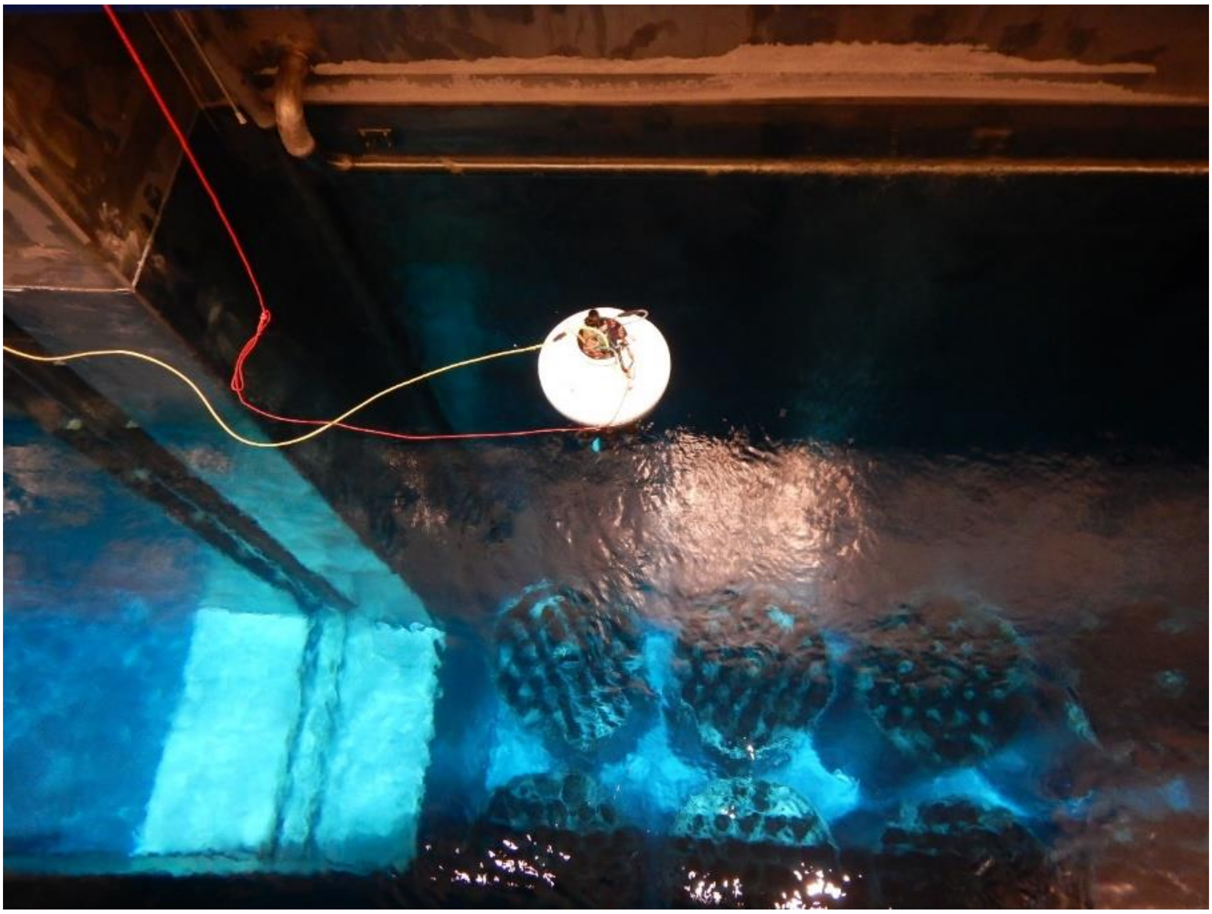
Technical Travel Report

USVs deployment at Loviisa NPP



1. Executive summary

Following the results of the IAEA Robotics Challenge [1] started in 2017, three Unmanned Surface Vehicles (USVs) from different suppliers were selected for a test deployment at a real facility. After several months of subsequent development, suppliers were able to improve their robotic systems to address key points of the failure and safety analysis performed by SGTS; the safety analysis report and up-to-date system specifications were then sent out to Member State Support Programmes (MSSPs) under active technology foresight umbrella task, seeking for deployment possibilities at spent fuel storage ponds. FIN SP replied positively to this request proposing to conduct a field test of all three systems at a KMPF interim spent fuel storage pond at Loviisa NPP. The purpose of the field test was to deploy the three USVs, discuss with the NPP operator the acceptability of systems, collect test data to prove the concept, perform technical evaluation of the system to finalize the procurement campaign for floating robots, and acquire practical experience to adjust requirements for future USV development.

Prior to deploying the USVs at a KMPF interim spent fuel storage pond, SGTND/Technology Foresight staff met the system suppliers in order to evaluate safety of the developed systems, receive training on using them in the field conditions, and acquire practical hands-on experience in assembling and controlling the USVs. In order to do so, they traveled to Budapest (Hungary) to the office of Datastart Ltd., and to Cumbria (UK) to the test facility of the University of Manchester. On 15 November 2018 all three USVs were additionally tested in the pond at Vienna model basin [2] in order to acquire more practical experience and validate the logistics/planning of the field testing.

Field tests at Loviisa NPP took place over two consecutive weeks and were preceded by obligatory safety training on 20 November 2018. Following the training, the staff accessed the area around the KMPF interim spent fuel storage pond, unpacked the equipment, and made required preparations for the tests. Two USVs (manufactured by KAERI and Datastart) were tested during two days of 21–22 November 2018; the third USV (manufactured by the University of Manchester) was tested the next week, on 28–29 November 2018.

