Urban search and rescue (USAR) focuses on locating and extracting people trapped in collapsed or damaged structures. Rescuers are under extreme time pressure; after 48 hours, victim mortality drastically increases owing to exposure and lack of food, water, and medical treatment. Rescuing can be as dangerous to the workers and the victims as the initial event. Moving through the structure or widening entry points for humans and equipment can cause further collapse, injuring or killing the trapped survivors or rescuers. Gas leaks and explosions are also possible. Rescue dogs can help reduce human risk and can enter smaller voids in the rubble than a human can, but they cannot replace a videocamera or structural-assessment equipment.

Lightweight mobile robots could benefit USAR while reducing the risk to humans and dogs. For example, they could:

- conduct tedious searches for survivors with a level of rigor that is normally fatiguing to humans,
- insert specialized sensors into the rubble and position them,
- collect visual and seismic data to assess structural damage,
- deposit radio transmitters or small amounts of food and medication with the survivors,
- guide the insertion of jaws-of-life tools, and
- identify the location of limbs to prevent workers from damaging a victim’s arm or leg during extraction.

Toward that end, my colleagues and I have been developing USAR mobile robot hardware and software. Two promising technologies have emerged that present interesting challenges for artificial intelligence: shape-shifting, marsupial robots.

**Why shape-shifting marsupials?**

In response to the recent earthquakes in Turkey and Mexico, the popular press has reported on many prototype USAR robots, including shape-shifting and serpentine (snake) robots. A shape-shifting robot can change configuration to adapt to its surroundings as it navigates through voids. A serpentine robot has flexible mechanical linkages giving it a high number of degrees of freedom. This lets the robot penetrate constricted voids and twist itself to follow tortuous tunnels.

Shape-shifting’s advantage is readily apparent from Figure 1. The figure shows one of the most accessible voids in a collapsed house used by the Hillsborough County, Florida, Fire Department for training. The void provides a maximum headroom of 0.5 meters through rubble, which severely limits traditional robots. More important, the headroom varies significantly, so one shape will be unlikely to penetrate and search all voids.

Although shape-shifting and serpentine robots can navigate through tight spaces, their significant limitations interfere with their being fielded. First, they consume a great deal of battery power and often require significant computation to control pose and process sensor data. These requirements often conflict with the need to keep them small. Second, the robot’s high number of degrees of freedom and its limited “mouse eye” view of the world make teleoperation difficult and cognitively fatiguing. Efficiently teleoperating these robots requires extensive training, for which rescue workers are unlikely to have time. Furthermore, rescue robots could actually interfere with a rescue if workers have to rescue a malfunctioning robot or if operating the robot is too inefficient.

Since 1996, my colleagues and I have focused on solving these problems by considering shape-shifting robots as a member of a cooperative, heterogeneous team of robots dubbed marsupial robots. A marsupial team consists of a large robot that carries one or more smaller robots to the task site, much like a kangaroo mother carries a joey in her pouch. A daughter robot can be any microrover, although our work has been with shape-shifters. Like a joey, the daughter robot is better protected in the pouch and can conserve energy or be recharged during transport. The mother can protect a delicate mechanism or sensor from collisions while it navigates through an irregular void. The mother can also carry a payload of batteries. The microrover can access this power through a tether. Carrying the batteries into the void and keeping them near the deployed microrovers helps keep the tether from tangling or from being cut as it rubs against sharp objects. Alternatively, a tetherless microrover can range for longer periods of time before having to return to the mother for recharging.

Unlike kangaroos, the mother robot might stay to support its daughter in highly cooperative roles. By doing so, the mother can provide off-board computation and centralized control. This will let the daughter remain small but still have sufficient processing to process sensor data and act intelligently. The mother can also serve as a communications relay station, with enough power to broadcast radio communications from the microrover through structures with large amounts of metal rebar back to the rescue workers. Additionally, the mother...
could supply an external viewpoint of the daughter’s location in the rubble as well as supplemental sensing; for example, “An object emanating heat is to your left.” Our experiments have already shown the efficacy of external views: humans can improve their teleoperation of a daughter by 31% when they use the views from both the mother’s and the daughter’s cameras.

The current members of our marsupial team at the University of South Florida are Silver Bullet, the mother, and Bujold, the daughter (see Figure 2). For the history behind them, see the “Marsupial evolution” sidebar.

