The World robot summit disaster robotics category – achievements of the 2018 preliminary competition

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\textbf{ABSTRACT}

The World Robot Summit is a robot Olympics and aims to be held in a different country every four years from 2020. The concept of the Plant Disaster Prevention challenge is daily inspections, checks, and emergency response in industrial plants, and in this competition, robots must carry out these types of missions in a mock-up plant. The concept of the Tunnel Disaster Response and Recovery challenge is emergency response to tunnel disasters, and is a simulation competition whereby teams compete to show their ability to deal with disasters, by collecting information and removing debris. The Standard Disaster Robotics challenge assesses, in the form of a contest, the standard performance levels of a robot that are necessary for disaster prevention and emergency response. The World Robot Summit Preliminary Competition was held at Tokyo Big Sight in October 2018, and 36 teams participated in the Disaster Robotics Category. UGVs and UAVs contended the merits of new technology for solving complex problems, using core technologies such as mobility, sensing, recognition, performing operations, human interface, autonomous intelligence etc., as well as system integration and implementation of strategies for completing missions, gaining high-level results.

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1. A competition for innovation

1.1. Objective

The World Robot Summit, is designed as a robot Olympics, and aims to be a competition held every four years in a different country, starting with the Fukushima-Aichi competition in 2020.

The Disaster Robotics Category, one of the four categories in the 2020 event, is a competition involving robots for maintenance of infrastructure and for disaster response. The three challenges below were designed for and implemented in the Preliminary Competition in October 2018.

- Plant Disaster Prevention Challenge
- Tunnel Disaster Response and Recovery Challenge
- Standard Disaster Robotics Challenge

YouTube videos with commentary [1] and photo albums [2] have been made publicly available, so please enjoy.

These challenges have the following objectives which were proposed to solve issues concerning infrastructure and disasters, by advancing and encouraging the widespread use of robotics in society.

- To act as an opportunity to introduce and advance robotics.
- To provide a place for the promotion and acceleration of R&D and demonstration experiments.
- To enhance technology related to robotics and nurture the seeds of realistic solutions.
- To cultivate the social consensus necessary to promote the implementation of disaster robotics in society.
- To not simply be just for entertainment, but to develop methods of solving social problems on a global scale, and establish a foundation for their social implementation.
- To lower barriers hindering the participation and entry of national governments.
1.2. A competition that creates innovation

Robot competitions are an open innovation method, playing a large part in the formation of technology, public infrastructure, and the shape of trends in a marketplace in its infancy. The result of this is the creation of a technical platform, that not only cultivates human resources, but encourages change in investors’ way of thinking, grows user acceptance, and provides the industrial world with the opportunity to extensively gather practical technological information.

For example, the DARPA Grand Challenge [3] and Urban Challenge [4] played a huge role in paving the way for self-driving cars. Previous to these competitions, few people believed that autonomous cars would be safe to drive in urban areas, and neither car manufacturers nor governments were optimistic. AUVSI International Aerial Robotics Competition [5] contributed to the creation of a platform for technology and the advancement of autonomous drones. In RoboCup [6], Aldebaran Robotics’ Nao [7] was used in the competition’s Standard Platform League, and in cooperation with the contest participants, Aldebaran developed Nao’s AI functions, resulting in it becoming the basis for Pepper [8]. RoboCup Rescue Robot League is a competition that judges the ability to search within a maze comprising of uneven ground and stairs. During the competition practical mobility of Quince and ability to collect information through mapping evolved, and it went on to contribute to surveys of the nuclear reactor buildings in the Fukushima Daiichi nuclear disaster as the first national robot actually used [9].

It is thought that without robot competitions this innovation could not have come about, and the social and economic effects are not small. Taking NHK Robo-Con [10] as an example, the objectives and character of competitions for education are different from those of competitions designed to generate social innovation, and so their challenges also differ greatly.

A particular social issue for disasters is that it is difficult for businesses in the private sector to tackle projects of this scale, and so it is necessary for national and local governments to bear this responsibility. Safety and water do not come for free. By their nature, these competitions should be carried out with government initiatives, and strive to raise standards of technology.

If a robot Olympics, built up from a competition with the concept of disaster and held through government leadership in each country by turn every four years, continued for 100 years, imagine what innovation could be generated throughout the world. When considering this, the World Robot Summit is a movement on the verge of bringing about a social revolution through robotics. The significance of it beginning now is great and is likely to be deeply ingrained in human history.

Thus, the WRS Preliminary Competition held at Tokyo Big Sight in October 2018, is a prelude, marking the eve of a revolution to go down in history.

