Micire, 2002). Many research groups have developed such robots. One of the well-known examples is the Souryu series rescue robots developed by Tokyo Institute of Technology, which are a kind of connected crawler vehicles that can travel in rubble (Takayama et al., 2003; Masayuki et al., 2004; Arai et al., 2008). Some rescue robots like HELIOS VIII are also mounted with a manipulator to accomplish some simple operations, for example, opening of the door and grasping of objects (Guarnieri et al., 2007). The second category of rescue robots which are not so many, aim to accomplish missions that need big power, for instance, cutting obstacles, jacking up heavy debris, and carrying victims. A series of jack robots named Bari-bari were designed by Tokyo Institute of Technology (Tsukagoshi et al., 2004, 2006, 2008). Researchers of Okayama University proposed a jack robot and a cutting robot driven by hydraulic actuators (Tanaka et al., 2005a; Tanaka et al., 2005b; Mori et al., 2005), which were able to cut obstacles and make spaces for other rescue robots to go into the debris.

According to the lessons from the search and rescue missions in ruins during Wenchuan earthquake in China's...
Sichuan province, National High Technology Research and Development Program of China funded “Public Safety and Rescue Robot Project” to develop a series of rescue robots to assist rescuers more efficiently, including robotic spreader (Zhang et al., 2014), jack robot (Zang et al., 2013; Zang et al., 2014), cutting robot (Zang et al., 2015), and lower extremity assistive exoskeletons (Zhu et al., 2013; Zhu et al., 2014). As part of this project, two novel rescue robots - a cutting robot and a jack robot have been developed. There are two main improvements in the proposed robots to make them more practical compared to the existing above mentioned cutting robots and jack robots. The first is power source. Although hydraulic actuators are suitable for heavy-duty rescue operations, their workspace is usually limited by hydraulic tube. So lithium batteries are used as the power source of the robots. In particular, a novel electric screw jack which is compact, self-contained and high-powered has been designed. The second is driving mechanism. In order to enforce the mobility on rugged terrains, multi-linked tracked driving mechanism has been adopted. The high performance of this kind of driving mechanism in urban rescue operations has been confirmed by researches (Arai et al., 2008).

The rest of this paper is organized as follows. Section 2 shows the main design idea of the two rescue robots. Section 3 introduces the system design and realization. The process and results of field tests are presented in Section 4. And some conclusions and remarks are given in Section 5.

2. Main design idea

The two rescue robots can accomplish search and rescue missions such as searching victims, cutting obstacles, jacking up debris, creating and maintaining passages in narrow spaces in post-disaster locations. Thus, there are several essential and important requirements for the robots, namely high mobility on irregular terrains, compact structure to be able to go through crevices and into tight spaces, as well as the ability to carry out rescue operations with equipped rescue tools.

To achieve the above tasks, the two rescue robots are developed following the steps described below. First of all, a snake-like rescue robot platform is designed using modular design method. The platform is composed of several modular crawler vehicles connected by joints with multi degrees of freedom (DOF). All the components are mounted inside the platform, resulting in a long and thin structure that enables the platform to enter narrow passages in the ruins. The independently driven crawlers make the platform highly mobile in post-disaster sites. After that, portable rescue tools including a cutter and a jack are designed. Then, in order to realize operations to the tools, manipulators with multi DOF are developed. By equipping the cutter or the jack and the corresponding manipulator inside the front segment of the platform, the cutting robot and jack robot are realized, as shown in Fig. 1.

![Fig. 1 Schematic diagram of the modular rescue robot.](image)

Fig. 1 Schematic diagram of the modular rescue robot.

Fig. 2 depicts the working images of the cutting robot. The cutting robot first moves to the obstacles controlled remotely by the operators. Then the cutter which is fixed at the end of the manipulator stretches out of the robot, adjusts to an appropriate pose for cutting and starts working. When finished, the cutter moves back to the inside and continues to the next task.

![Fig. 2 Working images of the cutting robot.](image)
Fig. 3 shows the working images of the jack robot. When reaching the destination place, the manipulator takes the jack out of the robot and puts it at a specified point for jack-up operation. Then the jack lifts up the debris to release buried survivor from pressure. Afterwards, one more jack tool can be easily equipped to the robot which provides common interface for the next task.

Fig. 3 Working images of the jack robot.

