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A Novel Rescue Robot: Hybrid Soft and Rigid Structures for Narrow Space Searching

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***Abstract*—We propose a novel rescue robot with hybrid soft and rigid structures, it is designed particularly for narrow space searching. The whole design focuses on improving the mobility and reliability to make it more applicable to disaster relief work. The rescue robot has highly integrated design, it is composed of two annular grippers with partially rigid structure, a soft actuator and a soft bending joint. Specially, we introduce self-adaptive structures to enable the robot to travel through different size of passages and maintain its current position when needed. The rescue robot is pneumatic, and 4-meter-long tube is used as container of air tubes and wires, which is sufficient for search area requirements in most situations. The performance of the rescue robot is evaluated by an artificial disastrous environment. It is proved that the rescue robot can successfully move forward in the disastrous environment. Moreover, the rescue robot can climb in an inclined acrylic pipe at a maximum angle of 25°.**

***Index Terms*—Pneumatic, rescue robot, self-adaptive structure, soft actuator.**

I. INTRODUCTION

EVERY year, plenty of natural and man-made disasters happened around the world, which caused a lot of damage to property and casualties. Except for taking preventive measures to these disasters, saving more survivors after disasters becomes really critical. Disaster-induced ruins are often complex and harsh, which bring great difficulties in rescuing survivors. Therefore, lots of researches have been done on developing search and rescue robots.

According to the movement modes, these robots can be divided into several categories: tracked robot, wheeled robot, legged robot, hybrid robot and bionic robot. Tracked rescue robots are commonly used for searching on the surface of ruins, including traditional tracked robots [1] and deformable tracked robots [2], [3]. Such robots can move quickly on rough terrain, but the large friction generated in the course of movement results in a great energy loss. Wheeled robots are also popular in performing search and rescue missions [4]. They have simple structure, high reliability, and can move quickly on a relatively flat ground. However, the poor performance in overcoming obstacle limits their applications in complex ruins. Legged robots generally have high mobility that can adapt to a variety of complex terrains, but their structures and control systems are often too complex. To improve these robots' mobility in complex environment, hybrid robots with combined motion mode were proposed, such as leg-wheel hybrid robot [5], leg-track hybrid robot [6], wheel-track hybrid robot [7] and leg-wheel-track hybrid robot [8]. These hybrid robots have outstanding performance in moving on the rubble, which are of great help in rescuing survivors on the surface of the ruins.

In contrast, rescuing the survivors who were buried in the rubble are always fraught with difficulties, such survivors are difficult to be located, moreover surroundings around them are complex and unstable, and usually a narrow, relatively closed space. Recently, bionic robots which are inspired by nature's creatures [9], such as snake, insect, fish and so on, are devoted to doing search and rescue work. The bio-inspired robot has high flexibility, strong obstacle ability and relatively small size, they bring solutions to searching in narrow spaces. For example, Wang et al. developed a tendon-sheath-driven searching and rescuing robot with a slender body [10]. Wright et al. [11] developed a Unified Snake, it has high flexibility and can move in the desert, quagmire, trees and ruins. Ito K et al. [12] developed a semi-autonomous serially connected multi-crawler robot for search and rescue. Tanaka et al. [13] designed an articulated mobile robot that can climb stairs, and also move in narrow spaces and on 3-D terrain. Choset et al. [14] designed a series of multi-link super-redundant robotsincludes a multi-link snake-like robot and spider-like robot.They can crawl and walk over difficult terrain. These rigid bionic robots

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have high precision in motion control, but with the expense of complex actuation systems. What's more, the rigid bodies usually have poor environment adaptability, which results in bad performance on deformable ground, such as soft soil, sand and mud [15].