2. Plant disaster prevention challenge

2.1. Objective

In manufacturing plants, oil refineries and iron works, from a perspective of disaster prevention, unmanned autonomous daily inspections and safety diagnostic work is desirable, particularly in the facilities and structures in places where it is difficult to deploy labor, or with dangerous working environments, such as offshore plants. Furthermore, by introducing robots, the rate of regular inspections could increase, and so malfunctions and accidents (explosions, gas leaks, fires, toxic gas or substance leaks), etc. caused by human error or facilities damaged by deterioration could be prevented. On top of this, facilities that operate under very high temperatures or in high-risk environments must stop running for inspections to be carried out. By making use of robots, it is possible to implement daily inspections while these facilities are running, and thereby increase the rate of operation.

Concurrently, in the case of pipes damaged by natural disaster, explosions and fires may occur due to flammable gas leaks. After a disaster occurs, together with quickly shutting off fuel pipes, if fire extinguishing equipment can be turned on in the vicinity of facilities where flammable gas is leaking, it is possible to rapidly deploy an initial firefighting response.

Moreover, it is very possible that robots capable of meeting these demands could also be used as disaster response robots. In particular, the monitoring technology of probe robots able to deal with narrow confined spaces can be used in the inspection and maintenance of narrow, confined areas; or dangerous places within public infrastructure and plants. In a disaster, these robots could also be used to investigate places where there is rubble and leaking flammable/poisonous gases. Making use of the technology of maintenance robots in public infrastructure and plants for disaster response could lead to achieving the implementation of disaster robotics in society.

2.2. Competition details

The Plant Disaster Prevention challenge is designed for teams to deal with daily inspections, surveys, as well as emergency response to problems which could occur
in operational plants such as manufacturing plants, oil refineries and iron works. Competition tasks and missions have been set up so as to demonstrate their ability to deal with a variety of facilities. The equipment required to be checked in the pre-competition were pipes, pumps, small tanks, boilers, and the surface of a large tank. In order to assess a plant inspection robot’s abilities, five missions were set up. These missions were carried out according to the inspection instructions, each with their own corresponding tasks (inspection, examination etc.). Each mission occurred in a designated zone, and the robot needed to maneuver between a specified start point and end points. The competition time was 20 min for each mission. Once all tasks in the mission had been completed, the robot must then return to the start point. However, the order in which the tasks were completed was up to the team’s discretion. The plant layout (2D, 3D CAD data), and information on each type of target (layout, model numbers etc.) were made public in advance. Figure 1 shows the competition field. Please refer to the rule book [11] for details of the rules.

2.3. Competition missions

2.3.1. Mission P1: routine inspection/Equipment regulation

In a typical plant, daily inspections are carried out several times a day by several members of staff. It is therefore desirable to work towards unmanned and automated inspections by using remote control/autonomous robots. Consequently, the tasks for P1 were envisioned as a round of inspections of the facilities and equipment in operation, taking readings of designated pressure and water level gauges, and reporting these readings, and carrying out specified adjustments to facilities and equipment (e.g. open and close valves). The objects of inspection were pipes, three sets of pumps and two tanks. See Figure 2 for an image of Mission P1.

2.3.2. Mission P2: detection of abnormalities

In plants, detailed inspections using measuring devices are regularly carried out. Through the use of sensing and analyzing technology, any abnormalities in the facilities and structures could be discovered while still in their early stages. In the tasks for P2, robots must rapidly discover abnormalities caused by dilapidation, deterioration, human error etc. in designated facilities and equipment, and report their place and details. Specifically, detecting gas leaks from pipes, abnormal temperatures, looseness and rust on bolts, as well as carrying out measurements of pumps with abnormal vibrations, [12], and the concentration of oxygen in tanks. See Figure 3 for an image of Mission P2.

2.3.3. Mission P3: equipment diagnosis

It can be assumed that every few years repairs and improvements of plants are made, and so it is necessary to carry out large scale inspections. When this happens, plant operations are stopped and cleaning may also take place, but by using robots the time operations are stopped could be shortened, and inspections in high or dangerous areas could be performed. The tasks in Mission P3 involve large structures such as groups of pipes, tanks, and ducts, and the robot must assess and diagnose the soundness of these facilities, and report any dilapidation or deterioration. For the pre-competition, structural abnormalities such as cracks, rust and voids were recreated on test piece boards, and a wooden wall imitating
Figure 2. Mission P1. (a) Pipes A: reading pressure gauge. (b) Tank: turning lever. (c) Tank: reading the water level and (d) Automated recognition of the pressure gauge.

Figure 3. Mission P2. (a) Pipes (B). (b) Pipes (B): detecting abnormal temperatures. (c) Pump: investigating abnormal vibrations and (d) Tank: measuring oxygen concentration.
the side of a large scale tank was prepared. The robot must report the results of its assessment of the following in each of the inspection areas. (1) Presence of cracks: Report position, length, and width of crack. (2) Presence of rust: report percentage of specified area covered in rust [13]. (3) Presence of void: Indicate the place of void. See Figure 4 for an image of Mission P3.

