THE IAEA ROBOTICS CHALLENGE – DEMONSTRATING ROBOTS FOR SAFEGUARDS INSPECTIONS

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Abstract

IAEA safeguards inspections often involve inspectors making repetitive, time-consuming measurements of nuclear material in parts of nuclear facilities that may be difficult to access or have elevated radiation levels. Advances in the field of robotics have opened up the possibility that autonomous systems could assist inspectors to complete repetitive inspection tasks more efficiently and consistently. This could free-up inspectors to concentrate more on other aspects of the safeguards mission, and help the IAEA to cope with the ever-increasing volumes of nuclear material under safeguards.

The IAEA Robotics Challenge, co-hosted by the Data61 innovation network of Australia’s Commonwealth Scientific and Industrial Research Organisation, took place in Brisbane in November 2017. The Challenge aimed to facilitate the development of new robotic systems to help the IAEA conduct inspections. Twelve teams of robotics experts from nine Member States each designed their own robots and brought them to Brisbane where they were required to autonomously navigate inside simulated nuclear facilities and carry out inspection tasks. In order to make the Challenge accessible to robotics experts with varying degrees of prior knowledge of safeguards, the Challenge was precisely defined by breaking it up into specific usage scenarios (such as navigation in the presence of obstacles, automatic recognition of items of nuclear material to be verified, and decontamination of the robotic system). A panel of experts evaluated the robotic systems based on their capability to fulfil the inspection scenarios.

The Robotics Challenge demonstrates the benefits of looking beyond traditional procurement channels to use crowdsourcing for the development of new technologies for verification. Among the systems demonstrated in the Challenge, unmanned surface vehicles for verifying spent fuel in ponds appear particularly promising. As a next step, the IAEA may work with selected robotics teams and Member States to conduct proof-of-concept deployments in real spent fuel ponds. The IAEA may award purchase agreements to the teams with the best robotic designs. This paper will discuss the lessons learned from conducting the Challenge and the prospects for robotics in safeguards inspections.

1. INTRODUCTION

The IAEA held a Robotics Challenge, culminating in a week-long demonstration of twelve robotic systems at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) site in Pullenvale, near Brisbane, Australia on 20-24 November 2017. The Robotics Challenge aimed to facilitate the development of new robotic systems to perform repetitive inspection tasks.

The Robotics Challenge involved teams of robotics experts designing their own robots to complete inspection tasks and submitting technical proposals to the IAEA. Teams with compliant proposals were then invited to participate in a “demonstration week” in which the robots were required to autonomously perform the inspection tasks in simulated nuclear facilities in accordance with detailed experimental protocols (no nuclear or radiological material was involved). Twelve teams from nine Member States participated in the demonstration week. Four teams produced Unmanned Surface Vehicles (USVs), which were designed to assist with verifying spent fuel in a storage pond by floating across the surface while holding a Cerenkov viewing device (CVD). The other eight teams produced Unmanned Ground Vehicles (UGVs) designed to assist inspectors by manoeuvring through facilities and storage areas, counting items of a specific geometry, recording their ID tags, and carrying specific IAEA instrument payloads. A panel of experts evaluated the robots against metrics related to their applicability to fulfilling key inspection scenarios.

As part of the Australian Safeguards Support Program (ASSP), the Australian Safeguards and Non-Proliferation Office (ASNO) assisted the IAEA by drafting a report evaluating each robot based on its capabilities/performance during the demonstration week [1].[1] Of the twelve robotic systems, three USVs are advancing to the next stage of development – proof-of-concept testing in real nuclear facilities. As this paper is being finalised, the Division of Technical and Scientific Services (SGTS) of the Department of Safeguards is in discussions with selected Member States on conducting proof-of-concept deployments with the three USVs in spent fuel ponds at reactors. The IAEA and the three USV teams are preparing safety analyses for the use of these USVs. Following proof-of-concept testing, the IAEA will invite any teams with technically acceptable USVs to submit proposals, and the Agency may award blanket purchase agreements through applicable IAEA procurement procedures.

The Robotics Challenge provided the IAEA with an opportunity to test the capabilities of a variety of modern robotic systems, including commercially available products and emerging prototypes. It demonstrated the potential of automation to improve the efficiency and effectiveness of inspection tasks. More broadly, it provides an example of a cost-effective way to crowdsource and trial new technologies for specific safeguards needs from suppliers outside the traditional safeguards community.

