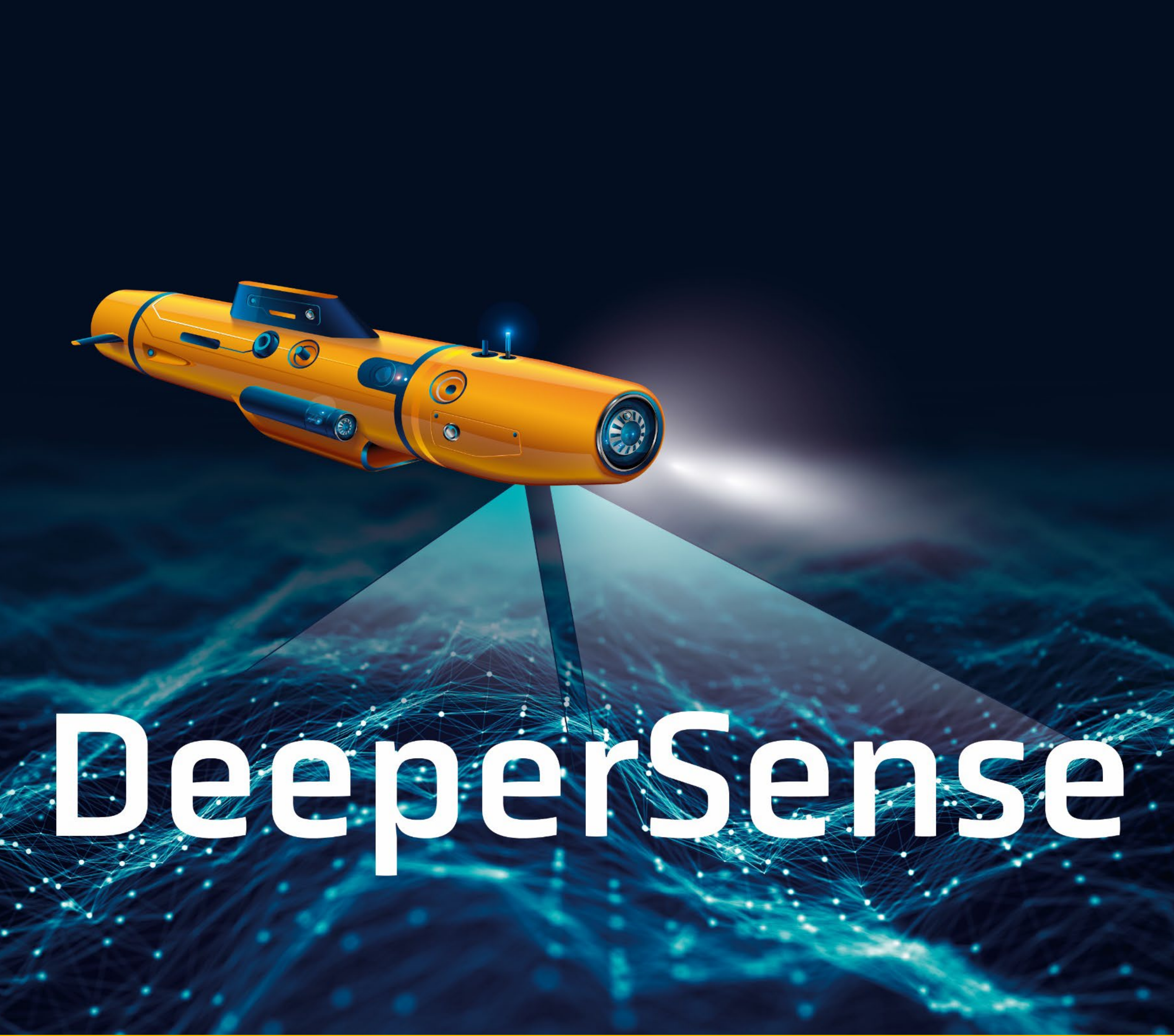

Verification & Demonstration Concept

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1. Executive Summary

The main objective of DeeperSense is to enable a significant improvement in non-visual sensing for underwater operations. Therefore, Artificial Intelligence (deep learning) will be applied to enable a knowledge transfer between sensors that use different physical sensing concepts and modalities.