During the deployment, both static capabilities (vertical stability of the USV, water-tightness of all structures) and dynamic capabilities (responsiveness to manual control, autonomous navigation, control of speed in currents from the water circulation pumps, obstacle avoidance) were verified. In addition, each USV carried an ICVD payload, recording the Cerenkov radiation from the spent fuel below the robot; the ICVD lenses were located below the water level, thus avoiding negative effects of water motion and reflections from the overhead lights.

In addition, standalone XCVD measurements were performed every day in a standard way (IAEA staff staying on the bridge) with the goal to collect reference data. Some first data collected with the ICVD mounted inside the USVs and with the XCVD in handheld mode were demonstrated to the facility operator, state authority, and the IAEA staff participating in the training on spent fuel verification (held at Loviisa NPP in parallel with the USV testing, but in other storage ponds) in order to demonstrate possible advantages of using robotized platforms.

Three prototype USVs were successfully deployed at Loviisa NPP, all being accepted by the facility operator and state authority with regard to operational safety. All three USVs could be operated, at all time, without safety failure. Collected ICVD data exhibited a strong Cerenkov collimation effect and proved usefulness of the method to overcome difficulties encountered during the traditional ICVD measurement campaign (e.g. strong water motion from the cooling pumps, inaccessible areas under the bridges, bright reflections from the overhead lights). The field test allowed to complete the technical evaluation of the three USVs, concluding the robotics challenge and triggering the next procurement phase; and also provided a useful insight into prioritizing follow-up USV developments.

2. Technical Report

2.1. USVs deployment protocol

Each USV was deployed at the same KMPF interim spent fuel storage pond; at any moment only a single system was undergoing testing to avoid possible impacts of navigation capabilities.

Each USV carried an instrument payload, containing (within a watertight hull) an ICVD tube with eye-piece replaced by a visual camera optically coupled to the tube, and connected to the mini-instrument laptop. The visual output from the camera was stored on an SSD drive without any processing, thus making the payload functionally equivalent to the usual ICVD. At this stage the USVs had no interface to control the payload, so the recording was started and stopped manually before/after putting the USV in water; the focus of ICVD was setup manually from the bridge and adjusted to accommodate filming from the water level.

