A2I2: Autonomous Aquatic Inspection and Intervention in Nuclear Storage Ponds

Document Version
Accepted author manuscript

Link to publication record in Manchester Research Explorer

Citation for published version (APA):
Watson, S., Cross, G., Green, P., Parsons, J., Routledge, P., Tudor, N., & Wood, T. (Accepted/In press). A2I2: Autonomous Aquatic Inspection and Intervention in Nuclear Storage Ponds. In *2021 ANS Winter Meeting and Technology Expo*

Published in:
2021 ANS Winter Meeting and Technology Expo

A2I2: Autonomous Aquatic Inspection and Intervention in Nuclear Storage Ponds

Simon Watson[1], Gary Cross[2], Peter Green[1], John Parsons[3,4], Peter Routledge[5], Nick Tudor[6], Terry Wood[7]

[1] *The University of Manchester, Manchester, UK, simon.watson@manchester.ac.uk; p.r.green@manchester.ac.uk*
[2] *Rovco Ltd., Bristol, UK, gary.cross@rovco.com*
[3] *Thales UK, Glasgow, UK*
[4] *Indigo Consulting, Henlow, UK, jfp@indigoconsulting.co.uk*
[5] *Forth Engineering (Cumbria), Cumbria, UK, peter@forth.uk.com*
[6] *D-RisQ Ltd., Malvern, UK, njt@drisq.com*
[7] *National Oceanographic Centre, Southampton, UK, terry.wood@noc.ac.uk*

INTRODUCTION

The inspection of nuclear storage ponds is critical to the safe operation of both legacy and modern nuclear facilities. Nuclear fuel ponds are traditionally used to store spent fuel rods. The water in the ponds acts as a radiological and thermal shield whilst the rods cool down before being sent for reprocessing. There are over 1000 nuclear storage ponds globally which require monitoring [1]. Whilst many of these facilities are indoor and well maintained, there are a number of legacy ponds, dating back to the 1950's, which are outdoor and require decommissioning [2].

Nuclear storage ponds can vary in size from small reactor-side ponds that can be 7 m x 7 m x 4 m, up to very large ponds that can be up to 100 m x 13 m x 7 m [3]. Monitoring of these ponds is either done my sample extraction or by the use of tele-operated tethered remotely operated vehicles (ROVs).

Tethered ROVs can be used for both inspections and maintenance activities, however the tether poses a significant challenge in terms of being snagged or tangled in complex structured environments [4]. Tele-operation requires a human operator, which is a highly skilled job and creates a limitation on how long the vehicles can be operated for. By removing the tether and increasing the level of autonomy, the full capabilities of ROVs could be realised.

SYSTEM OVERVIEW

The A2I2 project was set up to develop a tetherless, autonomous underwater vehicle, which could be used for inspections in both the nuclear and offshore industries. The consortium was comprised of Rovco Ltd., DRisQ Ltd., Forth Engineering, Thales, The National Oceanographic Centre (NOC) and the University of Manchester (UoM).

Four main areas were developed within the project; platform design, perception and localisation, wireless communication and verification of the autonomy. The rest of this paper will detail the work done in each of these areas.

Wireless Communications

If an ROV is tetherless, this implies that there is either no communication between it and the operators, or there is wireless communications. No communication is undesirable, especially in safety critical environments, so underwater wireless communications is required.

Wireless transmission in water is highly challenging. Air-based robots use radio-frequency (RF) systems, however they do not work in water due to the high absorption rate. Ocean-based systems often use acoustic transmission, however the data rates are very low. Optical transmission using visible light is a relatively new technology to the market and is able to transmit at much higher data rates, however it requires good water visibility to operate effectively and is subject to interference from external light sources [5].

