Abstract—An autonomous control system is developed for a shape-shifting robot "AMOEBA-I" to be possibly used in the urban terrain. Based on the sensors including GPS, electronic compass, inclinometer and encoder, the autonomous motions of AMOEBA-I are realized. The shape-shifting motion, navigation, obstacle-climbing motion, and obstacle avoidance are all autonomously performed in unstructured environments by the robot "AMOEBA-I". Experiments have been performed to validate the effectiveness of the developed autonomous control system.

Keywords: shape-shifting robot, autonomous control method, urban terrain

I. INTRODUCTION

The frequent nature disasters and man-made catastrophes during the last decades such as earthquake, typhoon, hurricane, earthquake, radiation and terrorist attack have aroused people’s attention on the importance of Urban Search and Rescue (USAR). Although people have more watchfulness than before, a large number of people still have died in unprofessional rescue due to inadequate equipment and being lack of professional manpower [1, 2]. Timely searching for victims and subsequent rescue operations from the rubble of collapsed buildings are highly required. Since these operations are very dangerous for human workers and even for trained dogs, autonomous mobile systems are highly needed to help in finding trapped victims. It is a great challenge to develop search and rescue robot that can actually work in the disaster site. The search and rescue robot research includes not only the robotics technology but also the rescue technology and the disaster science.

Researches sponsored by the countries and by the companies have resulted in the emergence of various kinds of search and rescue robots [1-12]. Since earthquake happens in Japan frequently, intelligent rescue systems with high information and robot technology have been expected to mitigate disaster damages, especially after the 1995 Hanshin-Awaji Earthquake. From 2002, “Special Project for Earthquake Disaster Mitigation in Urban Areas” (a 5 years project which also called DDT project) was launched by Ministry of Education, Culture, Sports, Science and Technology, in Japan. Various kinds of search and rescue robots have been developed such as Souryu (by Prof. Hirose, Tokyo Tech), Moira (by Prof. Osuka, Kobe Univ.), KOHGA (by Prof. Matsuno, University of Electro-Communications) and so on [3]. In America the rescue robot research has focused a lot attention too. Several robots were used for the search and detection operation in the collapsed World Trade Center building in September 2001 [2]. In University of South Florida (USF), Professor Murphy and her fellow have developed “Bujold”, a kind of search and rescue robot that has the ability of shape shifting and has been equipped with many sensors [4]. In Carnegie Mellon Robotics Institute, researchers have developed multi-joint robot for inspection [5]. Foster-Miller Company also carries out TALON Robot series for search and rescue mission [6]. In China, the shape-shifting robot named AMOEBA-I has been developed for search and rescue operation [7].

How to move automatically in the unstructured environment is a common problem for all kinds of the robot used in search and rescue operation. In this paper, we first provide a brief description of AMOEBA-I. Then, rules of autonomous shape-shifting for AMOEBA-I in urban terrain have been proposed according to the features of AMOEBA-I. Finally, experimental results from its autonomous motions (autonomous shape-shifting, autonomous navigation, autonomous climbing up obstacle and autonomous avoiding obstacle) have demonstrated that the autonomous control method based on the sensors is valid for AMOEBA-I in urban terrain.

II. THE FEATURES OF AMOEBA-I

AMOEBA-I is a kind of shape-shifting robot. The key advantage of AMOEBA-I is its adaptability to the environments through various configurations.

A. Structure of AMOEBA-I

AMOEBA-I is composed of three modules. A
A single-module is mainly composed of a link arm, a track driving system, an offset Yaw joint driving system, a Pitch joint driving system. The module in Fig.1 is a standard one and its main specifications are shown in Table I.

AMOEBA-I is repetitively composed of such kind module. It is a tracked robot which can overpass various terrains by transforming its configurations. The key advantage of this type over other link-type vehicle is its adaptability to environments through various configurations. The structure of the AMOEBA-I is shown in Fig.2.