3. System design and realization

3.1 Modular rescue robot platform

Based on modular design method, a multi-linked rescue robot platform is designed. As the virtual model shows in Fig. 4, it is composed of two identical crawler vehicles connected by a special three dimensional joint mechanism. Fig. 5 presents the structure of the joint mechanism, which has two layers. The upper layer includes two parallel active driving limbs. Each limb is composed of a driving motor located in the rear segment and a ball screw with universal joints on both end. The lower layer consists of junction plates with 3 DOF: pitch, yaw and roll. The DOF of pitch and yaw are actively controlled by the parallel limbs, while the DOF of roll is controlled by a brake. When the brake is engaged, the parallel limbs assure the joint mechanism of high stiffness and large load-bearing capacity. When the brake is released, the roll motion enables the segments to adapt to uneven surfaces for larger ground contact area. Fig. 6 illustrates the workspace of the joint mechanism. The maximum angle of elevation and angle of depression are 33° and 40° respectively, and the maximum yaw angle is 29°. The combination of tracks and flexible joints allows the rescue robot platform to move across irregular terrains and climb over vertical obstacles.

Fig. 4 Virtual model of the modular rescue robot platform.

Fig. 5 Structure of the joint mechanism.
Fig. 6 Workspace of the joint mechanism.

Fig. 7 shows the overview of the prototype of the rescue robot platform, which is about 1100 mm long, 260 mm wide and 220 mm high. Its weight is about 30 kg. The rescue robot platform uses lithium batteries as the power source. Main components including batteries, voltage converters, servo drivers, and motion controller are all equipped in the rear segment, leaving enough space for rescue tools in the front one. Two cameras are installed on the top of each segment to provide visual feedback to the operator.

Fig. 7 Prototype of the rescue robot platform.

Designed on the basis of modular design method, configuration of the rescue robot platform can be easily changed by adding more segments at the end in accordance with practical demands. Fig. 8 presents the virtual model of a three-linked tracked rescue robot platform. With respect to three-linked rescue robot, different kinds of rescue tools can be equipped in the front and rear segments to accomplish more rescue operations. And it has better obstacle climbing capability but bigger size and heavier weight compared with two-linked rescue robot.

Fig. 8 Three-linked tracked rescue robot platform.

3.2 Cutting robot

Fig. 9 The manipulator of the cutting robot.
The cutting robot is realized by equipping a cutter and a manipulator in the front segment of the rescue robot platform. The manipulator totally has three DOF - one translational DOF and two rotational DOF, as illustrated in Fig. 9. The rack is fixed on the body frame of the cutting robot. When the motor rotates, the manipulator moves along the rack, extending outward from the front segment. By rotating around joint 1 and joint 2, the cutter which is mounted at the end of joint 2 can adjust its position and orientation relative to the obstacles. In initial state, the manipulator is folded inside the robot. While cutting obstacles, it is deployable. The cutter uses a high speed whirling circular saw to cut obstacles made of steel, stone and woods. It can cut through steel bars with a maximum diameter of 10 mm. Fig. 10 presents the prototype of the cutting robot.

3.3 Jack robot

Analogously, the jack robot of which the prototype is presented in Fig. 11 is realized by equipping a jack tool and a manipulator in the front segment of the rescue robot platform. Fig. 12 shows the structure of the manipulator of the jack robot. The gear meshes with a rack which is fixed on the body frame of the jack robot. When the gear is driven to rotate, the manipulator extends outwardly along the rack. There is an electromagnetic gripper at the front of the manipulator to grasp and release the jack tool. A novel kind of high-powered electric jack tool, which is fully self-contained and small sized for portable use, is designed for the jack robot. The size of the jack tool shown in Fig. 11 is 180 mm in length, 130 mm in width and 120 mm in height. Its weight is about 4.5 kg. The jack tool can lift heavy loads weighing 500 kg up to 410 mm. In no-load condition, its lift-up speed is about 180 mm/min; while under the maximum load, the lift-up speed is adjusted to 90 mm/min to obtain a proper operating current of the driving motor. It should be noted that to satisfy the demands for different lift-up capacities, several jack tools with different sizes are developed in our project, and their details are not covered here.
In order to achieve a small size and a large travel distance at the same time, the jack tool adopts the structure of multiple layers screw sleeves that combines the basic theories of helix transmission and creative design. Fig. 13 presents the internal structure of the jack tool. The jack tool consists of motor, harmonic gear retarder, gears, multi screw sleeves, folding bracket and stand. The innermost sleeve has only external thread; the outermost sleeve has only internal thread; and other sleeves have both internal and external thread. Each inner sleeve is connected to outer sleeve through screw thread. The innermost sleeve is connected with the base by folding bracket. Harmonic gear retarder is used to enlarge the driving torque of motor to meet the demand for high power.

