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The AAAI 2006 Mobile Robot Competition and Exhibition

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■ The Fifteenth Annual AAAI Robot Competition and Exhibition was held at the National Conference on Artificial Intelligence in Boston, Massachusetts, in July 2006. This article describes the events that were held at the conference, including the Scavenger Hunt, Human Robot Interaction, and Robot Exhibition.

The Fifteenth Annual AAAI Mobile Robot Competition and Exhibition was held in conjunction with the National Conference on Artificial Intelligence (AAAI-06) July 17–20, 2006, in Boston, Massachusetts. The robot competition and exhibition has a long tradition of demonstrating innovative research in robotics (Rybski et al. 2006, Smart et al. 2005, Balch and Yanco 2005). From new approaches to canonical robotics problems to groundbreaking research in emerging areas, the robot program provides a forum for a diverse range of projects in mobile robotics. Recent years have witnessed a rise in the accessibility of mobile robot platforms with reasonably capable platforms being available for relatively low cost (Dodds and Tribblehorn 2006, Dodds et al. 2004) and not requiring a substantial effort to build hardware (Veloso et al. 2006) or software (Blank et al. 2003, Touretzky and Tira-Thompson 2005) architectures. Some participants at this year's robot competitions and exhibition demonstrated a range of projects using commodity robots, while others showcased unique construction. As robots become more accessible, the robot program is able to showcase work from a wide range of contributors. Building upon the success of the 2005 robot program, which represented a change from a large open convention hall to a more cluttered and noisy hotel environment, the 2006 robot events once again emphasized operation in natural unmodified environments in a hotel setting. Additionally, the Open Interaction event from the previous year further evolved into a Human-Robot Interaction (HRI) event.

Briefly, each event is described as follows:

Scavenger Hunt: Autonomous robots were required to search a cluttered and crowded environment for a defined list of objects and were judged on task performance.

Human-Robot Interaction: Teams submitted robots that demonstrate engaging interactions between people and robots. The robots perform tasks that were assessed for any of seven interaction categories. All categories were aimed at human-robot interaction and involved activities that intrinsically integrate perception and action.

Robot Exhibition: Teams demonstrate any relevant robotic/AI technology. Teams were judged not for first, second, or third prize awards but rather for recognition certificates that acknowledged innovative technologies.

The Mobile Robot Competition and Exhibition was cochaired by Paul E. Rybski from Carnegie Mellon University and Jeffrey Forbes from Duke University. Zach Dodds from Harvey Mudd College (HMC) and Paul Oh from Drexel University served as organizers for the Scavenger Hunt. Matthias Scheutz from University of Notre Dame established and managed the Human-Robot Interaction event. Debra Burhans from Canisius College coordinated the Robot Exhibition. Bob Avanzato from Penn State Abington chaired the mobile robot workshop.

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Figure 1. The Robots Participating in the AAAI 2006 Mobile Robot Competition and Exhibition.

In total, there were 19 teams that participated in all of the different events. Figure 1 shows all of the robots.

Scavenger Hunt

The 2006 AAAI Scavenger Hunt challenged the spatial reasoning abilities of the entering teams' robots, requiring them to locate and map a variety of objects at unknown locations within the conference environment. The set of objects was known ahead of time and consisted of commercially available brightly colored objects. While the objects could typically be found through color segmentation algorithms, color was insufficient to recognize the individual objects. That is, several objects had the same color, and thus the teams were required to also recognize the object's shape. Four objects of the set were selected and placed randomly in the environment for the robots to find.

The competition was divided into two phases: demonstration and challenge. In the demonstration phase, the teams were allowed to demonstrate some scavenger hunt-specific capability to the judges that was generally defined by the teams themselves. This phase was primarily designed to appeal to other robotic contest entries, educational projects, and systems that take novel AI approaches to environmental reasoning. In contrast, the challenge phase required the robots to search an area chosen by the judges for a subset of the objects (also chosen by the judges). Points were awarded to the teams based on six criteria: autonomy and shared autonomy, environmental modification, unexpected dynamic or human interactions, accuracy, range and completeness, and speed.

Autonomy and shared autonomy. Teams were allowed to enter with one or more robots and human operators, though every entrant was required to demonstrate AI techniques during the competition. Approaches resulting in systems with shared autonomy or full autonomy were to be considered on equal footing. However, shared autonomy did not mean fully teleoperated. Any robot exhibiting shared autonomy was required to demonstrated fully autonomous modes and the performance of the robot would be judged accordingly.

Environmental modification. Ideally, an entry would interact with the conference environment without modification. The robots were required to operate within the lighting, color, and spatial restrictions of the environment chosen by the judge. The number of people present was guaranteed to be low, however, so that the robots would not be required to navigate through crowds.

Unexpected, dynamic, and human interactions. A key aspect of the scavenger hunt competition is the potential for robots to interact with people present in the environment. This category assessed the robots' ability to handle unmodeled activity or changes in the environment. Robustness to such phenomena is a hallmark of intelligent spatial reasoning. As with the other judging criteria, participants could request onlookers and judges to keep to specific types of interactions. Robotic systems that make such requests for themselves would be judged even more favorably.