Activity	Data Rate
Auxiliary Sensor Data	0.35 kbit/s
Command and Control	10 kbit/s
Returning Point Cloud	25 kbit/s
Low-res video	6,000 kbit/s
High-res video	20,000 kbit/s

TABLE I. Data Rate Requirements

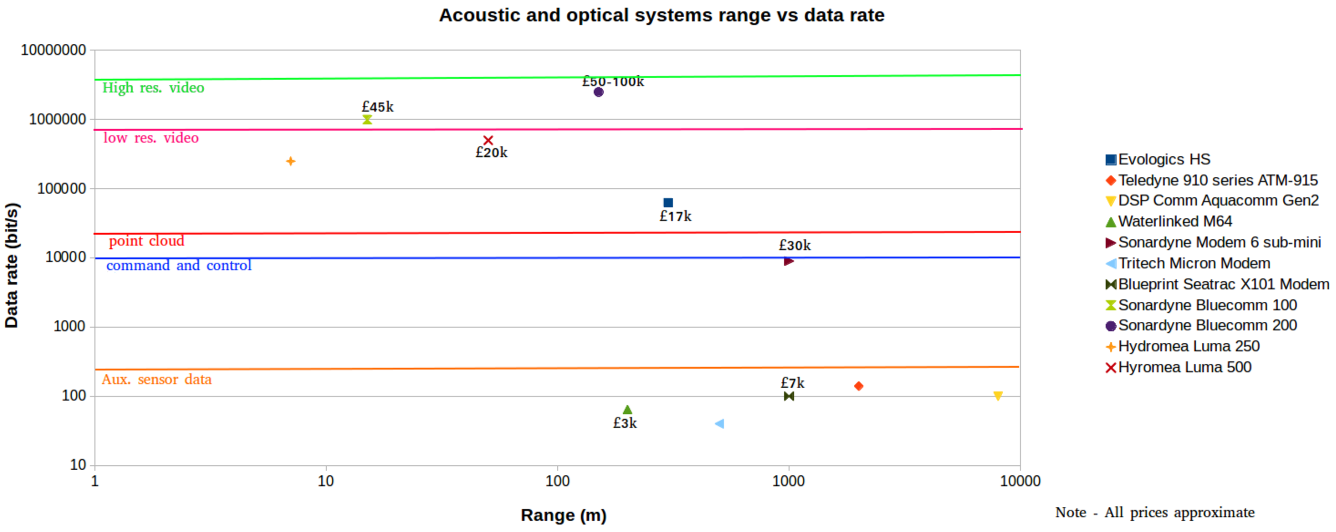
In collaboration with end users, a set of data transmission requirements were generated, which are shown in Table I. Figure 1 shows the data rates of commercially available systems compared to these requirements.

A key requirement from the end user was the transmission of video data back to the operators. This allows both real-time monitoring and potential wireless tele-operation. The only technology that can achieve this is optical.

Nuclear storage ponds are highly cluttered environments (ether structured or unstructured). This means that there is often not a line of sight to the edge of the ponds. Wireless communications requires transceivers on both the vehicle and on the shore. If there is no line of sight, there may be areas within the ponds which become communication dead-zones.

To overcome this issue, the A2I2 project proposed the use of a collaborative autonomous surface vehicle (ASV). The surface of storage ponds is kept free of obstacles, so the ASV can navigate freely around it. By mounting the shore-side transceiver on the bottom of the ASV, line of sight can be guaranteed for a much larger section of the pond (as long as the ROV does not go under an obstacle). Data can be transfered from the ASV to shore by a secure wi-fi connection.

For demonstration, a Hydromea Luma 500 optical communication system was used. It was mounted onto a BlueROV and a Mallard ASV [6]. Figure 2 shows wireless tele-operation of an ROV. A full video of the demonstration can be found at https://youtu.be/IvKAKxh7aj4. Real-time video transmission was also achieved over a distance of 2 m.



Note - All prices approximate

Fig. 1. Comparison of COTS Wireless Communication Systems

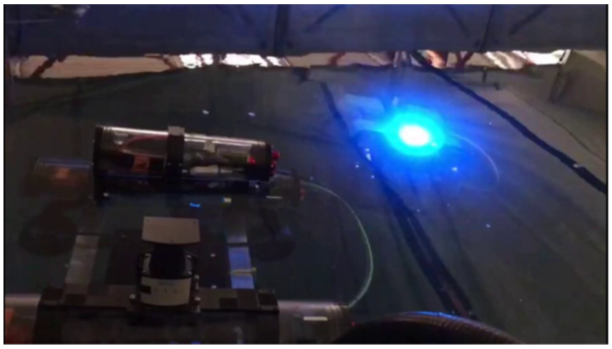


Fig. 2. Tetherless Tele-operation of an ROV

Platform Development

For the demonstration of the A2I2 system, a BlueROV2 was used as the subsurface vehicle, whilst as custom ASV was developed by Forth Engineering, known as the Lilypad.