2. PURPOSE AND STRUCTURE OF THE CHALLENGE

Some of the most common tasks undertaken by IAEA inspectors during field activities involve making repetitive, time-consuming non-destructive assay (NDA) measurements in parts of nuclear facilities and locations outside facilities (LOFs) that may be difficult to access or have elevated radiation levels. Autonomous robotic systems could assist inspectors to complete these inspection tasks more efficiently and consistently, thereby freeing up inspectors to concentrate more on other aspects of the safeguards mission. This could assist the IAEA to verify the increasing volumes of nuclear material under safeguards.[2]

The IAEA Robotics Challenge was open to any organisation, consortium, or individual, including commercial, non-commercial, and government entities. The Robotics Challenge website [3] was launched in May 2017 with the assistance of the IAEA Office of Public Information and Communication. The website included technical details for the challenge, instructions for prospective participants, and templates for their technical proposals.

SGTS selected usage scenarios for the IAEA Robotics Challenge, in consultation with the Operational Divisions of the Department of Safeguards and the IAEA Office of Procurement Services. The scenarios fell into two broad categories of potential robotic platforms: USVs and UGVs.

2.1. Usage scenarios for USVs

USVs are floating robots designed to autonomously propel themselves across the surface of a spent fuel pond while carrying a CVD in a vertical position.[3] A camera would be placed on the back of the CVD to enable the recording of images of the Cerenkov glow patterns from all spent fuel assemblies in the pond for subsequent analysis/review by the inspector. This would enable verification of spent fuel stored underwater without requiring the inspector to spend long periods of time standing over the pool looking at each assembly one at a

[1] To comply with the IAEA procurement rules, the public version of the report presents anonymised results: all participating systems are described under the names USV 1 to USV 4 and UGV 1 to UGV 8 in random order [1]. The full report is an IAEA restricted report under the reference SG-RP-14918.

[2] Based on the annual IAEA Safeguards Statements for 2015, 2016, and 2017, worldwide there are over 200,000 significant quantities (SQs) of nuclear material under IAEA safeguards and, on average, every day 12 more SQs are added to the material already under safeguards [2].

[3] Precise vertical alignment is important because Cerenkov radiation is highly collimated.

time through the CVD. For the USVs, the challenge was broken up into a series of contextual usage scenarios, including:

(a) The system always remains buoyant, no part can fall in the pond and the camera system remains protected from water.
(b) The payload (camera) remains stable and vertical.
(c) The system can be carried in a plane, unpacked and prepared by a single user.
(d) The system can be easily and thoroughly cleaned up and any trace of contaminated water can be eliminated.
(e) The positioning system should autonomously guide the USV within an accuracy of a few centimetres and propel itself across the whole pond without any user input (or external guiding infrastructure).

Each usage scenarios was further divided into criteria against which the performance of each USV was assessed.

2.2. Usage scenarios for UGVs

UGVs are rolling platforms designed to autonomously manoeuver through nuclear facilities while counting items of a specific geometry, recording their ID tags, verifying seals, and/or carrying specific IAEA instrument payloads. Like the USVs, the UGVs had a series of usage scenarios and criteria related to ease of transportation, quality of autonomous navigation, target recognition, positioning/mapping, and decontamination. (For full lists of usage scenarios and criteria, refer to [1].)

2.3. Technical proposals received

In total, 27 teams from 18 Member States submitted technical proposals. A panel of experts assessed the proposals in August/September 2017 based on their applicability to meeting the usage scenarios. Participants with the best proposals received funding from a €20,000 prize pool to help them pay for their travel expenses and participation in the demonstration week. All of the other teams with proposals that complied with the challenge requirements were also invited to bring their robots to participate in the demonstration week.

3. DEMONSTRATION WEEK

The Data61 innovation network of the CSIRO hosted the demonstration week of the challenge at its Pullenvale site from 20 to 24 November 2017. Eight UGV teams and four USV teams participated, each completing a series of experiments that simulated inspection tasks. Six observers from the IAEA, the CSIRO, ASNO, and the Fraunhofer Institute for Communication, Information Processing and Ergonomics (FKIE) with expertise in safeguards or robotics were selected to attend the demonstration week and assist with evaluating the robots based on the extent to which each robot fulfilled the usage scenarios.