![Fig.1 Structure of a single standard module of the improved prototype](image)

**TABLE I**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>316-539mm</td>
</tr>
<tr>
<td>Height</td>
<td>126mm</td>
</tr>
<tr>
<td>Breadth</td>
<td>176mm</td>
</tr>
<tr>
<td>Mass</td>
<td>5Kg</td>
</tr>
<tr>
<td>Gearing motor</td>
<td>20W-3</td>
</tr>
<tr>
<td>Power</td>
<td>DC24V, 2.5Ah</td>
</tr>
</tbody>
</table>

Nine kinds of configurations are available and among them, linear, triangular and parallel are the most fundamental symmetrical configurations as shown in Fig.3.

![Fig.3 Symmetrical configurations of AMOEBA-I](image)

The characteristics of AMOEBA-I can be generalized as:
- They have many non-isomorphic configurations. Their configuration can change automatically to adapt to the environment. With two or more modules, they pose line type and row type easily. For instance they can pass the narrow space and the hole in line and they can move on uneven terrain safely or steering easily in row.
- It is small, lightweight and easy to carry and it can resistance against dust, gas and other hostile environment.
- With hollow wheels and sealed body, it can move in shallow water. The wheel has been designed to be hollow inside for underwater case.
- It is modularized and manually reconfigurable. The modular robot has satisfied maintenance and interchangeableness. It is reconfigurable in urgent need. The connection and disconnection of the modules can be finished through the link arm and the link handle.

**B. Structure of the control system**

The control system is composed of a wireless module, a main control module, motor control modules and sensor-based feedback control modules. It adopts PC-and-MCU structure as shown in Fig.4.

![Fig.4 Structure of the control system](image)

Main control module is the robot's decision-making unit, which estimates its own position, and status of the environment provided by the feedback control module and
plans the robot’s movements using corresponding algorithms. It is also a communication interface between robot and human-supervision platform by transmitting data from sensors to human-supervision platform through wireless module. The motor control module decides the robot’s movement.

The sensor-based feedback system contains controllers 8 to 10 as well as inclinometer, electron compass, GPS and level-converter. It receives information from the environment and transmits the data to respective controllers in which pre-settled algorithms are used to deal with them, and then results are sent to the PC. MAX232s are used here to be the level-converter, which plays as bilateral converters between RS232 level and TTL.

III. RULES OF AUTONOMOUS SHAPE-SHIFTING FOR AMOEBA-I

AMOEBA-I can overpass various terrains by transforming its configurations. When AMOEBA-I moves automatically in the unstructured environment, it must use the sensors to know the environment, and select the optimal configuration according to the environment. So the rules of autonomous shape-shifting is very important for AMOEBA-I.

A. Comparison of motion performances of AMOEBA-I

In order to constitute the rules of autonomous shape-shifting for AMOEBA-I, we test the adaptability of AMOEBA-I in symmetrical configurations as shown in Fig.5.

We have gotten the performances of AMOEBA-I by the experiment results as shown in Table II.

In Table II, “A”, “B” and “C” stand for three levels as “good”, “general” and “bad” respectively. From Table II we can get conclusions as follows: The robot can climb up obstacles with satisfying performance as well as get across cabined spaces under linear configuration, which is a remarkable improvement for environment-adaptation. In triangular configuration, stability and the mobility of climbing slopes are very notable. Zero-radius turning can be realized easily under parallel configuration which makes it be more agilely and be minimum energy consumed.

B. Rules of autonomous shape-shifting

Since the robot mostly moves on flat ground, we choose parallel configuration as the initial configuration. The robot takes the following methods to recognize different ground and environment and adopts the most appropriate configuration. Here we will take the field, obstacle and slopes as examples respectively to show our rules of how to guide the robot to change its configuration.

1) Environments of uneven ground in the field: In this situation, data from the inclinometer are taken as the most important into consideration. If the obliquity does not exceed the threshold of 10 degrees, we define the ground as general uneven ground. The states fall into 2 kinds according to the specific feedback from inclinometer.
   - The slope’s gradient changes not fast (if mean square errors are smaller than 20 with 10 times’ continuously samplings), then the ground is thought to be flat and parallel configuration is taken.
   - The slope’s gradient changes rapidly (if mean square errors exceed 20 with 10 times’ continuously samplings), then the ground is thought to be uneven, and the robot takes the triangular configuration.

