Design and Basic Experiments of a Shape-shifting Mobile Robot for Urban Search and Rescue

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Abstract — The recent natural and man-made devastations have urged the research on the Urban Search and Rescue (USAR) robot systems. This paper presents a novel shape-shifting mobile robot system named as Amoeba II (A-II) for the urban search and rescue application. It has been designed with three degrees of freedom (DOFs) and two tracked drive systems. This robot consists of two modular mobile units and a joint unit. The mobile unit is a tracked mechanism to enforce the propulsion of robot. The joint unit can transform the robot shape for getting high mobility. A-II robot not only can adapt to the environment but also can change its body corresponding to focus space. It behaves two states including the parallel state (named as II state) and the linear state (named as I state). The parallel state enables the robot with high mobility on rough ground. With the linear state the robot can climb upstairs and go through narrow space such as the pipe, cave etc. Also, the joint unit can propel the robot to roll in sidewise direction. Especially, two modular A-II robots can be connected through jointing common interfaces on the joint unit to compose a stronger shape-shifting robot, which can transform the body into four wheels-driven vehicle. Finally, the elementary experimental results validate the adaptation and its mobility.

Index Terms — Rescue robot. Modular unit. Shape-shifting. Environment adaptation.

I. INTRODUCTION

The recent terrorist attacks, also the large scale natural disasters, have brought huge property and life loss. In the events, a lot of victims died due to the time-consuming rescue, because the rescue for victims after the disasters is under extreme time pressure. The search and rescue practice has shown that: after 48 hours, victim mortality drastically increases owing to exposure and lack of food, water, and medical treatment. Also, the search and rescue operation in the collapse building is too burden and very dangerous for the rescuers. Moreover, some rubble of the collapse building is inaccessible to the rescuers. In these conditions, the Urban Search and Rescue (USAR) mobile robot can be dispatched to the collapse building to complete the search and rescue task. For example, in the event of the NY World Trade Center collapse in 2001, mobile robots for searching victims were dispatched and performed rescue operation with limited success. Facing to the security, rapidness, heavy burden and environment complexity in search and rescue task, the researchers on the robot have designed many mobile robots to perform the search and rescue task. Especially, in recent years the urban search and rescue robot is attracting more and more researchers to study for the urgent application requirements.

The tasks of urban search and rescue robot have been cataloged as follows\textsuperscript{11}:

a) Conduct tedious searches for survivors with a level of rigor that is normally fatiguing to humans.

b) Insert specialized sensors into the rubble and position them.

c) Collect visual and seismic data to assess structural damage.

d) Deposit radio transmitters or small amounts of food and medication with the survivors.

e) Guide the insertion of jaws-of-life tools.

f) Identify the location of limbs to prevent workers from injuring a victim’s arm or leg during extraction.

Therefore, mobility is an essential character for the search and rescue robot to complete the above tasks. Moreover, the small bulk can enable the robot to go through the narrow spaces under the collapsed buildings. The lightweight of robot is the basic requirement for the rescuers easily carrying. However, the most traditional types of mobile robot can not meet the requirements:

a) Walking robot possesses high mobility, but the much consideration of stability and bulk prevent it from the urban search and rescue application. This type of robot is easy to get into the rubble under the collapsed buildings due to the high pressure and frail surface between the volas of robot and rubble.

b) Wheeled robot exhibits high velocity, but they can not climb over the obstacle that higher than its radius of wheel. This type of robot is easy to get into the rubble because the same reason as walking robot.

c) Crawler-based robot\textsuperscript{2-4} with high propulsion and large bulk is usually used in outdoor environment but difficult to enter the collapsed building.

