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REVIEW ARTICLE

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Current research, key performances and future development of search and rescue robots

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Abstract Frequent natural disasters and man-made catastrophes have threatened the safety of citizens and have attracted much more attention. The rescue mission under disaster environment is very complicated and dangerous for a rescue team. Search and rescue (SAR) robots can not only improve the efficiency of rescue operations but also reduce the casualty of rescuers. Robots can help rescue teams and even replace rescuers to perform dangerous missions. Search and rescue robots will play a more and more important role in the rescue operations. A survey of the research status of search and rescue robots in Japan, USA, China and other countries has been provided. According to current research, experiences and the lessons learned from applications, the five key performances of a search and rescue robot are survivability, mobility, sensing, communicability and operability. Multi-technique fusion and multi-agent intelligent network are considered to be requirements for the future development of the search and rescue robot. Disaster prevention, disaster reduction and disaster rescue are the important parts of national public safety. They are also crucial for the safety of citizens and their estates. Search and rescue robotic technique is an urgent needed, strategic and core technique for national development. It will be important and strategic for national economy and safety.

Keywords disaster, safety, search and rescue robot, current research, key performance, development tendency

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1 Introduction

In recent years, people's safety has been greatly threatened by frequent natural disasters such as earthquakes, fires and floods; the man-made dangers such as terrorism and armed conflicts; biochemical virus such as anthrax, severe acute respiratory syndrome (SARS), avian flu; and toxic substances and the radioactive substances such as nuclear leakage. They have attracted extensive concern. Although people have improved their alert and response capabilities to various disasters, there are still fewer adequate preparations for devastating disasters. Many people still died because of unprofessional and time pressure rescue operations [1–2]. A new field and challenge in robotic research is how to effectively fuse the multidisciplinary knowledge such as robotic technology, rescue technology and disaster science, hence develop intelligent robots for the search and rescue operations.

According to the time when a disaster occurs, a disaster rescue operation can be divided into three stages: the pre-disaster rescue operation, the on-disaster rescue and the post-disaster rescue operation. The pre-disaster rescue operation mainly aims at the disasters known in advance. The rescue operation includes disaster prevention and elimination of catastrophes, evacuation and transfer of materials. The on-disaster rescue operation aims at time-consumed disasters such as fire, flood, gas and radioactive substances. It mainly includes fighting against disasters. The post-disaster rescue refers to taking the search and rescue operation afterwards short-time disasters such as an earthquake and sudden explosions. There is no clear boundary among the above three stages. However, the rescue operation in all stages has two problems: the complexity of the environment and unpredictable dangers. Taking an urban environment as an example, the population of cities and the urban population density have quickly increased, which leads to that high-rise buildings, underground projects, large business establishments and cultural/entertainment facilities have been rapidly built. All these make the rescue operation too complicated to be dealt with. In some extremely dangerous catastrophes including the fire in an explosion, the flammable, explosive and toxic gases

and the easily second-collapse building site after an earthquake, the rescue staff are eager to know the inner situation when they can not perform an in-depth reconnaissance. In such a case, search and rescue robots can improve the efficiency of the rescue operation and medical treatment to reduce the casualties. They can not only help the rescue team in rescue operations, but also replace rescue staff in search and rescue missions. Generally, robots can play an increasingly important role in a disaster rescue operation.

2 Recent research on search and rescue robot

In recent years, especially after the 9.11 attack, many countries in the world began to develop various anti-explosive/anti-terrorism robots as well as search and rescue robots for disaster protections and relief in the sight of their national security strategies. Meanwhile, because a search and rescue robot has lots of potential applications and wide markets, some companies have also been involved in the research and development of search and rescue robots. Additionally, the international robot competition, Robot World Cup (RoboCup), initiates a special rescue competition "RoboCup Rescue", which has provided a test platform for the theory and simulation technology in rescue robotics. Currently, the technology of a search and rescue robot is developing from theoretical and experimental research to applications. In 2005, IEEE International Workshop on Safety, Security and Rescue Robotics (IEEE SSRR ′05), which held in June 2005 in Kobe, expected that robotics would provide an effective solution for the next-age disaster mitigation and become one of the indispensable components of the social infrastructure. The attendances came from 16 different countries or regions. Their research on rescue robotics is different, comprehensive and diversified because of the difference in the level of skills, geographic and political factors, disaster types, ruins and the robot tasks. In the following sections, a survey of the research status of search and rescue robots in Japan, USA, China and other countries will be introduced separately.

2.1 Japan

As a country with rich nuclear power and frequent earthquakes, Japan has performed a relatively comprehensive program to research and develop search and rescue robots. After the Hanshin Awaji (Kobe) earthquake in 1995, a complete disaster rescue and protection system has formed. Japan Ministry of Education, Sports, Culture, Science and Technology has launched a national project, Special Project for Earthquake Disaster Mitigation in Urban Areas (DDT Project) in 2002. A part of this project (Development of Advanced Robots and Information Systems for Disaster Response) aims at developing the advanced robots and information systems for disaster response. This project includes more than 30 groups with a period of five years. Participants include universities, companies and the national institute. The topics of the research include the robot systems of observation in environmental disasters, sensor technology, human interface technology and system integration. A public test site was established at Kawasaki for the project and the International Rescue System Institute was organized. The "Disaster Response Strategy" of the International Rescue System Institute is the core part of the DDT project. The major work in their plans is to conduct research on robotics, intelligent sensors, portable terminal devices and man-machine interface; to develop intelligent information collecting systems; as well as to transmit, compile and generalize the information by a network.

Professor Hirose who is in Tokyo Institute of Technology is one of the pioneers in rescue robot research. He has developed many robots in his laboratory such as "ACM", "GENBU", "SORYU" and other series prototypes in the view of biomimetics and the Super Mechano-Systems [3–4] (http://www-robot.mes.titech.ac.jp/robot.htm, 2005-8-25). With his colleagues and students, he has made great contributions to the biomimetics and its application in search and rescue operations. Figure 1 shows the parts of the rescue robots developed in Hirose's laboratory. Considering the most important thing is to locate the lives in debris and the robot must be in a narrow space, they have developed the SOURYU series. In the fire-fighting scene with water tubes, they have developed the water-driven multi-wheel robots named GENBU-I, GENBU-II and GENBU-III that use high-pressure water as their power to move and distribute water.

Professor Kamegawa in Tokyo Institute of Technology also proposed a new rescue robot platform [5]. As shown in Fig. 2, the robot is composed of multiple tracks and it can enter into a narrow space. With the active joints or passive joints between adjacent units, it is good at crossing barriers and adapting to the ground. In Kyoto University, Osuka et al. developed a four-section rescue robot "MOIRA" with four sides equipped tracks [6]. As shown in Fig. 3, the robot used each four motor to drive four tracks simultaneously and separately, which made it good at shuttling in the ruins and free of tipping.

