Sensor Information Processing in Robot Competitions and Real World Robotic Challenges

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Abstract

In this paper, we present an overview of technical approaches and algorithms used by university researchers in several recent international robot competitions and challenges, which include RoboCupRescue, Tsukuba Challenge, DARPA Urban Challenge, and MAGIC Challenge. All robot systems display the latest hardware and software modules needed for accurate localization, navigation, and exploration in difficult environments. In each case, key robotic research problems addressed by each challenge are presented, and a representative implementation of a robot system is provided. Finally, individual results from the fielded robots are presented, and opportunities for future work are discussed.

keywords: robot competitions, challenges, sensory processing.

1 Introduction

Over the past decade, robotic competitions involving students and hobbyists have become very popular. From an educational point of view, these competitions contribute to the learning of practical engineering skills needed to design and construct robotic systems for performing various tasks. Thus, many technical high schools and higher professional schools participate in robotic competitions, particularly in Japan. In these competitions, manufacturing costs of robots are minimized, allowing participants to focus on simple challenges in toy world settings with minimal requirements on expensive sensing equipment.

On the other hand, there has also been a recent trend in combining the latest robotics research in a competitive environment. One pioneering example is the RoboCup competition, which presents more challenging tasks and typically involves researchers from both universities and industry. State-of-the-art algorithms for planning, perception, localization and navigation are evaluated through various computational challenges, while the mechanical and electrical hardware counterparts are tested under tough real-world conditions. The costly nature of these research competitions usually calls for outside funding, typically involving sponsorship from universities and corporate partners.
To highlight some of the research questions addressed by these more advanced competitions, this paper summarizes the achievements in some representative robotics challenges. Four examples are discussed: RoboCupRescue, Tsukuba Challenge, DARPA Urban Challenge, and the MAGIC 2010 Challenge. We present the important role of sensor information processing in each of these events and discuss individual case studies about how particular robotic systems were implemented and how they performed.

2 RoboCupRescue

RoboCup, originally a football league for robots, started in 1997 as an annual international competition. Its goal is to promote research in robotic technology and artificial intelligence by learning during competitions [1]. Based on this approach, the RoboCupRescue league [2] was added to RoboCup in 2001 to support rescue robotics. It includes two leagues, the rescue simulation league and the real rescue robot league, which we describe in the following section.

In actual rescue scenarios such as massive earthquakes or fire disasters, robotic surveillance using tele-operated robots can be a useful tool to reduce the risk of rescue crews. Furthermore, because trained human rescuers may not be readily available, autonomous surveillance by robotic teams can be a very helpful tool. Therefore, the goal in RoboCupRescue competitions is to search and localize as many victims as possible within a certain time limit, by using tele-operated and/or autonomous robots. The competition field is a large maze, approximately 15 m in width and 15 m in length, with an uneven surface consisting of bumps, slopes, and stairs. The field is divided into three arenas: a yellow arena (easy locomotion), an orange arena (medium difficulty), and a red arena (very bumpy). Recently, a blue arena (for mobile manipulation) and a black/yellow arena (radio drop zone where only autonomous robots can pass through) were also added, but these new arenas will not be discussed further here. Some hallways and walls may contain simulated victims, i.e. mannequins containing a heat source to simulate human bodies. Figure 1 (a) shows an overview of the competition environment in RoboCupRescue 2009, (b) shows an example of the red arena, and (c) shows potential locations of a victim. In situations similar to the one depicted in Figure 1 (c), robots require long manipulators to survey hard to reach areas.

To complete the mission, robots have to demonstrate (1) mobility, (2) sensing, (3) mapping, and (4) autonomy. In recent RoboCupRescue competitions, large emphasis has been placed on mapping. Lower scores are awarded in cases where a victim has been located, but the map produced is inaccurate. More recently, autonomous operations have also become important in the competition. Current rules allow only one operator to enter the operating room. Furthermore, locating victims in a yellow area by tele-operated robots does not affect the scoring. Therefore, teams must prepare the robots for both tele-operation as well as autonomous operation to address the challenges in the different areas. The competition has been typically organized every summer over a period of six days, including team preparation, trials, qualifying stages, and the final stage.
Figure 1: (a) Overview of the target field in RoboCupRescue 2009 (upper), (b) example of the red arena step-field surface (lower left), and (c) robot surveying a hole in the wall (lower right).

