■ The thirteenth AAAI Mobile Robot Competition and Exhibition was once again collocated with AAAI-2204, in San Jose, California. As in previous years, the robot events drew competitors from both academia and industry to showcase state-of-the-art mobile robot software and systems in four organized events.

The thirteenth AAAI Mobile Robot Competition and Exhibition was held last July, in conjunction with the Nineteenth National Conference on Artificial Intelligence (AAAI 2004), in San Jose, California. The primary purpose of the Mobile Robot Competition and Exhibition is to bring together researchers and students from academe and industry to showcase the latest state-of-the-art mobile robot capabilities. This year saw the return of the Rescue Robot Competition, the Mobile Robot Exhibition, and the Robot Challenge, and the addition of a new event, the Open Interaction Event.

The Rescue Robot Competition

Figure 1. The NIST Reference Test Arena.

manage concurrent exploration of the yellow and orange arenas. Once the robot found a victim, its mapping system enabled the operator to record the necessary victim data in an online form, include images of the victim's situation and surrounding environment, and effectively note the location on the map. The Swarthmore team used this system to locate and map victims more quickly than the other teams, and so scored very well in each of its missions.

Second Place Awarded to MITRE

The MITRE team, from McLean, Virginia, deployed three semiautonomous robots controlled by a single operator. The team demonstrated multiple robot control by integrating semiautonomous teaming behaviors to explore the yellow and orange arenas and an effective custom interface. The three robots were similarly equipped with sensors for laser ranging, infrared proximity, sonar, and bumpers for navigation and mapping. To find victims they used custom pyroelectric sensors to detect body heat, along with a color pan-tilt-zoom camera. They were particularly noted for their approach to simultaneous localization and mapping (SLAM), with fused sensor data from all three robots displayed on a single map accurately showing the location of victims and obstacles.

This team's mapping implementation earned an award for innovation as well.

Third Place Awarded to PARC

The Palo Alto Research Center (PARC) team, from Palo Alto, California, competed with custom-built robotic systems predominantly developed by high school students associated with PARC's Institute for Educational Advancement. This team implemented two different modular serpentine designs, each teleoperated via tether, and an innovative localization approach. Equipped with cameras and microphones, the PARC team's robots were the only robots to explore the extremely confined spaces within the rubble-strewn red arena. The system also included a tanklike robot that deployed sensor motes for map creation.

Other Participants

Other participating teams demonstrated a wide variety of implementations (see figure 3). The team from the University of New Orleans used a small, field-deployable, tracked vehicle equipped with a color camera, thermal camera, and two-way audio. Its tether transmitted power along with video and audio to a hardened control unit used by the operator, while a second operator performed tether management

from the point of entry into the collapse. Teams from the Utah State University, UT, and the University of Manitoba, Canada, developed fully autonomous, custom robot implementations for the competition. These teams attempted to deploy inexpensive technologies that could be easily replicated, deployed in swarms, and considered expendable during search operations. The Scarabs team from Los Angeles, California, implemented a custom-built tracked robot.

Since the Eighteenth National Conference on Artificial Intelligence (held in 2002 in Edmonton, Alberta), the competitors in the Robot Rescue Competition have participated in a study of human-robot interaction (HRI) (Maxwell et al. 2004; Scholtz et al. 2004; Yanco, Drury, and Scholtz 2004). Performance data was captured and archived for teams taking part in the study, including video of robots moving within the arenas, video of the operator interfaces, and video of the operator workload/tendencies during each mission. Over these three competitions, we have observed four trends in the development of the systems: (1) increasing video area; (2) more teams generating maps; (3) improving interfaces, and (4) an increasing number of robots.

Increasing video area. We have seen a trend toward a larger portion of the screen area being devoted to showing the robot's-eye view of the world. To successfully find victims, the operator must have a good view of the environment. We have also found that operators rely heavily upon the video screen for navigation. Larger video windows make it easier to accomplish these tasks.