Figure 4 shows a deformation robot "CUBIC-R" developed by Tabata et al. [7]. With tracks around, this robot can be in a contraction model like a cubic and it can be turned into a variety of other models. Figure 5 shows the information collecting robot "MA-1" developed by Professor Matsuno et al. from the University of Electro-Communications [8]. Figure 6 is the rescue mobile robot "RESDOG" developed by Nagatani et al. in Okayama University (http://usm.sys.okayama-u.ac.jp/~keiji/Research/Prj-Rescue/rescue.html, 2005-08-25). In the bottom suspension of the robot, several passive triangle type tracks provide excellent terrain adaptability. Figure 7 shows the Utility Mobile Robot for Search (UMRS) series rescue robots developed by Professor Takamori in Kobe University [9]. The robots are expected to be used in inspection operations in ruins. The formers are track-type vehicles whereas the latter type adopts flexible driven joints.

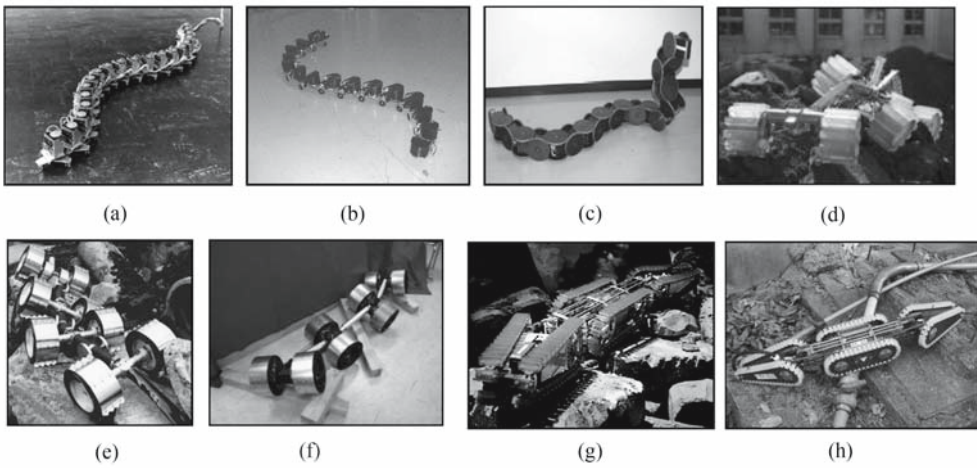

Fig. 1 Part of the search and rescue robots developed in Prof. Hirose's laboratory
(a) ACM III; (b) ACM-R2; (c) ACM-R3; (d) GENBU-I; (e) GENBU-II; (f) GENBU-III; (g) SOURYU-I; (h) SOURYU-II

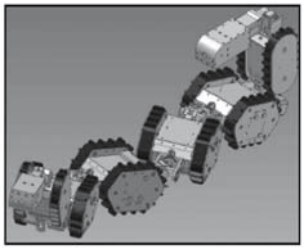

Fig. 2 Multi-unit rescue robot

Fig. 3 MOIRA

Fig. 4 CUBIC-R

Figure 8 shows the operation robot RESQ series and RaBOT developed by Japan Atomic Energy Agency for the implementation in the atomic nucleus radiation sites (http://www.jaeri.go.jp/english/press/2001/010314/, 2005-08-25; http://www.jaeri.go.jp/english/press/2001/010809/, 2005-08-25). By remotely controlled, RESQ series robots have designated missions such as collecting early information (RESQ-A), collecting detailed information (RESQ-B), and collecting sample (RESQ-C). RaBOT is co-developed by Japan Atomic Energy Agency, Naka Institute, and Fusion Nuclear Technology. With high mobility, it can easily go up or down stairs.

Fig. 5 MA-1

Fig. 6 RESDOG

In Chiba University, Nonami et al. performed an extensive research on mine detection robots and air unmanned planes (http://mec2.tm.chiba-u.jp/~nonami, 2005-08-25). As shown in Fig. 9(a)–(c), the detection system at the front of a mine detection robot has high sensitivity. The aerial search and rescue robot in Fig. 9(d) is wireless controlled by ground operators.

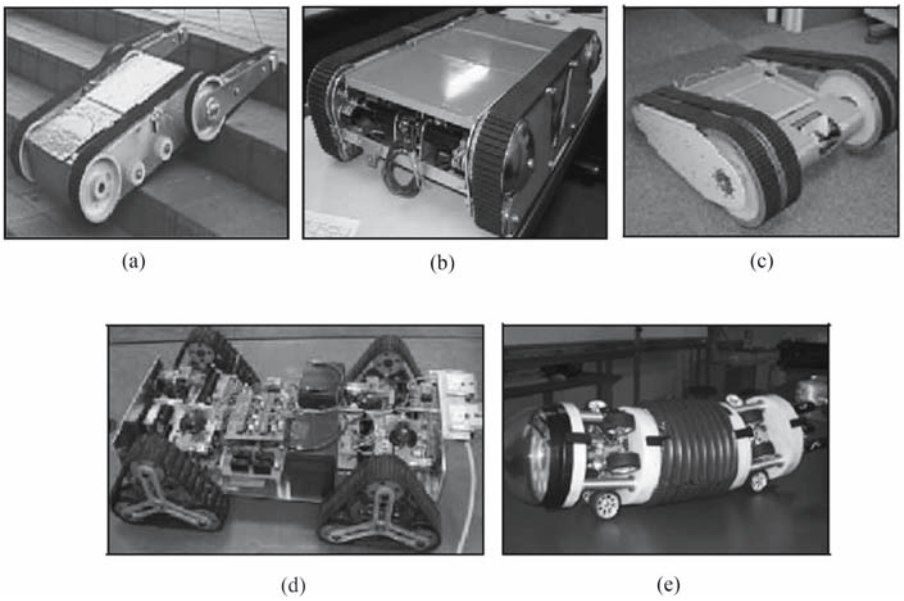

Fig. 7 UMRS series search and rescue robot
(a) UMRS-IV; (b) UMRS-V-M2; (c) UMRS-V-M3; (d) UMRS-V-S2; (e) UMRS-V-SNK

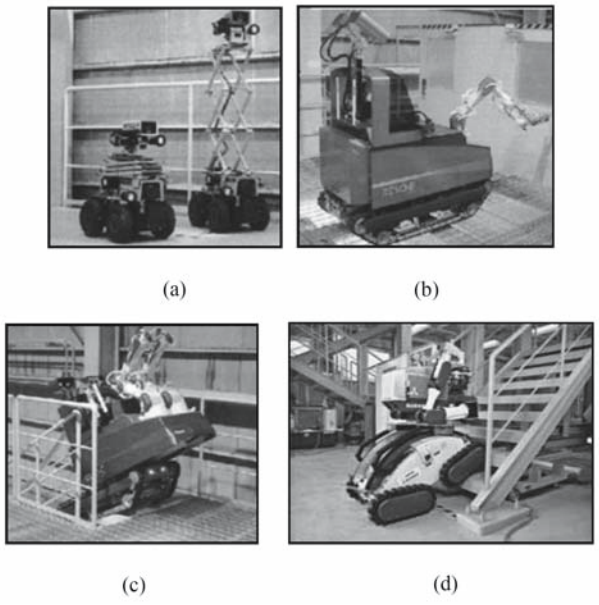

Fig. 8 Nuclear radiation operation robots in Japan
(a) RESQ-A; (b) RESQ-B; (c) RESQ-C; (d) RaBOT