In view of the defects of rigid rescue robot, many soft bionic robots with high flexibility, small size and light weight were developed to conduct search and rescue works. They are usually made of deformable materials, such as silicone rubber, shape memory alloys (SMA), electroactive polymers. Furthermore, most of these soft rescue robots are driven by compressed air, they can easily achieve specific movement by special design of the soft body. According to the movement modes, soft search robots can be divided into three categories: crawling robot [16], [17], peristaltic robot [18] and snake robot [19-21]. It was reported that a soft robot developed with flexible mesh structure can withstand external impacts such as thump, stampede [18]. A pneumatic robot with multiple simple segments can generate snake-like movement, and move through a variety of complex plane channels [19]. Greer J D et al. developed a growing robot [22] . Growth of the robot will result in the robot moving toward the destination. In general, with the utilization of deformable materials, soft robots can be easily designed with small size, light weight, large deformation and multiple degrees of freedom. However, these soft robots often cannot provide enough support force to keep their current position in ruins. In order to do some rescue operations after they reach the target location, studies should be carried out to strengthen the capacity of holding their posture in the complex environment of ruins.

In this paper, a novel rescue robot is developed for searching survivors and monitoring the environmental condition in the ruins. In order to achieve high flexibility, sufficient support force and adaptability in complex environment, both soft and rigid structure were considered in our design. The pneumatic rescue robot is inspired by inchworm who moves in the form of peristalsis, it has two annular grippers, a soft actuator and a soft bending joint. Systematic design of the rescue robot is presented in section 2, structure design of the whole robot is introduced in detail in section 3, especially, the design of self-adaptive spring is analyzed in section 4, the pneumatic control platform is illustrated in section 5, experiments for testing the performance of the rescue robot in the ruins were conducted in section 6, and conclusions are presented in section 7.

II. System Overview

The environment after disaster is usually complex, plenty of buildings collapsed and people may be buried in the rubble. Passages formed after disasters are usually too narrow that the rescue workers and even sniffer dogs cannot enter, therefore the rescue robot proposed here is designed specifically for confined spaces.

The systematic design of the rescue robot is proposed as Fig.1 shows, it contains four parts: rescue robot, flexible long tube, pneumatic drive system and control system. The rescue robot in the frontier is capable of navigating through the passage and feedback the image of the surroundings via a micro camera, the pneumatic drive system provides power for robot insertion, the compressed air is transferred through the flexible air tubes housed in the long tube, and rescue workers can observe the feedback images and control the robot's movement on the PC control interface. Moreover, to provide preliminary rescue operations, a manipulator can be fixed in front of the rescue robot. The remote control of the manipulator can be achieved by using tendon-sheath actuation system. In this paper, we focus on the design and mobility of rescue robot, the research on manipulator can refer to our previous study [12].

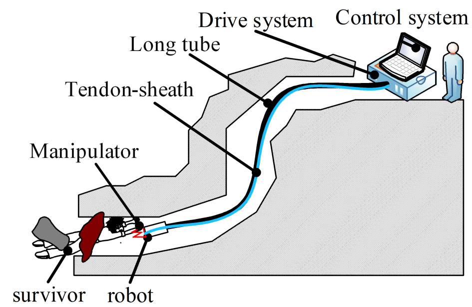

Fig. 1. Systematic design of the rescue robot.

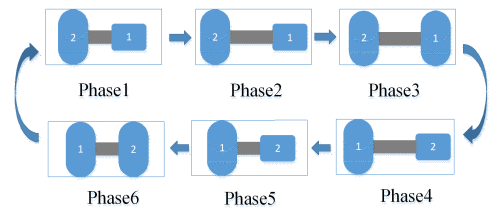

Fig. 2. The peristaltic motion of the rescue robot within a cycle.