2.3.4. Mission P4: disaster response: initial firefighting
During a boiler inspection, the sound of an explosion occurs, and it is believed that gas is leaking from decrepit pipes and that a fire has begun with smoke accumulating around the equipment. It is also possible that there is gas leaking from other equipment that could lead to further explosions, and so the area is too dangerous for people to approach. For the tasks in mission P4, the robot must carry out initial firefighting procedures in order to limit the spread of the disaster. It must close the relevant valves of each type of pipe on the corresponding equipment, turn on the fire extinguishers (foam extinguishing system) and close pipes channeling flammable gases or oils. While daily inspections based on the inspection instructions are being carried out, an alarm will sound, and the robot must turn on the fire extinguishers. The time of the alarm was 10 min after the start of mission in the preliminary competitions, and 15 min in the finals. See Figure 5 for an image of Mission P4.

2.3.5. Mission P5: disaster response: search for missing worker
In the middle of a daily inspection, an explosion occurs. A head count confirms a missing person, and the robot must carry out a search. For the tasks in Mission P5, after the alarm sounds, while removing rubble and debris, the robot should search for the missing worker and report their location. It must also measure the concentration of oxygen in the vicinity. The time of the alarm was 10 min after the start of mission in the preliminary competitions, and 15 min in the finals. As a surprise task, the robot must also read the scale of a pressure gauge while turning a valve handle to adjust to a specified pressure. It is a sophisticated task which requires the robot to recognize an erratically moving needle while simultaneously making fine adjustments. See Figure 6 for an image of Mission P5.

2.4. Method of assessment (method of scoring points)
Mission points are gained by the number of tasks (inspections/emergency procedures) completed in the target facilities set for each mission. As well as mission points, technical points may also be gained depending on the robot’s technical level. In the pre-competition, additional
Figure 5. Mission P4. (a) Boiler: turning lever. (b) Boiler: reading temperature and pressure. (c) Catwalk: traversing stairs and (d) Fire extinguishers: starting manually.

Figure 6. Mission P5. (a) Routine inspection: UGV/UAV coordination. (b) Complex task: adjusting pressure. (c) Disaster response: traversing pipe debris and (d) Disaster response: search for missing persons.
points were given for automatic recognition of meter scales, and for use of 3D SLAM.

2.5. Competition results

Nine teams participated in the pre-competition. Each team's name, affiliation, and country are shown in Table 1. The qualifying rounds took place over four days with teams attempting each Mission P1 to P4 twice, and their highest score was used for their final result. Each team's points were standardized by the maximum total points possible for each mission, and the top scoring four teams advanced to the finals. They then carried out Mission P5 for the final contest.

The competition results of the top six teams in the qualifying rounds were analyzed. Figure 7 shows the achievement rate for each mission in the qualifying round. The achievement rate for each mission was P1: 18%–35%, P2: 29%–94%, P3: 0%–63%, P4: 30%–100%. The results were that P1 and P3 had relatively low achievement rates. Regarding P1, one cause is that there were too many tasks to complete within the competition time limit. As for P3, it is thought that due to insufficient information supplied by the management side, teams were not able to sufficiently understand how to deal with the test pieces.

Next, every task in each mission was analysed.

**Table 1.** List of teams participating in the plant disaster prevention challenge.

| Name                        | Affiliation          | Country   |
|-----------------------------|----------------------|-----------|
| AIRRC & i-Robo AIR-K        | Mobile Robot Research| Japan     |
| Aisafu                      | Sanritz Auto, Fate, Aichi IT | Japan     |
| ATR, Kent                   | Kent State Univ USA  | USA       |
| Hector Darmstadt            | TU Darmstadt Germany | Germany   |
| Nexis-R                     | Nagaoka UT Japan     | Japan     |
| Quix                        | Tohoku Univ Japan    | Japan     |
| Raptors                     | Lodz UT Poland       | Poland    |
| TUMI ROBOTICS               | PU Catolica Peru Peru| Peru      |
| UEC Snake with Tohoku Gripper| Tohoku Univ Japan    | Japan     |

**Figure 7.** Mission achievement rate.

**Reading pressure gauges (P1):** As using images as a visual report was allowed, it was a task in which points could be gained relatively quickly. That the top two scoring teams used automatic recognition over a visual report demonstrates their robot's technical superiority. Moreover, this time the team that used a UAV was able to take close-up images giving them a high rate of success.

**Opening and closing of valves (P1):** Only one team was able to score points. Regarding the allotment of points for this task, it was comparatively difficult and required time to complete, so it is thought that many teams strategically avoided doing this task.

**Water level reading (P1):** Three teams attempted and scored points for this task. Suitable lighting needed to be used because the area was relatively dark.

**Detection of rust/looseness in bolts (P2):** This task had a high achievement rate because it could be completed by using a camera to check the match marks that were inscribed on the bolt fastenings.