The BlueROV was modified to include 9 HD cameras and two sonars to enable 360-degree collision avoidance. It also housed the vision perception system used for localisation and navigation. The Lilypad ASV had integrated thrusters and buoyancy to allow movement around the pond. Solar panels removed the need for a tether for power. The ROV could dock to the ASV for deployment and retrieval and a secure wi-fi connection allowed data to be transferred back to shore as shown in Figure 3.

Perception, Localisation and Navigation

The development of autonomous systems has surged in land, air and offshore surface domains, whilst underwater autonomous capabilities have remained somewhat stagnant; hindered in part by the limited choice and availability of sensors providing low fidelity positioning and range measurements. Consequently, navigation and control of an ROV or AUV for operation in unstructured and dynamic environments, remains a largely unsolved challenge for commercial application, particularly where navigation close to structures is required.

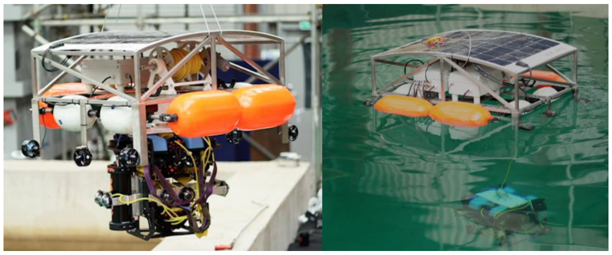


Fig. 3. Left: Deployment of Lilypad and ROV. Right: Operation of Lilypad and ROV

Most autonomous systems are restricted to waypoint navigation, using predefined paths or prior models, performing tasks such a cable and pipe following or long-range geological surveys. Almost no AUV performs real-time decision making, path planning with collision avoidance. A novel method has therefore been required to enable precise sensing and positioning, to support the accurate control required for autonomous detailed visual inspections.

The A2I2 project made use of the Rovco SubSLAM system for perception, localisation and navigation. Using a stereo-camera system with a working distance of 1.5 m, 3D reconstructions are generated which are used as the inputs to the path planning algorithms. The system is able to localise the robot relative to the 3D reconstruction, then plan paths to explore areas of interest. Figure 4 shows the system being tested and generating 3D reconstructions.

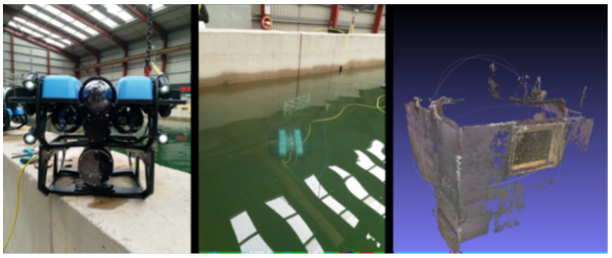


Fig. 4. Left: ROV with stereo camera mounted. Middle: Deployment in test pond. Right: 3D reconstruction of the test pond

Verification of Autonomy

Autonomous vehicles are not in wide use because of two linked problems: Lack of trust and the cost to gain adequate trust. From a safety and regulatory perspective, for any system there are always three questions to be answered:

- What is it supposed to do?
- Can you show me that it doesn't do what it is not supposed to do?
- What will happen when, not if, something goes wrong?

Most work concentrates on showing what a system will do, but the safety of the system is much more focused on the other two questions. For an autonomous system, the problem is much harder because autonomy is largely thought/expected to be vested in some form of Artificial Intelligence (AI). However, AI cannot be fully verified, so cannot be treated in the same way as existing approaches to software. Testing increases confidence, but how much test is sufficient and at what cost to gain sufficient confidence? Safety is hardly ever about the easy to demonstrate aspects of the system, the 99%, it is mostly about gaining confidence in the remaining 0.99999% that historically have been required for public trust. Unfortunately, AI is [relatively] easy to fool which lowers confidence so we need mechanisms to ensure that unwanted behaviour can be constrained. AI has tremendous advantages but will be restricted to niche applications unless safety is adequately addressed.