Obviously, snake-like robot with slim body has many advantages on the USAR application. It can go into the collapsed building through crevices and cracks by performing right gait among of many unique gaits. For example, the serpentine gait suits flat ground, twist-related gait suits uneven ground and concertina gait suits the crevices. Many snake-like robots had been developed since the first ACM was designed by Hirose\textsuperscript{5-7}. Our research group have built some snake-like robot\textsuperscript{12-16}, too. However, the snake-like robots are hard to be
used in USAR application by far due to the many reasons such as lack of propulsion and power as well as the complexity of motion planning. Therefore, many articulated robots\cite{8-10} with crawler have been developed for the propulsion requirements of USAR. The class of those robots only exhibited the long shape as the natural snake, but the propulsion that the snake uses the body winding to generate depends upon the crawlers fixed on the robot to generate. The MOIRA\cite{9} and OmniTread\cite{10} robot were designed with the crawlers around the robot. Experiments had exhibited the perfect capability of those robots. But, much complexity of motion planning due to hyper-redundancy in mechanism leads much decrease in mobility. Those articulated robots are defined as centipede-like robots for the active joint between the adjacent unit and active contacts with the ground as shown in Fig.1. Here, the active contact means that the robot directly generates the propulsion by driving the mechanism such as the drive wheel and track against the ground through the contact. The contact between the passive wheel and the ground is the passive contacts, which combines with the active joint to compose the snake-like robot. And the articulated robot with passive joints and active contacts is defined as trailer-like robot. Usually, two parallel crawlers possess much mobility. For example, the iRobot’s Packbot\cite{2} and the Inuktun’s MicroVGT\cite{3} are popular micro crawler robots, which have made a figure in the 911 event. The Souryu\cite{1} robot exhibited more advantages than the conventional track robot. In width those crawler robots are bigger than the snake-like robot, and in length they are shorter than the snake-like robot. Those characters counteract some application in the collapse buildings. Therefore, in this paper we design a new shape-shifting robot to overcome those shortcomings.

Based on the above analysis, in this paper, we describe the new mobile robot designed for the USAR mission, which is named as Amoeba II (A-II). The modular mechanism design and articulated structure are its main characteristic. The tracked drive is chosen as the actuation device to get enough propulsion. The requirements of design are listed as follows:

a) The robot should be slim enough to go through the cracks and crevices or pipes.

b) The robot can move on the rough ground, climb the pile and stairs.

c) The robot should be with high mobility and stability, or it can modulate its posture from instability to stability.

d) The robot should be with high integration and is radio-control.

e) The robot should be light-weight, small bulk and portable.

f) The robots can be connected to form another new robot.

The paper is organized as follows: Section II introduces the system of the A-II. Section III analyzes the mobility of the robot according to the environment. Section IV presents the experiments on A-II. Section V gives the conclusion of the work.

II. THE SYSTEM OF A-II

The design conception of A-II is based on the synthesis of track and snake-like robot structure. The collapsed building environment requires that robot with high propulsion not only can move fast in wide space but also can go through the crevices and climb up stairs. Though snake-like robot satisfies all the requirements, it can’t be threw into the outdoor due to some problems that have been described in section I. Thereby, we design a shape-shifting articulated robot A-II with track drive, which can change its body shape from a short figure as conventional vehicles to a long figure as the natural snake. The construction of A-II is shown in Fig.2a. The robot consists of two mobile units and a joint unit. The modular mobile unit is track-driving mechanism to generate propulsion of robot. The joint unit drives the two mobile units to form an appropriate shape for the locomotion. The A-II robot can carry two locomotion states including parallel state(named II state) and linear state(named I state), as shown in Fig.2b. The A-II robot can go through tight space in linear state. The parallel state as the main locomotion state enables A-II robot to move in rough terrain with high adaptability. The characteristic of two states will be described in the following section. The dimension and mass are also considered much to make A-II portable, as shown in Fig.2c. The worker can carry A-II with one hand.
Also, the robot can connect with another robot to form a large-scale A-II robot shown in Fig.3, which can get over big obstacles. Moreover, more A-II robots can be teamed to complete complex search task. The robots connection and team will be studied in future work. The two robots connection will enable the vehicle climb larger obstacles, and it can stand up to carry some objects.

The modular mobile unit should be designed with high environment adaptability and big contact area with ground to get enough propulsion. Though the tracks drive system loss much in energy consuming, it can supply the robot with large contact area and adaptability requirements. Therefore we choose the track as basic drive mechanism. The track is manufactured with tooth for getting high attachment coefficient. In the mobile unit shown in Fig.4, there are two high torque FutabaS3305 motors. One motor actuates the track through the reduction gears and the driving wheel. The other motor actuates the pitch DOF that connects the mobile unit and joint unit. The addition of pitch DOF is entirely for adaptation of the robot that will be introduced in the following section. Moreover, there is still enough space for the installment of the control circuit and the batteries in order to realize the high integration and radio control in future.