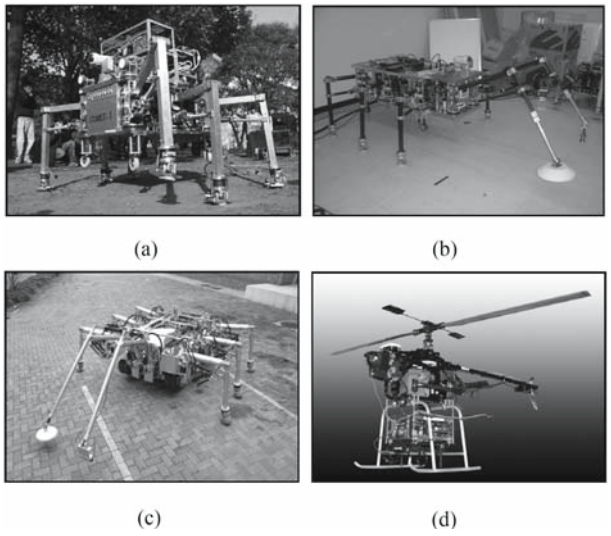

Fig. 9 Inspection robots developed in Chiba University
(a) COMET-I; (b) COMET-II; (c) COMET-III; (d) Autonomous Helicopter

In Japan, some large companies are also involved in the research and development of rescue robots. They usually cooperate with research institutes or universities. Enterprises provide the institute with the necessary fund support for the research and test site. They are also a bridge between products and markets. Figure 10 shows five robots developed by Toshiba, Mitsubishi Heavy Industries, Tmsuk and the other companies [10] (http://pc.watch.impress.co.jp/docs/2004/0325/tmsuk.htm, 2005-08-25). SMERT-M developed by Toshiba is a robot for the limited space on-site detection and the removal of dangerous materials. It can carry 5 kg. MARS-A is a deformable robot developed by Hitachi. It can switch valves, sample materials and lift 5 kg. SWAN is developed by Mitsubishi and has high adaptability to terrain. It can move medium size objects and handle about 10 kg. MENHIR is developed by Nissho Iwai for a radioactive environment. With the strong wrists the robot can carry 25–80 kg. Enryu T-52 is developed by Kitakyushu-based robot manufacturer Tmsuk Co., Ltd. It can remove heavy debris after large-scale disasters such as earthquakes. It is 2.4 m × 3.5 m × 3.45 m. Mounted on the caterpillar tracks that were powered by a diesel engine, it can chug along at 3 kph, guided by the operator perching in the protected cabin at the front of the

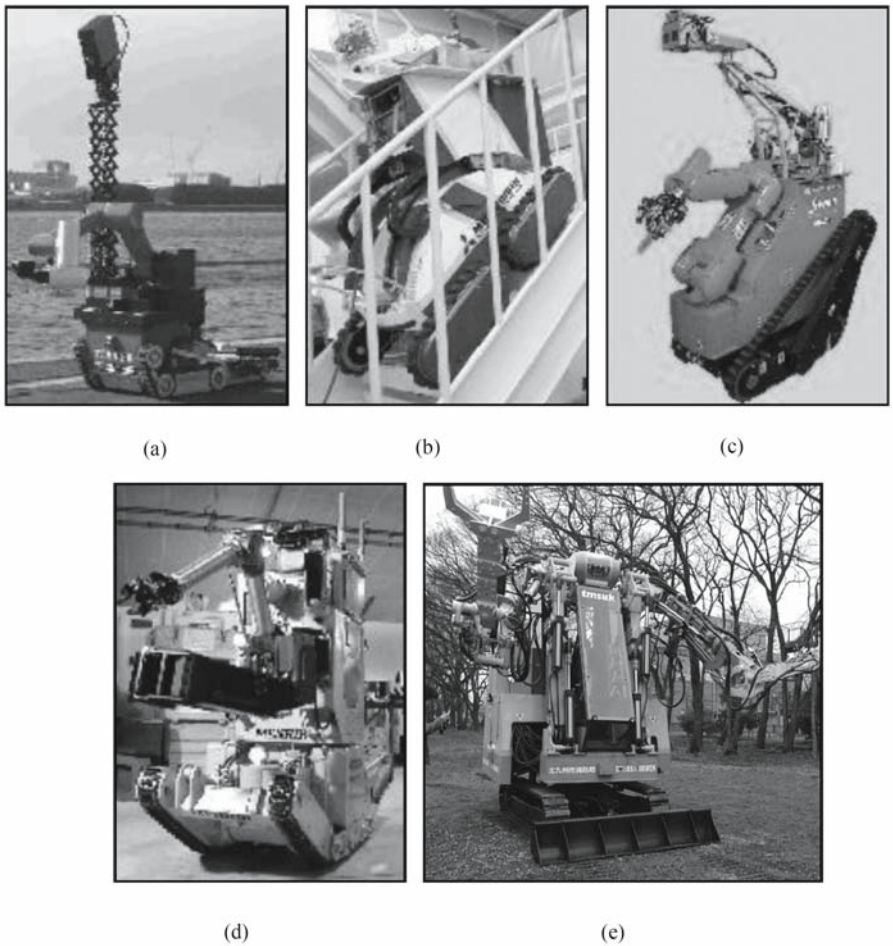

Fig. 10 Search and rescue robots developed by Japan companies
(a) SMERT-M; (b) MARS-A; (c) SWAN; (d) MENHIR; (e) T-52 rescue dragon

robot. Enryu's most striking feature is its two huge hydraulically operated arms with moving steel grips. Each of them can be stretched to 5 m and can lift up 500 kg.

2.2 USA

After the 9.11 attack, search and rescue robotic technology has attracted increasing attention in USA. The rescue operation at the 9.11 attack is considered to be the first application for search and rescue robots. Lieutenant Colonel John Blitch (ret.), the director of the Center for Robotic Assisted Search and Rescue (CRASAR), requested a team of robot experts and suppliers to assist in search efforts at the World Trade Center (WTC) disaster site. New York City's Office of Emergency Management directly requested CRASAR's response. After several hours of the terrorist attack, CRASAR quickly responded to the WTC disaster. This is the first known application of robots for USAR. Eight types of the rescue robots are shown in Fig. 11 [11].

As shown in Fig. 11(a)–(c), some types of robots from Inuktun are Micro VGTV, Micro Traces and Mini Traces, respectively. They have been mostly used in ruins for their small size and light weight. Among them, Micro VGTV and Micro Traces were proved to be more efficient than Mini Trace in constrained space. Foster-Miller companies also used the three robots: Talon, SOLEM and Urbot shown in Fig. 11(d)–(f). With the better sensor and load-carrying capacity, they are larger than the robots from Inuktun because they have the NASA's military background. SOLEM was used in ruins. Talon and Urbot were used for the inspection in interior buildings. The iRobot also used two types of robots in rescue operations: Packbot and ATRV. The tracked Packbot had remarkable traction and self-adjustment ability. The big ATRV had a large wheeled mobile platform.