**Detection of abnormalities in pipes and pumps (P2):** Concerning the detection of abnormal vibrations in the pumps and abnormal temperatures in the pipes, the achievement rate was relatively high. For abnormal vibrations, there was also a team that used measuring equipment. The achievement rate of the task whereby teams must detect the point of gas leaks was low.

**Measuring the concentration of oxygen in the tank:** Teams who used a UAV had an advantage in this task. However, they also needed to consider the effect of the UAV’s rotors on their concentration readings.

**Cracks (P3):** Teams using UAVs could reliably inspect cracks in high places, and had a 58% achievement rate when measuring the length and width. However, other teams despite employing the zoom function on their robot’s cameras had an achievement rate of less than 25%. It could be guessed that the reason for this is the optical resolution of the cameras was not enough to be able to measure the width of the cracks.

**Rust (P3):** This task could be completed using a simple image processing program, and so a high achievement rate was expected. However, only two teams were able to gain an achievement rate of over 75%. Additionally, the achievement rate detecting rust in high areas was low.

**Void (P3):** Three teams scored points, and their achievement rate was 50 to 60%. At present, the common method of assessment for detecting voids is to use a hammer to detect changes in sound. Therefore, it is necessary for the robot to be equipped with
a microphone and an end effector able to grasp a hammer. Moreover, a manipulator control capable of operating a hammering test and an acoustic analysis program should also be equipped. However, it is thought that the participating teams were not able to focus their efforts on developing this equipment. It can be guessed that in light of this task’s difficulty and the resources needed to complete it, the low achievement rate for this task was due to tactical avoidance by the teams.

Reading pressure gauge/thermometer (P4): For Mission P4, the pressure gauge and thermometer were installed at the top of the catwalk which surrounded the boiler. Each team had an almost 100% achievement rate, but only two teams actually reached the top of the catwalk, with the other teams taking measurements from below. Larger UGV’s had difficulty due to the narrow width of the catwalk.

Opening and closing of lever handle (P4): After a disaster alarm sounded, only one team was able to turn the lever handle connected to the fuel pipe. Three teams were able to do the manual operation of the lever handle task. The team that completed the task after the disaster occurred gained the highest score.

2.6. Results and knowledge gained

- Most teams carried out visual inspections and adjustments based on image data taken using remote-controlled robots. However, what led to high scores was the use of a handling assistance system that includes data on the robot’s location gained through 3D SLAM within the 3D CAD model; (Figure 8) as well as actively attempting all kinds of automatic recognition (meters, rust) through image processing. These challenges demonstrated the advantage of introducing robotic technology through an increase in the objectivity of inspection results and the accuracy of the diagnostic results. On the other hand, more teams were expected to have attempted tasks relating to manipulation, such as opening and closing valves.
- The competition missions and their tasks where designed by choosing procedures common in actual inspections of plants. It is thought that the level of success for each task and increase in the accuracy of the diagnostic results, demonstrates the significance of the use of robots for plant inspections. On the other hand, from the viewpoint of the standard test method, the components of each task were sorted for relevance in plant inspections, and these competition tasks were recreated within a mock-up plant. > From the results of this competition, the technical issues that occur in actual plants were sufficiently recreated. However, concerning the method of recreating abnormalities and irregularities in each of the facilities used in Missions P2 and P3, further scrutiny of the manufacturing methods and difficulty level of the design is needed.
3. Tunnel disaster response and recovery challenge

3.1. Competition objectives

The Tunnel Disaster Response and Recovery challenge aims to use robots to carry out a rapid and precise disaster response in tunnels damaged by disasters such as earthquakes. It is a competition whereby robots compete through their abilities to respond to disaster by gathering information and traversing rubble etc. In the 2020 competition, it is hoped that actual robots will be able to compete rather than simulations. In this competition, through the development of Chorenoid [15,16] by the National Institute of Advanced Industrial Science and Technology (AIST), we implemented a simulation competition similar to that of the Japan Virtual Robotics Challenge (JVRC) [17,18] in 2015. It was a contest that assessed the ability of control software in disaster response robots, and the robot’s operating technology for dealing with disasters.

3.2. Competition details

The tasks for the Tunnel Disaster Response and Recovery challenge were decided based on actual conditions dealt with by experts in disaster response technology, what a robot’s underlying technologies can cope with, and the ability to carry out an assessment of the robot’s underlying technology. Accordingly, six missions were designed for this challenge, with tasks consisting of driving over debris, moving through narrow, confined spaces, maintaining routes, searching for victims, investigating the environment in and around cars involved in the rescue, surveying damage, and responding to smoke and fire. The missions were also designed taking into consideration that they would be carried out on the same field and under the same settings. The tasks set consisted of heavy work such as traversing debris, moving through narrow spaces such as rubble, and data collection that makes use of maneuverability. Depending on the objective of the task, the size of the robot required changed. For this reason, small-sized robots (S size) that can move through triangular holes with sides of 60 cm, medium-sized robots (M size) that can move through holes with 80 cm sides, and large-sized robots (L size) that could fit through anything bigger were stipulated. The missions and tasks were designed taking these sizes into consideration. The robot models used in the competition were two publicly-offered platform robots (construction robot ‘Dual Arm Construction Robot’ [19], and four-legged robot ‘WAREC-1’ [20]). Otherwise, robots were supplied by universities or developed by the individual teams. The main robots are shown in Figure 9. The plan is to continue to use these robots in the 2020 competition too. The competition field was, as far as possible, created as a mock-up of a real disaster site. However, after taking into consideration the competition, field reproduction, and ease of controlling the level of difficulty in the non-simulation in 2020, abstract obstacles were used. The time for each mission is shown in Table 2. For further information on the rules, field, and missions, please see the rulebook [21].