Working principle of jack-up process is depicted as follows. When the motor rotates, outermost sleeve is driven to rotate by gear transmission. Since the rotary motion is limited by folding bracket, the innermost sleeve can only move upward and then lift up the load. When the first sleeve reaches the limit position, the second sleeve is pulled to move upward along with the first one. Based on this, the stand on the top of jack tool continually rises until reaching the maximum height. Due to the self-locking effect of helix transmission, the jack tool can support the load steadily even if the motor is power off and stops running. Similarly, when the motor rotates in the opposite direction, each sleeve moves back to the initial position. In this way, the jack tool is realized. Considering that the load may incline when being lifted up, the stand is mounted on the oscillating bearing, enabling the stand to fit with the surface of the load.

The jack tool is required to support heavy load steadily and reliably in the rescue process. So it is necessary to verify the strength and security of the jack tool when bearing heavy load before processing. Finite element analysis is accomplished using the software ANSYS Workbench. Import the virtual prototype model of the jack tool built in Pro/E into ANSYS Workbench and set material properties, contacts, element size and external load for each part. After solving, the equivalent stress contour and elastic strain contour are obtained, shown in Fig. 14. The analysis results indicate that the stress and strain of jack tool meet the design requirements.

![Fig. 14 Finite element analysis results including stress nephogram (left) and strain nephogram (right) of the jack tool.](image-url)
3.4 Control system

The control system hardware architecture of the rescue robots consists of three layers – operation box, robot system and execution unit, as shown in Fig. 15. The operation box, illustrated in Fig. 16, includes microcomputer, monitor, wireless module, knob, joysticks and buttons. The robot system includes motion controller, wireless module and cameras. And the execution unit includes servo drivers, motors and encoders. The microcomputer communicates with the robot system through Modbus protocol via wireless networks, sending commands to the motion controller, and receiving returned data. The servo drivers are connected to the motion controller via CAN bus, ensuring the control system a high expansibility.

![Fig. 15 Hardware architecture of the control system.](image)

![Fig. 16 Picture of the operation box.](image)

![Fig. 17 Camera views of the jack robot.](image)
Watching the robot directly or the view from the cameras displayed on the monitor in real time, operators can control the rescue robot remotely using the operation box. The wireless communication modules can work stably and reliably at a distance of 30 meters. The focal length of the cameras is 2.8 mm, providing a horizontal field angle as wide as 90°. As an example, the camera views of the jack robot are presented in Fig. 17, among which the left-hand shows the view when the jack tool is lifting up a large box, and the right-hand shows the view when the robot is moving in the corridor. These images demonstrate that the field of view and sharpness of pictures are satisfying.

4. Field tests

Field tests are carried out in the national training base for urban search and rescue to verify the abilities and potential of the two rescue robots. The tests contain two parts: driving abilities tests and rescue capabilities tests.

4.1 Driving abilities tests

High mobility on irregular terrains and adaptability to various landforms are the most basic capabilities for the rescue robots. So we tested their driving abilities under different conditions, including maximum speed, minimum turning radius, running on bumpy road, scrambling over vertical obstacles and ditches, riding over zigzag obstacles, climbing slopes, climbing stairs, as well as running on ruins.

The maximum speed and minimum turning radius of the rescue robots were tested first of all, shown in Fig. 18. The results showed that the maximum speed reached 0.8 m/s when the rescue robot ran along a straight line on the flat floor. In theory, the rescue robot could turn at an original point using differential steering. However, the turning radius could not achieve zero because of the velocity errors and different friction forces on each track. The experimentally measured minimum turning radius was about 100 mm.

Fig. 18 Tests of maximum speed and minimum turning radius.

In the test of running on bumpy road, we chose a 10 meters long road which was paved with small stones and bricks, as shown in Fig. 19. To enable the robot to adapt to the bumpy road, the brake of the joint mechanism that controls the roll DOF between the two segments was released. The result in Fig. 20 showed that the robot could run smoothly on the road.

Fig. 19 Snapshot of the bumpy road.