More teams generating maps. Over the years, we have seen more robot entries create maps of the environment. This trend can be attributed to rules changes that encourage machine-created maps. It might also be attributed to the fact that maps can help to provide an awareness of where the robot is in the environment.

Improving interfaces. Interaction with the robot systems has, in general, become much easier. Text-based interfaces are now rare. There is reduced window occlusion in the interfaces. In general, teams have moved to using a single monitor for a display; however, this year we saw two teams introduce interfaces that included multiple monitors. While this increases the amount of useful information that can be displayed, it also increases the cognitive load on the operator.

Increasing numbers of robots. Five of this year's seven competitors had multirobot entries. In contrast to prior years, most of the entries had robots that operated concurrently.

Figure 2. The AAAI 2004 Rescue Robot Award Recipients.

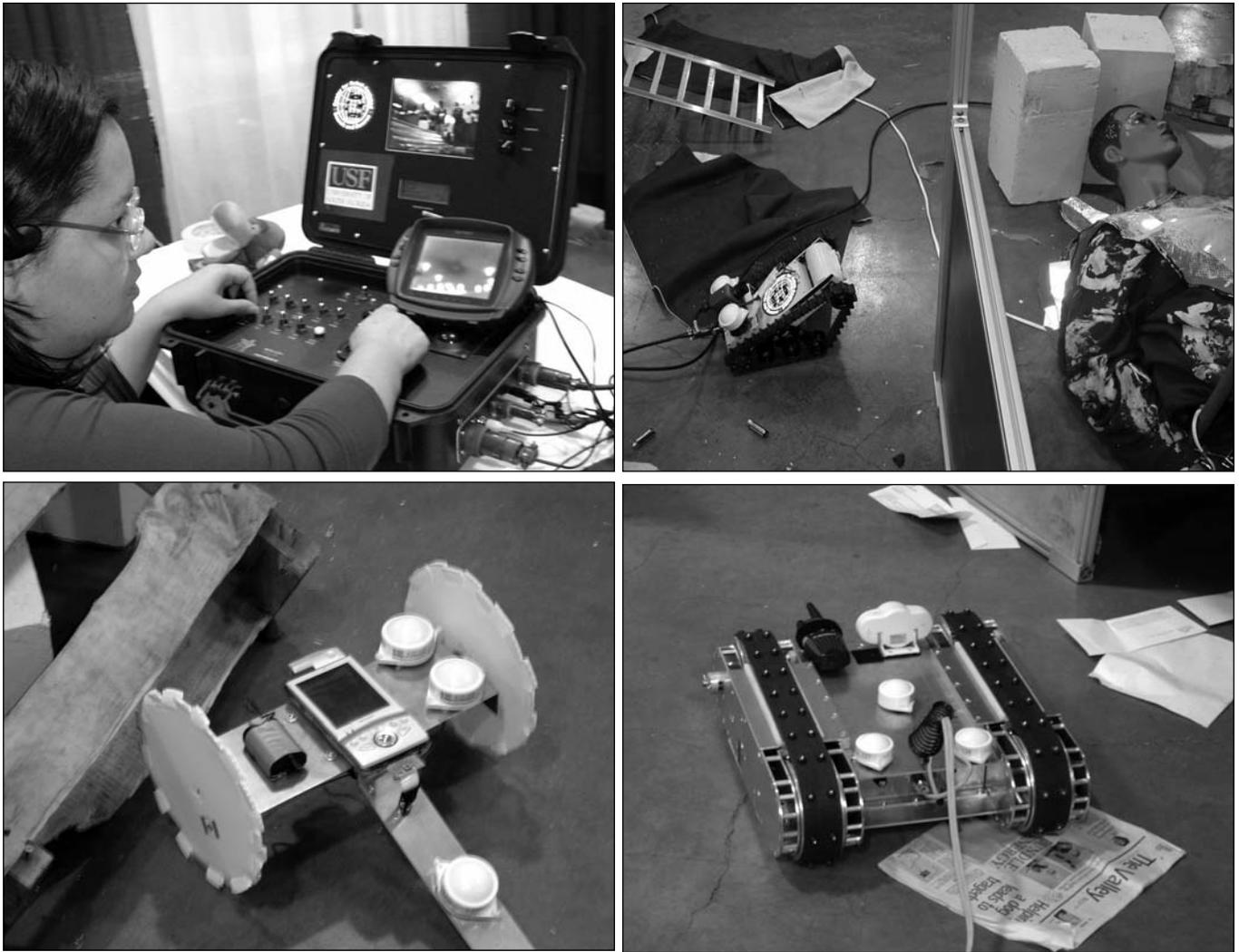*Top:* Swarthmore College. *Middle:* MITRE. *Bottom:* PARC.