3.2.1. Mission T1: traversing Obstacles

This is a mission where teams competed through their ability to drive in narrow, confined spaces caused by uneven ground and rubble on roads that have been damaged, have collapsed or buckled up after a disaster such as an earthquake. Control and operability of UGV’s and UAV’s in narrow spaces were assessed through a heavy-duty robot’s maneuverability in handling obstacles, and the mobility on uneven ground of small to medium robots that favor maneuverability. The field used depended on the size of the robot.

Figure 10 shows an example of the abstract obstacles used as the uneven ground for the large-sized robots. Figure 11 shows the medium-sized Spider robot and large-sized Dual Arm robot moving through a confined space in task T1-C.

3.2.2. Mission T2: examining a vehicle

In this mission, robots must carry out an examination of the outside, inside and surroundings of a vehicle inside the tunnel, and they were assessed on their ability to quickly identify irregularities in the area. The examination of the outside of the vehicle is to identify signs of damage, and the examination of the area surrounding the vehicle is to identify any leaking substances. The examination of the inside of the vehicle is to check if there
Figure 9. Robot model used in competition. (A) Dual-arm construction robot: length 2 m, height 1.7 m (not inc. arm). (B) WAREC-1: full-height 2.7 m. (C) Spider: full-height 1.1 m, height 0.6 m (height to the base of arm). (D) Multicopter: height $\times$ length $0.7 \times 0.7$ m.

Table 2. Time for each mission (minutes).

| Mission | C Preliminary | C Final and Semi Final |
|---------|---------------|------------------------|
|         | Simulated Time | Computational Time | Simulated Time | Computational Time |
| T1      | 10            | 25                     | 10            | 25                    |
| T2      | 15            | 40                     | 15            | 40                    |
| T3      | 20            | 55                     | 20            | 55                    |
| T4      | 15            | 40                     | 20            | 40                    |
| T5      | 15            | 40                     | 20            | 40                    |
| T6      | 15            | 40                     | 20            | 40                    |

Figure 10. Abstract obstacles used as uneven ground.
are any victims and their condition. This challenge used QR codes attached to a cylinder base as targets (as used in JVRC) [17,18] to demonstrate that checks related to the vehicle and the victim's condition were completed. Figure 12 shows the Dual Arm robot and a view from its camera as it carries out an investigation of a victim needing rescue (task T2-A).

3.2.3. Mission T3: investigation and rescue within a vehicle using tools
This mission assessed the robot's dexterity in using tools designed for humans, and the method of rescue. Typically, rescue workers use a spreader to break open a door to allow someone inside to escape. Two tasks were designed based on specialist robots that use technology to break down doors, and the methods of rescue workers. In one, only the lock needed to be broken (and then the door can be opened), and in the other, the lock and 2 hinges must be broken (and then the door can be pulled off and removed). Figure 13 shows the Dual Arm robot using the spreader to break the door's hinges and remove the door.

3.2.4. Mission T4: maintaining a route
This mission's objective was to maintain the routes needed by evacuees and rescue workers, and assesses the robot's ability to move through and extract the rubble and cargo scattered on the road. Abstract obstacles were used as debris. Here, the robot should move L-shaped obstacles of differing densities and composed of four cubes, as well as cylinders and L-shaped columns. Figure 14 shows the Dual Arm robot transferring an obstacle (task T4-B), and extracting an obstacle (task T4-C).

3.2.5. Mission T5: extinguishing fire
This mission assessed the abilities involved in firefighting by using a fire hydrant that was part of the tunnel's firefighting equipment. This fire hydrant was modelled on actual equipment used in tunnels, but the task was also designed taking into consideration the controls needed for a robot to extinguish a fire, and how this would be...
Figure 13. Breaking down door with spreader (task T3-B).

Figure 14. Transferring an obstacle (task T4-B), and extracting an obstacle (task T4-C).

recreated as a simulation. The task’s steps, up until the fire is extinguished, are as follows: open the fire hydrant’s door, pull out the hose, attach the hose to the nozzle, operate the fire hydrants valve, move to near to the source of the fire, operate the nozzle’s lever, and spray water towards the base of the fire. Figure 15 shows the Dual Arm robot extinguishing the fire. The left figure shows an image from Dual Arm’s camera. The operator used this image to fight the fire.