2) Environments of obstacles: When obstacles are in its way, the robot takes one of the 3 following configurations according to the feedback information from encoder and the motor currents.
   - Parallel configuration: If the output of the encoder keeps changing for 10 seconds, at the same time the input current of the motor jumps up and stays at a high value, we can conclude that the robot has some obstacles in its
way and it cannot get over, so the robot changes into triangular configuration.

- Triangular configuration: If the output of the encoder keeps changing for 10 seconds, at the same time the input current of the motor jumps up and stays at a high value, we can conclude that the robot meets some large obstacles hard to pass. In this environment, the configuration alters into linear form.

- Linear configuration: If the output of the encoder keeps changing for 10 seconds, at the same time the input current of the motor jumps up and stays at a high value, which means large obstacles are in the way and the robot has to avoid them with utilizing information from electron compass and encoder.

3) Environments of slopes: Information from the inclinometer is at the first place to be considered when the robot gets over obstacles with certain gradients. The strategy of its locomotion is illuminaed as:

- The gradients range in [0, 10°]: In this situation, there is no need to alter the robot’s configuration.
- The gradients range in [10°, 20°]: Triangular configuration which is prone to get over obstacles and has good stability is available.
- The gradients range in [20°, 30°]: Take linear configuration for the robot may overcome tough obstacles in this kind.
- The gradients exceed 30°. Steer clear of the slopes using data from electron compass and encoder.

In a word, the robot can judge its surroundings accurately by analyzing data from sensors. Moreover, it can take different configurations to adapt to the environment and complete the mission designated.

IV. AUTONOMOUS NAVIGATION METHOD

We used GPS to provide geographic coordinates. Some calculation should be done to get the robot’s present position and the difference between its present and target position. Set these differences as the norm angles of electron compass, the robot will move towards target position.

As is shown in Fig.6, O is set to be the mobile robot’s initial position, whose geodetic coordinates are (L0, B0), and P the target position with its geodetic coordinates at (LP, BP). The dashed circle is the confines of the range in which the robot may stop at the range of allowable error. After the robot covers a certain distance, it stops at A (LA, BA) to adjust its orientation. As it passed B (LB, BB), it enters GPS blind zone. At C, the robot makes its orientation adjustment utilizing geodetic coordinates concluded through information of inertial components. The robot leaves GPS blind zone from the moment it gets to D (LD, BD). Suppose it meets an obstacle at E, the navigation program will stop and a program of obstacle-get-over or obstacle-avoidance will take charge until it gets over or passes by the obstacle. The robot changes its configuration at F and alters into its former shape at G (LG, BG). In this graph, H (LH, BH) is its end point.

![Fig.6 Autonomous navigation of AMOEBA-I](image)

After we select an end point, OP’s direction represented by α can be ascertained.

$$\alpha = \frac{L_p - L_{12} \cos B_o}{B_p - B_o}$$  \hspace{1cm} (1)

The electron compass gives the robot’s deflexion angle γ (the angle to Y axis) at its initial position. Therefore, in the beginning, the robot has to turn θ, which can be calculated by

$$\theta = \alpha - \gamma$$  \hspace{1cm} (2)

If θ > 0, it turns left, while it turns right if θ < 0, otherwise it goes straightforward.

Suppose the robot reaches a where GPS fails after certain periods (the interval between the robot samples the GPS values), it starts to calculate its position and orientation using the record of inertia components.