2.1 Implementation example

Here, we would like to introduce an example of a sensing and mapping system that participated in RoboCupRescue. The team “Pelican United”, comprised of students and faculty from Chiba Institute of Technology, the National Institute of Advanced Industrial Science and Technology (AIST), and Tohoku University (including one of the authors), participated in the competition in 2009. Details about the implementation are described in [3]. Figure 2 (a) shows a tele-operated robot, and (b) an autonomous robot. To improve mobility on rough terrains, both robots used platform bases with four individual tracks for locomotion.

Color and infrared cameras mounted on the expansion arm of the tele-operated robot, in addition to a microphone and a \( \text{CO}_2 \) sensor, were used to detect simulated victims in hard-to-access areas. In addition, a 2D laser range scanner mounted on the base of the robot was used to map and identify the locations of victims. During the competition, the robot successfully found 15 victims in the semi-final and final rounds (total 60 min), but the map obtained by the robot was not of high quality.

On the other hand, the autonomous robot used a 3D laser range scanner to map the environment.
To correct the irregularity of the data for the walls and to construct a global map in real-time, we employed the iterative closest point (ICP) algorithm [4] [5]. Figure 3 shows the map acquired during RoboCupRescue 2009 [3]. The robot also used an infrared camera to find victims, but it did not work properly because the height of the camera was not adjustable.

2.2 Competition results and future work

During the world championships of RoboCupRescue from 2007 to 2011, all winning teams originated from Thailand. In Thailand, an annual domestic competition serves to qualify teams for the international competition. Therefore, the most qualified robots were repeatedly tested, and the human operators had received extensive training. Other all participating teams are also continually improving their hardware and software algorithms, because the rules of the competition become stricter every year to be more
realistic disaster environments. For example, there were slippy obstacles, such as scraps of newspaper, on the target field in 2010, but not in 2009. In such tough conditions, recent teams had a capability to develop accurate maps. This is one clear evidence that the competition accelerated robotic technologies.

Currently, the test environment is very structured and artificial, and the simulated victims are located in pre-determined locations. However, in real disaster situations, because environments are much more unstructured, it is considerably more difficult to locate potential victims. As robot technology and sensing algorithms improve, the competition environments will be modified accordingly to match realistic conditions and keep the researchers appropriately challenged.

3 Tsukuba Challenge

The Tsukuba Challenge, formally called the “Real World Robot Challenge (RWRC)”, started as an annual technical challenge in 2007. The aim of the challenge is to develop safe and reliable mobile robot systems operating in realistic outdoor environments and interacting with people. The major task of the Tsukuba Challenge in 2010 was to navigate robots autonomously through outdoor courses, such as pedestrian paths, sidewalks and a park, as shown in Figure 4. The total length of the path was approximately 1.1 km, within which common pedestrians were present. Figure 5 shows some typical scenes from the course. The participants in the challenges included not only university laboratories and companies, but also a number of private hobbyist teams.

The task of the challenge was quite simple: to navigate a robot along the given path. However, in this challenge, there were two strict and important rules: (1) the robot could not injure or cause any discomfort to people, and (2) the robot and/or the participants could not alter the environment. To comply with the first rule, the maximum size of the robot was restricted. Moreover, before robots were allowed into the competition environment, a mandatory safety inspection of the robots was performed. The inspection assessed whether each robot contained any exposed edges or presented any pinching hazards, in order to
ensure everyone’s safety, and in particular children.

With respect to the second rule, teams were allowed to use any onboard sensors on their robots, but prohibited the use of external devices, such as artificial landmarks or beacon systems. In addition, it was not allowed to collide with any objects, especially with people on the course.

Each team had several days to practice robot navigation and obstacle avoidance before the semi-final and final rounds. In 2010, a total of eight days in September, October, and November were allocated for practice runs. On those days, each team conducted measurements of the environment, tested their obstacle avoidance functions, and performed practice runs. In the semi-final stage, each team had two chances to navigate a short course (240 m). Teams that succeeded in completing the course were qualified to the final round (1.4 km).