The aim for A2I2 was to extract the benefits of AI (in this case Rovco Vaarst sub-SLAM) on a tetherless vehicle while ensuring that the system is safe. The D-RisQ contribution was to provide a capability that allows the sub-SLAM system to gather the required visual coverage of the artefact but to provide a safety monitor that can take over if safety is about to be compromised. This capability was transparently and cost effectively developed to provide the assurance of vehicle behaviour.

The software was developed in close collaboration with the end user, Sellafield Ltd. and the Office for Nuclear Regulation (ONR). For the demonstrations, two hazards were identified to be avoided:

- Splash: Spray from the vehicle motors must be avoided.
- Collision: The vehicle must not hit any other object in the pond or the sides of the pond.

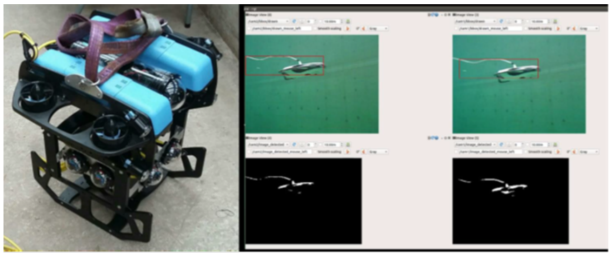


Fig. 5. Left: ROV with collision avoidance hardware. Right: collision avoidance in operation

Figure 5 shows the software in operation, acting to stop the ROV from colliding with a wall.

CONCLUSIONS

The A2I2 project has demonstrated the potential of using collaborative, autonomous surface and sub-surface robots for the inspection of nuclear storage ponds. Proof-of-concept vehicles have been demonstrated which are being developed further in collaboration with end users.

A number of challenges still remain to be investigated, including robust wireless communications in challenging water conditions (turbidity, variable ambient lighting), variable autonomy mission planning and shared autonomy control, and the acceptance of safe autonomous systems into safety critical environments.

ACKNOWLEDGMENTS

This material is based upon work supported by Innovate UK (IUK), A2I2, Project Number 104822 and Engineering and Physical Science Research Council (EPSRC), RAIN Hub, Project Number EP/R026084/1.

REFERENCES

1. H. F. BEER, J. BORQUE LINAN, G. A. BROWN, D. CARLISLE, R. DEMNER, B. IRONS, M. LARAIA, V. MICHAL, A. PEKAR, O. ŠOTIĆ, L. VALENCIA, and S. WLATERS, "IAEA Nuclear Energy Series No. NW-T-2.6: Decommissioning of Pools in Nuclear Facilities," Tech. rep., IAEA (2015).
2. S. F. JACKSON, S. D. MONK, and Z. RIAZ, "An investigation towards real time dose rate monitoring, and fuel rod detection in a First Generation Magnox Storage Pond (FGMSP)," *Applied Radiation and Isotopes*, **94**, 254 – 259 (2014).
3. "Challenge: ROV Positioning in Featureless Pond Environments," Tech. rep., Game Changers (2021).
4. O. TORTORICI, C. ANTHIERENS, V. HUGEL, and H. BARTHELEMY, "Towards active self-management of umbilical linking ROV and USV for safer submarine missions," *IFAC-PapersOnLine*, **52**, *21*, 265–270 (2019), 12th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles CAMS 2019.

5. M. F. ALI, D. N. K. JAYAKODY, Y. A. CHURSIN, S. AFFES, and S. DMITRY, “Recent Advances and Future Directions on Underwater Wireless Communications,” *Archives of Computational Methods in Engineering*, **27**, 1379–1412 (2020).
6. K. GROVES, A. WEST, K. GORNICKI, S. WATSON, J. CARRASCO, and B. LENNOX, “MallARD: An Autonomous Aquatic Surface Vehicle for Inspection and Monitoring of Wet Nuclear Storage Facilities,” *Robotics*, **8**, *2* (2019).