FIG. 1. Participating teams unpack their robots in the shed at CSIRO Data61 on the first day of the demonstration week.

To minimise safety and security risks and testing complexity during the demonstration week, all experiments took place in a safe environment without any sources of radiation and without any risk of radioactive contamination. The CSIRO constructed a 900 m^2 shed (Figure 1) and subdivided it into experiment areas using temporary barriers. The CSIRO mounted cameras around the experiment areas and set up a video wall to assist observers and participants to track the performance of each robot.

3.1. USV experiments

The USV experiment area consisted of an indoor swimming pool with images of fuel assemblies across the bottom. The swimming pool was divided into two ponds by a temporary wall placed along the waterline (see Figure 2). Each pond featured images of a different type of fuel assembly with small spaces between neighbouring assemblies and larger spaces for racks in-between groups of assemblies. To test any visual-based navigation used by USVs, some of the images included fuel assembly construction elements that partly hid the pins, while others had missing pins. Each pond also featured a variety of construction elements, such as pipes, which acted as obstacles to navigation. A pool pump was used to create currents of comparable strength to those found in some spent fuel storage ponds. Some of the spaces in the fuel assembly pattern were blank (either white or black) to simulate empty storage spaces and non-fuel items.

Since the fuel assembly images did not produce Cerenkov radiation, the CVD was replaced with a mockup payload with the same overall dimensions and weight (see Figure 3). Each team was required to mount the payload on its USV in such a way that the payload remained dry and was able to record images of the bottom of the pond.

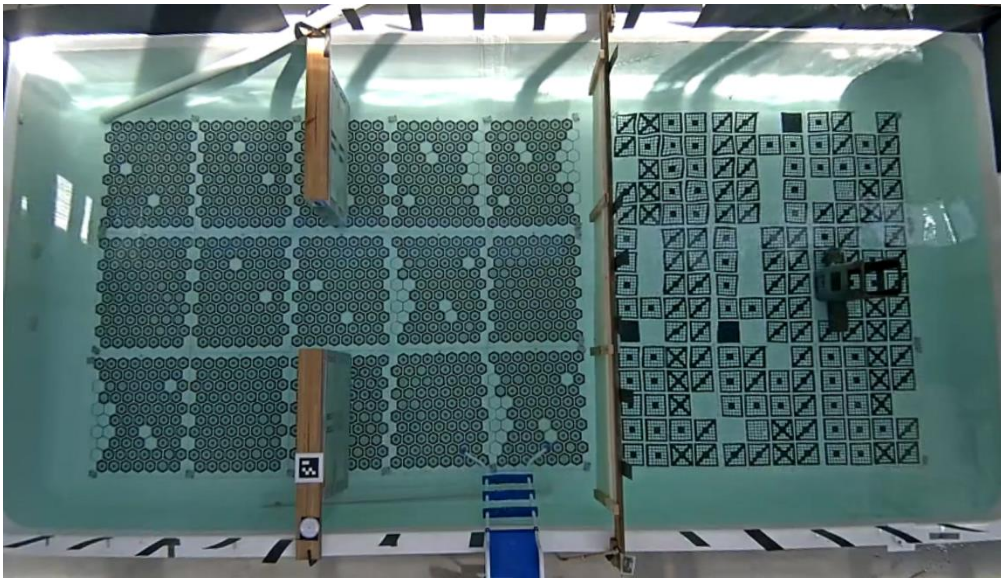

FIG. 2. The pool showing the two simulated spent fuel ponds and some of the obstacles.

FIG. 3. The mockup CVD used as the payload for the USVs.

The USVs were required to navigate through each pond, attempting to cover all fuel assemblies by floating over each one in 20 minutes. The speeds of the USVs were limited to ensure stable video recording.

Each USV also completed experiments in which it was required to navigate to a randomly selected fuel assembly, film it by hovering for 1 minute, and produce a stable video recording centred on the specified assembly. This simulates the longer exposure time needed to analyse older spent fuel with less intense Cerenkov radiation.

During the demonstration week, the pool was modified periodically by introducing new obstacles in order to test the robots' abilities to cope with unknown or changing environments.