Accuracy. In order to convey its reasoning about the environment, each scavenger hunt entry was required to try to create and convey one or more representations of its surroundings. Many such "maps" were possible, for example, traditional dense maps, sparse, loosely connected collections of landmark locations, networks of learned parameters, or other summaries of the systems' spatial input data. Novel representations or approaches integrating diverse facets of AI were all welcome. Judges were to consider both the accuracy and utility of these representations in the demonstration and challenge phases of the competition.

Range and completeness. Judges assessed the subset of the conference environment that each system can cope with, especially in light of the particular sensors available to each entry. For example, a system equipped with a laser range finder would be expected to reason about a larger swath of area than one with only a set of infrared (IR) sensors. "Completeness" considerations included the variety of sensory modalities supported and their extent.

Speed. Finishing the tasks quickly was a desirable trait for a robotic entry, but speed was not as important as a system's ability to interact with and reason about the (relatively) unmodified conference environment.

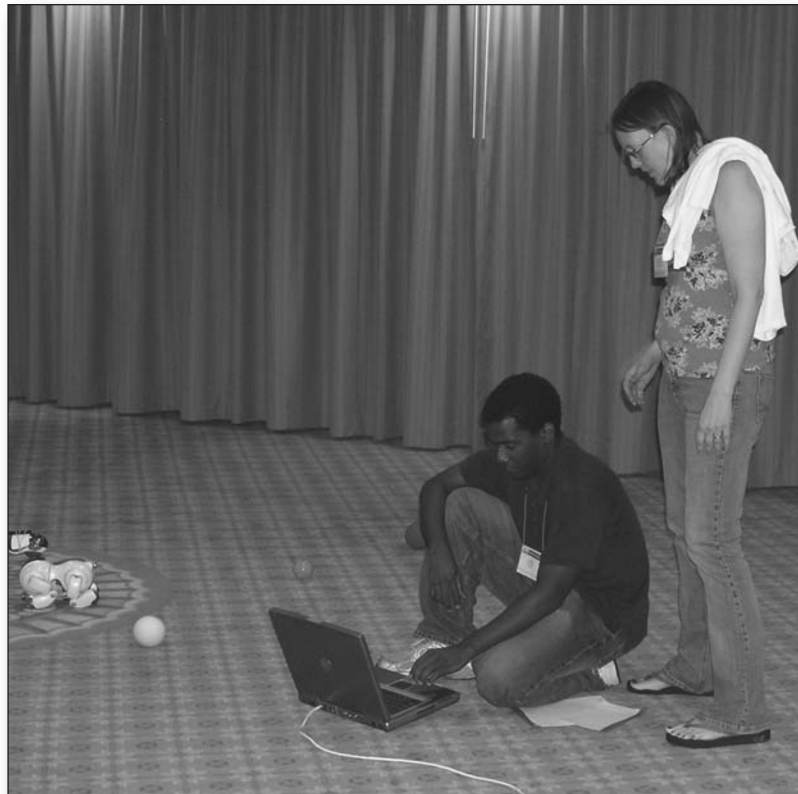

Figure 2. The Canisius Griffins' Aibo-Based Scavenger Hunt Entry.

Six teams participated, with each taking a very different approach to the problem.

The Canisius Griffins'' AIBO-based entry, shown in figure 2, had attended the AAAI exhibition in 2005 and returned with additional capabilities for wandering, recognizing, and approaching known objects. During its trial and competition runs, the dog showed a typically canine sensitivity to crowds –– in this case, it was the interference of many wireless signals that caused problems. Even so, the entry did locate one of the objects and set off looking for more before losing its communication link with the pyro-based controller running offboard.

Bridgewater State entered a home-built platform based on the Xport Robot Controller, shown in figure 3. Using a color camera for object sensing and a pair of felt-tipped pens to extend its tactile sensors' range, the robot successfully found two objects. In each run, its color segmentation also locked onto a piece of clothing from the crowd gathered around the robot's workspace—sending the robot scurrying after members of the audience. This low-cost entry demonstrated that successful participation requires only a commitment of energy and effort—not a large financial outlay.