Each USV deployment included:

- preparation of the system: unpacking, assembly, software configuration, check;
- insertion of the instrument payload;
- putting the USV into the spent fuel storage pond (using the facility-operated overhead crane and operator-approved ropes);
- operating the USV in manual mode: checking stability of the system, its water-tightness, and propulsion capabilities to move against the current from the water circulation pumps; when applicable, the manual mode was also used to move the USV along the pond to let it create its digital map;
- operating the USV in autonomous mode: checking the USV capability to cover programmed surface area while maintaining control of direction/speed and avoiding impacts to the walls and pond equipment;
- retrieving the system from the storage pond (using the facility-operated overhead crane); cleaning: jet-washing over the pond and wiping dry;
- retrieving the instrument payload;
- checking the system for contamination (operated by the facility radiation protection staff using smear samples); and
- packing the system into its transportation case.

All three USVs were operated by internal power (battery), but featured a long floating cable connecting them to the control station. This cable could also have been used to retrieve the system from the water in case of failure; in addition, a rope, used to put the system in and retrieve out of the water, remained always tethered to the system as a safety precaution.

The observations from deploying the three robotic systems are elaborated in the next section.

Figure 1 Cleaning procedure - jet-washing over the pond; the system was wiped dry afterwards. The overhead crane, operated by the facility staff, was used for putting the USV in and retrieving it out of the storage pond.

2.2. Deployment observations

2.2.1. USV1 – KAERI

USV KAERI is a multiple-pontoon vessel: side pontoons are needed to ensure buoyancy and stability, while the central pontoon hosts battery and board electronics. The instrument payload is located in front of the USV (outside its frame base), thus allowing to film fuel assemblies located close to the pond walls – but negatively impacting the vertical stability of the USV during manoeuvres. The USV design and choice of materials ensured very easy assembly/disassembly procedure (could be done by a single person) and relatively easy cleaning after deployment.

The four thrusters are located at the pontoons and are oriented in a way to allow the USV float in any direction and turning on spot; they were powerful enough to allow the USV float against strong current from the pumps.

The only own sensor of the USV is a downward-pointing visual camera; its output is processed in order to identify fuel assembly pattern and ensure navigation using it as reference. However, this approach did not work during the deployment: the camera was not properly focused on the right distance (and no focus adjustment was possible in real time), so the image processing results were not suitable to enable autonomous navigation or even features like stabilized movement, position holding, and obstacle avoidance.

USV KAERI was therefore only operated in manual mode, from the control laptop. The robot was controlled in a way to float on top of the spent fuel baskets, however limitations of the manual control led to misaligned trajectory and jumping speed – which in turn negatively impacted the quality of recorded images.

Except this navigation issue, the USV performed well: it was successfully deployed in the pond at first attempt on 21 November 2018, could be operated at all time without safety failures and had not raised any safety concerns from the facility operator.

Figure 2 USV KAERI deployed at an interim spent fuel storage pond.

2.2.2. USV2 – Datastart

USV Datastart is a buoy-like vessel: all main components, including system electronics, battery, and instrument payload are hosted within a single watertight hull; the only components outside of it are the LIDAR (on top of the tube), the thrusters (below the water level), and the stabilization disk around the hull to add extra buoyancy. The assembly procedure involved many steps and was quite complex (two persons were required to perform it). However the USV design and choice of materials ensured very easy cleaning after deployment.

While vertical stability was ensured by design, the round cross-section of the USV and closely positioned thrusters made it difficult to maintain the constant yaw when floating in straight direction – the system was turning more than needed and sometimes had the tether and the interface cable twisted around it which complicated further floating. The thrusting power was not fully sufficient to resist the current from the water circulation pumps – the USV was thus not able to stay steady or keep straight movement close to the exhaust pipes, which negatively impacted the completeness of the recorded data.

The autonomous navigation was implemented using a simultaneous location and mapping (SLAM) algorithm relying on the data from 2D LIDAR. There was a connectivity problem between the LIDAR and the USV on the first test day (21 November 2018), so the system was only tested in manual mode; the connectivity was restored so the autonomous navigation was tested the next day (22 November 2018) and performed well – however the control interface for programming the mission should be improved in terms of usability.