Immediately outside the shed, the CSIRO provided an area to practice decontamination of the robots. Each USV was coated in a commercial substance that fluoresces under ultraviolet light, which acted as a surrogate for radioactive contamination. Each team was responsible for "decontaminating" its USV by washing it down with a water jet, cleaning detergents, and brushes. An ultraviolet light was used to evaluate the thoroughness of the decontamination, search for contamination "traps", and assess the extent to which the USV's design was adapted to the decontamination process.

3.2. UGV experiments

The UGV experiment area consisted of three rooms. The first used a series of 200-litre drums, placed on their sides in a simple pattern with ID labels on their ends, to simulate UF_6 cylinders. The UGVs were required to record the ID label on each drum with a camera while carrying a mockup version of the electrically cooled germanium system (ECGS) and positioning it correctly to perform enrichment measurements.

The second room used similar drums, arranged randomly (with most of them upright) with ID labels placed on any accessible surface, to simulate dry cask storage. Gaps between drums were as narrow as about 75 cm and, in addition to the ID labels, other bits of torn paper were placed on the drums to act as distractors to UGVs seeking to automatically recognise the ID labels. Each UGV was required to autonomously detect all of the drums, find the ID labels on the drums, and position the payload close to each ID label to ensure that it was properly recorded.

The third room acted as a mock warehouse with a variety of storage shelves, cardboard boxes, and other items arranged randomly. The room was set up to assess each UGV's capabilities to build a complete and accurate 3D scan for verification of inventories of bulk materials stored in difficult-to-access conditions, assessment of volumes of material, and detection of changes to storage areas over time.

Each room incorporated a variety of other obstacles, ranging in size from electrical cords to wooden pallets, to simulate real-life conditions, forcing the UGVs to either traverse the obstacles or navigate around them. During the demonstration week, the drums, boxes, and shelves in the three rooms were rearranged slightly to test the UGVs' abilities to cope with unknown or changing environments.

FIG. 4. Simulated UF6 cylinders (left) and dry storage casks (right).

3.3. The teams

The four USV teams that took part in the demonstration week used a wide variety of approaches to tackle the usage scenarios. For preliminary configuration prior to a mission and receipt of data during a mission, some teams relied on tether cables, while others used wireless communications. For autonomous navigation, some teams relied primarily on visual recognition of the fuel assemblies, while others used a 2D LIDAR or other sensors to map the pond and then either traversed the pond in stripes or used frontier-based exploration. For ease of decontamination, some teams focused on designing their USV to be free of inadvertent contamination traps along the surfaces that make contact with the water, while others ensured that contaminated parts could be easily disposed of and replaced. From an operational standpoint, three of the systems had the considerable advantage of being easy to configure, requiring minimal manual input, and having straightforward user interfaces. From a safety standpoint, the USVs successfully avoided colliding with obstacles and dropping any items in the pond.

The eight UGVs used a variety of combinations of LIDAR units, depth-sensing cameras, and other sensors for navigation, although dedicated 3D LIDAR units appeared to be the most useful for generating high quality maps/scans. In terms of size, each UGV struck a different balance between transportability on a plane, manoeuvrability in tight spaces, and ability to carry a large payload across an uneven surface.

The report [1] contains a full description of each robot, along with an evaluation of the system against each of the criteria for each contextual usage scenario.

FIG. 5. Robots participating in the demonstration week at CSIRO Data61.

4. NEXT STEPS

4.1. USVs: conducting proof-of-concept testing

The Robotics Challenge demonstrated the potential of USVs to assist inspectors to verify spent fuel in ponds in an efficient and consistent manner, allowing the inspector to perform other tasks while the USV is operating. USVs may also improve the effectiveness of verification with CVDs since they eliminate the effects of surface reflections and turbulence, and allow images to be taken closer to the spent fuel. Furthermore, a USV could significantly reduce the amount of time that operators have to spend moving the bridge over the spent fuel pond for inspectors, thereby reducing the burden on operators.

Based on the outcomes of the demonstration week, the IAEA has selected three USVs to advance to the next stage of development, proof-of-concept tests in real spent fuel ponds. SGTS is in discussions with selected Member States with a view to identifying opportunities to conduct proof-of-concept deployments with the three USVs in spent fuel ponds at their reactors. SGTS has also worked with the teams to prepare safety analyses for the tests, analysing the potential consequences for the spent fuel pond of a variety of incidents, failures or accidents that could conceivably occur while using a USV.

