The IROS 2016 Competitions

By Hyungpil Moon, Yu Sun, Jacky Baltes, and Si Jung Kim

The International Conference on Intelligent Robots and Systems (IROS) 2016 hosted three robot challenges in Daejeon, South Korea. They were the fourth Humanoid Robot Application Challenge (HRAC 2016), the Robotic Grasping and Manipulation Competition (RGMC), and the Autonomous Drone Racing (ADR) face-off in the Mos Espa Daejeon Arena. The motivation for holding these competitions at IROS 2016 was to provide members of the IEEE Robotics and Automation Society with a unique technical-demonstration setting for research labs from both academia and industry to show off the state-of-the-art implementation of robotic technologies. Attendees interacted with live technological results and shared their visions and solutions to hardware and algorithmic implementation in various robots.

While the HRAC has been a continuing challenge since 2013, with a different theme each year, the RGMC and ADR were events that debuted at IROS 2016. The competitions were held on 11 and 12 October 2016, and the winners of each competition were announced during the awards luncheon on 13 October 2016. A unique feature was that the IROS 2016 competition events were live-streamed to the Internet and a hotel in Las Vegas.

HRAC 2016: "Robot Magic"

Apart from the rivalry involved, the idea of the HRAC is to encourage novel and innovative applications in humanoid robotics and to provide teams with opportunities to present their ideas in an entertaining setting, even if the ideas may not yet be completely developed. So one goal is to provide an open and friendly forum to discuss ideas and research in humanoid robotics. Therefore, one of the features of the IROS 2016 fourth HRAC was that the challenge rules would be defined only in broad terms and that judging would be based on a team of experts and on the other participants.

The theme for this HRAC was "Robot Magic." Magicians have entertained crowds for centuries. They seemingly produce rabbits out of hats, make cards disappear in front of your eyes, read minds, levitate flowers, and escape from locked coffins. One of the key reasons for focusing on magic was the realization that attention plays a crucial role in human intelligence. However, relatively little research has been done on attention in artificial intelligence. For example, most computer vision algorithms are expected to find and label all objects in an image from the start. Humans, however, will focus their attention on only parts of the image and then use this information to guide the interpretation of the rest of the image. This is why it is easy to fool humans using optical illusions.

Good magicians are masters of misdirection, using biases in human attention, perception, and reasoning to their advantage. For example, they make people focus on their right hand, while the trick happens in their left. So, research into robotics can greatly benefit from a better understanding of these aspects of human intelligence, since it will allow robots not only to better understand and manipulate their environment but to better interact with humans. Furthermore, certain types of magic require abilities that are important for robots in many other applications, such as small-scale manipulation of various objects. In particular, sleight of hand requires fast, dexterous manipulation of small objects, such as cards or coins. Some magic tricks also require novel research into advanced computer vision algorithms. For example, for a well-executed peek not to be obvious, fast object recognition and tracking as well as distraction are required.

Another interesting aspect of robot magic is that new magic tricks can be created using the special capabilities of robots and exploiting the fact that humans quickly anthropomorphize robots. For example, the well-known saw-a-person-in-half trick can easily be done with a robot since 1) the kinematics of the robot are different and 2) a robot could be separated into different parts that could communicate wirelessly. Other examples are card tricks that rely on stacked decks (i.e., decks with a known order of some or all the cards). Ordinary humans are unable to memorize the order of 52 cards at random in an instant, nor can they compute the necessary shuffle moves to bring the cards into the desired order. Therefore, tricks using stacked decks usually involve the magician or an assistant producing a preordered deck and then performing several fake shuffles (i.e., shuffles that do not change the order of the cards or only do so predictably). A robot, on the other hand, has no problem memorizing the order of 52 cards and then coming up with the right

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shuffling moves to bring the cards into a desired order (Figure 1). The way people respond to these tricks will help us understand the social impact of robots and how to deal with people's misconceptions about robots and their capabilities.

Figure 1. In contrast to humans, a robot can in an instant memorize the order of the cards or identify that the nine of diamonds is missing. This could easily be exploited in a variety of magic tricks.

Participants

The qualification of teams for the HRAC 2016 was done as in previous years. Teams had to submit an extended abstract and a video of their robot performing all or part of their trick. Fifteen submissions were received, and ten teams qualified for the event. However, due to various problems, such as visa and funding issues, only seven teams took part in the competition. See Table 1 for a list of the participating teams.