The entry with the loftiest ambitions was

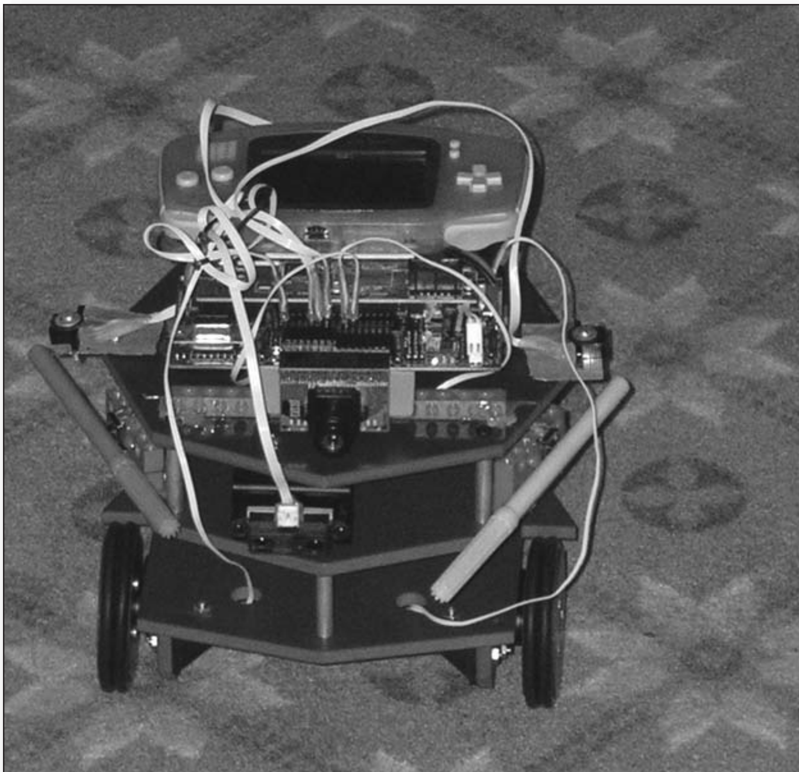

Figure 3. The Bridgewater State Scavenger Hunt Entry Built around an Xport Robot Controller.

Figure 4. The Bryn Mawr Aerial Entry for the Scavenger Hunt Competition.

Bryn Mawr College's aerial robot, a blimp with a sonar altimeter and wireless color vision, shown in figure 4. Pyrobot, python-based robot control and visualization software, integrated these sensors with the four propellers. The resulting interface provided visual feedback on tracked objects and auditory feedback of the sonar's altitude readings, and enabled audience members to take control of the blimp and gain an appreciation of the significant challenges of control in three dimensions with lighter-than-air dynamics.

A team of UCLA graduate students entered a pair of Evolution ER1 platforms, named the HOBOS, or Highly Organized Bunch of Scavengers, shown in figure 5. Using on-board laptops for their computation, the team demonstrated a number of object and spatial-reasoning algorithms: D* mapping, a real-time replanning variant of A*, spatial decomposition for team-exploration of an environment, and a SIFT-based visual recognition routine that allowed for significant pose variation and robustness to illumination changes that can plague color-segmentation approaches.

The Idaho National Laboratory (INL) brought a platform based on an iRobot ATRV-Mini that highlighted a seamless sharing of autonomy between human and robot, shown in figure 6. INL's rich and intuitive interface allows natural specification of wandering direction and waypoints. The interface updates in real time the robot's map of its surroundings using data from the on-board laser range finder. Meanwhile, from a distance, the human operator identifies and marks objects through the real-time video feed; they are immediately added and annotated within the map. The tandem system correctly found and mapped all four of the hidden objects during its competition run.

The MobileRobots Inc. Pioneer-based entry from Kansas State University (KSU), shown in figure 7, also found and mapped four of the scavenger hunt objects during the competition. This entry, however, ran fully autonomously with an a priori map of the environment. It combined sonar-based Monte Carlo localization and dead-reckoning to estimate its position, and then added objects to the map on the fly, recognizing them based on their color signature in YUV space. The autonomous system correctly found and mapped all four of the hidden objects during its run. The KSU entry earned 2006's first place in the AAAI Robotics Scavenger Hunt due to the best overall performance based on all of the judging criteria.

Results

Kansas State University demonstrated the greatest technical capabilities in terms of fully autonomous exploration, map building, and object detection and took first place overall. The demonstration of shared autonomy by INL awarded them a Judges' Choice Award for Outstanding Human-Robot Interface. The UCLA HOBOS' integration of many cutting-edge technologies into a single robot earned them a Judges' Choice Award for Outstanding Adaptation of Current Research. Technical achievement awards were awarded to Bridgewater State College for Leveraging Commodity Components, Canisius College for Educational Integration of Robotics, and Bryn Mawr for Innovative Hardware Design.

Human-Robot Interaction Competition

Building on the success of the Open Interaction Event in 2005, the goal of the AAAI 2006 Human-Robot Interaction competition was to demonstrate engaging interactions between people and robots. The 2006 HRI competition provided a structured framework that allowed teams to compete directly in seven predefined categories and, moreover, allowed judges to evaluate the employed AI techniques and their level of sophistication better. Critically, all categories were aimed at human-robot interaction and involved activities that intrinsically integrate perception and action and, furthermore, involved one or more higher-level AI techniques (for example, natural language understanding, reasoning, learning). There were seven categories that the robots could enter.

The first category was recognition/reaction to motions and gestures. In this category, the robots were required to demonstrate the ability to correctly identify a nonverbal gesture or motion sequence of a person and react to it in an intelligent fashion.