The mother. To Silver Bullet’s Power Wheels chassis, we’ve attached an onboard computer and a radio Ethernet link, GPS, six sonars for navigation, inclinometers, and a panning sensor pod consisting of two cameras plus a thermal sensor for detecting survivors. The robot uses Ackerman (car) steering and has a footprint approximately 1 meter long by 0.9 meter wide.

Silver Bullet’s onboard computer is a Pentium-class AMD K7 450-MHz processor with 16 Mbytes of RAM and a 700-Mbyte hard drive. The computer contains redundant Matrox Meteor frame grabbers. Silver Bullet can use the second frame grabber to process images from Bujold’s camera. The operating system is Linux, and all programs are written in C++. Power comes from either household current or one lightweight 12 V motorcycle battery. Silver Bullet also carries two 12 V batteries as a power supply for Bujold. Silver Bullet is sturdy enough to carry up to 70 pounds of payload in addition to Bujold.

The shape-shifting daughter. Bujold is a commercially available tracked chemical-inspection microrobot built by Inuktun Services of Canada. She has a camera, microphone, and two headlights. The camera can tilt 180 degrees independently of the physical configuration. We added a microphone for hearing survivors and a video transmitter to send images directly to a human.

The daughter robot’s smaller size is more consistent with a fieldable USAR robot. She has a footprint approximately 0.35 m long by 0.15 m wide. Her height can vary from approximately 0.15 m to 0.3 m. She is physically connected to Silver Bullet at all times through a 100-foot power and data tether, which is on a self-feeding, motorized spool.

Bujold can change between three canonical configurations: sitting up and facing forward, sitting up and facing backward, and laying flat (see Figure 3). Changes from one configuration to another are termed major transitions and reflect changes in the robot’s task or environment. For example, when autonomously docking with the mother, Bujold undergoes three major transitions. First, she finds the mother, using the sitting up and facing forward configuration to gain sufficient height to see the mother’s visual landmarks. But because of Bujold’s tether, she must back into the mother to dock. Therefore, once she has found the mother, she must effect the second transition to sitting up and facing backward to move backward to the ramp. Once at the ramp, Bujold undergoes the third transition to laying flat to climb the ramp and park in the narrow compartment. She can also assume a continuous set of intermediary poses within the three canonical configura-

Figure 1. Views of a collapsed two-story building at the Hillsborough County Fire Department urban search and rescue training site, showing the narrow, often vertical entry points into a pancaked structure.

Figure 2. Left to right: The microrover Bujold is deployed from inside the car-like Silver Bullet through a rear gate, much like a kangaroo carrying its young. It then operates connected by a tether or umbilical cord to a power supply and computer on the mother.
***Marsupial evolution***

In 1995, John Blitch, one of my graduate students at the Colorado School of Mines, participated in the rescue at the Oklahoma City bombing. His experiences motivated his MS thesis in AI and operations research, which, in addition to the expert system work, analyzed the set of commercially available microrovers.1

His research convinced me of both the humanitarian need for USAR robots and of USAR’s suitability as a robotics test domain, especially as an application where many inexpensive microrobots might prove more effective than one big robot. The director of the Minority Engineering Program, Julian Martinez, and I decided to create a two-year National Science Foundation Research Experience for Undergraduates site grant in USAR robots. Under the grant, 10 undergraduate students in engineering majors from around the country would converge for two summers to refurbish homogeneous fire-fighting mobile robots donated by the Bureau of Mines and program them to work cooperatively for mine rescue. We intended this to provide a motivating, humanitarian project for the students to gain hands-on experience and work together in groups, while investigating the basic research issues in cooperative homogeneous robots for USAR.

**Bad timing?**

The award of the NSF REU grant unfortunately coincided almost exactly with the decommissioning of the Bureau of Mines by Congress. The decommissioning prevented bureau personnel from following through with promised donations of time and personnel to repair the robots to the minimum level suitable for undergraduates. With the permission of Harry Hedges, the NSF program manager, we substituted the original task of instrumenting and programming two donated robots with building and programming a single mobile robot using a Fisher-Price Power Wheels battery-powered children’s jeep as a base and inexpensive, off-the-shelf consumer electronics, supplemented with a donation from the Gates Foundation.

The construction and programming of a fully autonomous jeep robot met the grant’s pedagogical objectives.2 It gave the participants hands-on experience with design and implementation. But the modified research plan would not directly expose the students to the issues in coordinating robot teams, a key AI area.

**A robot is born…**

In the meantime, Erika Rogers, a professor at California Polytechnic State University (Cal Poly), and I received an NSF research instrumentation grant that let us purchase four robots, including two commercially available microrobots suitable for USAR.1 One of the robots we purchased was “Bujold,” a shape-shifting robot.