The Competition

Some teams had technical difficulties during preparation, but in the end, five teams demonstrated their magic act to the judges and the audience. The following describes the teams and their tricks.

Table 1. The participating teams.

Team Name	Team Leader	Affiliation
	Rodrigo da Silva Guerra	Universidade Federal de Santa Maria, Brazil
4Dudes	SeungYeon Kang	Sejong University, South Korea
Taipei Snipers	Jacky Baltes	National Taiwan Normal University, Taiwan
Dadigers	Jae Young Moon	Purdue University, United States
	Marco Prata	Seed Robotics, United Kingdom
Snobots	Meng Cheng Lau	University of Manitoba, Canada
Charles	Young-Jae Ryoo	Mokpo University, South Korea

Team Charles, Mokpo University, South Korea (First Place)

The Charles team demonstrated several magic tricks that can be purchased from a magic store (Figure 2). Their first trick showed the robot pouring water from one cup into another. The robot then showed that the water magically disappeared from the second cup. The second cup was filled with sodium polyacrylate, which absorbs moisture and turns it into a gel. The water became a translucent gel, and the audience believed the cup was empty. A second trick was a falling coin trick. A member of the audience signed a coin that was dropped on top of a bottle. But the coin seemed to fall magically through the top and into the bottle. The trick works by dropping the coin into an opening in the back of the bottle. The student who acted as magician for the trick cleverly covered the hidden slot when allowing the top of the bottle to be examined by an audience member. Team Charles used the flexibility and range of motion of its robot to great effect. The team members calculated both forward and inverse kinematics solutions for the arms, and managed to combine their magic act with catchy music and dance routines, which impressed the judges.

Team Snobots, University of Manitoba, Winnipeg, Canada (Second Place)

The Snobots team performed a comedy magic trick using a Robotis OP humanoid robot. The human magician started the act, but then the robot took over. The trick is a variant of the reverso trick, where three cards preselected by the assistant are magically flipped face up in a face-down deck. One of the main difficulties of the project was the detection and identification of the three cards out of the deck. The team used OpenCV to threshold the image and then to detect the contour of the cards. The detection was fully autonomous, but the magician had to wear a black glove, or else the hand holding the card would confuse the contour detection. The identification of the card was based on the top-left edge with its markers. The 30 × 30 image of the number and suit were converted into a 900-feature vector, and a standard multilayer perceptron was trained using back propagation. The system also used an online learning approach; that is, if the user indicated that one of the cards had been misclassified, the robot would ask for an additional three samples of the misclassified cards and redo its training. This approach could easily lead to overfitting, but in this case it worked well, since only one deck of cards under the given set of conditions had to be correctly identified. All interaction with the user was via speech recognition (Pockstsphinx), speech generation (eSpeak), and gestures.

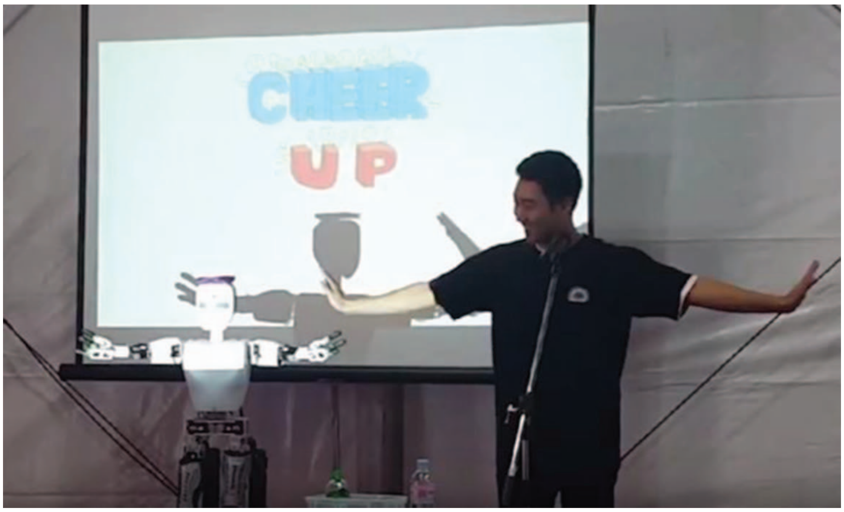

Figure 2. Team Charles included several small routines in its performance.