Timing was not a big factor in the competition, and a speed limit was imposed to keep pedestrians safe. All teams that completed the final course were considered winners.

3.1 Implementation example

Key research areas in this challenge for a mobile robot are localization and obstacle detection (and avoidance) in a wide variety of environments. Localization is critical because the environment includes tall buildings and trees, which can disrupt GPS signals. Therefore, for localization, a large number of teams that completed the course used matching algorithms relying on a prior map of the environment. In this section, we describe the robot called “Papyrus II”, shown in Figure 6(a), developed by the team “FuRo-outdoor” at the Chiba Institute of Technology [6]. This team completed the navigation missions in both 2009 (shown in Figure 6(b)) and 2010.

The robot relies for navigation on gyro-assisted odometry and a rotating laser range scanner, without the assistance of GPS. Two complementary gyroscopes aligned on the same yaw axis compensate each other’s drift, and significantly improve the robot’s odometry in an outdoor environment. In addition, the
Figure 6: (a) Mobile robot Papyrus II (left photo) and (b) crossing the goal line (right photo). [6].

Figure 7: (a) Swing motion of 2D laser range scanner (left), (b) gimbal mechanism of the scanner (center), and (c) 3D map obtained by the 3D laser range scanner (right) [6].

2D laser scanner is actuated in a sweeping pattern to obtain a very dense and accurate 3D map. The laser scanner, gimbals-mechanism, and the resulting 3D data are shown in Figure 7. The gyroscope odometry and the scanned data were tightly synchronized to obtain very accurate local 3D maps. Self-localization was performed by fusing the positions estimated from the gyro-assisted odometry with the measurements of the 3D scanner, using a particle filter [7]. Finally, the robot reached the goal after navigating through the 1 km course in 32 min and 44 s.

3.2 Challenge results and future work

In the Tsukuba challenge in 2008, there were 47 participating teams, of which two teams passed the semi-finals, and only one team completed the final course. In 2010, the number of participating teams increased to 64, of which 32 teams completed the course in the semi-finals, and 7 teams completed the final course. Over the years, the number of successful teams increased, even though the course has become slightly longer and more difficult. This is clear evidence that the level of robot technology among the participating teams is dramatically improving.
One of the reasons of the above rapid progress is information disclosure. After the challenge, all teams are obligated to disclose technical information during a workshop organized by the Tsukuba challenge committee. Furthermore, some of the technologies and algorithms developed for the challenges were published in recent conference papers [8] [9] [10].

Over the past five years, the New Technology Foundation in Japan has supported the Tsukuba challenge. To date, there are no plans for the competition after 2011, but we hope it will be continued, because it presents a great opportunity for robotic researchers to conduct field trials of their systems in a real world environment.

Finally, we would like to note that the challenges would not be possible without the cooperation of the city of Tsukuba, Ibaraki police, local businesses, local residents, and numerous volunteers.

4 DARPA Urban Challenge

The 2007 Defense Advanced Research Projects Agency (DARPA) Urban Challenge was the third and latest in a series of prize competitions sponsored by DARPA to spur development of driverless vehicles. The goal of the DARPA Urban Challenges were to build an autonomous ground vehicle that could execute a simulated military supply mission safely and effectively in a mock urban area [11]. Compared with previous DARPA Grand Challenges, the 2007 DARPA Urban Challenge necessitated that robot vehicles perform autonomous driving maneuvers safely, in the presence of traffic consisting of other robots and vehicles operated by professional human drivers.

Some of the challenges that the robots faced included being able to follow accurately a lane within prescribed lane boundaries, detect and avoid moving traffic, stop and drive in new lanes in the presence of other vehicles, and park in constrained spaces in dynamic environments. All participating teams were given prior maps of an urban environment consisting of sets of sparse GPS waypoints that charted the course of the competition. In the final competition, the participating robots, along with the other robots and vehicles operated by the human drivers, simultaneously navigated through the 60 miles of the course, constrained by a time limit of 6 h and an upper speed limit of 30 miles/h.