As the undergraduate students were working on removing plastic from the Power Wheels body, we noticed that the rear had an unused compartment, much like a car trunk but with no access. Someone suggested we cut a door into the compartment, providing storage space. After a few moments of humorous speculation as to what a USAR robot’s compartment would store (beer and brandy dominated the suggestions), someone mentioned wittily that the robot should carry another robot, like a cascading nest of Chinese boxes. The entire team immediately realized that indeed Bujold might fit in the compartment, which would let us realize the first known implementation of a true marsupial robot. Rita Virginia Rodriguez, program manager for the NSF research instrumentation grant, encouraged this dual use of equipment. So, the NSF REU grant statement of work changed for a third time to a homogeneous team of robots for USAR.

The REU team completed construction of the mother robot (dubbed “Silver Bullet”) and interfaced Bujold at the end of 1996. They exhibited the marsupial team and their basic search algorithms at the Mobile Robot Exhibition at the 1997 AAAI National Conference on Artificial Intelligence and at the 1998 Autonomous Agents Conference. (Bujold’s namesake, science fiction author Lois McMaster Bujold, was at that exhibition). Two members of the team, Damian Diaz and Travis Flowers, adapted Silver Bullet’s search and rescue software for the “Find Life on Mars” event of the Mobile Robot Competition; their entry took third place in the Technical Challenge event before a hardware failure prevented them from competing in the final event.

In 1998, Karen Tichenor, Director of Women in Science, Engineering, and Math, joined us in a new two-year REU site grant.
it should automatically assume the safest, most stable configuration. Likewise, if the robot is operating in terrain where it cannot achieve the correct configuration for the desired velocity, the robot should go only as fast as is safe. Another important factor in USAR is the void characteristics. The mechanical design might be such that certain shape transitions are not possible; for example, flattening might require a wider void.

Our experiences strongly argue for an AI approach to robotic shape control. The fundamental lesson we’ve learned is that we must treat the robot as a situated agent: its task and the characteristics of its current environment determine the appropriate configuration. The second tenet is that control must be ecological: the robot changes its configuration in response to directly perceivable events in its environment. For example, if Bujold is docking, she changes to sitting upright, facing backward immediately upon detecting the landmark, just as an insect might lower itself to fit in a hole. Changes should be purely reactive and based on exteroceptive cues, eliminating the need for computationally expensive world models or projections of its upcoming state.

Working together. Silver Bullet and Bujold can be operated in any combination of autonomy: Silver Bullet can direct Bujold; Bujold can be controlled by her own dedicated software agents running on Silver Bullet’s computer; or Bujold can be teleoperated with Silver Bullet acting as a communication relay for the radio Ethernet. Likewise, Silver Bullet can be controlled either autonomously or semiautomously, or teleoperated.

We’re developing software for the marsupial team to operate autonomously to search an area as completely and efficiently as it can. With this software, control of both robots is behavior-based and implemented as part of the Sensor Fusion Effects hybrid deliberative/reactive architecture. Silver Bullet has reactive behaviors for indoor and outdoor navigation, as well as biologically inspired search. The team uses GPS (when the signal is available) for localization and for remembering the path to a survivor.

A typical scenario begins in the warm zone, the zone around the collapsed area where the essential rescue personnel and equipment are. The human operator gives Silver Bullet instructions and any contextual information such as floor plans and the

Figure A. The USAR (urban search and rescue) test room at the USF Perceptual Robotics Laboratory as seen over the mother robot Silver Bullet’s shoulder. The daughter robot Bujold is in the bottom center of the image.

year concentrated on improving instrumentation and experimentation with the marsupial concept. The second year concentrated on individual research projects to upgrade the robots’ sensing and navigational abilities, and we exhibited the team at AAAI ‘99.

Heading south

Late in 1998, I moved to the University of South Florida. Once there, we created a simulated USAR test site: a children’s bedroom where an unconscious or frightened child might hide or fall into an easily missed location (see Figure A). At USF, the work with marsupials has increased exponentially. Under funding from DARPA and SAIC, we are working on three issues associated with marsupial teams. The first is how one or more daughters can autonomously dock with the mother—particularly, how the mother and daughters can actively cooperate to speed up loading. Because USAR is a time-critical domain, any time reduction for these tasks should result in more people rescued. The second issue is how the robots can provide surrogate sensing for damaged peers or even the mother. This will let a blind robot see through another robot’s eyes and move to safety or follow the other robot out. These robustness strategies should alleviate the concern that rescue robots will be more trouble than they are worth. The third issue is physical cooperation with little or no communication, whereby one robot might climb on top of another robot to get a better view or navigate a steep slope.