Team Taipei Snipers, National Taiwan Normal University, Taipei (Third Place)

The Taipei Snipers team combined three different magic techniques (peek, equivocation, and mind reading) into a single trick performed using a member of the audience. First, the robot peeked at the bottom card in the deck. The initial stages of the vision pipeline to find the contour were similar to those of the Snobots described previously. However, the Taipei Snipers used a histogram-based approach to identify the card. The volunteer was then asked to create three piles by cutting the deck twice and placing them in a row.

Equivocation (also called *magician's choice*) is an old technique used in many magic tricks. A volunteer makes a choice or a sequence of seemingly free choices, but ends up making the choice preferred by the magician. This is possible because the magician chooses how to interpret each choice (Figure 3).

At this stage, the robot knows only the bottom card of pile 1, so we want the volunteer to select pile 1. The volunteer is then asked to place a magic wand between two piles. If the volunteer places the wand between pile 1 and 2, then the robot will answer, "You selected pile 1, please remove piles 2 and 3." If, on the other hand, the wand is placed between piles 2 and 3, then the robot will say, "You don't like pile 3, please remove it," thus leaving piles 1 and 2 on the table. Then the robot will ask the volunteer to select a remaining pile (pile 1 or pile 2) by touching it. If the volunteer touches pile 1, the robot will respond with "You selected pile 1, please remove pile 2," but if the volunteer selects pile 2, then the robot will respond with "Please remove the pile you selected." So independent of what the volunteer chooses, we will always leave pile 1 on the table. The user is then asked to pick up the pile and look at the bottom card, the card that the robot peeked at earlier.

The vision processing for the equivocation uses region-based segmentation to find the location of the three card piles on the table. Motion between and on top of the card piles is used to find the magic wand and the pile the user selects by hand (Figure 4).

The robot could now simply reveal the card by announcing it. However, to make the trick more fun and more interactive for the audience, the robot pretends to read the person's mind. The robot asks a series of questions, to which the volunteer can answer either truthfully or lie or remain quiet.

Many magicians present different personalities during their act. The Taipei Snipers team supported different personalities by having each response labeled according to several features (e.g., aggressive versus comical). When selecting a response, the robot calculates how well a response matches the desired personality of the magician. For example, when responding to a volunteer's lie, a comical magician is more likely to select "Did you forget your glasses?" with a rating of 0.8 for comical, than with "Dirty liar," with a rating of –0.8.