*Figure 3. Other Teams Included (top) the University of New Orleans,
(bottom left) the University of Manitoba, and (bottom right) the Scarabs.*

There have also been changes in the difficulty of the victim placement. In the past two years, victims can be on the surface, trapped, in a void, or entombed. The ratio of victims in each of these categories changes to make the task more difficult as the rounds progress, with no surface victims likely to be present by the final round. Additionally, the number of victims is reduced as the rounds progress, making it more difficult to find victims in the later rounds.

This year's competition featured the recently developed robot localization and tracking system used to capture quantitative robot performance data. NIST deployed this tracking system, which uses golf-ball size radio frequency tags affixed to the robots (actively chirping ultra wideband signals), to capture time-stamped location data and produce graphical overview displays of robot position within the arena for each mission. This tracking data is helpful to reconstruct missions and identify both successes and failures but is not yet incorporated into the performance metric used for scoring. However, measures such as "percent of arena searched," "average search speed," and other such metrics can be determined and will be considered for inclusion in future events.

Also on display during the competition were recently developed virtual robot/arena environments called USARsim.[2] These high-fidelity simulation tools, developed principally by the University of Pittsburgh, allow robot programmers and mechanical designers access to virtual collapsed structures and USAR-specific robots. They enable researchers to develop robotic behaviors, demonstrate advanced capabilities, and iterate mechanical designs without the dif-

ficulties associated with physical robot hardware. Currently, the NIST arenas and some more realistic testing facilities are modeled, along with a variety of actual robots. Plans to include entire building collapse models are underway for demonstration next year. The goal of future competitions is to combine development efforts from both the simulated and physical environments, quicken the pace of advancement of practical robot capabilities, and demonstrate comprehensive emergency response scenarios.

Overall, the competition goals were achieved this year by evaluating state-of-the-art technologies, methods, and algorithms applied to search and rescue robots through objective testing in relevant environments, statistically significant repetitions, and comprehensive data collection. Although several teams demonstrated advances in certain key capabilities, more collaboration between teams is needed to produce ultimately effective systems for deployment. When viewed as a stepping-stone between the laboratory and the real world, this competition provided an important opportunity to foster such collaborative efforts and further raised expectations for next year's implementations. It also enticed many new researchers into the field of USAR robots.

The Mobile Robot Exhibition

The purpose of the Robot Exhibition is to give researchers an opportunity to present their latest robotics and embodied AI research in a noncompetitive environment.

Due to various hardware failures that plagued the exhibitors, only three teams were able to participate in the event this year: The MU Mites from the University of Missouri at Columbia, the Stony Brook Robot Design Team from the State University of New York at Stony Brook, and a team from Washington University in St. Louis. The research presented spanned human-robot interaction, multimodal interfaces, and robotic architectures.