In USA, a lot of university research centers, national research institutes and companies also conduct researches on search and rescue robots. In Center for Robotic Assisted Search and Rescue (CRASAR), a non-profit research center based at the University of Florida that is led by Robin Murphy CRASAR, has developed many robotic technologies to assist search and rescue teams [12]. As shown in Fig. 12(a), the rescue robot Bujold is equipped with medical sensors. The tracked robot has high mobility and excellent detection capabilities. Meanwhile, the robot can collect information

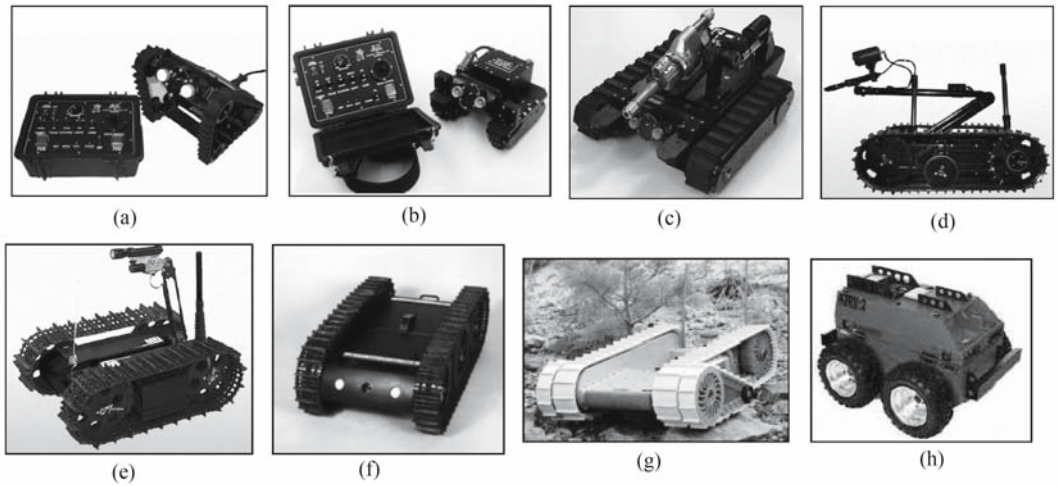

Fig. 11 Search and rescue robots used in World Trade Center's rescue operation
(a) Micro VGTV; (b) Micro Traces; (c) Mini Traces; (d) Talon; (e) SOLEM; (f) Urbot; (g) Packbot; (h) ATRV

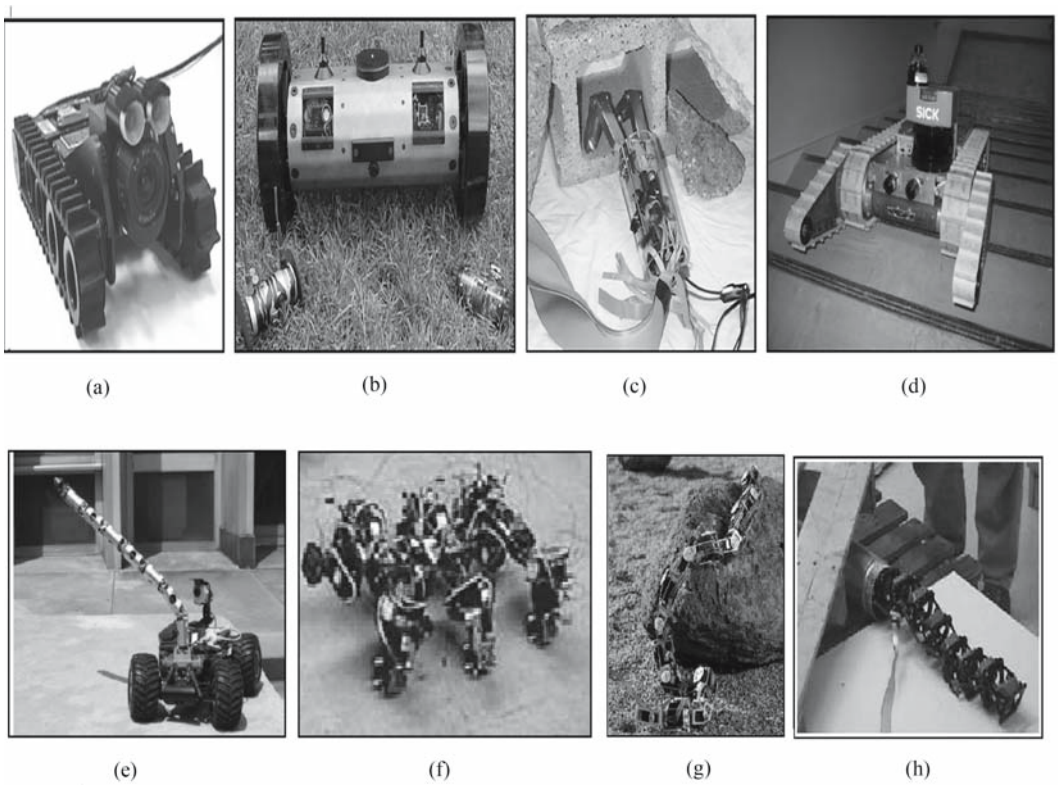

Fig. 12 Several search and rescue robots developed in USA
(a) Bujold; (b) SCOUT; (c) TerminatorBot; (d) Tracked robot; (e) USAR ETR; (f) CONRO robot; (g) Snakebot; (h) PolyBot

such as survivors, physical information and environmental information and then transmit them outside. The SCOUT robot in Fig. 12(b) is developed by Stoeter et al. from the University of Minnesota [13]. With simple sensor modules, locomotion unit, and specialized operational tool, it can be used for multi-robot's parallel information collection. The robot has flexible protection wheels on outer side. With two inspection/locomotion arms, TerminatorBot, the physical structure of which is very cleverly designed as shown in Fig. 12(c) [14], is developed by Larson et al. in the same university. The multi-sensor rescue robot in Fig. 12(d) is developed by Helmick et al. from California Institute of Technology [15]. With the fast stair climbing ability, it is simple and easy to be controlled. Figure 12(e) provides a rescue mobile robot with an elephant nose like a manipulator developed by Wolf et al. from Carnegie Mellon University [16]. The mobile robot has a mobile platform, which can greatly increase the mobility and exploration space of the

manipulator. Figure 12(f) shows a modular reconfigurable rescue robot CONRO developed by Shen et al. from Southern California University [17]. It can change its configuration into different ones including snake, six-legged, or circle upon the requirement. Figure 12(g) is a three-dimensional locomotion snake-like robot developed by Haith et al. from NASA (http://media.nasaexplores.com/lessons/02-014/fullarticle.pdf, 2005-08-25). It has high mobility under unstructured environments. Figure 12(h) is a modular reconfigurable robot PolyBot designed by Yim et al. from the research center PARC [18]. It can fluently change its configuration to adapt to different terrains.