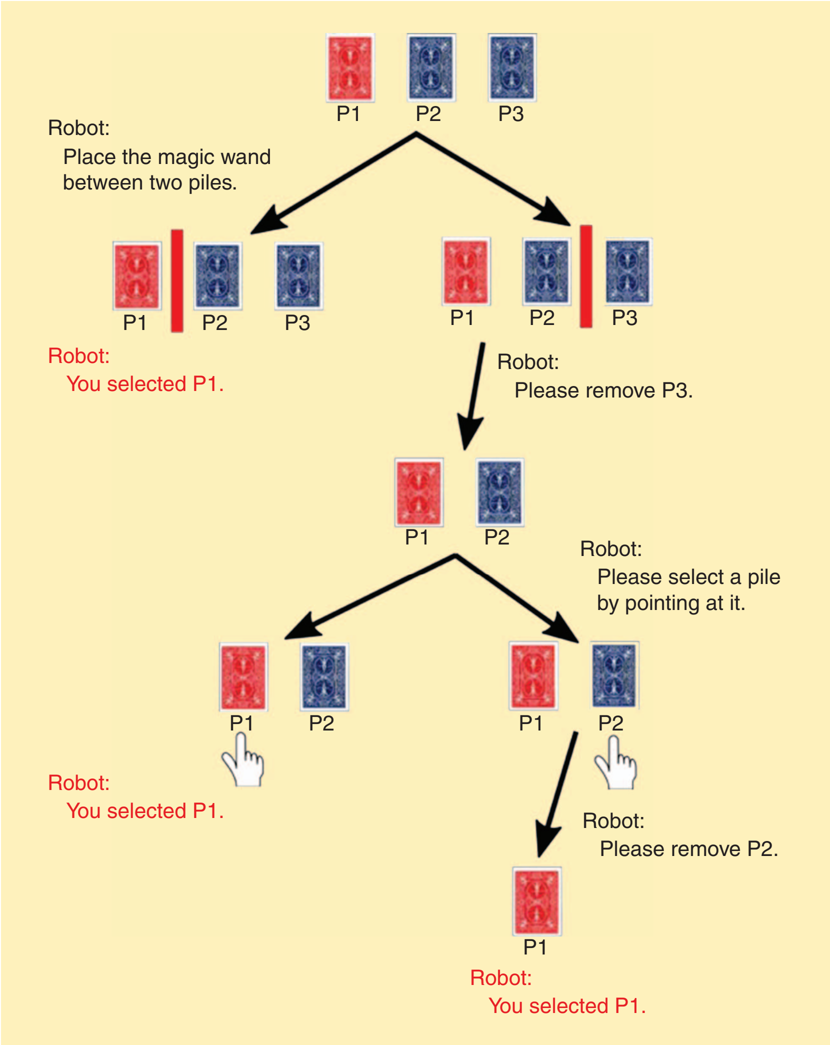

Figure 3. The magician's choice. By asking a volunteer to choose a pile (P) by placing a magic wand between piles or pointing at a pile but not telling the person what the choice entails, we can guarantee that P1 will always remain on the table.

Figure 4. Team Taipei Snipers used region-based segmentation and motion detection to find the magic wand and the selected card deck.

The illusion of mind reading is augmented by the robot displaying a false color overlay over the face of the volunteer that randomly fluctuates with a base period of 80 beats/min. The idea is to give the wrong perception that the robot is monitoring the volunteer's heartbeat to detect whether the person is lying or not (Figure 5).

Future Perspective

Based on feedback through our questionnaire after the event, we know that all participants enjoyed HRAC 2016.

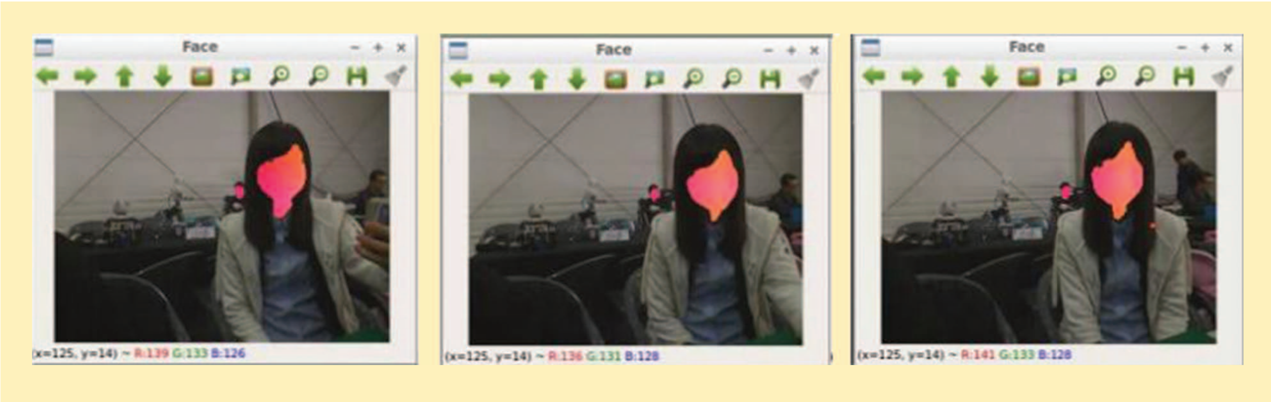

Figure 5. The fake mind-reading visualization of a volunteer. The detected skin color is modulated at about 80 beats/min., giving the audience the impression that the robot is looking for slight variations in skin tone.

This was undoubtedly due in large part to the great organization of the event by Prof. Hyungpil Moon and the rest of the IROS 2016 Organizing Committee (OC).

The HRAC competition was originally designed to have a new theme every year. However, after consultation with the teams, we decided that changing the theme every year did not allow teams a chance to explore research opportunities in those areas sufficiently, so we decided to use "Robot Magic" again as a theme for 2017. Several teams have already started to discuss their ideas for next year's competition.