3.2.6. Mission T6: shoring and breaching
This mission assessed the ability to shore, and breach to check the inside of a vehicle trapped under rubble. In reality, rescue workers would assemble parts for shoring on site, but for this mission, it was supposed that rescue workers would assemble the parts in a relatively safe area, and the robot would then take these to the dangerous area to install. For the breaching task, robots were required to make 0.1 m holes in concrete using tools that weighed 30 kg. For shoring, separate tools were prepared for both the large-sized robots and the medium-sized robots leading to differences in the tasks. Figure 16 shows shoring (task T6-A) and breaching (task T6-B) by the Dual Arm robot. When breaching, the drill vibrates, and the hand of the robot’s arm uses a counterforce against these vibrations.

3.3. Competition results
Table 3 shows the results of the 8 participating teams and the robot they used. In the ‘Robots’ column, the letters D, W, S, M, T stand for the robots used by the teams. These are respectively, Dual Arm, WAREC, Spider, Multicopter, and a team’s original robot. All participating teams were from Japan. DNQ in the ‘Rank’ column indicates the team failed to pass the qualifying round, and Q
indicates that they passed. The figures in Table 3 ‘Pre’, ‘Semi-F’ and ‘Final’ columns are each team’s score standardized by the top score. The scores are the sum of the points gained for completing the tasks set for each mission (task points); the points gained for completing missions early (time points); the points gained for acquiring information about the conditions of the field etc. (condition points). Figure 17 shows the distribution of points by task, time and condition in the semi-finals and finals. From Table 3 and Figure 17 we can see the tiny difference in scores in the semi-finals become much wider in the final due to the difference in points earned through fast times. In the final, the difficulty level of all tasks was raised, and unlike in the semi-finals, the contest took place without allowing the teams to first see the field. However, with REL/UoA’s steady robot operation and control, they managed to take first place.

### 3.4. Recreating robots through simulation

The Dual Arm and Spider robots use a crawler movement mechanism and a multiple fingered end effector attached to the arms. Dual Arm robot has two arms and is able to nimbly perform grasping jobs, such as transferring something from one hand to the other. In this competition, crawler component pieces and finger parts were precisely modelled, and a simulation of movement over uneven surfaces and handling of tools was recreated. Figure 18 shows the collection of board shaped parts used to recreate the crawler, and how this crawler changes shape as it moves over uneven ground. Therefore, in tasks which included uneven ground, the movements equivalent to that of an actual robot could be recreated, and it was possible to assess the accuracy of the control of balanced movement, as well as the precision of grasping movements under unstable conditions. Moreover, the points valued highly this time were guarantees against communication delays, autonomous operation, and the use of multiple robots at points apart.

### 3.5. Results and knowledge gained

Figure 19 shows the ratio of each mission’s achievement rate, comparing the maximum points that could
Table 3. Competition results.

| Team          | Affiliation | Robots | Pre  | Semi-F | Final | Rank | Org   |
|---------------|-------------|--------|------|--------|-------|------|-------|
| REL/UoA       | Univ Aizu   | D+S    | 100  | 100    | 100   | 1    | Univ  |
| Masaru Season 2| –           | D+M    | 82.7 | 99.6   | 75.9  | 2    | Private |
| ODENS         | Osaka ECU   | D      | 72.2 | 96.2   | 53.7  | 3    | Univ  |
| Team TNK      | –           | D+S    | 60.2 | 90.5   | –     | Q    | Private |
| FUDAI-KOSEN   | Osaka PUCT  | D      | 71.1 | 87.7   | –     | Q    | Univ  |
| NADO          | Rogiken     | S+M    | 36.0 | 41.1   | –     | Q    | Private |
| MID           | MID A Promo | W+M    | 13.5 | –      | –     | DNQ  | Company |
| MEJB-KINDAI   | Kindai Univ | T      | 0    | –      | –     | DNQ  | Univ  |

Figure 17. Point distribution for each team.

be gained completing the tasks for each mission, and the points gained by the six teams that progressed on to the semi-finals. With the aim of raising the level of difficulty in the semi-finals, smoke was released in the field, however, in comparison to the qualifying rounds, the achievement rate actually increased. Moreover, the level of difficulty was raised even further in the final, but in most of the missions the achievement rate did not fall as much as expected. The cause could be that through carrying out missions, the control methods of the robot improved and the proficiency level of the operators increased. In contrast to real robots, with simulations, there is no risk of damaging the robot, and it is possible to industriously and repeatedly attempt the missions, making it easier to get the gist of them. It can be imagined that it is for this reason that the method of controlling the robots improved, and the proficiency level of the operators increased so quickly in the competition.