4.1 Implementation example

The Ben Franklin racing team, formed by students and faculty from the University of Pennsylvania and Lehigh University, and engineers from Lockheed Martin Advanced Technology Laboratory, was one of only six teams to complete successfully the competition [12]. In under a year and with a limited budget, the Ben Franklin Racing Team was able to construct “Little Ben,” a drive-by-wire Toyota Prius equipped with an array of onboard sensors and computers, shown in Figure 8.

Hardware and software systems were specially selected to meet the objectives for desired detection distances (1–60 m) and processing time. Sensors and their respective mounting positions were chosen
Figure 8: Little Ben is a Toyota Prius hybrid vehicle modified for drive-by-wire operation, equipped with an onboard array of sensors and computers.

Figure 9: LIDAR and vision sensors mounted on Little Ben.

to maximize their long-range detection characteristics. Drive-by-wire actuation and computer hardware systems were configured to minimize processing latencies. Similarly, embedded software modules were optimized to accurately detect dangerous situations with minimum computational delay.

The primary sensor rack was designed to be quickly mounted and unmounted as a single structure, without having to recalibrate the sensors. A Velodyne HD Laser Imaging Detection and Ranging (LIDAR) provided a fully unobstructed 360° azimuthal view of the surrounding road. In addition, a set of forward- and rear-facing SICK LMS-291 LIDAR sensors were also utilized. These 90° field-of-view sensors were tilted downward, in order to detect the ground at approximately 7 m ahead of and behind the vehicle. In these positions, the SICK LIDARs simultaneously provide ground plane, obstacle, and lane marking detection.

Several sensors were also mounted on the hood of the car. A Point Grey Bumblebee color stereo camera with a horizontal 50° field of view, and a frame rate of 15 Hz was used to track colored lane markings and to model the ground plane in front of the vehicle. Three compact Hokuyo URG-04LX LIDAR scanners were also used to cover blind spots in sensor coverage at short ranges around the vehicle. Two of the scanners were mounted underneath the side mirrors for detecting obstacles, such as curbs at the sides of
the front wheels, as well as nearby lane markings on the ground. The third sensor was mounted above the rear bumper and allowed for accurate maneuvering between tightly spaced obstacles while the vehicle was driving in reverse.

The software architecture for the vehicle was divided hierarchically into a series of modules, which communicated via interprocess communication messaging. At the lower levels of the architecture were the drive controller responsible for actuating the vehicle controls, and the pose module, which integrated readings from the GPS and inertial navigation system to provide accurate pose information. At the highest level of the architecture, the mission-planning module read the appropriate route-network definition and mission files to determine the optimal sequencing of waypoints needed to complete the competition objectives. Next, the sensor modules gathered data from all LIDARs and the stereo camera to provide probabilistic real-time estimates of the terrain, road markings, and modeled static and dynamic obstacles. These modules consolidated the large amounts of sensor data into a compact representation. This representation was structured with respect to the vehicle’s local reference frame, and was used for mapping, planning, and navigation.

4.2 Challenge results and future work

Figure 10 shows representative output from the sensors, as well as a map built during the final competition. Traversable ground and obstacles are clearly delimited in the map, along with the proposed path generated by the high level routing and navigation modules. Little Ben finished the competition in approximately 5 h and 5 min, about 55 min behind the first-place finisher from Carnegie Mellon University [13] and second-place finisher from Stanford [14], giving it an overall average speed of 11.2 miles/h (18.1 km/h) over the entire course.

This case study shows how a system of GPS/INS, LIDARs, and vision sensors can provide real-time information sufficient for autonomous driving. Work to improve the overall reliability and robustness of self-driving cars is continuing, most notably by researchers at Google [15].
5 MAGIC 2010 Competition

The Australian and US Departments of Defense jointly sponsored the 2010 Multi Autonomous Ground-robotic International Challenge (MAGIC 2010) to develop the next-generation team of ground vehicle robots [16]. The goal of the challenge was to develop a team of robots that could explore and map a large dynamic urban environment, as well as locate, classify and respond to threats. Participants were to demonstrate a large robotic team operating effectively with limited guidance from human operators. An example of an environment the robots needed to explore is shown in Figure 11.