After one period, the robot moves to B, whose geodetic coordinates can be calculated by

$$B_a = B_4 + \frac{Vt \cos \gamma}{K_1}$$  \hspace{1cm} (3)

$$L_a = L_4 + \frac{Vt \sin \gamma}{K_2}$$  \hspace{1cm} (4)

In Eqs. (3) and (4), V is the velocity of robot, γ represents its including angle to Y axis and t is its motion period. K1 is chosen to be 30.8 m/s, which is the distance between the adjacent latitude divided by minutes along the same longitude.

$$K_2 = K_1 \cos B_4$$  \hspace{1cm} (5)

K2 in Eq.(5) denotes the distance along BA latitude between
every one minute longitudes. Whether it turns left or right can be concluded by Eqs (1) and (2). Therefore, even if GPS system cannot receive the satellites’ signals, orientation program by inertia components is automatically performed, in which data from the encoder, electron compass and inclinometer together with the previous GPS’s information are used to conclude the robot’s presence geodetic coordinates to make sure its navigation works correctly. When it gets out of the blind zone, GPS system starts to work for the robot’s orientation.

E-F-G is the path followed by the robot when it gets over the obstacles after shape-shifting or round the obstacle directly. In this process, the robot checks the obstacles first. If the obstacle is too tough to get over, obstacle-avoidance program runs to make the robot pass by the obstacle. If it founds that the obstacle can be got over after shape-shifting, it will withdraw a certain distance and change into a more appropriate configuration. After getting over the obstacle, the robot will take a more efficient configuration, reorient itself and move towards the target.

In addition, the robot checks whether it reaches the target position every period by calculating the distance between its position and the target. Suppose that the robot’s present position is C (L<sub>C</sub>, B<sub>C</sub>, α<sub>C</sub>), then the distance to the target position P can be gotten by

\[ L = \sqrt{(K_2(B - B_C))^2 + (K_2(L - L_C))^2} \] (6)

As a measurement error lies in GPS system, the distance from P to C signed as L cannot be simply used to decide whether the robot has reached its target. If L’s error lies at a tolerable range, the robot is thought to be get to the aim point; If not, then we let C replace B, recalculate a and do the conclusion and analysis as has been illuminated in the above paragraphs until we get an L that meets the error tolerance.

V. EXPERIMENTS AND ANALYSIS

Autonomous navigation experiments free of obstacles as well as experiments in the environment where the robot has to reshape itself to get over the small obstacles have been made on AMOEBA-I.

1) Experiment system and Experimental field: The experiment system include one console and one AMOEBA-I. Experimental field is located in the yard of SIA (Shenyang Institute of Automation). The experiment system and Experimental field to validate the autonomous navigation and shape-shifting algorithm are shown in Fig. 7.

2) Autonomous motion in the no-obstacle situation: AMOEBA-I has moved automatically from starting point to end point on the lawn located in SIA. There is no-obstacle situation in the way that AMOEBA-I move on. Process of autonomous motion is shown in Fig. 8.

In the experiment, we set the target position at 41°45.6950°N/123°26.5642°E.

Fig. 8 (a) shows the robot’s orientation before the aim point was set, with its position at 41°45.6945°N/3°26.5345°E measured by GPS devices and the electron compass read 135 degrees.

Fig. 8 (b) shows that after the aim point was set, the robot adjusted itself to face the target.

Fig. 8 (c) shows one of the several adjustments on the way caused by the errors of GPS (<15m) and electron compass (-30–30).

Fig. 8 (d) shows the robot stopped near the target at 41°45.6948°N/123°26.5340°E.

3) Autonomous motion in the small obstacle situation: The process of robot’s autonomous navigation and autonomous shape-shifting is shown in Fig. 9.
Autonomous motion, when AMOEBA-I encountered a small angle vertical obstructions or obstacles with small slope, it can make a reaction in time and automatically change into other configuration with strong ability to climb up obstacle directly and approximate the target point.

VI. CONCLUSION

With global considerations of the shape-shifting robot and its locomotion environments, this paper presented a multi-sensor-based autonomous control system for the robot "AMOEBA-I" to move outdoors. Experiments have validated the effectiveness of the system. Since the urban search and rescue environments are usually unstructured and unpredictable, we believe that the shape changing should be an ideal solution to improve the rescue robot's mobility, flexibility, and adaptability. This paper provides a fundamental approach for robot's possible operation in more complex environments.

ACKNOWLEDGEMENT

This research is supported partly by China National High-Technology 863 Program No.2006AA04Z254.

REFERENCES