As in many robot competitions, judges are easily swayed by catchy music and a dazzling performance by the human assistants. This is in spite of the fact that the instructions to the judges allocated 20 points each for interaction and technical complexity. Next year, we will improve our metric for judging. We also hope to include some professional magicians as members of the judging panel.

One problem common to all the teams was speech recognition. It was slow and error prone, in spite of the fact that each team used its own dictionary and grammar. In the future, teams will work on improving this aspect of their work, since speech is an integral part of human–robot interaction.

The RGMC

An OC for the RGMC was formed during the International Conference on Robotics and Automation 2016. But besides the nine members of the RGMC OC, many RAS members contributed to the preparation of the competition. Researchers from around the world sent in competition tasks and grasping objects. Companies pledged to donate either hardware for the competition or prizes. The Korean government provided generous travel support for the competing teams. After selecting 18 manipulation tasks, the RGMC OC members clearly defined the tasks and the rules for the competition. Nine of the 18 tasks were released on the competition website on 16 July 2016.

The competition had three tracks:

- Track 1: Hand-in-hand grasping
- Track 2: Fully autonomous
- Track 3: Simulation.

Regarding the first track, while many researchers today are working on robotic grasping and manipulation, not everyone who has a robotic arm is willing to deal with the shipping, going through customs, and otherwise risking damage to their US$100,000 equipment. Robotic hands, on the other hand, are usually easy to carry internationally. So we created the hand-in-hand grasping track to attract researchers who could not bring a robotic arm to the competition site in Daejeon. But even robotic hands are, in general, very expensive. So, to encourage the participation of researchers interested in solving computation problems, we included the simulation track.

With real robotic systems, there are two tracks and two stages for each track. Each team was provided a station at the competition site. Ten objects were placed in a bin, and the manipulation environment was set up at the station.

Track 1: Hand-in-Hand Grasping

Stage 1: Pick and Place

Ten objects were randomly placed in a shopping basket. The goal was to pick the objects up and place them at predefined spots on a table one by one. A detailed description of the objects is available online (http://www.rhgm.org/activities/competition_iros2016/objects_published.pdf). Each team had five attempts to complete the pick-and-place stage. All five attempts were to be completed in 30 min. A human operator (a volunteer) held the robotic hand and performed grasping by precisely following the instructions displayed on a computer screen. The instructions were automatically generated by the team's computer. No human input or teleoperation from the team was allowed during the grasping or placing.

Stage 2: Manipulation

A detailed description of the manipulation tasks is available online (http://www.rhgm.org/activities/competition_iros2016/tasks_published.pdf). The contestants had 120 min to gain as many points as possible. As in the pick-and-place stage, a volunteer human operator held the robotic hand and carefully followed computer screen instructions to perform grasping. As before, the instructions were automatically generated by the team's computer. Any human input or teleoperation during the grasping was not allowed. After the grasping, the competing robotic hand could be directly operated by a human operator (Figure 6).

Track 2: Fully Autonomous

In this track, a complete robotic system was used. All grasping tasks were performed autonomously, without any human input. Teleoperation was allowed in some of the interactive manipulation tasks.

Stage 1: Pick and Place

Just as in track 1, ten objects were put in a shopping basket in no particular order. The goal was to take the objects one by one and place them at specific spots on a table. A detailed description of the objects is available at http://www.rhgm.org/activities/competition_iros2016/objects_published.pdf. Each team could try five times in 30 min to complete the pick-and-place stage.

Stage 2: Manipulation

A detailed description of the manipulation tasks is available at http://www.rhgm.org/activities/competition_iros2016/tasks_published.pdf. The contestants had 120 min to gain all the points they could. Two of the manipulation tasks are shown in Figure 7.

Track 3: Simulation

The simulation repository and readme are available online (https://github.com/krishauser/IROS2016Manipulation-Challenge). A detailed description of the competition setup and tasks in this track is also available online (http://www.rhgm.org/activities/competition_iros2016/simulation.pdf).

Competition Description

Seven teams registered for the track 1 competition, five teams for the track 2, and four teams for the track 3. In the end, one team couldn't come to Daejeon because of visa issues. All the other teams participated in the competition. Two of the four teams in the simulation track participated remotely.

(a) (b)

Figure 6. A hand-in-hand manipulation task. (a) An operator handles the UNIPI-IIT-QB's gripper in a hammering task and (b) a scissor cutting task.