The Urbie series shown in Fig. 13 is jointly developed by JPL, iROBT, CMU and USC from the Mobile Robot program. In the DARPA Advanced Technology Office, this program has enlisted JPL's Machine Vision Group in leading the design and implementation of its perception urban robot. Urbie's initial purpose is mobile military reconnaissance in the city terrain; therefore, many of its features will also make it useful to police, emergency and rescue personnel. With the hybrid structures with track, wheel and leg, the robot is rugged and well-suited for hostile environments and its autonomy lends Urbie in many different applications. Such robots could investigate urban environments contaminated with radiation, biological warfare, or chemical spills. They could also be used for search and rescue in earthquake-struck buildings and other disaster zones (http://robotics.jpl.nasa.gov/tasks/tmr/ hybrid.html, 2005-08-25).

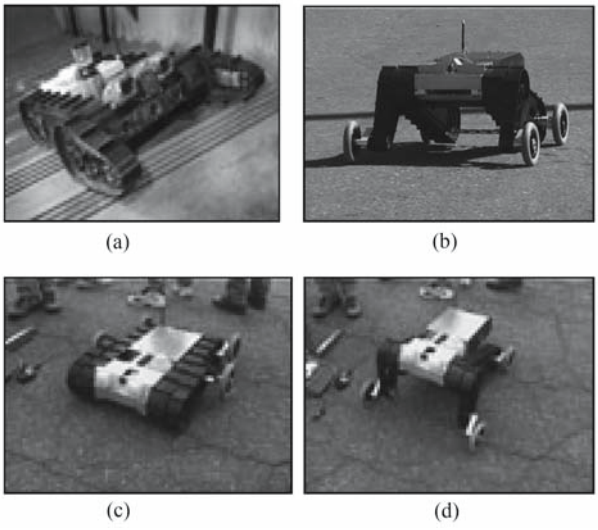

Fig. 13 Urbie series search and rescue robots
(a) Urbie; (b) Urbie Hybrid1T; (c) Urbie Hybrid3T; (d) Urbie Hybrid5T

In USA, the search and rescue UVA or helicopter also attracts the researchers' great attention. The Vision-guided robot helicopters shown in Fig. 14(a) from CMU can quickly and systematically search a very large area to locate the victims of an accident or a natural disaster. They can be sacrificed under very dangerous conditions to save human lives. Prime examples include flying close to a forest fire to look for stranded individuals, searching in contaminated areas and identifying potential radioactive leaks after a nuclear reactor accident (http://www-2.cs.cmu.edu/afs/cs/project/chopper/www/index.html, 2005-08-25). The AR Yamaha Rmax shown in Fig. 14(b) is an autonomous UAV from NASA Ames Research Center, which provides a platform for intelligent surveillance in application domains ranging from security and military operations to scientific information gathering and land management (http://human-factors.arc.nasa.gov/apex/docs/papers/aaaiss04/aaaiss04.html, 2005-08-25). The rescue helicopter shown in Fig. 14(c) comes from Air Search Rescue. This association is exclusively organized for charitable, humanitarian and educational purposes, more specifically, it is a qualified Multi-Rescue Disaster and Missing persons organization which provides life saving search, rescue and recovery with involvement of law enforcement, fire rescue, emergency medical and general services such as specially trained canine search dogs, underwater scuba recovery teams, ground search with ATV's, helicopters, airplanes, with no compensation for services render, all our non-paid Board of Directors and volunteers provide around the clock emergency services (http://www.airsearchrescue.com/helicopter_main.htm, 2005-08-25).

2.3 China

In China, robotic scientists were aware of the importance of the research and development of search and rescue robots since the 1970s. Many universities and institutes had laid stress on the search and rescue robots in various fields such as underwater rescue robot, UAVs, and UGVs [19–21].

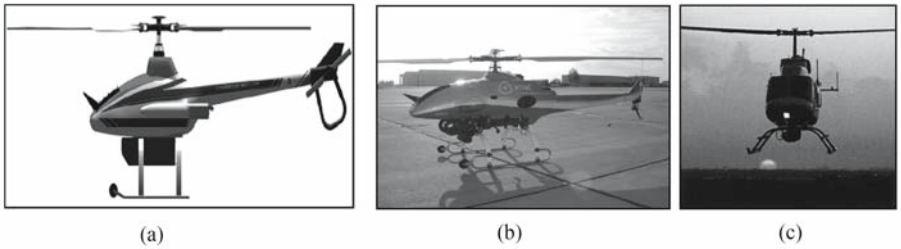

Fig. 14 Several aerial search and rescue robots in USA
(a) CMU Helicopter; (b) AR Yamaha Rmax; (c) Air Search Rescue Helicopter

In disaster's search and rescue application, notable achievements had been made in. In June 2002, the national 863 project—"tracked and wheeled fire-fighting robot" that jointly held by Shanghai Fire Research Institute of Ministry of Public Security, Shanghai Jiaotong University and Shanghai Fire Bureau were successfully completed. The fire-fighting robot, also known as a self-propelled water bubble fire fighting vehicle, is a new type of fire rescue equipment with various fire-fighting techniques. The fire fighting robot shown in Fig. 15 are developed by Shanghai Qiangshi Fire-fighting Equipment Ltd. Co., which were sponsored by Shanghai Fire Research Institute of Ministry of Public Security. The fire-fighting robots, which come from the laboratory to the production workshop and at last to fighting in the real fire, greatly improve the fire rescue equipment of China (http://www.qs119.com/asp/product_list.asp (in Chinese), 2005-08-25).

To complete the national tenth-five "863" Program "robot operating in dangerous and extreme environment" and to meet the requirement of advanced robots in national's anti-terrorist, riot and unexpected incidents, the experts from the "Robotic Technology Group" organized two symposiums with the theme of "dangerous and extreme environment robots" in March 2003 and "sudden emergency response advanced robot" in August 2003, respectively. In October 2003, the Ministry of Science and Technology, the Ministry of Public Security, Headquarters of Chinese People's Armed Police Force and the automation field of the tenth-five 863 Program first proposed the theme of anti-terrorist and against riot robot research with the aim to develop the extreme environment robot. Especially on October 30, 2003, in the first anti-terrorism and against-riot robot symposium, proposals had been proposed to develop the public security robot for the 2008 Olympic Games and the 2010 World Expos. A complete public intelligent protection and rescue system for the Olympic playgrounds or the other important places will be set up with the assistant of advanced inspection robots for ground, wall and pipe, mini UAV for ultra-low-altitude flight and the inspection robot for shallow water.