Inchworm has three basic motion units: the anterior feet, the flexible body, and the posterior feet. It can move forward by its feet, and accompanied by the flexion and extension of its body, in which the anterior and posterior feet alternately used as a fixer. Refer to the movement mode of inchworm, the proposed rescue robot has two annular grippers and a soft body. The two annular grippers perform as the anterior and posterior feet respectively, the soft body can provide bending and stretching motions, the whole rescue robot is driven by compressed air. As Fig.2 shows, rectangles 1 and 2 represent the anterior gripper and posterior gripper respectively, the grey rectangle in the middle is the soft body. The rescue robot can generate peristaltic motion by the following phases:

Phase 1: The posterior gripper expands until it grips on the surroundings firmly;

Phase 2: The posterior gripper is kept at the current position while the soft body elongates, as a result the anterior gripper is pushed forward;

Phase 3: The anterior gripper expands for catching the surroundings;

Phase 4: The posterior gripper contracts to its original state;

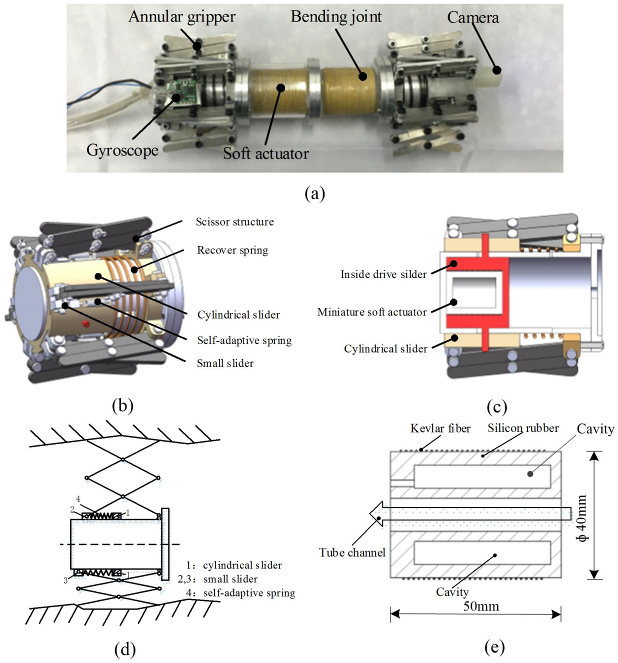

Fig. 3. Schematic of rescue robot mechanism.

Phase 5: The soft body contracts to its original state, thereupon the posterior gripper moves forward;

Phase 6: The posterior gripper expands again;

Then it returns to phase 1, a cycle of peristaltic motion is accomplished. The displacement of the whole rescue robot within a cycle equals to the elongation of the soft body.

III. Mechanism Design

The rescue robot, shown in Fig.3, is composed of two annular grippers, a soft actuator, and a bending joint, the soft actuator produces elongation while the bending joint generates the bending movement. A gyroscope is installed to detect the robot's posture in real time, and the camera on the robot shows the surroundings, they are important for operators to control the rescue robot. In general, the length of the robot is 220mm, and the minimum diameter of the annular gripper is 80mm.

A. Annular Gripper

The annular gripper should grip on the surroundings to fix the rescue robot's position, nevertheless the surroundings are often irregular, and the cross section of accessible passages varies a lot in size and shape, which bring great challenges to the effective grasp of the annular griper. In order to work in the complex passages, scissor structures are adopted in the design of annular griper. Scissor structures are quite common used in daily life such as retractable door and scissor lift platform, it can expand in large scale and contract to small dimension.

Fig.3(b) and Fig.3(c) show the 3D model of annular gripper, it has six uniformly arranged scissor structures, a cylindrical slider and a recover spring. The diameter of annular gripper can expand from 80mm to 240mm. As Fig.3(c) shows, there is an inside drive slider and a miniature soft actuator inside the annular gripper, the drive slider will slide forward if the miniature soft actuator is inflated, as a result the cylindrical slider will move forward and drive the scissor structures to expand correspondingly. In order to adapt to the complex environment in ruins, self-adaptive design of the annular gripper was considered. As is depicted in Fig.3(d), the scissor structure which already contact with the outside passage will stop expanding, and the corresponding self-adaptive springs will elongate to compensate the displacement of the cylindrical slider. Eventually, each scissor structure will expand to different scales to fit the surroundings. Once the soft actuator deflates, the gripper will contract under the drive of the recover spring.