(a) (b)

Figure 7. The robotic manipulators of (a) Team Dorabo & Cobot and (b) Team SKKU perform autonomous manipulation tasks.

Day 1

The competition started on 11 October at 1:30 p.m. with the manipulation tasks. The hand- in-hand track was first. Each team had 2 h to finish all ten manipulation tasks. Multiple teams completed the tasks without losing any points. The fastest team was UNIPI-IIT-QB, which completed all ten tasks in 22.28 min. The paper-cutting task took them about 10 min.

At 4 p.m., after a half hour of rest for the teams, the fully autonomous track started, with five teams competing. During the competition, the teams were allowed to perform teleoperation during the manipulation tasks but not during the grasping. However, none of the teams were able to finish all the tasks. The Tshinghua team gained the most points but used the whole 2 h. The Dorabot & Cobot team gained fewer points but used much less time. No team was able to attempt the paper-cutting task. Several teams tried the nail-hammering task but failed, mainly because of the lack of strength in the robotic hand and arm. Based on the results and comparing the tracks, we could see that in the hand-in-hand case human intelligence could correct for some of the flaws in the design of the robotic arm and hands. The computer vision component was barely used in the two tracks in this stage of the competition. For many tasks, basic power grasps were good enough, and many robotic hands were good at performing power grasps. However, tasks that required dexterous manipulation were difficult, because of the robotic appendages' lack of dexterity and inability to produce more sophisticated grasps.

Day 2

On 12 October, all the teams competed in a pick-and-place task on three different tracks. First, from 9 to 9:30 a.m., four teams competed in the simulation track on two tasks. One was picking items from a bookshelf into a bin and the other was picking balls from one bin to another. Duke University won this track, with 26 successful pick-and-placements.

At 10 a.m., we started the pick-and-place for the autonomous track. Now all five teams had to use vision to recognize objects in the shopping basket, pick them, and place them either in a box or at a defined location with the correct orientation.

They had a half hour to do that. The Tsinghua team was able to pick out and place four items, Dorabot & Cobot three, and SKKU two. The teams encountered real-life problems, such as the hammer in the basket blocking grippers, or the bag of chips being too big to grasp even though they were able to move things around in the basket.

The last competition track was the hand-in-hand. All six teams were able to use the robotic hands to pick all the objects from the baskets and place them in the defined location. Some teams lost points, though, because some items were dropped during transport.

The fastest team again was UNIPI-IIT-QB, which finished everything without losing any points in 1.08 min, while Northeastern University (China) was able to finish everything in 5.25 min without dropping anything. The brilliant robotic-hand designs were almost perfect for pick-and-place tasks. However, intelligence in perception, reasoning, and dealing with difficult situations still has a long way to go.

Altogether, the winners were

- Track 1 (total 300 points)
  1) UNIPI-IIT-QB: 300 points, time: 22.28 + 1.08 min
  2) University of Colorado–Boulder: 300 points, time: 32.12 + 11.04 min
  3) Tsinghua University: 299 points
- Track 2 (total 300 points)
  1) Tsinghua University: 165 points
  2) Dorabot & Cobot: 155 points
- Track 3 (total 45 points)
  1) Duke University: 26 points.

Overall, the competition was a success. We will organize the RGMC again in IROS 2017. The details will be released on rhgm.org. Figure 8 shows two scenes from the RGMC.

The ADR in Mos Espa Daejeon Arena

Human pilot drone racing is becoming popular as a new-generation hobby and also as a rising professional sport. Recent drone racing games showcase the agility of drones flying through a zigzag, narrow, confined racing circuit. An onboard camera and head-mounted display goggles provide the pilot with first person view, allowing human pilots to display their amazing control techniques. In contrast, autonomous drone flight at high speed through such a demanding environment still remains a difficult challenge. Nonetheless, drones that can negotiate such complex surroundings can provide a killer app for future drone applications, where drones must fly through a maze of obstacles and, for example, search for survivors at accident scenes.

The IROS 2016 ADR in the Mos Espa Daejeon Arena, held on 12 October, was a technical challenge sponsored by the Korean Ministry of Trade, Industry, and Energy that aimed to provide worldwide robotics researchers with a technology showroom for autonomous flight and to promote solutions for agile autonomous drone flight in daunting environments. The technical challenges combined the optimal time path planning, flight and tracking control, obstacle detection, localization, and fault detection and recovery for drones.