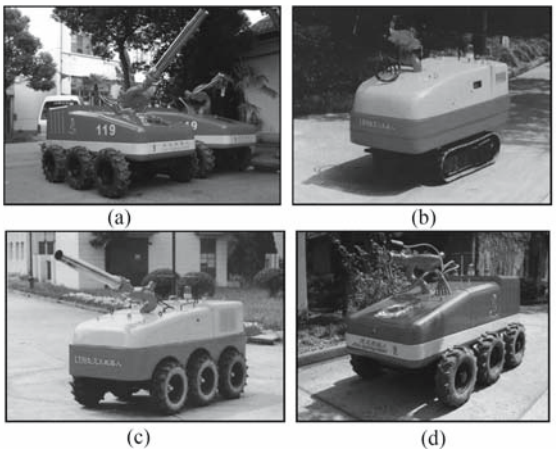

Fig. 15 Fire-fighting robots in China

With fund support of the national 863 program, the Shenyang Institute of Automation (SIA), Chinese Academy of Sciences (CAS) had developed a serious of dangerous and extreme environment robots where search and rescue robots were an important part. The snake-like robot in Fig. 16(a) is developed for unstructured environment's inspection and rescue operations [20]. With a wireless control system, the snake-like robot can use manifold of 3D locomotion gaits such as serpentine, concertina, side-locomotion and rolling. The onsite scene can be transmitted to the operator by the micro-camera installed on the head of the snake-like robot. Based on the study of the snake-like robot, a link-type reconfigurable modular tracked robot named AMOEBA-I had been developed in SIA for a search and rescue operation. This robot has three modules, nine mobile configurations and three symmetrical configurations: line type, triangle type shown in Fig. 16(b) and row type. It can change its configurations and gaits to meet the requirement of

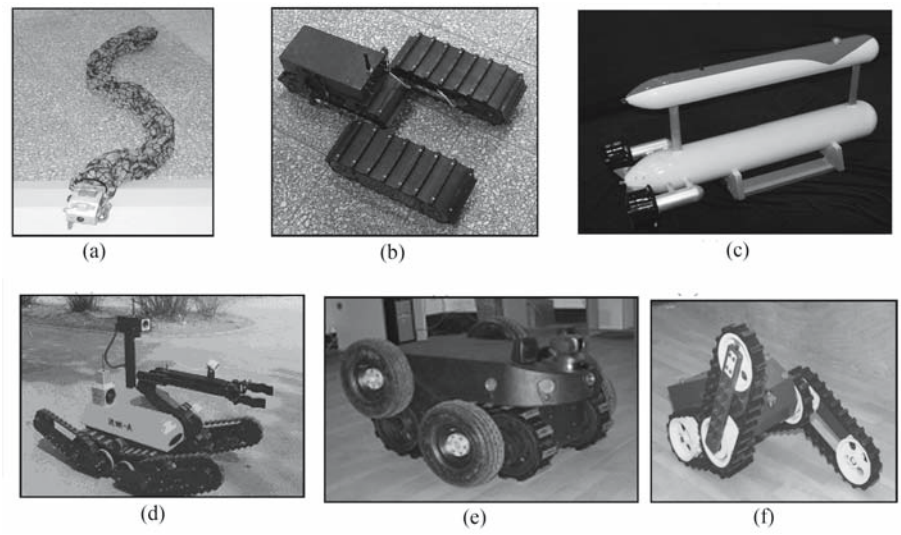

Fig. 16 Search and rescue robots developed in SIA

environments and tasks [22,23]. The water surface rescue robot shown in Fig. 16(c) is under wireless control within a distance of 1 km.

As shown in Fig. 16(d), the product prototype of an extreme environment robot, which can complete anti-terrorism and against-riot task, had been successfully developed by SIA and Guangzhou Weifu Company with authorized copyright. The prototype shown in Fig. 16(e) is the next generation of the anti-terrorism and against-riot robot. The robot with compound structures of the wheel, leg and track shown in Fig. 16(f) is recently developed in SIA for the unstructured environment mobile robot. It can overcome the complex environments such as rugged terrain, obstacles and stairs. It can also be widely used in inspection, investigation, handling, fire fighting and destruction of dangerous materials. On September 12, 2005, the "China-Japan Rescue and Safety Robotics Center" was set up in Shenyang. The center is jointly sponsored by SIA and the International Rescue System in Japan with the aim of achieving a strong alliance to promote the robotic technology in search and rescue application.

2.4 Other countries

After the 9.11 attack, the research on search and rescue robot has also attracted the attention of other countries. The Artificial Intelligence Laboratory of System Science and Engineering Institute, Rome University in Italy initiated the "Rescue Project". The Canadian Department of Defense established the search and rescue robot research project for the national security. Researchers and RoboCup participants in England, Iran and other countries also have shown great interests in the mechanism, sensor, control and simulation of search and rescue robots.

In the RobCup 2001, Sharif University was the only competitor that could travel in the orange and red arenas. The present version of Sharif University's rescue robot EMDAD1, as shown in Fig. 17(a), is a tele-operated robot. An operator remotely controls the robot through a TCP/IP wireless local-area network (WLAN) and receives the images and sounds of the scene when the robot is moving on. The software developed for this robot consists of a user-friendly interface, control programs, simple versions of path drawing and planning and stereo vision image processing programs. In the next version, additional software will be used to provide more autonomy for victim detection, collision avoidance and decision making (http://linux.ce.sharif.ac.ir/~mobasser/RESCUE1.HTM, 2005-08-25). In the Robocup 2003, which held in Padova, Italy, the first three robot winners in sequence are the "ROBRNO" shown in Fig. 17(b) from Brno University of Technology, Czech Republic, the "Cedra" shown in Fig. 17(c) from Sharif University of Technology, Iran, and the "IUTMicrobot" shown in Fig. 17 (d) from Isfahan University of Technology, Iran (http://www.dis.uniroma1.it/~rescue/, 2005-08-25).

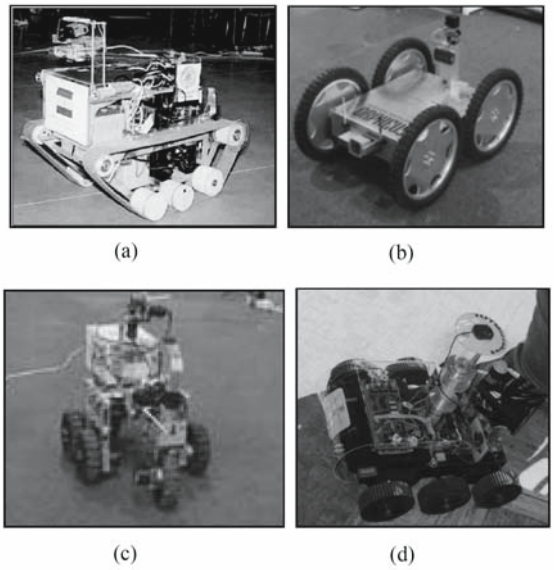

Fig. 17 Several robots in RoboCup
(a) EMDAD1; (b) Robrno; (c) Cedra; (d) IUTMicrobot

3 Key performances of search and rescue robot

The working environment of search and rescue robots is unpredictable and unstructured. Both the environment and the task are dangerous for the robots. According to the exiting research of search and rescue robots in the world and the experiences and lessons learned in their application in the 9.11 attack, the most key performances required for a search and rescue robot are survivability, mobility, sensor, communication and operation [11,22,24–26].