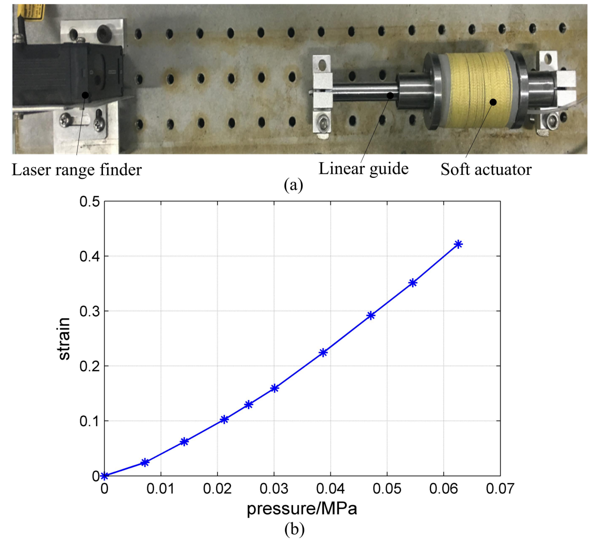

Fig. 4. Experiment for testing the mechanical property of soft actuator: (a) Experimental platform; (b) Experimental results.

B. Soft Actuator

The soft actuator and the miniature soft actuator in annular gripper are manufactured by the same method, they are made of silicon rubber and high-intensity Kevlar fiber with a diameter of 0.38mm. There is a cavity inside the cylinder made of silicon rubber, and the Kevlar fiber wraps densely around the cylinder like a spring with a screw pitch of 0.5mm to transform the expansion into axial direction.Similar to the structure of the miniature soft actuator, the soft actuator in the middle of the rescue robot is shown in Fig.3(e), the tube channel was placed in the axis position for the convenience of control and installation.

The mechanical property of soft actuator was tested by the experiment shown in Fig.4. The experimental platform consists of the soft actuator, linear guide, and laser range finder (KEYENCE-IL300). The soft actuator will elongate on the occasion of inflation, the elongation was measured by the laser range finder, and the driven pressure of the soft actuator was measured by pressure sensor. The pressure and the corresponding strain in the experiment were recorded in Fig.4(b). It can be seen that there is an approximate linear

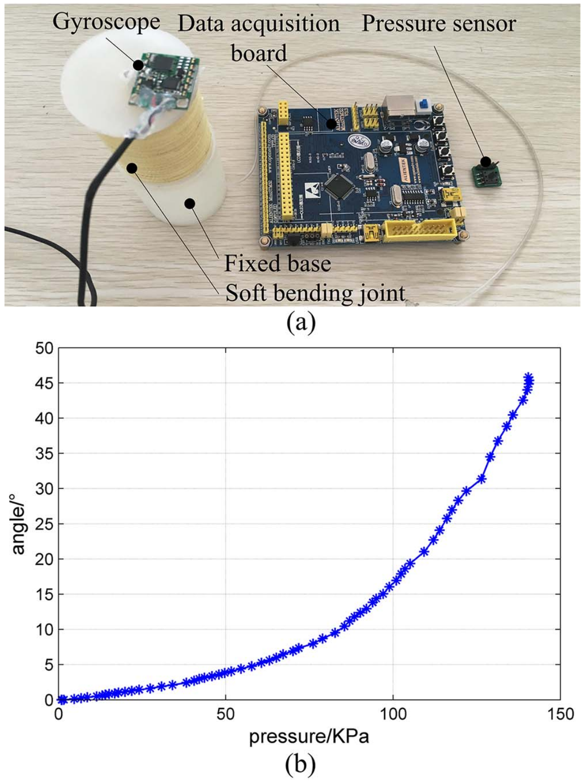

Fig. 5. Experiment for measuring bending angle of soft bending joint: (a) Experiment setup; (b) Experimental results.

relationship between the driven pressure and the strain of the soft actuator.