Competition Description

Racing was held in an indoor track that contained five testing elements: high-speed flight on a straight path through open gates, sharp turns, a horizontal zigzag path, a spiral upward path through closed gates, and negotiating a dynamic obstacle. Detailed information about this track is available online at http://ris.skku.edu/home/iros2016racing.html. To facilitate localization, each track gate had a QR code with the gate's identification number. Robot size was limited to 1 m × 1 m × 1 m with all components fully extended, but the robot type was not confined to popular quadrotors. The drone was allowed to have any type of onboard sensors, including vision (visible or infrared), lidar, laser, radar, and ultrasound.

For each team, the competition began when it placed its drone at the takeoff point with the system ready. Once the team said "Start!" the team members did not control their drone in any way until it completed its attempt by landing. In other words, the drone was operated completely autonomously without any form of human intervention during the trial. Each team was

(a)

(b)

Figure 8. A view of (a) the RGMC competition and (b) all the participants.

(a) (b)

Figure 9. (a) The ADR track and (b) a drone passing through a closed gate.

given 30 min, during which time it could run its robot through the designated course as many times as they wished, passing through each gate in sequence (Figure 9). During each attempt, the gate identifications and time were recorded, and the team's best time was selected as its official score.

Competition Results

Initially, a total of 11 teams registered for the competition, but due to issues such as fund-raising and technical readiness, only three teams (Team Korea Advanced Institute of Science and Technology (KAIST) Indoor Racing Drone (KIRD) of KAIST Korea; Team Micro Air Vehicle (MAV)-lab of Technische Universiteit (TU) Delft, The Netherlands; and Team Eidgenössische Technische Hochschule Zürich (ETHZ) Autonomous Systems Lab (ASL)/Agile & Dexterous Robotics Lab (ADRL), Switzerland) finally competed in the arena. Instead of autonomous flight, Team Coanda of Sungkyunkwan University showed interesting demonstration runs of their unidentified flying object-like drone. The awards ceremony is shown in Figure 10, and the competition results follow.

Team KIRD, KAIST, South Korea (First Place)

- Team members: Sunggoo Jung, Hanseob Lee, Sungwook Cho, Dasol Lee, HeeMin Shin, Jaehyun Lee, HyunGi Kim, Jaemin Kang, and David Hyunchul Shim
- Record: 01:26.5 through gate 10.

Team MAV-lab, TU Delft, The Netherlands (Second Place)

- Team members: Guido de Croon, Roland Meertens, Ewoud Smeur, Sjoerd Tijmons, Matej Karasek, Chrisophe de Wagter, Shuo Li, Coen de Visser, Isabella Haij, and Michaël Ozo
- Record: 02:42.3 through gate 10.

Team ETHZ ASL/ADRL, Switzerland (Third Place)

- Team members: Michael Burri, Helen Oleynikova, Rik Bä hnemann, Mina Kamel, Zachary Taylor, Alex Millane, Dominik Schindler, Inkyu Sa, Michael Pantic, and Roland Siegwart
- Record: 00:51.4 through gate 5.

Discussion

During the competition, it seemed that all the teams struggled with gate recognition because of drone pose stabilizing and cluttered gates of a monotonic orange color. One team's strategy was to use the stereo vision-based direct visual servoing, not global navigation. This approach suffered from the cluttered gates because small offsets from the safe, planned path caused collisions with either the safety net or the neighboring gate. Also, all teams used visual recognition for finding the gates, and the small camera-view angle caused recognition failure after sharp turns.

All of the competing teams reached the region of the sharp-turn path through closed gates, and the best performance was passing through gate 10 with a 01:26.5 lap time. By the way, a human pilot was able to complete the entire 26-gate course in 01:31.1 on his second trial. Team KIRD passed through gate 7 at 01:10.35.

All of the participating teams felt that the racing track was very challenging, mainly due to the density of closed gates and lack of visual cues. To achieve a more realistic likeness of an indoor

Figure 10. The ADR awards ceremony.

Figure 11. Some snapshots of the HRAC.

disaster response, it will be considered to revise the track in terms of changing the gate color to simple dark gray or introducing overhung wired obstacles.