The second category was emotion recognition and expression. Robots entering this category had to recognize human emotion in any of its multimodal forms, including facial expressions, tone of voice, and content of speech, and demonstrate that recognition.

The third category was natural language understanding and action execution. To compete in this entry, robots were required to demonstrate some understanding and execution of verbal requests.

The fourth category was perceptual learning. This category tested the ability of robots to learn through human teaching and subsequent recognition and categorization of people, objects, locations, or actions.

The fifth category was perception, reasoning, and action. Robots competing in this category had to demonstrate some nontrivial under-

Figure 5. UCLA's Scavenger Hunt Robots Based on the Evolution Robotics ER1 Platform.

Figure 6. Scavenger Hunt Entry from the Idaho National Laboratory.

Figure 7. Entry from Kansas State Participating in the Scavenger Hunt.

standing of the world around them, for example reasoning effectively about the state of objects, people, or locations that the robot has observed but that are occluded or have passed outside the robot's active sensor range.

The sixth category was shared attention, common workspace, and intent detection. This category tested the robot's ability to evaluate verbal and nonverbal conversational cues in order to infer additional information about the human being conversed with. Examples of this category might be for the robot to follow human eye gaze to determine objects of interest in the environment, or to derive human intent from multimodal information including gestures, body language, facial expressions, head movements, prosodic information, and linguistic expression.

The seventh, and final category, was the integration challenge. Entries in the last category were required to demonstrate extended multimodal interaction that combined at least three of the above six categories. This category was designed to subsume the AAAI Robot Challenge event by allowing teams to either perform that challenge again or to demonstrate a new challenge of similar complexity. The AAAI Robot Challenge, as a specific instance of the integration challenge, effectively demonstrated category 1, by starting the robot at the entrance to the conference center and having it find its way autonomously to the registration desk; category 2, where the robot registers itself for the conference; category 3, by having the robot perform volunteer duties as required; category 4, which had the robot interact with conference attendees; and category 5, where the robot reported at a prescribed time to a conference hall to give a talk.

Technical and Audience Evaluations

The competition consisted of two evaluations: a technical evaluation judged by four independent experts in human-robot interaction and an interaction evaluation by the audience.

The technical evaluation was based on the above categories and each team had up to 15 minutes to demonstrate categories 1 through 6 and an additional 10 minutes for category 7 (the integration challenge). The criteria used for evaluating each category were (1) appropriateness for category; (2) robot performance; (3) effectiveness of interaction; (4) ease of interaction; (5) complexity of architecture; (6) robustness of architecture; (7) novelty of architecture; and (8) level of integration of different AI components

Numbers were assigned to each criterion and the sum of all criteria scores was used to determine a category score. The category winner was the team with the highest average score for that category. All category winners received technical recognition awards. The team with the most categories won the technical competition and received the judges favorite award (the difference in difficulty of the seven categories was accounted for by weighting each category with a predetermined factor).

The audience interaction evaluation required conference attendees to interact with a robot and to fill out an evaluation form. The tasks were not tied to the seven categories. Rather, it was up to the individual teams to decide what task their robot should perform. Teams were also responsible for recruiting evaluators from the audience. This could be done either by the team members themselves (such as if the audience is sparse) or, preferably, by the robot.

The audience evaluation was focused on interaction aspects (rather than including architectural aspects). The criteria included the appropriateness of robot for task (did not fit, fit partly, fit well), robot performance (did not work, worked partly, worked well), the effectiveness of interaction (ineffective, partly effective, effective), the ease of interaction (difficult, fair, easy), the complexity of interaction (low, medium, high), the robustness of interaction (brittle, fairly robust, highly robust), the level of entertainment (tedious, fair, fun), and the level of novelty of interaction (none, some novel aspects, many novel aspects).

Again as in the technical evaluation, numeric scores were computed for each criterion, and the sum of the average scores was used to determine the overall winner.

The Participants

The teams that participated in the HRI competition included the LABORIUS team, the team from Washington University, and the team from the University of Notre Dame.

The LABORIUS team from the University of Sherbrooke, Canada, fielded a robot named Spartacus, shown in figure 8. The Spartacus architecture integrates planning and scheduling, sound source localization, tracking and separation, message reading, speech recognition and generation, and autonomous navigation capabilities on board a custom-made interactive robot. It also includes various mechanisms for human-robot interaction, system analysis, and online debugging.

The team from Washington University fielded a robot called Lewis, shown in figure 9. Lewis has gained fame as “robot photographer” and integrates visual perception, planning, and navigation capabilities, using a novel graphical interface for directing the robot.

The team from the University of Notre Dame entered a robot called ND Rudy, shown in figure 10. ND Rudy integrates natural language

Figure 8. Spartacus, from the University of Sherbrooke, 0an Entry in the HRI Competition.

processing and understanding with action execution. It has been used in several human-robot interaction studies to study the effect of affect recognition and expression on the performance of mixed human-robot teams.