The test of Datastart USV ended prematurely due to a built-in feature triggered by a bug – the USV considered its position as tilted and disarmed the thrusters out of safety precautions, even though it remained vertical all the time. This was fixed by restarting the system, after which the USV was driven manually and retrieved from the pond. Except for these small issue, the USV performed well: it was successfully deployed in the pond and had not raised any safety concerns from the facility operator.

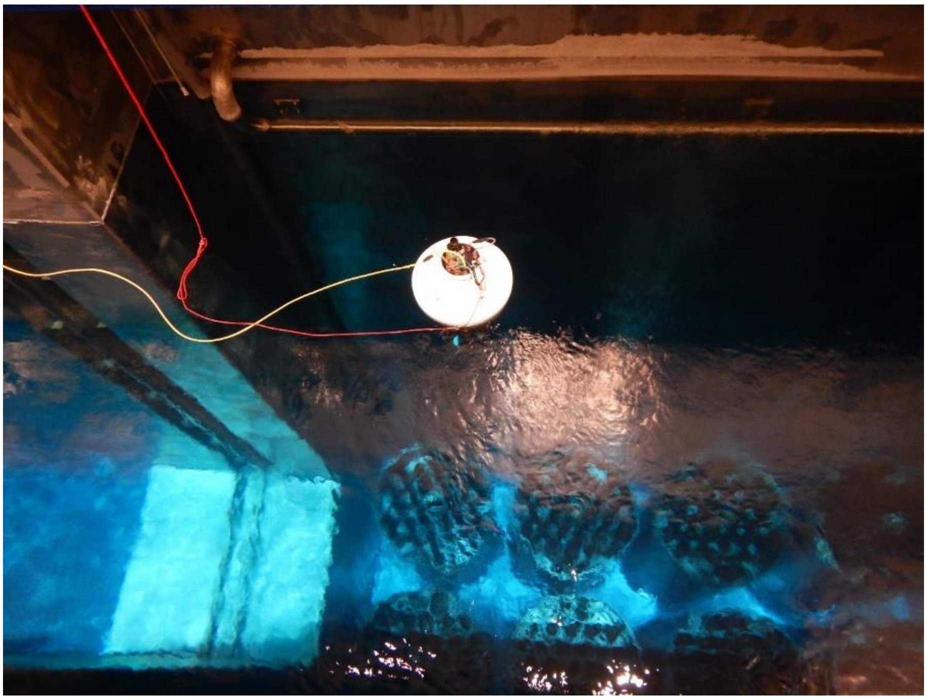


Figure 3 USV Datastart deployed at an interim spent fuel storage pond. Note the strong surface turbulences, generated by the water pumps that could not be turned off for safety reasons, preventing any potential ICVD verification from the surface.

Figure 4 USV Datastart deployed in the interim spent fuel storage pond. Note the walking bridge over the water, preventing a proper alignment of ICVD or using SFAT when performing verification close to the walls. The USV could navigate below the bridge.

2.2.3. USV3 – University of Manchester

USV University of Manchester is a dual-pontoon vessel: side pontoons ensure buoyancy and stability, while hosting battery (in one pontoon) and board electronics (in another one). The instrument payload is located in its watertight hull attached to the USV frame in the centre of the robot, thus ensuring excellent balance of the USV during manoeuvres. The trade-off of such architecture is impossibility to film fuel assemblies located close to the pond walls. The assembly procedure involved many steps and was of medium complexity – the USV can be prepared for deployment by a single person. The USV design featured many connecting cables that made cleaning more complicated (as compared to other USVs).

The four thrusters are located in the corners of the frame and are oriented in a way to allow the USV float in any direction and turning on spot. They were powerful, so that the USV was capable of floating at high speed (which was limited by board electronics for safety reasons) even against a strong current from the pumps.