The large sized Dual Arm robot was able to accomplish tasks that needed complex manipulator control, such as the use of the spreader (task T3-B), extracting cylinder shaped obstacles (task T4-C), and extinguishing fires (task T5-D). Furthermore, it was able to drive over uneven ground of continuous steps with a height of 0.2 m, demonstrating that it is sufficiently able to deal with tunnel disasters. The middle-sized Spider robot was not able to demonstrate mobility across the uneven ground of Mission T1. Furthermore, as it only has one arm, it was not able to pass objects from one hand to the other like the Dual Arm robot, and so took time to complete tasks such as extracting the cylindrical obstacles (task T4-C). The winning team REL/UoA was able to accomplish the tasks in a short time through coordinated operation of these two robots. For example, by using the Dual Arm robot to pick up and move the Spider robot when it became unable to move, and placing it in places where it was able to use its camera to get an objective view. Three teams used the Multicopter robot to gather information on the environment, however, a few teams also created an application to increase productivity by using the 3D location data gained to view obstacles from a variety of perspectives. In tunnel disaster response, UAV’s are not only used to quickly gather information of the disaster situation, but also to relay information to people and UGV’s about the condition of complex obstacles created by disasters inside tunnels, and can be used as a tool to improve the productivity of operations.

Figure 18. Crawler model and crawler moving over uneven ground.
Figure 19. Mission achievement rate.

As this challenge was a simulation competition, it was difficult creating tasks that replicated actual problems. However, the tasks implemented contained the underlying technology necessary for disaster response. Moreover, with the latest version of Choreonoid [22] the developed tasks unfolded with precision. In addition, the core elements of the tasks became the point at issue in the contests, meaning the competition could be implemented in a form close to that of one with actual robots.

Moving towards 2020, in this challenge simulation functioned as a tool to quickly develop disaster response robots’ control and operations, and to assess robot’s abilities, and it is anticipated to contribute to the rapid installation of robotics in society.

The plan now is to design a competition that will be implemented with actual robots in 2020.

4. Standard disaster robotics challenge

4.1. Objectives

In the Standard Disaster Robotics Challenge (hereafter referred to as the New STM Challenge), the standard performance levels (e.g. mobility, sensing, information collection, wireless communication, remote control on-site deployment, durability, and energy-saving) required for disaster prevention and response are individually assessed in a robot competition. New Standard performance test methods (STMs) differ from the current NIST STMs which are mainly for urban search and rescue (USAR) and explosive ordnance disposal (EOD) [23]. Instead they have been developed specifically for infrastructure disaster prevention and response, and aim to complement NIST STMs.

4.2. Competition tasks

Based on the NIST STM configuration, a 1.2 m square pallet was used as the basic component of the competition field. By examining the rules of Plant Disaster Prevention Challenge and Tunnel Disaster Response and Recovery Challenges in the World Robot Summit Disaster Robotics Category, we have extracted STMs specifically for infrastructure disaster prevention and response. The following eight tasks were used in the competition. Please see the rule book [24] for the details of the competition rules.

4.2.1. (MAN1) negotiate (Figure 20)

This task evaluates the mobility performance in a narrow environment emulating a disaster site. The robots compete to move through the course within a set time. 4.8 m is the standard distance of the course, and obstacles were placed giving the robot a margin of 20% its width. The obstacles consist of eight movable vertical and diagonal sticks, where the relative position between the obstacles and the robot would be difficult to recognize by a robot's camera, and so being devised to assess mobility peculiar to narrow areas [25].

4.2.2. (MOB1) catwalk (Figure 21)

This task evaluates the mobility performance in a plant, and the robots compete to move through the course within a set time. The task course is composed of 60 cm wide corridors and staircases, with a material commonly used in a plant (checker plate) covering the floor.

4.2.3. (MOB2) grating/Checker plate (Figure 22)

This task evaluates the mobility performance in a plant, and the robots compete to move through the course within a set time. The task course is composed of successive 15-degree slopes, with a material commonly used in a plant (checker plate) covering the floor.

4.2.4. (DEX1) meter/Valve (Figure 23)

This task evaluates the manipulation performance in a plant, and the robots compete by reading meters and rotating valves 90 degrees as many times as possible within a set time. The task involves ten meters and five valves at varied heights and depths.

4.2.5. (DEX2) l-shaped obstacle (Figure 24)

This task evaluates the manipulation performance in a non-disaster situation, and the robots compete by moving an obstacle to a designated position as many times as possible within a set time. The obstacle is L-shaped and its movement is constrained to a specific direction and in a certain order. The robot is positioned on a level surface.

4.2.6. (EXP1) large-area inspection (Figure 25)

This task evaluates the inspection performance of a wall structure, and the robots compete by identifying inspection targets as many times as possible within a set time.
4.2.7. (EXP2) duct/Culvert (Figure 26)
This task evaluates the inspection performance of a cylindrical structure, and the robots compete by identifying the inspection targets as many times as possible within a set time. The targets and their inspection procedure are the same as in EXP1. The targets are placed inside and outside of the structure.