Results

Only Spartacus and ND Rudy participated in the technical evaluation. Spartacus participated in categories 4, 5, and 6, receiving average scores of 18.75, 19.75, and 18, respectively, while ND Rudy participated in categories 3 and 4 receiving scores 16.5 and 16, respectively.

Figure 9. Lewis, from Washington University, an Entry in the HRI Competition.

Spartacus thus won categories 4, 5, and 6 and thus the overall technical competition, while ND Rudy won category 3.

All three robots participated in the audience evaluation. Again, Spartacus received the overall highest score (12.96), followed by Lewis (12.50) and ND Rudy (11.5), even though there were not enough data points for the last two robots for the numbers to be reliable.

Overall, the competition showed that the robustness of a robotic system, which includes the integration of software components, the effectiveness of the control flow among them, and the reliability of the hardware platform, are prerequisite for HRI—without them, even the most engaging HRI capabilities will not come to life.

Robot Exhibition

Fifteen teams participated in the AAAI 2006 Mobile Robot Exhibition event. The robots ranged from human sized to small Lego bots, from complex cognitive architectures to simple behaviors, and from cutting-edge research to educational projects. Teams came from a variety of schools, including undergraduate colleges and research universities.

Spartacus, shown in figure 8, from the University of Sherbrooke's LABORIOUS team, is a human-scale research robot that integrates planning and scheduling, sound source localization, tracking and separation, message reading, speech recognition and generation, and autonomous navigation capabilities. Spartacus was the winner of the Challenge competition in 2005 and additional work was done to improve its capabilities for the HRI competition this year. Some of the demonstrated features include speaker localization with a microphone array and visual tracking of the speaker with a pan/tilt camera.

The Claytronics team from Carnegie Mellon University, shown in figure 11, demonstrated planar Claytronics atoms (catoms) that move by cooperatively energizing electromagnets. The catoms also cooperate to provide power to each other, eliminating the need for an onboard battery or for more than one catom to have a tether.

CMAssist, from Carnegie Mellon University, shown in figure 12, demonstrated two robots based on the Evolution ER1 platform that participated and placed second overall in the new RoboCup@Home home robotic assistant competition this year. Their focus includes recognition and detection of human presence and activities, where the observation of human activities enables the robot to learn more about its environment.

Harvard University's team, Collective Construction by Lego Robots, shown in figure 13, presented a demonstration of a multirobot system that built two-dimensional structures from building blocks. The robots embodied simple, identical behaviors and used the partially built structure as a form of indirect communication.

DIAS, the Drexel Integrated ATV System from Drexel University, focuses on search and rescue missions. The team exhibited an ATV and a helicopter, shown in figure 14, and showed videos of it in action in the field.

The Rowan University IMAPS (Interactive

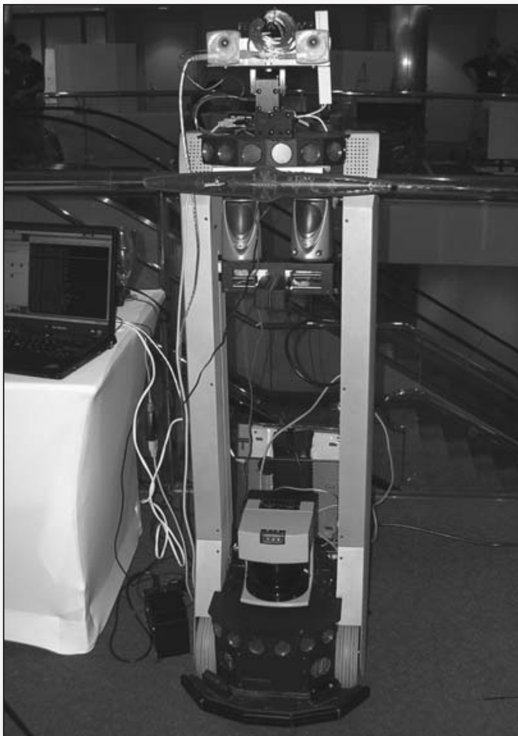

Figure 10. ND Rudy, from the University of Notre Dame, an Entry in the HRI Competition.