C. Bending Joint

On occasion of moving in the ruins, the rescue robot has to adjust its posture and movement direction frequently. Similar to the soft actuator introduced in Fig.3(e), a soft bending joint is developed with high flexibility. As Fig.3(e) shows, the soft bending actuator is a cylinder with the diameter of 40mm and the length of 50mm. It has four independent cavities with fan-shaped section. The joint can bend to different directions and angles by inflating or deflating the corresponding cavities to appropriate extent.

Experiment was carried out to verify the relationship between the driven pressure and the bending angle of the soft bending joint, the experiment setup is illustrated in Fig.5. The soft bending joint was placed on the fixed base, the bending angle was measured by gyroscope (accuracy of $0.01°$), and the driven pressure was measured by pressure sensor, signals from the two sensors were collected via the data acquisition board. The experiment was conducted with only one cavity inflated, the experimental result on the driven pressure and the corresponding bending angle is presented in Fig.5 (b). The bending angle increases steadily when the pressure is below 90 KPa, whereas rapid growth will show up if the pressure exceeds 100 KPa. Moreover, the maximum bending angle of the soft bending joint under no-load condition is $47°$.

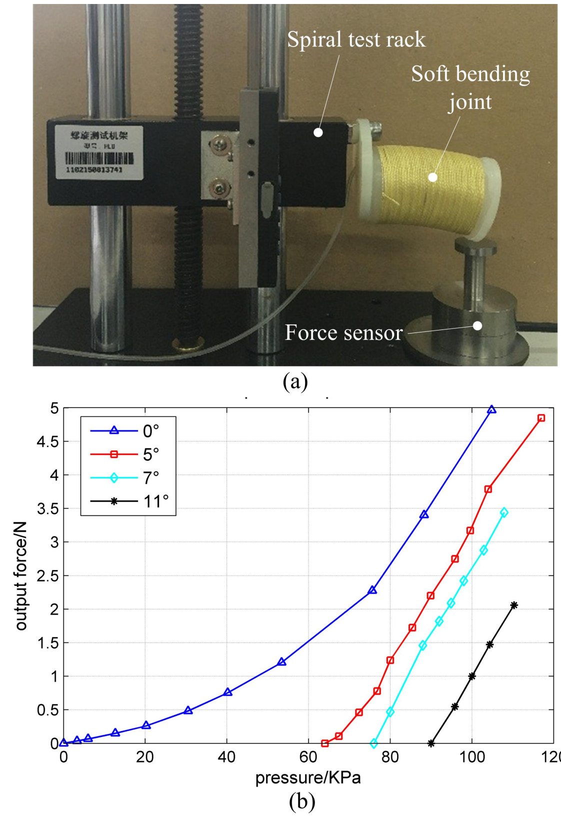

Fig. 6. Experiment for testing the output force of the soft bending joint: (a) Experiment setup; (b) Experimental results.

The output force of the soft bending joint determines the ability of motion change under the frictional resistance in the ruins. Therefore, as illustrating in Fig.6, an experiment for testing the output force of the bending joint under different pressure is performed. The experiment setup is composed of the spiral test rack, force sensor (FSG15N1A), pressure sensor, and the soft bending joint. The soft bending joint was fixed on the spiral test rack whose height can be adjusted, as a result, the initial location of the soft bending joint can be changed for generating different bending angles. The force sensor was placed below the bending joint for measuring the output force, the pressure sensor was used for measuring the driven pressure in the joint. It should be pointed out that only one cavity was inflated in the process of the measurement. The relation between output force and driven pressure of the soft bending joint under four different bending angles $(0°, 5°, 7°, 11°)$ were tested, and shown in Fig.6 (b). According to the experiment results, the output force increases with the growing pressure, and decreases with the rising bending angle. It is because that part of energy produced by the compressed air will be transferred into the strain energy of the bending joint, and large bending angle certainly consumes more strain energy. According to (2), the friction is calculated as 2.4N, whereas the bending angle can output 5N (under pressure of 105KPa, initial bending angle of $0°$), thus the bending joint is qualified for the rescue robot.