The aim of design joint unit is to modulate shape of the robot according to the space limit. The joint unit shown in Fig.5 can drive the A-II robot from the parallel state to the linear state to go through the narrow space, which is the familiar condition in the collapsed building. The joint unit is actuated by a FutabaS3305 motor with the 2:1 addition reduction ratio. The passive wheels are fixed on the joint unit to help the robot to climb over obstacle. A group of gears are setup in the joint unit to modulate the relative position and angle between the two mobile units. The relative position determines the distance of the two mobile units while the robot exhibits parallel state. The relative angle determines the turn angle while the robot exhibits linear state. The DC motor actuates two turning spur gears through the driving spur gear and middle spur gear, as shown in Fig.6. The void side of turning spur gear is cut off for saving space. In future, the video camera will be fixed on this joint unit to get the vision information. The dimension of A-II robot is shown in Fig.7. And the specification of A-II is listed in table 1.

At present, the A-II robot is control through Futaba control panel. It can control the robot to change shape and climb obstacles. The mobility and stability of A-II will be analyzed in the following section.

Table 1 The specification of A-II

| Actuators | FutabaS3305(modified) |
|-----------|-----------------------|
| Materials | Aluminum              |
| Dimension[mm³] | 604x60x502 or 62x182x50 |
| Weight[kg] | 3.2                   |
| Output torque[Nm] | 1.78                  |
| Max. velocity[m/s] | 0.065                 |
| Space limit[mm³] | 60x60                  |
| Workspace of Pitch[degree] | -120~120              |

III. The Mobility of A-II Robot

To design the A-II robot is mainly for the application of USAR. Mobility and adaptability are the most important indexes to this class of robot. With high mobility the robot can move on rugged ground and get over obstacles or up stairs. And with high adaptability the robot can move along the ground stably.
A-II robot exhibits high environment adaptability and mobility in both parallel state and linear state. In parallel state, the robot can move directly and change movement direction. When two mobile units move in the same direction with the same velocity, the robot will move forward or backward. When the two mobile units move in different direction with the same velocity, the robot will make a turning motion. At the same time, the pitch DOF can modulate the angle of two mobile units to realize the contact between the ground and the mobile units. Also, the yaw DOF can modulate the angle in transverse direction of two mobile units to realize the complete contact. But the complete contact needs too much consideration on the control method, which will be finished in future work. Fig.8 shows the shape of A-II robot on the different ground, which adequately exhibits the environment adaptability. The structure of the familiar PackBot showed high performance on the mobility, which enabled it to get over obstacles. Up to now, it is a useful practical structure, and the similar structure was used on many mobile robots. The Fig.8(a) shows that A-II robot can get over obstacle by using the pitch DOF to lift the joint unit like the PackBot robot. The Fig.8(b) shows that the robot can move on the rugged ground by actuating the pitch DOF at different angles, which shows higher performance on the adaptability than the PackBot robot. Fig.9 shows that the robot moves in the pipe or on the V-shape ground by actuating the yaw DOF according to ground shape and the pitch DOF to let the joint unit vertical to the mobile unit. The track of mobile unit contacts completely the surface of the pipe and V-shape ground to guarantee the propulsion of movement.

In the collapsed buildings, there are usually many stairs that the robot must pass through. Therefore, the capability that robot passing through stairs is the basic requirement of USAR robot. The researchers on the mechanism design have designed many structures to get over the stairs, among of which the articulated structure has been adopted on the USAR robot due to its validity. Here the articulated structure means that the tracks or the corresponding part of the robot is articulated connection, does not only mean the articulated robot. For example, The PackBot that adopted the articulated structure tracks is not articulated robot. The articulated robot A-II exhibits good performance on climbing over the stairs. The A-II robot can not pass through stairs by using the parallel state due to the small dimension. But it can change the body shape from parallel state to linear state to pass through the stairs. Fig.10 shows the process that A-II is passing through stairs. In step 1, the robot lifts up front mobile unit. In step 2, the robot moves forward and front mobile unit moves on the stairs. In step 3, the robot lifts up the body by using the pitch DOF on front mobile unit. In step 4, the robot moves forward and goes up the stairs.