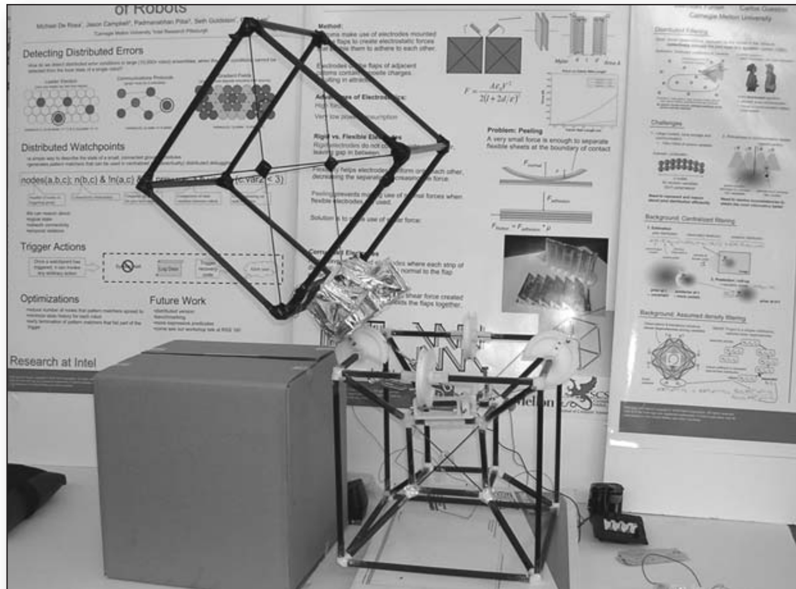

Figure 11. Claytronics, from Carnegie Mellon University, Demonstrated Catoms.

Figure 12. CMAssist, from Carnegie Mellon University, Demonstrated Person Detection, Tracking, and Interaction.

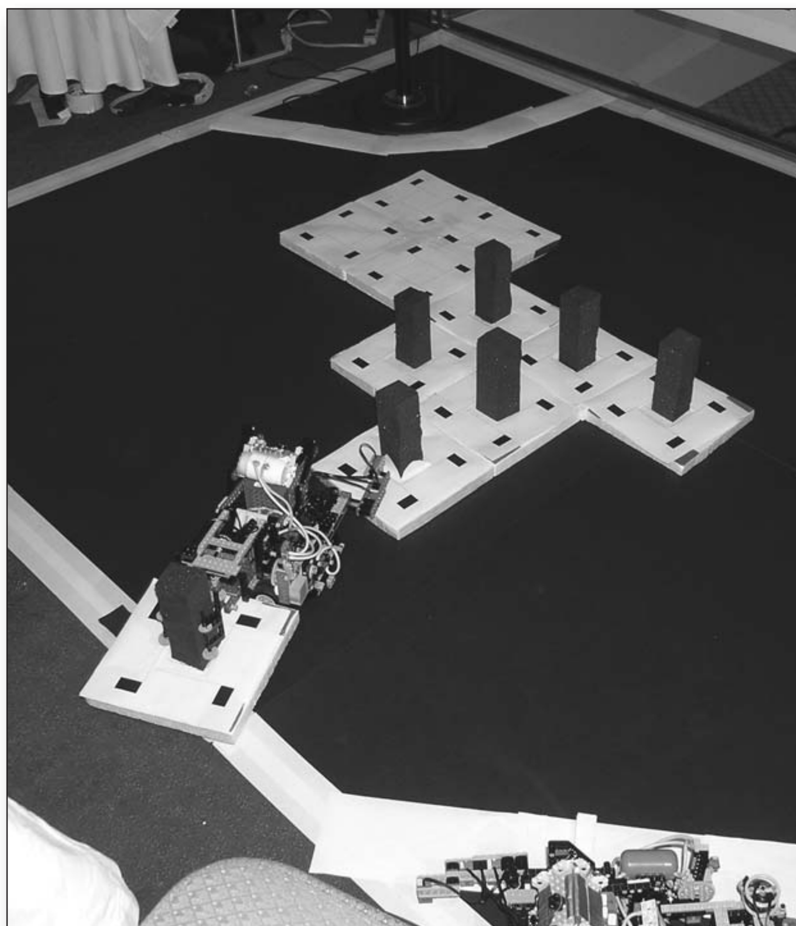

Figure 13. Harvard University Demonstrated the Collective Construction by Lego Robots Research Project in the Exhibition.

Figure 14. Drexel University ATV and Helicopter's Exhibition Entry.

Figure 15. Rowan University Exhibited Its Interactive Mobile Aqua Probing and Surveillance (IMAPS) Robot.

Mobile Aqua Probing and Surveillance) team (figure 15) displayed an aquatic robotic device designed to observe wildlife, test water parameters, and search for pollution sources.

The Idaho National Laboratory Robot and Human Systems Group, shown in figure 6, showcased a suite of integrated behaviors for characterizing and representing remote or hazardous areas. The demonstration highlighted their work in mixed initiative robot control architectures, SLAM, Augmented Virtuality, and Occupancy Change Detection.

Tulane Robotics (figure 16) demonstrated several projects using AIBOs, including an interactive game for young children that uses a Dance Revolution mat.

The UCLA HOBOS, shown in figure 5, exhibited Evolution ER1s that have the ability to localize themselves, recognize a set of objects, and communicate with peer robots to share location and coordinate exploration of the search space.

The College of New Jersey Interactive Robot Team presented Taro, a newly developed humanoid robot shown in figure 17. The team described the solid hardware foundation on which the robot was constructed and described research plans for integrating additional intelligence in the future.

The Bryn Mawr Pyro Robotics team demonstrated two different projects. The first was in developmental robotics, showing how an Aibo, shown in figure 18, can learn about its environment as it interacts with toys designed to stimulate a baby. The second was a robotic blimp designed and built at Bryn Mawr. As the blimp navigated the venue's air space, observers were able to watch its camera feed.