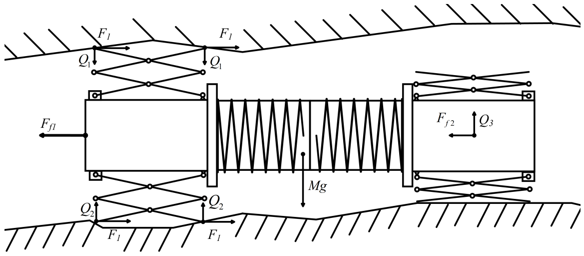

Fig. 7. Mechanical model of rescue robot.

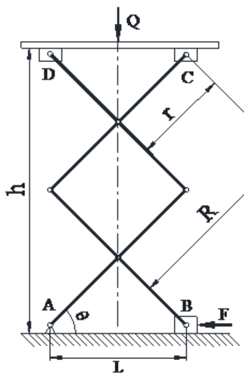

Fig. 8. Mechanical model of the scissor structure.

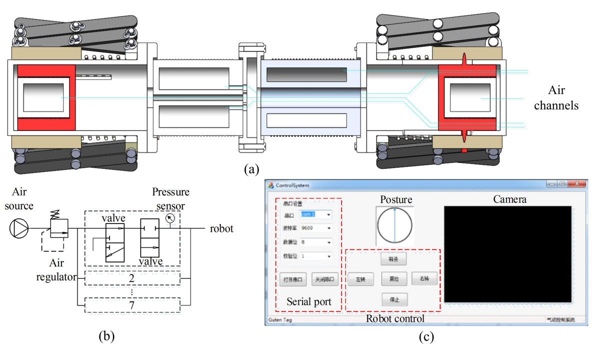

Fig. 9. Control system of the rescue robot: (a) Air channels in the rescue robot; (b) Pneumatic control platform; (c) Control interface.

IV. Design of Self-adaptive Spring

Griping on the surroundings firmly is a pre-requisite for the rescue robot to move forward. The friction between the annular gripper and the surroundings depends on the tension of the self-adaptive spring. If self-adaptive springs are too soft, the annular grippers cannot provide enough support force, whereas too hard springs will challenge the driving force of the miniature soft actuator. Thus it is necessary to analyze the forces of the annular gripper before designing the self-adaptive springs.

After the acceleration resistance, air resistance, and other minor resistance ignored, the mechanical model of the rescue robot can be simplified as Fig.7 shows. Q is the support force of the scissor structure, F is the friction force between the expanded scissor structure and the surroundings. The index numbers, range from 1 to 6, correspond to the six scissor structures. F_{f1} represents the friction between the long silicone tube and the surroundings, while F_{f2} represents the friction between the rescue robot and the ground. M is the weight of the whole robot, it was measured as 0.7 kg. g is the gravity acceleration ($g = 9.8N/s^2$). The rescue robot can move forward if the relationships between these forces satisfy the following equation:

$$\sum_{x=1}^{6} F_x = \sum_{x=1}^{6} Q_x f \geq F_{f1} + F_{f2} \tag{1}$$

Where f is the static friction coefficient between the scissor structures and the surroundings. To increase the friction, rubbers were used on the ends of scissor structures. Therefore, f refers to the static friction coefficient between rubber and stone, which ranges from 0.6-0.9, here $f = 0.7$ was assumed.

As the environment of the passages in the ruins are complex, F_{f1} which stands for the friction between silicone tube and surroundings varied during the robot's movement. F_{f1} was measured by experiment, a silicone tube (length of 5m) moved in the ruins with low and nearly uniform speed. In the experiment, the friction ranged from 1N to 8.4N. In fact, only 4m long tube was utilized in actual design, here the maximum friction 8.4N was considered as F_{f1} in the design of the self-adaptive spring.