To achieve this in a user-driven way the following 3 different use-cases will be addressed:

- Hybrid AUV for diver safety monitoring - **SONAVision** for Diver Monitoring (THW, DFKI, KRA)
- Surveying and monitoring complex benthic environments - **EagleEye** for Collision Avoidance (INPA, UH)
- Efficient exploration and mapping of the sea bottom - **SmartSeafloorScan** for Seabed Mapping (TA, UDG)

While Deliverable 2.1 defines the requirements for each of the three use cases, this deliverable (D2.5) describes the validation processes necessary to ensure that the requirements for each use-case are met. On a general note, the fulfilment of the bulk of the requirements can be easily answered by stating “yes” or “no” (see e.g. Table 2), whereas the evaluation of the quality of a generated image is more challenging.

2. General validation Strategy

The technology development process within the project takes place in individual steps that might be repeated iteratively to meet the functional requirements defined in Deliverable 2.1. For each development step there will also be a validation step that compares the current results with the desired outcome.

The general project objective is to develop algorithms that are able to interpret sensor signals from one sensor modality (e.g. acoustic sensor signals) based on interpretations learned form another sensor modality (e.g. optical sensors) to overcome the limitations of the former in specific environments. An example is the improved display of low-resolution sonar signals based on a scene-interpretation previously learned from high-resolution optical images. This type of inter-sensoric learning will be realized with deep learning methods.

The general task is similar for each use-case, but, having different sensor configurations and a focus on different items, the algorithm training has to be performed individually. On top of this central functionality, the output of the trained algorithm will be used as an input for various use-case specific active functionalities of autonomous underwater vehicles (AUV) as e.g., collision avoidance or a follow mode. Therefore, a real time version of the algorithms will be developed and implemented on the AUV hardware. All in all, the main aspects of the development process that need to be assessed are:

- Performance of the acoustic sensor interpretation by the algorithm
- Real time functionality on AUV hardware
- Performance of the AUV functionalities based on the algorithm output

The technology development initially takes place in the laboratory and is then tested and further developed in the field. Consequently, the validation process will also be split into Lab Validation (LV) which will take place in an ideal environment and Field Validation (FV) which has to be performed in the target environment.

The detailed characteristics of Lab and Field Validation are overlapping in some aspects but can be characterized as shown in Table 1.

Table 1 Different characteristics of Lab- and Field Validation

	Lab Validation	**Field Validation**
Location	Ideal environment	Target Environment
Data source	Legacy Data; Synthetic Data; Real-World Data	Real-World Data
Sensor position	Lab-Setup or target platform	Sensors carried by target platform (AUV)
Ground truth	Available in high quality	Not always available / low quality
Data processing	Mainly offline, online/real-time	Mainly real-time
Algorithm validation	Comparing to ground truth	Expert Opinion for validation, ground truth if available

3. Algorithm Lab Validation

During algorithm training a ground truth (GT) is necessary as a reference teaching the algorithm what it should be seeing in the sonar signal. Once the algorithm is trained sufficiently the same GT can be used as a benchmark for the quality of the generated synthetic image. This strategy has the advantage that it can objectively give a measure of how good the algorithm performs on its task. This strategy will be used manly during the lab validation.

3.1. Lab Validation - SONAVision for Diver Monitoring

In the former documents the algorithm was referred to as Sound2Vision and will be called SONAVision from now on as it was discussed that it is a better representation of what the algorithm actually does.

The SONAVision algorithm will be mainly validated according to the following two criteria, (1) its capability of reconstructing realistic visual-like images from sonar data, and (2) its capability to correctly estimate the position of the diver in the reconstructed image. In case the reconstruction is good enough to not only identify the diver, but also his shape and position of his extremities, an additional criterion will be used to validate the algorithm: (3) its capability to correctly estimate the body pose of the diver in the reconstructed image.

An effective way to evaluate the first criterion is to compare the reconstruction of the algorithm against a corresponding ground truth image, i.e., a clear paired image of the divers during their activities. This can be achieved by mounting a camera and the sonar on the same structure, arranging them to match the desired view to acquire the ground truth images. Furthermore, we will use depth images from stereo camera and a laser scanner, in case the 3D information is also represented during the reconstruction.