The University of Missouri, Columbia presented a group of small Lego robots built using Botball kits (figure 4). The MU Mites robots perform group behaviors by moving in formations based on recognized gestures sketched on a personal digital assistant (PDA). The user sketches a configuration of robot icons with an arrow to designate the relative direction of travel. Hidden Markov models were trained to recognize sketched symbols, such as arrows, rectangles, ellipses, and lines. The sketch interface also supports editing commands such as making an x to delete a robot from the formation or mov-

Figure 4. The University of Missouri Mites.

ing the robot icons to form a new formation. Commands are sent from the PDA to the HandyBoard controlling the robots using the infrared (IR) port; the PDA is programmed to send Sony remote control signals that are received and interpreted by the HandyBoard. Formations are accomplished by using distributed control with no explicit communication between robots. Each robot has brightly colored panels on the rear and sides, as well as a color camera (the CMU cam) mounted on a servomotor. The robots stay in formation by tracking the appropriate color.

The Stony Brook Robot Design Team has focused on three main areas of research in the creation of JESTER (joke entertainment system with trivia-emitted responses, figure 5) navigation, computer vision, and user interface and human interaction.

JESTER's navigation system uses both infrared sensors and computer vision to avoid obstacles and distinguish between people and other objects. There are six infrared sensors used in JESTER. When any of these sensors detect an object, the robot base stops moving and lets the computer vision determine the next step. A motion-detection system, modified from Konrad Rzeszutek's Motion Detection Toolkit,[3] determines whether there is motion in front of the robot and thus distinguishes between facing into a crowd and facing a wall.

The interface and human interaction com-

Figure 5. JESTER with AAAI-04 Attendees.

ponents were designed keeping in mind the principle that humanlike avatars help ease the interaction between robots and human users. Most avatars do not have a sense of emotion or a means to visually portray their emotions. Thus, through integrating a realistic avatar through software created by Haptek Technology with an intelligent conversation system, the interface is able both to respond to human inputs appropriately and to react with a display of appropriate emotions. The end result is that users spend an average of approximately 40 percent more time interacting with the system, with 92 percent of users reporting that they enjoyed their experience, compared to 84 percent of users interacting with the nonemotional interface.

One of the most challenging aspects of the mobile robotics is the task of integration. Researchers in fields as diverse as motion planning, machine learning, and computer vision typically write components since mobile robots depend on all of these technologies. Combining these heterogeneous components into a stable system is more than just a middleware challenge since each part of the system has its own failure modes, which may be exacerbated by placement in a complex system. Correct handling of faults is not just a quality of service issue, but also a safety issue since the robots interact with humans often in crowded environments.

To address these problems, Washington University in St. Louis has developed a framework that allows implementation of numerous perceptual and control tasks as individual processes, or services, which interact according to explicitly defined interfaces. These interfaces

allow abstracting the information provided by each component in the system in order to ease integration. Running services in many small processes improves fault tolerance since any number of services can fail due to programming faults without affecting the rest of the system.

While it is clearly important to be able to handle a wide range of failures, application authors should not be required to implement routines to test and react in every known mode of failure for every application, even if the failures are abstracted to a common interface. Thus, the framework also provides transparent fault-tolerance to users of system services. Errors in software and hardware are detected, and corrective action is taken. Services can be restarted or removed from the system, and clients are reconnected to the same service or to another service implementing the same interface without intervention from the application programmer. The Washington University team successfully demonstrated its failure-tolerant framework on its robot, Lewis (figure 6).

The Robot Challenge

The Robot Challenge is an event designed to encourage and showcase research in robot-human interaction and operations in typical human environments. The goal of the Robot Challenge is to design a robot system that can fully participate in the AAAI conference by registering, navigating around the conference hall using natural landmarks and human assistance, provide information on the conference and local area, have casual conversation with other conference attendees, and give a talk and take questions. The common thread among all of these subtasks is interaction with humans, who are often not intimately familiar with mobile robot systems.