HMC-Escher, from Harvey Mudd College, demonstrated Erdos (figure 19), a peripheral robot platform developed at HMC based on iRobot's Roomba vacuum cleaner. The team's focus is on low-cost robotics platforms for undergraduate research projects as well as robotics education.

Snarpy from Canisius and Hamilton Colleges demonstrated a cognitive architecture that integrates SNePS (Semantic Network Processing System) with Pyro (Python Robotics) using AIBO dogs, shown in figure 2.

The Educational Robotics team from Brooklyn College (City University of New York) presented a number of educational projects designed to engage undergraduates with robotics through teaching, research and outreach (figure 20). They use robotics in numerous courses and work with Legos, AIBOs, and simulators.

The Griffins from Canisius College presented several undergraduate research projects using Lego robots, shown in figure 21 as well as a Lego robot simulator the team has created to help with robotics education.

The Lewis team from Washington University in St. Louis brought its human-sized research robot, shown in figure 9, which specializes in human-robot interaction.

Workshop

A robot workshop was held on the last day of the AAAI conference to allow participants to present short talks on their robot research activities, experiences, and reflections on the robot conference events and discuss future directions. Every team was given 10 minutes to formally present the research and educational aspects of their competition or exhibition entry. Awards for the exhibition event, scavenger hunt, and human interaction were presented to the various teams. Several of the awards were sponsored by Road Narrows Robotics. Finally, a presentation about next year's event was given, and the event was wrapped up with a general invitation for all to attend the next year. Figure 22 shows some of the awards and technical presentations at the workshop.

Summary

The 2006 robot event required the robots to operate within very unstructured environments. The venues for the Scavenger Hunt and Human-Robot Interaction competitions were rapidly set up by defining an area in the exhibition hallways and setting up the objects to be located. In each case, the audience was informed that they were requested to give the robots some space, but there was no specific mandate that required them to do so. Thus, the robots needed to be able to handle the possibility of people moving about them. This was particularly evident in the Human-Robot Interaction competition when the robots were taken to a reception where they needed to operate when being completely surrounded by people.

In the scavenger hunt task, the objects were once again known ahead of time and thus the teams could obtain them in order to practice with them. Advances in commodity electronics and computation made it possible for a simple device such as an Xport Robot Controller to perform in this event. The successful runs of each of the different teams accentuate the importance of evolution in the competitions as teams rise to the challenges and succeed in them. The scavenger hunt task will evolve significantly into next year, in order to raise the bar and challenge researchers to tackle even more difficult problems.

The emergence of the Human-Robot Interaction competition reflects the current state of the research field. The area of HRI is just starting to come into its own and gain global acceptance as an established area of research (Goodrich, Schultz, and Bruemmer 2006). This is also evidenced with the advent of the first ever Human-Robot Interaction conference held earlier in 2006. There are significant challenges for participating in an HRI event, however. This includes having a fully integrated robotic system that fuses a myriad of different sensing and reasoning modalities. Custom hardware is still a requirement for many participants as well. In time, the specific requirements of a successful HRI-capable robot will be established and some commercial venture will likely step forward to produce a commercial off the shelf (COTS) solution. Until then, however, the HRI competition allows researchers to actively explore the questions of what allows for effec-

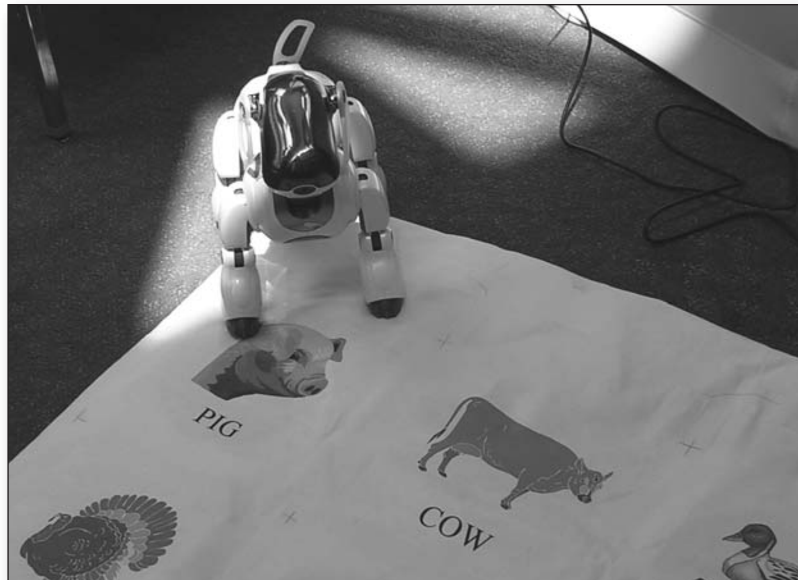

Figure 16. Exhibition Entry from Tulane University That Demonstrated How Robotics Can Be Used as Part of an Interactive Game for Young Children.