To evaluate how similar the reconstruction of the models is compared to the ground truth, i.e., captured paired images, similarity metrics will be used. These correspond to an objective assessment of the model, making them an ideal validation method. Unfortunately, the ground truth images can only be captured during activities, where no dirt is produced, and a certain visibility and lighting is guaranteed. In case the camera cannot capture the image properly, subjective assessments must be carried out hereby to evaluate how realistic and visual-like the reconstructions of the models are (see Table 2).

The activities divers may perform during data collection and validation can be split into clean activities that do not produce dirt like e.g.:

- pipe fitting
- screwing metallic screws
- tightening nut and bolt
- picking up wooden blocks

and activities that do produce dirt like e.g.:

- metal scraping
- drilling wooden log
- pipe cutting
- metal polishing

- flashing light sticks
- underwater welding

As location for the lab validation two options are available:

1. RIC DFKI indoor basin in Bremen
2. Former tank wash basin in Neu-Ulm

The bulk of the lab validation activities will be performed in the DFKI indoor basin as it has ideal conditions, such as accessibility, clear water and a stable water velocity etc. The activities of the divers that will produce dirt cannot be performed in the DFKI indoor basin. In this case the tank wash basin will be used which is 2,75m deep and has a dimension of 22m x 19,5m at the top and 17,2m x 10m at the bottom. The water visibility will deteriorate gradually as divers perform activities that result in fine particulate matter to be spread in the water column. This will give us the opportunity to validate the performance of the algorithm in bad- or no visibility situations.

These validation experiments will be carried out in a similar fashion to the data collection experiments, where the divers from THW will perform their tasks while being monitored using sonar and camera sensors. The sonar and cameras will be mounted onto the Jetfloat-platform used for training data collection and described in deliverable D2.4. This setup is shown in a picture in Figure 1, that was taken during the first data collection session at DFKI. The aim of this setup is to generate ground truth data using the camera by which the output of the SONAVision algorithms will be validated against.

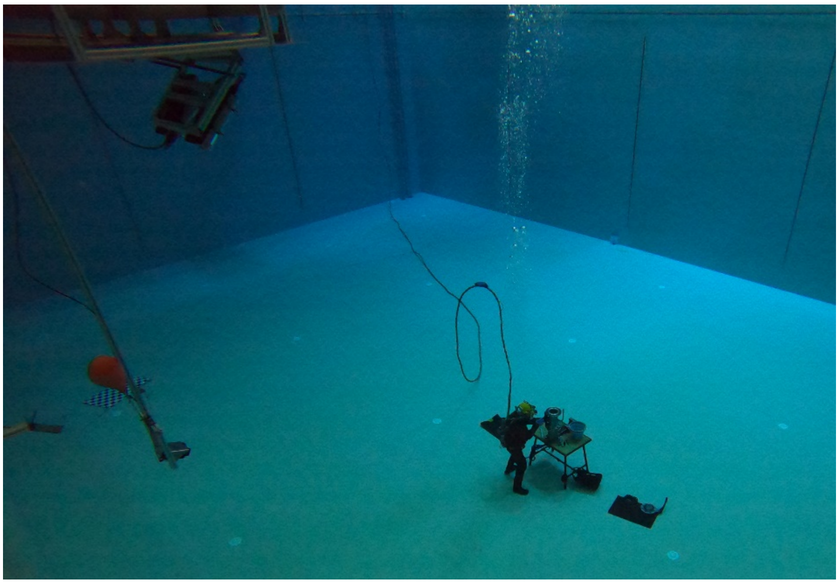

Figure 1 Diver working at the bottom of the DFKI indoor basin, on the left side the Jetfloat-platform is visible with a boom carrying the Sonar

To capture the position and body pose of the diver during the activities at DFKI's indoor basin and hence, evaluate the algorithm according to the second and third criteria, we will use the Qualisys Motion Capture System, planned to be installed at the facilities by the end of 2021. The system uses optical motion capture technology that makes it possible to track objects in large volumes underwater. You can track the position of individual points or the position and orientation of an object with six degrees of freedom (6DOF) (Qualisys, 2021). Although the system is planned to be installed at DFKI's indoor basin to mainly track AUVs, the company used it already to capture the motion of swimmers in a collaboration between the Swedish Swim Federation, Chalmers University and Qualisys, Sweden (Langholz, Westman, & Karlsteen, 2016). The study was carried out to analyze the biomechanics of swimmers to help them improve their swimming techniques. We believe we could use the system in the same manner to track the body pose and motion of the divers. This will give us the required ground truth data to evaluate how accurate the models can estimate the divers' position and body pose.