One of the key challenges for this event remains reliable perception in a dynamic, uncertain environment. With people and other robots moving about, opening and closing of doors, and the occasional rearrangement of (possible previously mapped) furniture, matching sensor readings to a previously learned map is difficult. This problem can be addressed through the use of probabilistic reasoning, based on the robot's likely position, but as the uncertainty grows, it is possible for the robot to become irrecoverably lost. Currently, becoming lost requires the intervention by an operator to reinitialize the system.

The single entrant in the 2004 Robot Challenge was Lewis, developed by a team at Washington University in St. Louis (see figure 6).

Figure 6. Lewis, from Washington University in St. Louis.

Lewis is an iRobot B21r robot with a pair of cameras, a laser range finder, sonars, and bump sensors to aid in navigation. Lewis uses the CMU CARMEN mapping package[4] to build maps and navigate in dynamic environments. People interact with Lewis through an onboard keyboard and touchscreen interface. The main improvement over the 2003 highly successful entry (at the International Joint Conference on Artificial Intelligence in Acapulco, Mexico) was the addition of a highly fault-tolerant autonomic control framework. This framework consists of two elements: (1) a finite state-machine-based controller that sequences individual task-achieving behaviors, and (2) a service-based middleware layer that provides robustness in the face of hardware and software failures.

Lewis was intended to begin the Robot Challenge at the elevator on the first floor of the conference center. After requesting help with the elevator button, Lewis sensed when the elevator door opened, entered the elevator and asked for the second floor button to be pressed. On sensing the elevator door opening for a second time,

Figure 7. Grace (left, behind desk), from Carnegie Mellon University, Interacting with Lewis.

Lewis exited the elevator and looked for a special sign indicating the proper registration booth. Lewis then navigated to the appropriate booth, continually avoiding obstacles in its way. Once at the booth, Lewis waited in line until it got to the head of the line. Once the robot was at the front of the line, it interacted with the registrar using preprogrammed speech scripts and keyboard input. Finally, Lewis followed a guide, either another (red) robot or a human wearing a red shirt, to the exhibition hall.

An additional obstacle to success in the Ro-

bot Challenge event continues to be the robustness of the complete robot system and the ability to gracefully recover from failures in both hardware and software. Particularly difficult to deal with are failures induced by noisy sensing. While dealing with the elevator, Lewis had mixed success in determining the open/closed status of the elevator door, and performance was unreliable. Inaccurate sensor information caused Lewis to switch operational modes at the wrong time, and the robot sometimes believed it was entering the elevator when it was exiting. Success in locating and navigating to the registration booth was also mixed; confusion over status related to riding in the elevator did not allow Lewis to properly switch from elevator mode to sign-finding mode.

One of the most anticipated parts of the demonstration was an intended robot-robot natural interaction expected between Lewis and Grace (Carnegie Mellon University's roboceptionist, described later) at registration. Repeated failures to produce a conversation that was recognized by both robots were exacerbated by the need to turn off much of Grace's language-processing ability, again showing the difficulty in integrating complete systems in a real-world setting.

The difficulties in getting robots out of the lab and into the real world are slowly being addressed but remain largely unsolved. Unreliable sensing in dynamic environments can confuse robots and lead to failures; these failures are not yet adequately identified or recovered autonomously, due to the complex and dynamic nature of the environment. Overemphasis on autonomy limits failure recovery; if a person becomes confused, he or she would request help to become reoriented, but the robots in the Robot Challenge event do not yet use this recovery mode. The area of natural language and gesture understanding remains a particularly open area of research. The facility with which humans can interpret language, drawing from a huge vocabulary and from rules of syntax learned over a long period of time, cannot yet be matched by a robot system. Hand-designed dictionaries and key-word matching without syntax cannot approximate this level of detail, and learning algorithms have not yet been successfully applied to learning language. Entries in the Robot Challenge explicitly addressing these issues would be very welcome.