F_{f2} can be calculated as

$$F_{f2} = \frac{1}{2} Mgf = 2.4N \tag{2}$$

Then (1) can be concluded as

$$\sum_{x=1}^{6} Q_x f \geq F_{f1} + F_{f2} = 10.8N \tag{3}$$

The mechanical model of the scissor structure is shown in Fig.8, h is the height of the expanded structure, R is half length of the scissor lever and $R = 2r$, θ is the angle between the scissor bar and the horizontal, L is the distance of the slider B and fixed point A. Q is the load, while F is the drive force that provided by self-adaptive springs.

From the geometric relations of the scissor structure, we can know that:

$$L = 2rcos\theta \tag{4}$$

$$h = 4rsin\theta \tag{5}$$

Supposing that the virtual displacement of the slider B under the horizontal force F is dL, the virtual displacement of the upper plane under the load Q is dh , then the derivation of (4) and (5) can be expressed as

$$dL/d\theta = -2rsin\theta \tag{6}$$

$$dh/d\theta = 4rcos\theta \tag{7}$$

According to the principle of virtual displacement, we can get

$$Qdh + FdL = 0 \tag{8}$$

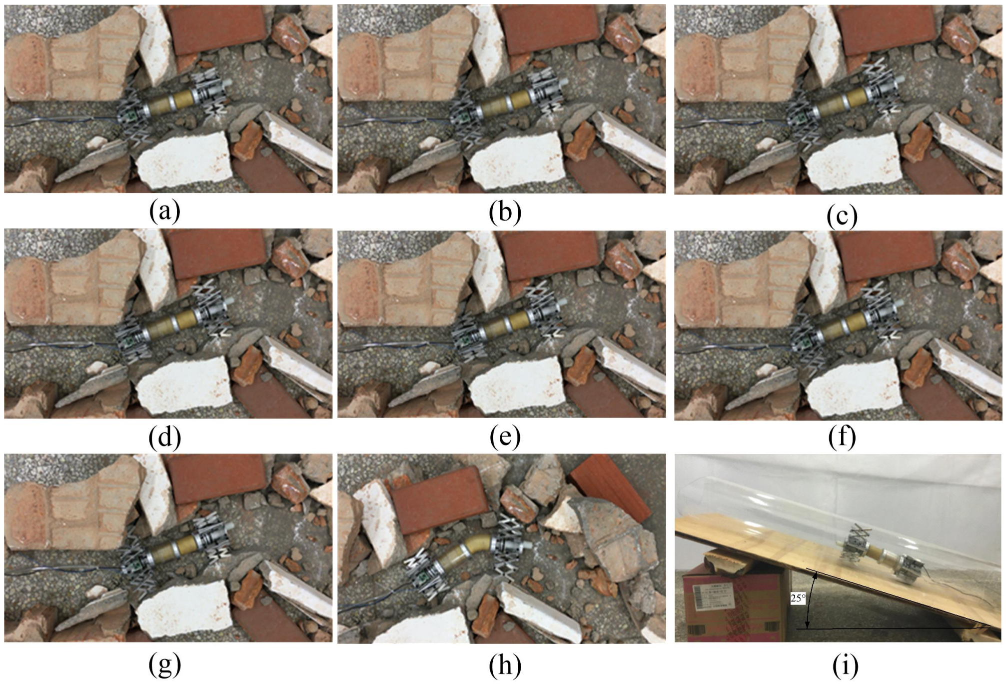

Fig. 10. Experiments for evaluating the performance of rescue robot: (a)-(h) experiment of the rescue robot in artificial disastrous environment. (i)Climbing experiment of the rescue robot.

The following equation can be achieved from (6) to (8)

$$Q = -FdL/dh = \frac{F}{2} tan\theta \tag{9}$$

Then (3) can be rewritten as

$$\sum_{x=1}^{6} \frac{F_x}{2} tan\theta f \geq 10.8N \tag{10}$$

As $f = 0.7$, $\theta = 10°$ in the original state of the scissor structure, the maximum F is calculated as 29.1N. The self-adaptive spring is designed with stiffness of 2.4 N/mm. Each scissor structure has two self-adaptive springs, thus the maximum driven force generated by the self-adaptive spring is $F_{max} = 2 \times 2.4 \times 15 = 72N$, which is adequate to the application requirements.