The autonomous navigation was implemented using a simultaneous location and mapping (SLAM) algorithm relying on the data from 2D LIDAR, located on top of the payload tube. The navigation worked correctly during multiple deployments without any failure, however current implementation of map building being started automatically at robot start-up required that the robot was switched on when already in the pond and without ropes in the LIDAR's field of view – the map would contain artefacts otherwise. The control interface for the mission programming was quite user-friendly.

USV University of Manchester was operated in manual mode in the beginning of each run in order to build the pond map, and was then switched to autonomous mode. In this mode, the working area was setup over the pond map; as the LIDAR was not capable of detecting small obstacles (e.g. ladders and water-level measuring rods), setting up the working area required extra attention. The trajectory was then built automatically based on parametrized safety distance, gap between the stripes, and yaw (keeping constant camera orientation was helpful for data post-processing). The speed was set up to a low value (2–3 cm/s) to enable recording of old spent fuel assemblies at a longer exposure, and the USV was capable of maintaining this low speed (with reference to the pond) even in fast current from the water circulation pumps. These ensured good quality of the collected visual data.

The USV performed well and had not encountered any operational issue: it was successfully deployed in the pond multiple times on 28–29 November 2018, and also deployed (following suggestion of the facility operator) in a closed part of the pond containing older spent fuel.

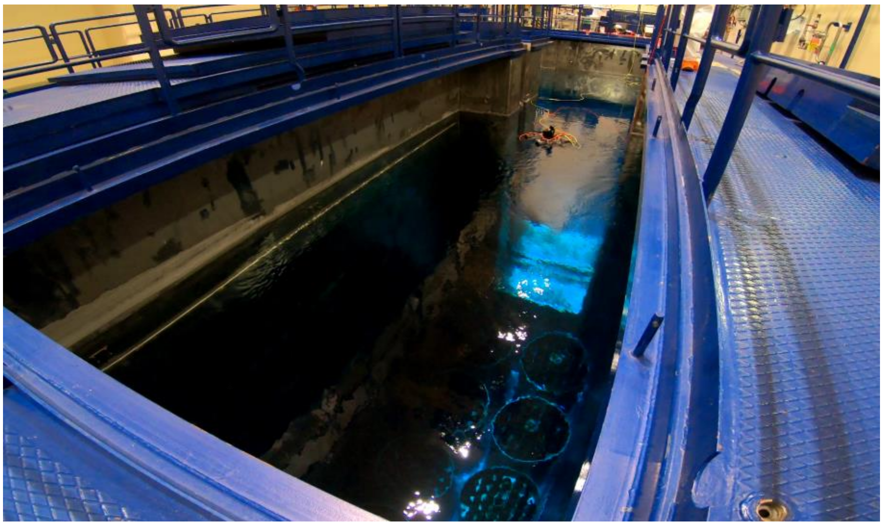


Figure 5 USV University of Manchester deployed at an interim spent fuel storage pond

3. Conclusions

Three prototype USVs were successfully deployed at an interim spend fuel storage pond; all could be operated at all time without any safety failure threatening the safety of the spent fuel or facility equipment. The deployments were observed by Loviisa NPP operator and STUK state authority and generated overall positive feedback – with an informal invitation to test updated USV next year in a bigger storage pond at the same facility.

The data collected with the USV instrument payload, despite the current technical limitation of having no interface to control their recording settings during operation, were of good quality and exhibited strong Cerenkov collimation effect with pin-to-pin resolution. The fact of having ICVD lenses below the water surface contributed to the enhanced visual quality of the images (compared to what one could see in the ICVD from the bridge): artefacts from the surface water motion and reflections from overhead lights were not present in the recorded images.