The Qualisys Motion Capture System will be permanently integrated at the DFKI's indoor basin and cannot be transported to THW's outdoor pool. Instead, we will use visual fiducia markers attached to diver and several cameras strategically position to capture the position of the diver to the extent possible during the experiments at THW's outdoor pool.

3.2. LAB VALIDATION - EAGLEEYE FOR COLLISION AVOIDANCE

In lab validation we will validate two tasks. First, correct matching between the optic and acoustic images. Second, using the matching for obstacle avoidance. For initial validation we will split the existing data into training and test data. The algorithm training will be performed with the training data. The performance of the trained algorithm will then be validated using the test data.

Additionally, we will use the stonefish simulation with simulated 3D scenes to test obstacle avoidance. This will be done by instructing the AUV to move from point A to B, with obstacles en route.

The lab validation will be concluded in our test pool. We will position objects with known dimensions in the pool, such as barrels (examples in Figure 2) and inflated buoys and run the matching method. Here we will use both, the Alice AUV and our modified blueROV.

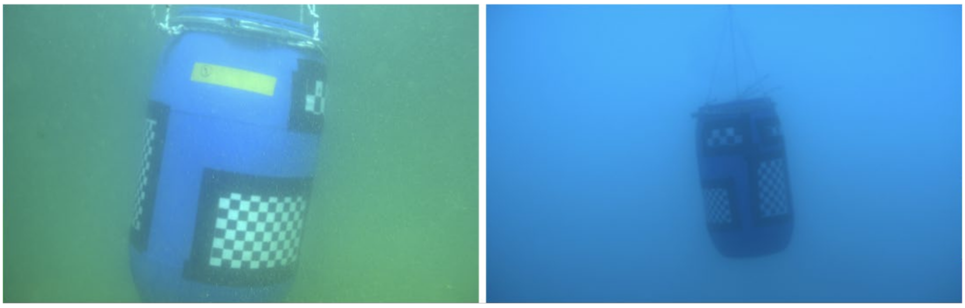

Figure 2 An example of an artificial object for validation. Several textured targets have been mounted on a large barrel. [Left] Imaged at the test pool. [Right] Imaged at sea.

3.3. LAB VALIDATION - SMARTSEAFLOORSCAN FOR SEABED MAPPING

The lab validation of the SmartSeafloorScan algorithms can be divided into two components. The first component pertains to the classification of the seafloor using acoustic sensors with performance comparable to that afforded by optical sensors. The second addresses the use of an AUV capable of changing its behaviour in real-time, based on the perception provided by the seafloor classification algorithms.

Regarding the first component, the SmartSeafloorScan algorithms will be tested and validated using data collected by TA either during their routine survey activities or during specially organized data collection events tailored for DeeperSense. As such, the 'lab verification' of the algorithms will be conducted post-mission, i.e., off-line and using previously acquired data. This data will consist of annotated side-scan sonar data, optical video data and multi-beam bathymetry whenever available. The annotation is conducted by TA marine geology experts that can provide a layer of ground-truth to the acoustic data.

Regarding the second component, the AUV will be equipped with the Klein 3000 side scan sonar and tested initially in the test pool of the Center for Underwater Robotics (CIRS) of the UdG. This effort will be done in order to verify and validate the performance of the hardware integration. The planned sensor integration is illustrated in Figure 3. The reactive aspect of the AUV behaviour will be tested using the StoneFish environment, which is able to run the software of the control architecture of the AUV, and simulate its dynamics. However, the StoneFish environment lacks a native simulation of a side scan sonar. Although the mission behaviour aspects can be tested with a simulated side scan sonar, the extension of the StoneFish environment to accommodate it will be researched.