V. Control System

The soft rescue robot is driven by compressed air, as shown in Fig.9(a), there are seven air channels that correspond to the cavities in pneumatic actuators. The pneumatic control platform was established as Fig.9(b) shows, it consists of a STM32 circuit board, a precise air regulator, miniature solenoid valves and pressure sensors. In addition, a visualized control interface was designed for controlling the rescue robot in a convenient way, it is programmed on Microsoft visual studio. As shown in Fig.9(c), serial port parameters can be set on the control panel and the robot can be controlled through the control panel. Besides, robot posture and the camera images will be displayed on the screen all the time to aid the robot operation.

VI. Experimental Results

An artificial disastrous environment was built with stones bricks and gravels for investigating the performance of the rescue robot. The width of the built passage is 100mm-280mm, and some small stones are set as obstacles. Fig.10 (a) - (h) show the peristaltic motion of the rescue robot in the experiment. It can be described exactly as Fig.3 shows, which started with the expanded posterior gripper (shown in Fig.10 (a)) and ended with the expanded posterior gripper after moved forward (shown in Fig.10 (f)), afterwards the rescue robot entered the next cycle (shown in Fig.10 (g)). Fig.10 (h) demonstrates the scene that the rescue robot went through the curved passage with the angle of 130°. In general, the rescue robot can move forward in the passage at a speed of around 100mm/min.

As the passages in the ruins are complex and irregular, the rescue robots may encounter passages with uphill or downhill. To exam the mobility of the rescue robot in inclined passages, the climbing experiment is carried out. As Fig.10 (i) shows, the passage is a smooth one-meter-long acrylic tube with a diameter of 143mm. Experimental results show that the maximum climbing angle of the robot reaches 25°, but the smooth inner wall of acrylic tube challenges the support force of the annular gripper to certain extent.

VII. Conclusion

This paper presents a novel rescue robot which aims to searching in the ruins and feedback the surroundings by camera in real-time. The rescue robot has two expansible annular grippers, an extensible soft actuator and a bending joint, it can peristalsis as an inchworm. The long tube is 4 meters long, it is enough for searching in most areas after the disaster. The maximum diameter of the rescue robot in original state is 80mm, thus it is well suited to the narrow passages. The self-adaptive springs on the annular gripper were designed based on the mechanical analysis of the rescue robot, in order to ensure sufficient support force during the movement of rescue robot. The soft actuators and bending joint are all made of silicon rubber and high-intensity Kevlar fiber. Experiments were carried out to demonstrate the considerable amount of deformation provided by the soft actuators (0.4 strain under 63 KPa) as well as the bending joint (45° under 140 KPa). Moreover, the output force of the bending joint at different angles were measured, it can be concluded that small bending angles and high pressure will bring out large output force (5N under pressure of 105KPa and bending angle of 0°).

An artificial disastrous environment was established to evaluate the performance of the rescue robot. The robot can move forward and through the corner in the built passage successfully, and the average moving speed is about 100mm/min. In addition, climbing experiment was performed in the tilted acrylic tube, and the maximum climbing angle is 25°.

The rescue robot has compact structure, low production costs, and easy to control. It is driven by compressed air and can move in the passage with the diameter from 80mm to 240mm. The rescue robot can locate itself by the self-adaptive annular gripper, so it is convenient for the robot to carry out other rescue operations in this case, moreover the self-adaptive contact force reduces the likelihood of causing further collapse. In addition, once the robot fails in the passage, we can pull it out by the long tube to protect the rescue passage from being blocked. It undoubtedly increases the feasibility of the robot in practical application. It should be noted that the rescue robot has limited climbing ability and movement speed, further study will focus on the two issues. The size and weight should be optimized for enhancing the performance of the rescue robot, new high-strength materials will considered for our future research.

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