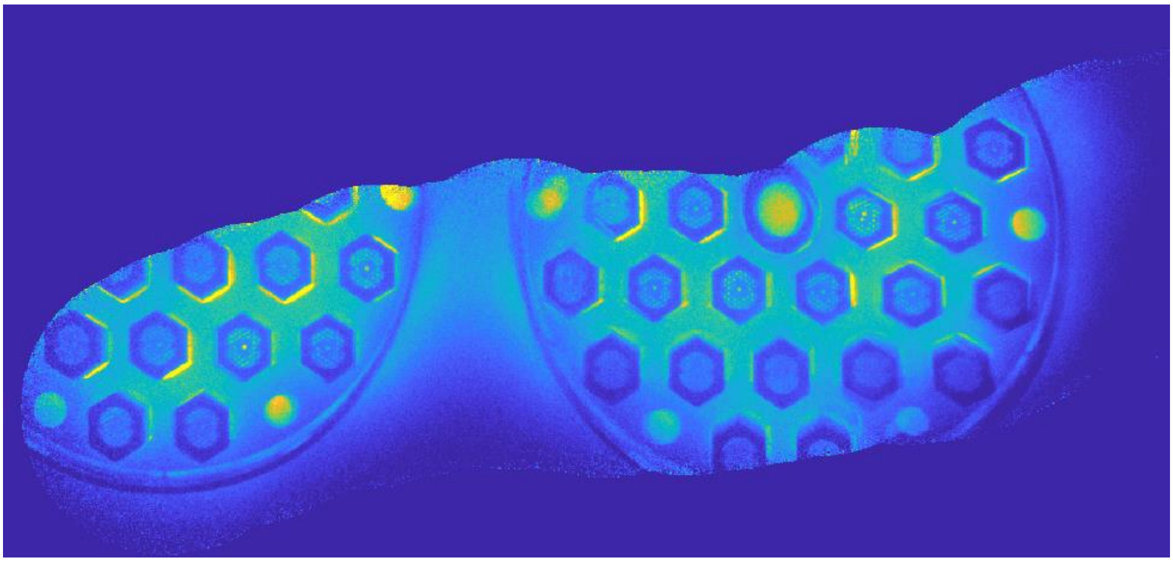


Figure 6 Assembly map built through USV: current XCVD algorithm does not deal well with the rotations of the USV (artifacts visible at the edge of the circles); the slight balancing of the USV when swimming against a water pump makes it difficult to work with longer exposure values, desirable for better sensitivity, but an internal gimbal would help.

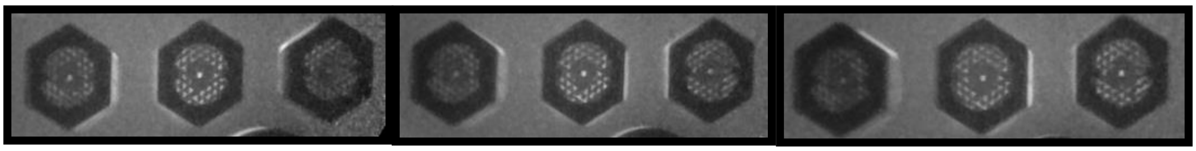


Figure 7 Series of images showing the very precise collimation effect (at pin by pin level) observed underwater. Refraction, surface disturbances, and greater distance decrease the visibility of the collimation effect when observing from the bridge using conventional ICVD.