The A-II can move in the pipe with both states, which increases the possibility that robot enter the collapsed buildings through the pipe, as shown in Fig.11. Also, A-II can be used in the pipe inspect application. If the pipe is very smooth due to the carrying liquid or gas, the robot can use the two mobile units to support opposite wall of pipe to actuate the pitch DOF to add supporting force on the pipe to increase the frictional force in order to avoid the slide, as shown in Fig.11.

The mass distribution of A-II must be considered much, because it affects robot mobility. For example, if the mass of joint unit is larger than the mass of two mobile units, the robot can not lift up the joint unit to get over the obstacle shown in Fig.8. In design, the authors have analyzed the critical state shown in Fig.12. In this state, the robot can balance itself by
using the joint unit and one mobile unit, while the other mobile unit is in the vertical position. In this state, the balance can be expressed as

\[ m_1 L_1 > m_2 L_2 \]  

(1)

where \( m_1 = m_2 = 1.2 \text{kg} \), \( m_c = 0.8 \text{kg} \), \( L_1 = 77 \text{mm} \), \( L_2 = 35 \text{mm} \). 

\( L_1 \) is the distance from the center of the mobile unit to the axis of pitch DOF. \( L_2 \) is the distance from the axis of pitch DOF to the CG of the joint unit. The (1) is adequately satisfied. Even though A-II robot overturned in some rough conditions, it still can move with the tracks of mobile units because of the symmetrical design on the whole robot. Moreover, there is a worse condition that only the side of mobile units contacting with the ground. At this time, the track is unavailable due to the department from the ground. The robot can modulate it to appropriate state with the pitch and yaw DOF, which will be described in below.

The track vehicles consume much energy in the shape shifting process. So the dynamic shape shifting method is chosen to change the state of A-II. The movement of the mobile unit benefits shape shifting as Fig. 13 shown. The radius of turning in the joint state can be calculated as shown in Fig.14, while in the two mobile unit move at same velocity. The equation is expressed as below

\[ R = \frac{L_{m} + 2(L_f + L_f) \cos \theta}{2 \sin \theta} \]  

(2)

where \( R \) is the radius of turning; \( L_m \) is the center distance of the two turning spur gear as shown in Fig.6; \( L_f \) is the distance from the center of the mobile unit to the axis of pitch DOF. \( L_f \) is the distance from the center of turning spur gear to the axis of pitch DOF. \( \theta \) is the angle of yaw DOF. When \( \theta = 0^\circ \), the robot configures a straight line, the radius of turning \( R \) is \( \infty \), which is identical with the result of (2). When \( \theta = 90^\circ \), the robot configures the parallel state and the robot turns at the original position, the radius of turning \( R \) is \( L_m / 2 \), which is identical with the result of (2), too.

Moreover, A-II robot can perform the side rolling motion, which can modulate the robot from the unworkable state to the movement state. When A-II robot turned over on the rough condition, this method can help the robot to its work state. Of course, the side rolling motion can do the side movement too. As shown in Fig.15, the pitch and yaw DOF are actuated according to the angle changing in the Fig.15. Consequently, the robot would move along the lateral direction of the robot. The robot can get over obstacles by using this motion. In Fig.15, the red rectangle means the active joint that is being actuated by the DC motor. The black circle and rectangle represent the inactive joints that keep present angles.

IV. EXPERIMENTS

The prototype of A-II robot has been manufactured for the experimental test. And the basic experiments have been done for the performance validation of A-II robot. Fig.16 shows that A-II robot changes from the parallel state to the linear state to go through the cave condition. Also, A-II robot can move on the gravel or on the V-shape ground as shown in Fig.17.

V. CONCLUSIONS AND FUTURE WORKS

In this paper, the Amoeba II robot for the USAR was introduced. The construction and work state of A-II robot were given. The adaptability and mobility of A-II robot were analyzed for the USAR application. The experiments on A-II robot exhibited the efficiency of a new type structure of rescue robot.

In the future, the big mode of A-II will be constructed with the modular A-II robots to get over big obstacle and carry objects, because the A-II can not get over big obstacle for its small dimension. The big mode of A-II is shown in Fig.3,
which can move as track vehicle or the leg vehicle. The connection of two A-II robots will be design in the future.

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