4.2.8. (SEC) secret (Figure 27)
This task evaluates the manipulation performance in a disaster situation, and the robots compete by moving an obstacle to a designated position as many times as possible within a set time. This task is the same as DEX2 but differs in that the floor consists of discontinuous 15-degree slopes. The two secret tasks with altered levels of difficulty are referred to as SEC1 and SEC2. In order to account for the competing robot’s performance further, and to make the competition more attractive, details of the secret task are provided immediately before the competition begins.

4.3. Competition results

4.3.1. Robots in the competition
Robots in the competition could be of any form (provided that the maximum weight of the robot is 130 kg and the maximum size at the start is 1.2 m$^3$). Only one robot system may compete (UGV+UAV can be considered one system), and there may be only one operator. Many teams used a crawler mechanism with sub-crawlers (flippers) (e.g. Figure 21(b)). Three teams used both a UGV and a UAV (e.g. Figure 20(b)). Unique robots; a snake robot and a UGV with dual arms (Figure 24(b)), also participated. Most of the teams belonged mainly to universities, but some teams were from companies who competed with robots that were in development for production (Figure 22(b) and 23(b)). A robot which is waterproof (examined by video prior to the competition) and
explosion-proof (examined by certification) could obtain 5% extra points for each of these technologies. However, only one team obtained 5% extra points for being waterproof.

### 4.3.2. Competition procedure

19 teams in total (9 foreign and 10 domestic) participated in the competition. Each task has a duration of up to 30 min; 5 min for setup, 15 min for operation, 10 min for removal from the arena. The top four teams that participated in the finals were selected based on the results of the 4-days preliminary. In the finals, each of the teams must attempt each of the tasks once within 20 min. The total points for all tasks decided the winner.

### 4.3.3. Point distribution

The most points scored for each of the tasks in the preliminaries are summarized in the following Table 4. The radar charts of all task points for the four finalists are depicted in Figure 28, where the points are normalized by the highest points gained for each of the tasks (For each task, the best task obtains 100 and the others obtain points proportionally).

| Task | Score per task | Score points per min. | unit |
|------|----------------|-----------------------|------|
| MAN1 | 245            | 16                    | meter|
| MOB1 | 151            | 10                    | meter|
| MOB2 | 420            | 28                    | meter|
| DEX1 | 56             | 3.7                   | item |
| DEX2 | 150            | 10                    | repetition|
| EXP1 | 105            | 7                     | item |
| EXP2 | 54             | 3.6                   | item |
| SEC1 | 14             | 0.9                   | repetition|
| SEC2 | 12             | 0.8                   | repetition|

### 4.4. Result and knowledge gained

- 196 tasks were performed in the 4-days preliminaries, providing valuable data for the WRS main competition in 2020.
- As in Table 4, teams obtained a consistent amount of points for each of the tasks. This implies the difficulty of the tasks was largely adequate.
- As in Figure 28, the winning robot (=1st place in the preliminaries) (Figure 25(b)) was an all-around one which obtained a high score for all tasks. The other finalists (Figure 23(b) and 27(b)) were specialists in specific task categories (e.g. MOB and DEX).
Originally, DEX2 was designed in order to evaluate mobile manipulation performance, that is, robots are expected to move, manipulate, move, manipulate, (and repeat), to score points. However, during the competition, a team found an unintended method of scoring points, (by simply repeatedly manipulating without moving), and many teams followed the same method. This indicates the importance of considering the diversity of robot performance when designing a task.

UAVs were mostly used for inspection independently from UGVs, and tight cooperation between UAV and UGV, e.g. a UAV providing a birds-eye-view image to a UGV, was limited. Use of UAVs is expected soon to
Figure 27. (SEC) Secret (L-shaped obstacle on uneven terrain): Obstacle manipulation task in a disaster situation. (a) Field and (b) Competition.

Figure 28. Score point radar charts of finalists (top 4 teams in preliminary). The points are normalized by the highest as 100.

5. Conclusions

The 2018 Preliminary Competition has significant value as preparation for the main Fukushima-Aichi Competition in 2020, and the overall feedback from the participating teams and the audience was great. The following points were the results of a process of careful considerations, and were valued highly: frequent changes to the competition rules, as fair competition management as
possible, support for teams such as transportation costs, and commentary throughout the competition.

It is hoped that in the 2020 Fukushima-Aichi Competition the objectives 1 laid out will be achieved, there will be progress towards innovations of robots for society, many teams will partcipate and many people will collaborate. Finally, though everyone's cooperation, it is hoped that the way will be clear for the next 100 year of robot innovation.

Notes
1. Securing an area by inserting a brace
2. Making a hole in places such as a wall

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No potential conflict of interest was reported by the authors.

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