The first proof-of-concept test would involve using each USV in “passive mode”, meaning that the USV would be placed on the surface of the spent fuel pond with the propulsion and navigation systems switched off. An operator could stand on the bridge and manually move the USV across the pond using a tether or a pole, while the USV records images of the Cerenkov glow from the spent fuel. Subsequent tests would involve switching the propulsion and navigation systems on, allowing the USV to autonomously navigate through the pond. At the end of the test(s) the USV would be removed from the pond and decontaminated.

During testing, images of the Cerenkov glow taken by each USV would be compared with images taken by an inspector from the bridge in the traditional way.

Following proof-of-concept testing, any USV team or teams evaluated technically acceptable will be invited to submit commercial proposals in accordance with the IAEA procurement rules. Each team's proposals will be subject to evaluation, after which procurement contracts may be awarded to the best teams. During this process, SGTS will work with the Operational Divisions, Member States, and operators to determine the modalities and logistics for routine deployment of USVs. If a purchase agreement is awarded, training will be provided to inspectors on the transport, assembly, and use of the USV units.

4.2. UGVs: developing more precise specifications

Although the Robotics Challenge produced several UGVs with promising features, none of the presented solutions was found technically acceptable. A UGV is necessarily a large, new instrument which would be used in autonomous mode. The IAEA would need to carefully manage the risks of deploying these instruments in real nuclear facilities. States and facility operators might be reluctant to permit realistic field testing in relevant nuclear facilities for any of the UGV systems presented during the demonstration week unless modifications and additional testing were implemented first. Among the more common issues during the challenge, some of the UGVs were not able to reliably navigate to items of interest (such as drums and ID labels) in complex environments without significant intervention (e.g. manual driving) by the operator, while others were not readily adaptable to the decontamination process.

The IAEA plans to use the outcomes of the Robotics Challenge to develop more precise user requirement specifications for a UGV and then request a system built from scratch to meet the requirements the IAEA has after the challenge.

5. CONCLUSIONS AND LESSONS LEARNED

Technology development and procurement for safeguards has traditionally faced obstacles due to safeguards being a small, niche market with limited economies of scale. There is a limited number of traditional suppliers in the UN marketplace with only limited commercial incentives to develop new technologies for safeguards. Building on the success of the IAEA's CVD Challenge in 2016,[4] the Robotics Challenge proved to be an effective way of moving beyond traditional procurement channels to engage the broader scientific community in highly specialised technology development for safeguards. This is important because safeguards-relevant technical innovations may come from research and development organisations with little or no prior knowledge of safeguards. Many of the teams competing in the Robotics Challenge had originally developed their robots for use in completely different contexts but found that they could be readily adapted for use in safeguards inspections.

A key factor in the success of a crowdsourcing challenge is accurately defining the problem in a way that is accessible and engaging to research and development organisations outside the traditional safeguards community. In the case of the Robotics Challenge, this was accomplished by breaking the challenge up into contextual usage scenarios and giving teams detailed experimental protocols.

The Robotics Challenge illustrates the importance of engaging several divisions of the IAEA in innovation. SGTS was primarily responsible for designing the parameters of the challenge. Since the challenge format represents an extension from traditional approaches to procurement, the Office of Procurement Services was involved from the outset to ensure full compliance with IAEA procurement rules. Operational Divisions within the Department of Safeguards were also consulted to establish the requirements for new robotic systems since these divisions will ultimately be responsible for using them. The Office of Public Information and Communication assisted with designing the website and maximising visibility among potential participants through the use of social media.

[4] The CVD Challenge focussed on software solutions for image reconstruction to improve CVD images.

The Robotics Challenge also highlights the key role of Member State Support Programmes (MSSPs) at each stage of innovation. The Division of Concepts and Planning liaised with MSSPs and MSSPs in turn helped to advertise the challenge and identify potential participants. MSSPs also provided expert observers. The ASSP contributed by having the CSIRO host the challenge and by ASNO providing a technical writer to help process the data and compile the report evaluating the robots.

Support from Member States will continue to be crucial to the development of robots. In July 2018, the IAEA created an MSSP task proposal specifically for field testing USVs with the next generation CVD in real spent fuel ponds. If this proof-of-concept testing proceeds as planned, is accepted by facility operators and found to be beneficial by inspectors, within a few years these robots may be assisting IAEA inspectors in the field.

REFERENCES

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