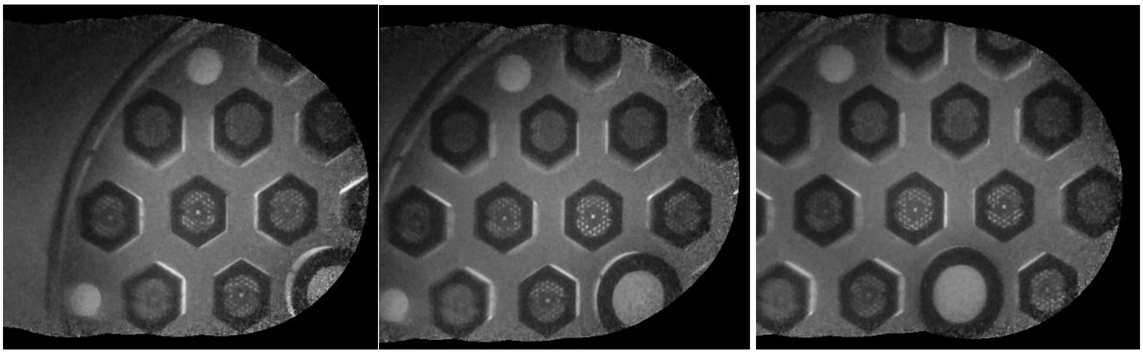


Figure 8 Full field of view captured from the USV

The capabilities of the USV to follow programmed trajectory at a constant low speed (maintaining the same camera yaw angle when such an option is implemented) allowed to record the images at extended exposure time and post-process them using XCVD algorithms (including image stacking, digital stabilization, and visual enhancement) to obtain good visualization of Cerenkov radiation even from old fuel assemblies. Using usual ICVD for verification of such assemblies would not lead to any conclusion, thus confirming the usefulness of deploying robotized systems.

The configuration of the KMPF interim spent fuel storage pond involves wide walking bridge along the pond sides; about 30% of all stored fuel assemblies are therefore out of reach to apply conventional verification using SFAT or ICVD, and workarounds are required. Small height of all 3 USVs allowed them to float under the bridge close to the pond edges, and thus obtain Cerenkov images of most of the fuel assemblies.

The observations of the USVs during the test deployment at Loviisa NPP were focused on assessing systems' design, stability, manoeuvrability, autonomous navigation capabilities, and suitability to normal inspection workflow (including considerations for logistics, assembly procedures, and ease of decontamination). The three USVs system had very different designs allowing to prove-test several engineering approaches and make the following conclusions:

- The buoy-like design ensures a better vertical stability of the USV and is preferred as all main system parts are hosted within a single watertight hull (which leads to easier cleaning/decontamination). The system assembly should be simplified to the extent possible and contain few steps that can be performed in any order by a single user.
- It is important to equip USV with smaller thrusters to ensure smooth movements, however they should be put at a significant distance from the centre of mass to ensure the USV course stability. The thrusters should be powerful enough to allow floating against currents from the water circulation pumps.
- LIDAR is required as a primary sensor for autonomous navigation, as visual-based sensing does not work reliably. Additional sensors (e.g. IMUs, proximity sensors, first-place camera) may be advantageous for obstacle avoidance.
- Manual control mode shall be reserved for experts only. A simpler control interface with commands like 'go to a given point', 'hold the current position', and 'cover the defined working area' shall be developed for normal system users (e.g. inspectors and SGTS staff). Simple interface for programming the USV mission (setting work area and safety distance to the obstacles, start point, gaps, constant yaw, and speed) is important.
- Given that the configuration of the storage ponds does not change often, possibility to save and load the pond map is needed to avoid building the map from scratch at every launch.

SLAM algorithm implementation shall tolerate the presence of small moving objects within LIDAR's field of view, such as cables and ropes tethering the USV. Obstacle avoidance shall be implemented for larger/static objects, such as pond equipment.

- The USV shall implement control interface allowing to change the mission parameters in real time, to communicate with the instrument payload (start/stop data acquisition, adjust recording settings), and to monitor important indicators such as USV equipment status and battery charge.
- Cable interface for data transfer between the USV and its control laptop is not convenient (a cable needs to be cleaned after deployment, and it may also limit some manoeuvres when twisted around the USV body), but it can be used as a safety tether. Provisions for a wireless control compliant with facility regulations (e.g. free-space optical or Li-Fi) shall be considered.

The detailed assessment of the USVs based on pre-defined criteria was provided in a separate technical evaluation report for MTPS to finalize the procurement campaign. The recommendations on further USV development were formulated in a separate statement of work document and provided to the selected supplier under concluded development contract.

4. References

[1] IAEA Robotics Challenge https://challenge.iaea.org/challenges/2017-SG-Robotics

[2] Vienna model basin https://www.sva.at/