Live Streams

The three robotic challenges at the 2016 IROS were media streamed. The media streaming included video and audio content sent in compressed data as a continuous-stream package over the Internet that was watched instantly at a remote site without downloading a file to play it. The media streaming for the IROS 2016 competitions was a two-day broadcasting service held on Tuesday, 11 October, and Wednesday, 12 October. It was an inaugural live broadcasting event for the IROS conferences streamed through YouTube Live inside and outside the conference venue. The broadcasting system was installed on Sunday 9 October and tested on Monday 10 October. We had several meetings to check the systems and roles, review the program and scripts, and practice before broadcasting. The IROS 2016 media streaming broadcast the following three challenges.

The HRAC

The HRAC challenge was broadcast on Tuesday 11 October from around 1 to 6 p.m. as well as on Wednesday, 12 October from around 9 a.m. to 12 p.m. The challenge was to perform magical tricks on a stage with one or more robots. One broadcast camera was used to stream the performances on the stage (Figure 11).

Figure 12. Commentator Kenneth Lee of the University of Nevada–Las Vegas handles a gripper.

The RGMC

The RGMC competition was broadcast during the same time as the HRAC was streamed, on Tuesday, 11 October from about 1 to 6 p.m. as well as on Wednesday, 12 October from about 9 a.m. to 12 p.m. The RGMC had two stages with two separate tracks in each stage. The first stage was the hand-in-hand, with track 1 being a pick-and-place and track 2 manipulation. To the casual observer, it seemed like this challenge had more participants than the HRAC. The RGMC took place at each participant's station (Figure 12), not on a stage, as with the HRAC, which required an additional mobile camera to stream the event.

The ADR Challenge

The ADR was streamed on Wednesday, 12 October from 1 to around 6 p.m. It was billed as the featured competition at IROS 2016. The broadcast format was to provide interviews by at least one member of the participating teams as a guest commentator. The interviews took place during the racing as they would have on a professional broadcasting show (Figure 13). This idea was suggested by Dr. Hyungpil Moon, who was the leading coorganizer of the competition. We combined humor with questions and answers to keep the live audience engaged and entertained. This format was particularly helpful during the moments when a drone would crash or otherwise fail in its attempt, and we were able to keep the viewers engaged with interesting facts.

Figure 13. Commenting at the ADR challenge.

Broadcasting Within the Conference

The streaming was displayed on a monitor in the main conference lobby, as shown in Figure 14. All the streamed programs were advertised at the conference site, and the conference media team posted them on the main conference website.

Broadcasting Outside the Conference

The media-streaming URL was sent to the Caesar's Hotel in Las Vegas, Nevada. Executives from several of the hotels on the Las Vegas Strip and people from other venues watched. People from Switzerland, The Netherlands, the United States, and Brazil contacted us to get the streaming URL and watch the ADR.

Figure 14. Broadcasting within the conference site.

Figure 15. Broadcasting outside the conference site.

The Internet Bandwidth

The Internet bandwidth on the first day of media streaming, Tuesday, 11 October, was 2.69 Mb/s. It was not good enough to provide quality live streaming for the competitions. The network, was improved, and the bandwidth on the next day, Wednesday, 12 October, was 23.98 Mb/s.

The IROS 2016 Competition Survey

We asked a total of 80 conference attendees about the competition after finishing all the events on the last day. The survey was taken inside the competition area, and we selected potential interviewees at random. Among the 80, 22 were contestants who participated in the events and 58 were audience members. Their overall experience was good, as the median value of their responses was eight out of ten. Regarding whether they would be interested in participating in one of the three competitions next year, their responses were indeterminate, with a median value of five.

We received interesting, positive, and constructive comments from different perspectives. One stream of comments was that the competition provided an opportunity to meet with people from different fields. Most people mentioned that it was a great opportunity to see different robotic structures and performances. Several attendees commented favorably about how the conference created an international arena where people came from all over the world to meet and discuss their interests. One comment was that there should be more ADR contestants. Similar to this was an observation that the competition should be announced earlier to recruit more applicants.

We would like to acknowledge the support provided by the conference organizers and the sponsors for each competition. Special thanks are due to the IROS 2016 Organizing Committee and the Korean Ministry of Trade, Industry, and Energy for providing travel support to the qualified participating teams.

More information about each of the challenges is available at http://iros2016.org/competition.html.