3.1 Survivability

Survivability of search and rescue robot mainly reflects the reliability, durability and adaptability of a robot platform. Survivability in the possible environment with the dangerous gas, toxic liquid, biochemical materials, radio-active substances, extreme temperatures and the risk of secondary collapse is very important. For instance, in a fire disaster, the robot platform should overcome the extremely high temperature and be paid special attention in materials selection. In a dangerous gas or toxic liquid, the robots must face the threat caused by toxic corrosion; therefore, both material selection and structural sealing are important. In the disaster ruins with acute edges, the safety of the robot's wires and the surface hardness should be considered. Considering the power supply of search and rescue robots, both the wired supply and the wireless way are required to ensure the rescue operation hours.

Another requirement in the survivability of a search and rescue robot is the flexibility of software and hardware to take different actions in different cases, region and operations. Disasters are so changeable that disasters of the same type will not result in similar damages, and the same disaster

in different regions will have different effects. Therefore, a search and rescue robot should have adequate adaptability and forecast for the changing environments. Robots should have the intelligence to respond to the challenges and the instable/disturbing factors in the environment.

3.2 Mobility

A robot's mobile platform is very important because the mobility is urgently required in a search and rescue environment. The working environment is complex with too many debris and narrow spaces. The robot should be small enough to overcome it. However, it should be much larger to overcome the surrounding obstacles because it is easy to get tipover if the center of gravity is too high. On the other hand, the robot should overcome the obstacles as many as possible. The stability and the self-adjusting ability are very important in avoiding dropping into fragments. Being repeated, modularized and fault-tolerance, the link-type snake-like structure is proved to be one of the most efficient mechanisms for the search and rescue operation. In the unstructured environment, it is unavoidable that the robot will be damaged or part of it will fail out, therefore, fault-tolerance and fault-handling are important in such cases. Recently, a reconfigurable modular search and rescue robot is considered to be an ideal solution for the paradox.

Moreover, the disaster ground is usually soft for dusts, muddy for water leakage from the water pipe or firefighting equipment and rugged for debris, the robot should have high mobility and adaptability in such case. Regarding the existing wheeled, tracked and legged type mobile mechanism, the hybrid mobile structures have been extensively adopted.

3.3 Sensor

Sensors are the most vulnerable components for a search and rescue robot. They have three applications: robot control, environmental inspection and victims or survivals detection. In robot control, the robot must be aware of its right position, posture, speed and inner status to keep itself work normally. Such equipment includes charge coupled device (CCD) cameras, laser rangefinders, ultrasonic range finder, contact sensors, force sensors, infrared sensors and global position system (GPS) sensors. In environmental inspection, environmental information is very important for robot's working status, operation efficiency, saving energy and preventing accidents. Environmental inspection includes air quality (oxygen, hydrogen sulfide, methane and carbon dioxide) inspection and detection of temperature, humidity and radioactive substances. Environmental information determines the effects on a human body to avoid the rescuer getting into the similar dangerous situation. Environmental inspection includes both environmental geology and topography for the two reasons: 1) to avoid the environments with obvious threat to robots; b) to avoid causing greater damage and a secondary collapse. The static/dynamic ground, as well as its shape and characteristics, is usually different. Therefore, terrain detection is difficult. In victim or survivals detection, objects include the victims or survivals' body, clothing, footprint, voice information, temperature information, apparel information, position information and the unique human-ray findings, are used to judge the existence information and lives of victims. Under some special cases, the same detection system can also be used to search for the victims of animals.

In a sensor system, the video information is crucial to a search and rescue robot because in rescue process the video information can be utilized by the operator to get the on-site observation. A video can be used like the vision information collector for the remote operator to find the victims. However, a camera is not the ideal visual navigation or the victim's inspection equipment. A head lamp must be equipped for each camera first. In collapsed buildings, all the ground has a thick layer of dust that leads to all the things being gray. If the victims have slight movements, the dust of the ground will be significantly changed. Therefore, color camera is indispensable. New technology such as digital temperature camera has good recognition ability, but it has too high requirement to an operator. Sonar can not work at such a case, because there are too many edges and corners that are non-continuous. The ground-penetrating radar, microwave radar and laser detector have good results; therefore, the cost and energy consumption are unbearable. Another solution is to use the artificial intelligence technology, nanotechnology, or bionic technology to develop low cost sensors.

The information processing and fusion problem exists in multi-sensors. Because the search and rescue operation has the limited ability in data processing, most complex tasks such as information and data processing should be designated to outer computers. This will impair its real-time performance. Therefore, the distribution of this task should be reasonable.

3.4 Communication

Communications of a search and rescue robot include three aspects: between operators and robots, between operators and victims, and among many rescue robots. All communications should be wireless. The ideal situation is that the autonomous robot has the ability to move in all environments, locate the victims, and then communicate with a rescue team. In fact, there is a lot of software processing and it is difficult for the robot to complete it independently. A human-machine interface is indispensable. Rescuers must predicate what will happen to make good use of existing resources. In many cases, the robot is not only a tool, but also the substitute of operators. Therefore, communications between operators and robots include the robot control and the effective transmitting of information collected by robots. The two main factors are the accuracy of control commands and the completeness of signal processing.

Communications between operators and survivals are mainly voice and image transmission. Important bilateral audio transmission equipment is microphone. According to

audio interaction, survivors can not only know the arrival of rescue teams but also guide the rescue operation to further look for other victims. An audio message is a very good tool, but it also has shortcomings. The rescue scene is very noisy with the roar of various machines. Voice discrimination is difficult. The communication among rescue robots is blocked by ruins. Currently, there is no efficient way to accomplish this, whereas, it is really urgent to be solved.

3.5 Operation

The capability of an operation is considered to be a synthetical index of a search and rescue robot. Mainly two issues exist. The operability denotes that the robots are easily to be operated. The manipulative ability denotes that the robots have the operational ability to some tasks. In operability, different types of rescue robots perform differently. The robot must be controllable and easy to be controlled. The mostly used platforms are light-weighted, small-sized, and portable. The manipulative ability globally embodies the survivability, mobility, sensors, communication and human-machine interface. It mainly includes the following three aspects.

1) Exploration. The commander and operator determine the location of the dangerous disaster scene and then use the rescue robots for data sampling and recording or recording the building's 3D Geographic Information System (GIS) and physical information. According to the information, the rescue commander or correlative staff determines whether the working site is safe or not to minimize the risk of rescue teams.

2) Search. The search and rescue robot goes into the narrow space or caves where is unavailable to the rescue team to search or identify the victims or survivals.

3) Rescue assistant. The rescue robot provides a series of services such as carrying the necessary equipment, supplying the urgently needed material to the survivals, being the mobile communications interim, communicating with the operators and the survivals, planning the safe route for the survivals, saving the survivals independently, protecting the survivals from unpredictable dropping fragments, and transporting the victims or survivals.

Generally, there are different requirements for the rescue robots at different rescue stages. The rescue robot or the rescue operation should adapt to the requirements and perform corresponding operations.