Fig. 20 Running on bumpy road.
Fig. 21 shows the test of scrambling over vertical obstacles and ditch, which is aimed to verify the validity of the joint mechanism, especially the pitch motion. The obstacles are about 350 mm high, and the ditch is about 400 mm wide. When climbing the vertical obstacle, the rescue robot adjusted its posture using the joint mechanism to increase the contact surface between the tracks and the ground and obstacles. The results showed that the robot could surmount the obstacles and ditches easily.

Fig. 21 Scrambling over obstacles and ditches.

Fig. 22 shows the test of riding over zigzag obstacles. The obstacles are about 200 mm high, and the distance between two zigzags is about 320 mm. This kind of obstacles is very difficult for some robots because the tracks may be stuck by the jagged edges. However, for the two proposed robots, the pitch angle between the front and rear segments can be actively controlled. Therefore, when the robot was stuck, by adjusting its posture, it could keep running forward and cross the obstacles.

Fig. 22 Riding over zigzag obstacles.

The test of climbing slopes was carried out using different slopes including 30, 45 and 60 degrees. After several trials, we found the robot could make its way at the 30 and 45 degrees slope easily except the 60 degrees slope. Fig. 23 presents the results of climbing a 45 degrees slope. In our opinion, the results were quite satisfying because this slope is even hard for humans to climb.

Fig. 23 Climbing 45 degrees slope.

Fig. 24 shows the test of climbing stairs. The stairs we used had four steps. Each step was 450 mm wide and 180 mm high. From the results, we found the robot climbed the stairs easily.

Fig. 24 Climbing stairs.

The test of running on ruins was at the site of a real collapsed house, where there were wooden pillars and beams, concrete slabs, bricks and steel tubes. The robot was controlled to enter the house through the ruins. Fig. 25 shows the results of this test.
4.2 Rescue capabilities tests

In this part, we designed a test to verify the abilities of the rescue robots to perform rescue missions. A dummy was buried in a house under concrete slabs whose weight was about 300 kg, as shown in Fig. 26. But the entrance to the house was blocked by a heavy concrete slab which weighs about 400 kg. The maximum space between the slab and the ground was about 200mm in height, and the minimum space was only 30 mm. The spaces were too small for the rescue robots to go through. And the passage to enter the house was disrupted by a metal bar with the diameter of 10 mm. The rescue robots need to perform three tasks: firstly lift up the slab at the entrance, then cut the steel bar in the passage, and finally lift up the slabs off the dummy.

The missions were accomplished by collaborative efforts of three rescue robots - a robotic spreader (Zhang et al., 2014), our jack robot and cutting robot. All the robots were operated remotely at a distance of 30 meters. In the first task, there was not enough workspace for our jack robot. So we used the robotic spreader to open the narrow gap from 30 mm to 160mm, as shown in Fig. 28 (1). But the space was still not large enough. Then the jack robot moved to the block and put the jack tool under the block, as shown in Fig. 28 (2). The jack tool lifted the block up to 300 mm and maintained the space, as shown in Fig. 28 (3). In the second task, the cutting robot passed under the block, entered the passage and cut the steel bar to clear barriers, as shown in Fig. 28 (4), Fig. 28 (5) and Fig. 28 (6). The steel bar was cut in less than 20 seconds. In the final task, another jack tool was installed on the jack robot. Then the jack robot entered...
the house and lifted up the slabs on the dummy, as shown in Fig. 28 (7), Fig. 28 (8), and Fig. 28 (9). Up to this point, all the missions were completed successfully. The whole process took about 8 minutes.

5. Conclusion

In this paper, a cutting robot and a jack robot which can cut obstacles and jack up heavy load in tight spaces in the post-disaster environment have been developed and then tested in the national training base for urban search and rescue. Due to the combination of tracks and flexible joints, the two rescue robots have high mobility on irregular terrains. And the tests on various landforms verified our design.

The two rescue robots were also tested to perform rescue missions, including cutting obstacles, making and maintaining spaces for other tools. The missions were accomplished well through collaboration among three rescue robots.

From the tests, we also found that the lithium batteries allow the rescue robots to work for at least four hours. The wireless communication modules can work steadily at a distance of 30 meters. All these results suggest that our rescue robots can play some role in disaster relief operations.

In the future, we will try to improve the autonomy of the two rescue robots. We also plan to develop more rescue robots which can cut and remove large obstacles.

Acknowledgement

The work reported in this paper is supported by National Magnetic Confinement Fusion Science Program “Multi-Purpose Remote Handling System with Large-Scale Heavy Load Arm”(Grant 2012GB102004) and the National Hi-tech Research and Development Program of China(Grant 2012AA041505).

References

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