Independently of DARPA funding, we are working with Howie Choset at Carnegie Mellon University, combining our marsupial work with his serpentine research to support a snake robot in the field. We have also recently begun to focus on the issues unique to shape-shifting robots.

References


likelihood of survivors in an area. Silver Bullet then plans the search’s subgoals; for example, she might try to reach the deepest interior because that is where survivors are predicted to be. We call this a semantic search.\(^3\)

When Silver Bullet enters the hot zone, or collapsed area, she attempts to navigate to her first subgoal using her sonars. While she travels, she uses sensor fusion to detect a survivor based on affordances (the possibilities that the environment affords the robot) such as vision cues (for example, flesh and blood color, and motion), heat, and sound. This opportunistic search is incomplete because the robot is processing sensor data gathered as a by-product of navigation instead of from an active search. When Sil-

**Beyond USAR**

Independently of the urban search and rescue (USAR) domain, marsupial robots have much to offer the AI community. Other likely domains include planetary exploration, military applications, and hazardous material handling. We are working with Aerovironment, a California firm that makes unmanned aerial vehicles, on marsupial ground–aerial teams. Under this approach, a ground robot would carry a team of Micro Air Vehicles to an interesting place, then launch the MAVs for a better view. The mother robot could process the sensor data, then recover and recharge the flying daughters and move on to explore a new area. Possible applications are military battlefield assessment and planetary exploration.

By definition, USAR marsupial teams exhibit three types of heterogeneity of interest to the AI community. The first is physical heterogeneity. The mother and daughters are physically different, and we can increase the level of heterogeneity by using heterogeneous daughters. Second, the team members exhibit dynamic behavioral heterogeneity, where their behaviors must change to accomplish tasks in the mission. For example, the mother might have one set of behaviors associated with rapidly transporting the daughters to the task site. This set might be quite different from the behaviors and deliberation needed to maintain a communications link, fuse data collected by the daughters, or give new commands. As another example, the mother could reprogram the daughters in the field for another task. Third, USAR marsupial robots will function in conjunction with one or more human agents. This highlights the differences in cognitive capabilities between agents, leading to cognitive heterogeneity.\(^1\)

Marsupial teams also make an interesting testbed for evaluating solutions for several multiagent issues.\(^2\) For example, marsupial teams can test theories on homogeneous noncommunicating or communicating agents if the daughters are homogeneous. The team also supports testing of heterogeneous noncommunicating agents if the mother and daughters operate independently, such as with the docking behavior. This gives rise to research in benevolence versus competitiveness, modeling each agent’s intentions and goals, resource management, social conventions, and roles. Many of these issues also arise in heterogeneous communicating agents, which mother–daughter communication supports. Finally, marsupials are a good testbed because the number of daughters per mother is limited only by the hardware available, not by a domain theory.

**References**


ver Bullet reaches her subgoal, she performs a systematic search of that area, with sensor coverage driving vehicle navigation.

At this point, the operator might decide to deploy Bujold. One such case is when Silver Bullet has high confidence in detecting a survivor. She stops and attempts to get the best point of view, then alerts the operator. The operator then deploys Bujold to gather more information or to position the microphone for better reception. Another case is if Silver Bullet is blocked or is progressing slowly. Experiments show that the marsupial team can cooperatively reach destinations that the individual robots cannot, and can reach destinations faster over long distances.4

The future. This year, we will get a new marsupial team consisting of one Real World Interface ATRV-JR mother robot and three IS Robotics Urban daughter robots (see Figure 4 for an example of a mother–daughter team). We are also upgrading Silver Bullet to carry both Bujold internally and an Urban on top. The Urbans are also shape-shifters, are fully autonomous, and have radio communications. This configuration will eliminate the tether and extend our marsupial work to deal with flocks of communicating and noncommunicating homogeneous daughters. (See the “Beyond USAR” sidebar for more on this and other research areas.)

Marsupial and shape-shifting robots for USAR is still a very new field. Although USAR is frequently cited as a possible beneficiary of mobile robot technology, platforms and algorithms specifically for search and rescue activities are relatively new. We hope that our experiences with these technologies, the DARPA Tactical Mobile Robot agenda, and the formation of the RoboCup Rescue competition will encourage others to develop the necessary platforms and software.

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