4 Developmental tendencies for search and rescue robot

China is one of the few countries with serious disasters in the world. The frequent disasters have various types and wide geographic distribution [27–29]. The representative disasters such as traffic accidents, mine disasters, earthquakes, floods, fires and typhoons-based disaster in China brought great destruction to public safety and national economy and attracted great attention of the experts/scholars in the related fields [30–32]. Currently, the research on the search and rescue robot mainly refers to the implementation of a single platform. Because the search and rescue robots gradually come from laboratory into the application, and with the environmental and manipulative requirements of search and rescue robots, many technologies integration and multi-agent networks are the future developmental tendencies of search and rescue robots.

4.1 Integration of various technologies

Because a search and rescue robot is developed for the dangerous and complex disaster environment, the research and development of a search and rescue robot and using autonomous intelligent robots in disaster environments to search and rescue are new challenges in robotics research. A disaster environment has uncertain and unpredictable characteristics. Autonomy, flexibility, redundancy, fault-tolerance, reliability, practicality and durability are the key performances of a rescue robot in the application. When in a real application, it is inevitable to use the remote control and monitor technology, human-computer interaction, multi-sensor technology, navigation and positioning technology, machine intelligence, network technology, multi-agent coordination and control technology and the specially related technologies for the disaster scene. Figure 18 shows some of the traditional disciplines such as mechanical technology, sensor technology, control technology, signal processing technology, computer science and some newly subjects such as artificial intelligence technology, new energy technology, new materials technology, multi-sensor data fusion technology, network technology, remote operation of remote control technology, ergonomics, bionics, and a number of related disciplines such as psychology and disaster science, engineering, rescue, the ruins of engineering, geology, nursing, and other technical disciplines. Various categories of knowledge's integration will provide an effective operation of the rescue robot system. It can be safely obtained that a search and rescue robot system is the core technology that urgently needed by national development in a high strategy level. It involves a lot of factors such as national security, national economy and national technology competitiveness. It will play an important role and have a major strategic significance in the national economy development and security.

4.2 Multi-agent network

In a disaster rescue operation, the ground rescue robots, unmanned aerial helicopters, ground rescue workers, medical personnel and ground ambulance vehicles form a multi-agent three-dimensional network to achieve multi-agent communication and information sharing. As shown in Fig. 19, they are distributing in the disaster area, defended area, and public areas to perform rescue operations. The disaster area refers to

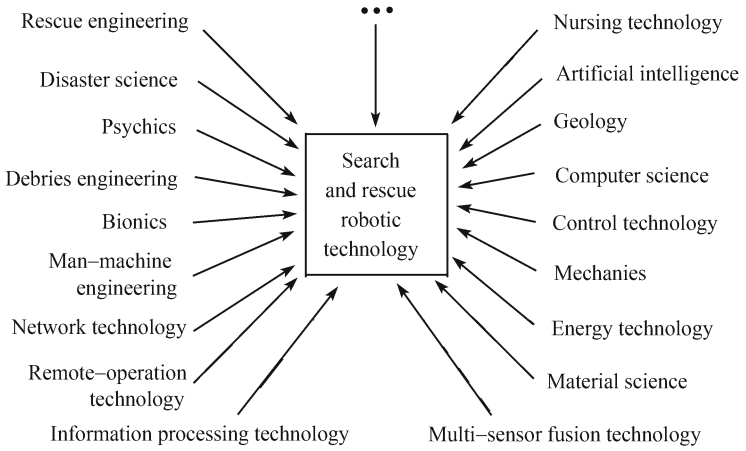

Fig. 18 Integration of a variety of technologies

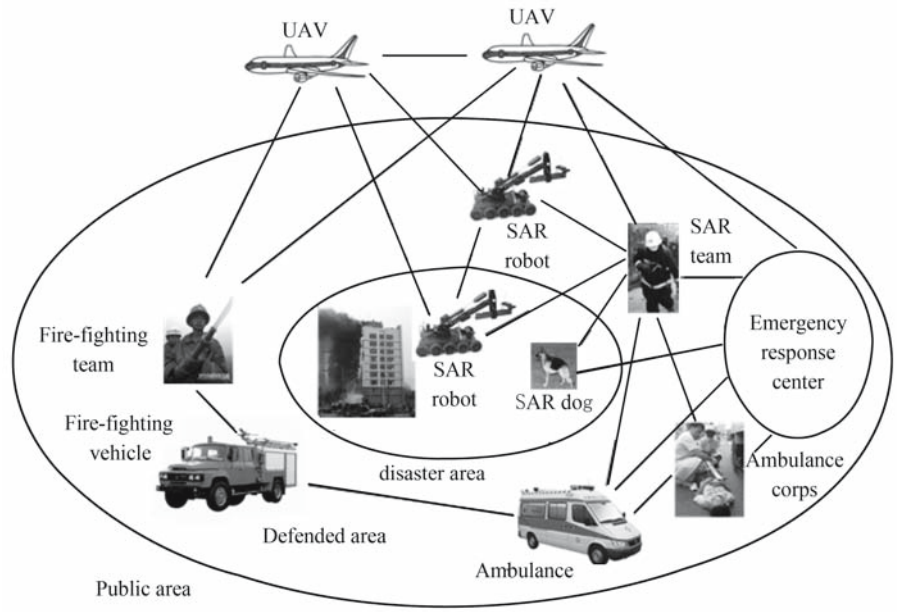

Fig. 19 Multi-agent network for search and rescue

the disaster sites where a catastrophe may continue to occur. Compared with the disaster area, a public area is the relatively safe area facing the public and the media. The defended area separating the disaster area and the public area is used for an emergency rescue operation. Ground mobile robots can be designated with variety of different tasks. Ground robot teams need to have mobility in ground, shallow marshes and swamps. It is very important to rapidly and correctly collect the information in order to initial rescue activities. Therefore, unmanned helicopter systems and a rescue center should be the transit points for information. The information provided by UAV facilitates rescue teams facilitating the detailed investigation and the rescue plan. Unmanned aerial helicopters are unusually transported by rescue vehicles. Operators in a rescue vehicle operate the UAV to investigate the disaster scene to provide high-value information by using high-precision GPS and inertial navigation detection to achieve high-precision flight path and the high-precision measurement of observing locus. Medical staff and ambulances are mainly organized for the rehabilitation and treatment for rescued personnel. The complex rescue network will be a large-scale intelligent rescue system.

5 Conclusion

Disaster prevention, mitigation and rescue severely affect the safety of people's lives and their properties. A rescue operation plays an important role in public safety. In an extremely dangerous and terrible disaster, search and rescue robots can replace rescuers and help them in related rescue operations. Search and rescue robots have wide applications

not only in an urban search and rescue operation, fire protection, public security, mining and environmental protection, but also in other areas such as national defense, military and even planetary exploration. Search and rescue robotic technology is urgently needed and is one of the core technologies at a national strategic level. It will play an important role and have a major strategic significance in the development and security of the national economy.

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