Figure 17. College of New Jersey Exhibition Robot Taro.

Figure 18. An Exhibition Entry from Bryn Mawr Demonstrating a Research Effort in Developmental Robotics.

Figure 19. Erdos: A Roomba Robot Exhibited by Harvey Mudd College.

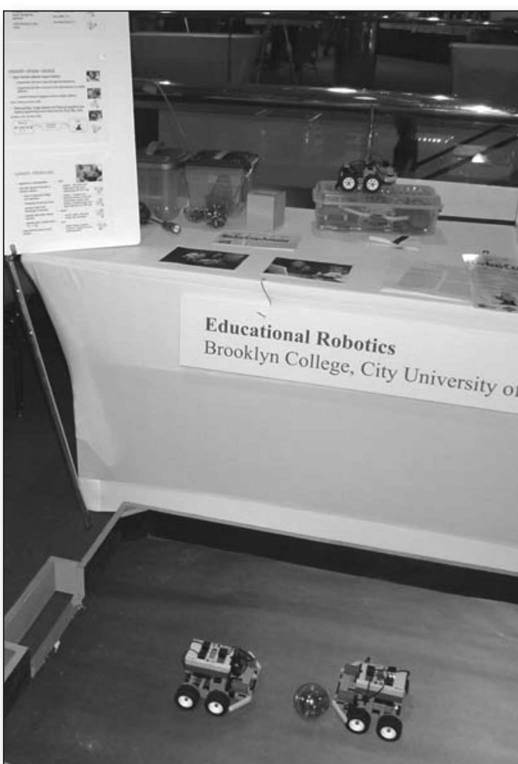

Figure 20. The Exhibition from the Educational Robotics Team from Brooklyn College.

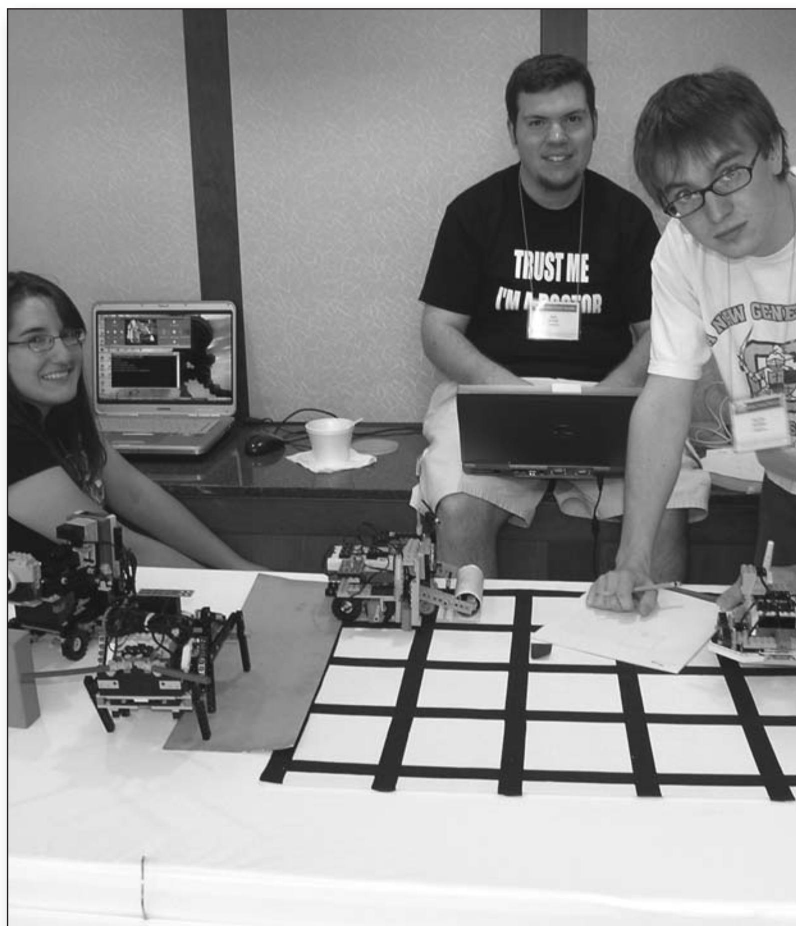

Figure 21. Lego Robots Developed as Part of Undergraduate Research Projects At Canisius College.

Figure 22. Presentations and Awards at the Robot Workshop.

tive interaction. These questions will continue to expand and define this exciting research area. The 2007 Mobile Robot Competition and Exhibition will be cochaired by Jeffrey Forbes (Duke University) and Paul Oh (Drexel University). The theme for the program is “Cultivating robotics through practice,” with the goal of bringing together robotics researchers to work on challenges. The competition will center around three challenges: semantic vision, human-robot interaction, and integration. In addition, the exhibition will continue to highlight research outside of the competition areas. The exhibition organizers will encourage all researchers who submit a paper on robotics to the technical program of the conference to participate in the exhibition.

Acknowledgements

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