The Open Interaction Event

The Open Interaction Event was a new addition to the AAAI robot program for 2004, aimed at showcasing the latest results in the area of robot-human interaction. The only requirement for entry in this event was that the robot systems have some significant interaction with humans. Four teams entered the Open Interaction Event in 2004: B-dog (University of New Orleans), Grace and George (Carnegie Mellon University and the Naval Research Laboratory), the University of Missouri Mites, and JESTER (State University of New York at Stony Brook). The MU Mites and JESTER were described earlier, since they were also entered in other events.

Grace (figure 7) and George (figure 8), both iRobot B21 robots, acted as a robot receptionist (Grace) and robot guide (George) for conference attendees. Both robots displayed an expressive computer-animated face on a flat-panel LCD monitor as the central element of their robot-human interaction. Rather than using error-prone speech-recognition systems, both robots accepted human input via an attached keyboard.

Grace spent the conference behind a desk close to the registration area, interacting with the attendees. Most of the interactions involved "small talk" about her origin and capabilities, although Grace was also capable of providing information on local restaurants and how to find them. This information was stored in an on-board database, and accessed through a natural language interface based on the NRL NAUTILUS system (Wauchope 1990). Unfortunately, George was not able to perform its full set of guiding duties, due to some last-minute integration problems. However, George was successfully stationed outside of the exhibit hall and interacted with conference attendees in a manner similar to Grace.

Conclusions and the Future

Mobile robots are complex systems, and deploying them in a public venue is challenging. As always, hardware failures and systems integration issues reared their heads, forcing some teams to demonstrate only a subset of their whole systems. However, despite these problems, the robot events once again proved to be a success, showcasing the state of the art in mobile robotics research and exposing members of the more general AI community to the field.

The 2005 Mobile Robot Competition and Exhibition will be cochaired by Sheila Tejada (University of New Orleans) and Paul Rybski (Carnegie Mellon University) and will mark a departure from the traditional format. In the past, the conference with which the event is collocated has been held in a convention cen-

Figure 8. Left: George, from Carnegie Mellon University. Right: George's Face.

ter, with an exhibition hall in which the robots can operate. In 2005, the Twentieth National Conference on Artificial Intelligence (AAAI-05) and the AAAI mobile robot events will be held in a hotel. This means that all of the entrants will be forced to deal with a less structured environment as they compete in the events. This change reflects the growing maturity of the field and the robustness of our systems. In the past decade, the competition has gone from specially designed robot-friendly environments to the clutter and uncertainty of the real world, and the events at next year's competition are sure to showcase this change.

Acknowledgements

We would like to thank all of the competitors who came to San Jose in 2004. Once again, despite the ever-present hardware failures and integration problems, they successfully demonstrated the state of the art in mobile robotics research. The competitors would also like to thank the San Jose Convention Center for keeping the air conditioning and plumbing running for the duration of the conference.

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The general cochairs for the 2004 event were Bill Smart and Sheila Tejada. The event chairs were Ashley Stroupe (Robot Challenge), Bruce Maxwell (Open Interaction), Magda Bugajska (Robot Exhibition), and Jenn Casper and Adam Jacoff (Robot Rescue). The robot workshop was organized by Ric Crabbe.

Notes

1. See http://robotarenas.nist.gov/competitions.htm.

2. See http://usl.sis.pitt.edu/ulab.

3. See K. Rzeszutek's Motion Detection Toolkit: http://darnok.com/programming/motion-detection/

4. See the Carnegie Mellon Robot Navigation Toolkit

developed by M. Montemerlo, N. Roy, and S. Thrun, http://www-2.cs.cmu.edu/~carmen.

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Sheila Tejada is currently an assistant professor in the Computer Science Department at the University of New Orleans. She was awarded her master's and doctoral degrees in computer science from the University of Southern California in 1998 and 2002, respectively. Tejada has developed awarding-winning robots, such as the robot YODA, which took the silver medal at the AAAI office navigation robot cpo.00sco,y-