This challenge was unique in that it encompassed a large number of unsolved problems across multiple spatial and temporal scales. Many technical issues needed to be addressed, ranging from fine-grained perception and control problems at the level of the individual robot, to high-level human-machine interfaces and multi-agent coordination. These problems included perception, localization, and navigation by an individual robot, mapping static and dynamic features from multiple sensor sources, planning efficient search and neutralization strategies across multiple robots, and interfacing autonomous robot behaviors with strategic human decision-making.

5.1 Implementation example

Here, we describe the technical approach of the UPenn team, consisting of students and faculty from the School of Engineering and Applied Science at the University of Pennsylvania. Conceptually, the robot team was designed according to a hierarchical decomposition of perceptual, planning, and control algorithms at both the individual robot and team scales. This allowed for efficient high-level guidance
from human operators, while simultaneously allowing the robots to operate in an autonomous manner most of the time.

Individual robots were constructed using a lightweight, all-terrain robot vehicle base with high current DC motors and rugged wheels, capable of traversing over 10 cm tall obstacles and traveling at speeds up to 2 m/s. The sensor suite for each robot consisted of a horizontal-scanning Hokuyo LIDAR, a vertical-scanning Hokuyo LIDAR, an omni-directional catoptric color camera, a panning frontal view color camera, Hall-effect wheel encoders, a 6 DOF strap down inertial measurement unit, and a GPS receiver. These sensors and the UPenn robot team are shown in Figure 12.

Members of the robot team communicated with each other and with the human ground station via a set of redundant radio links. This enabled nearby robots to relay messages from distant robots to the ground station. The onboard perceptual system processed the information received from the multiple cameras and LIDAR sensors on each robot. Vision algorithms were used to automatically detect red objects of interest, and the range depths of potential objects were computed by correlating the size of the region with information from the LIDAR sensors. These object descriptions were then relayed to human operators for final target confirmation and verification, who interacted with the robots through a graphical user interface modeled after a real-time strategy game.

The localization and mapping modules relied on the LIDAR sensors, which were configured to scan in horizontal and vertical planes in order to model uneven terrains. The range data acquired by these two sensors were integrated with measurements provided by the motor encoders and inertial measurement unit, and simultaneous localization and mapping (SLAM) techniques were employed to build a local map of the environment surrounding the robot. The probabilistic maps generated by the different robots were then fused at the ground station to provide a global view of the environment as seen by the various robots.
5.2 Challenge results and future work

Figure 13 shows the map produced by five of the UPenn robots mapping a large area (Old Rams Shed) filled with various obstacles, such as hay mazes and barrels. These robots were able to successfully explore and map this large area in approximately 30 min, resulting in the UPenn team winning this portion of the challenge [18]. In the overall competition, the UPenn team successfully completed two out of three phases (none of the teams were able to complete the extremely challenging third phase), and finished in second place, behind the University of Michigan team [17].

Current work is focused on incorporating aerial quadrotor robots to form truly heterogeneous robot teams capable of long-term surveillance in difficult environments. Aerial robots have the ability to fly above terrains too difficult to traverse, and to obtain a full range of 3D perspective sensing data. Unfortunately, aerial robots have short flight times due to limitations imposed by their batteries. We have developed a magnetic landing mechanism, shown in Figure 14, which merges the capabilities of aerial robots with those of ground vehicles. Future experiments are planned to demonstrate how to process the information collected by such teams of robots.

6 Conclusions

All four examples presented (RobocupRescue, Tsukuba Challenge, DARPA Urban Challenge, and MAGIC2010 Challenge) illustrate some of the current shortcomings in fielding robots in real-world situations. Nevertheless, these robots displayed state-of-the-art performance capabilities in processing information from onboard sensors to map, plan and navigate in difficult environments. Complementary sensor systems
are used to fuse vision, LIDAR, odometry, and inertial information to construct accurate world representations. Current research seeks to extend these capabilities and further improve the performance of these robotic systems. We look forward to seeing how new robots will perform in future planned robot competitions and challenges.

REFERENCES