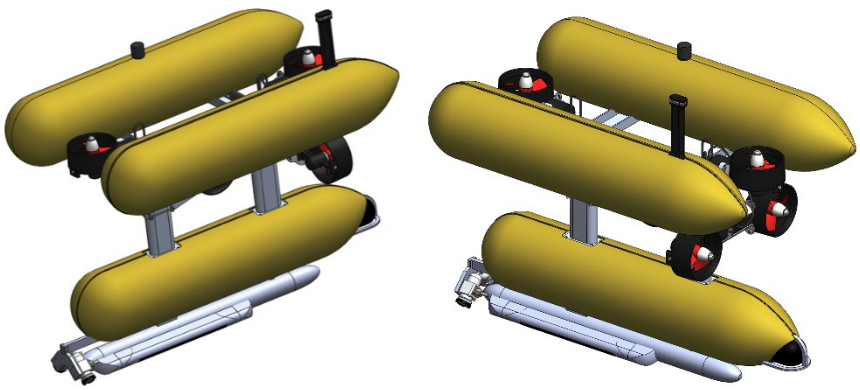

Figure 3 CAD views of the planned hardware integration for the Girona1000 AUV, comprising the Klein 3000 side scan sonar and two optical cameras. The cameras are fitted in front of the sonar, and oriented in a slanted sideways configuration to match the two sonar tracks.

4. Algorithm Field Validation & Use Case Field Demonstration

The field validation will be performed in order to test how the system performs outside an ideal environment and with varying visibility. As the ground truth will only be available in clear water, human interpretation of the generated image will be necessary to evaluate the performance of the system.

4.1. Field Validation - SONAVision for Diver Monitoring

The aim of the field validation is to test the capabilities of the SONAVision algorithm in a natural environment where the operating conditions cannot be easily controlled as in the lab setting. For that purpose, the field validation will mainly take place in the "Stadtwaldsee" lake in Bremen in Germany (shown in Figure 4). Besides the proximity to the DFKI facilities, this lake exhibits low water visibility especially during the spring and summer seasons due to marine growth and has a maximum depth of 15 m, which makes this location a suitable candidate for validating the SONAVision algorithm.

Figure 4 The Stadtwaldsee (also known as Unisee) in Bremen, Germany.

The sensors will be carried by an underwater vehicle during the field validation, which can be operated remotely from the surface and could stream data to the operator in real-time. In this setup, the SONAVision algorithm will be deployed onto one of DFKI's AUVs, Flatfish or Dagon. Both vehicles can be operated remotely and could be fitted with a FLS as a payload as shown in Figure 5.

Figure 5 The AUVs Flatfish (top) and Dagon (bottom) equipped with the Gemini 720i FLS.

When operating in a realistic scenario, visibility through the water is often disturbed due to particulate matter suspended in the water column. Additionally, the activities performed by the divers like drilling, cutting, welding or blasting would create more agitation in the water column deteriorating further the visibility. Thus, one of the main challenges that this scenario poses is the difficulty to acquire ground truth data from cameras in complete white-out situations.

To remedy this situation, the following procedures will be followed to validate the SONAVision algorithm in the field. One idea for creating visual data is to collect some camera footage of the divers and the mockup environment before any diver activities commence. This way some visual samples can be collected before any dirt is produced, to give an impression on how the scene might look like. This data could be used later to qualitatively compare to the reconstructed image by the SONAVision algorithm, however no quantitative metrics could be used in this situation as no ground truth image could be paired with reconstructed samples.

In the case where the visibility is very bad that no clear ground truth image is possible at all, human interpretation of the generated image will be used as a fallback. As the reconstruction is meant to help the THW's operators during the monitoring of the divers' activities, their human judgement of the image reconstruction is a valuable assessment and will be used to evaluate the algorithm. However, human evaluation has several disadvantages, namely, human judgment is subjective in nature and often includes biases, making very difficult to achieve a consistent opinion across multiple human judges. For this case a set of standard evaluation criteria will be followed where a questionnaire will be developed containing questions that the human operator will use to evaluate the quality of the generated image. An example of such questionnaire is given in Table 2. Note that this example is not final and will be subject to modifications later.

Table 2 Example of questions that can be used to evaluate the quality of the generated image

Question	Type
Is the diver's torso detectable?	Yes/no
Are the diver's limbs detectable?	Yes/no
Can the tool used by the diver be identified?	Yes/no
Objects the diver is working on are visible?	Yes/no
The surrounding of the diver is visible?	Yes/no

Furthermore, there are no standardized metrics and approaches to human assessment. Therefore, a suite of qualitative and quantitative automatic techniques will be additionally used based on the quality of the reconstructed synthetic images, such as the ones commonly used to assess GAN generators.

For the case of position estimation of the divers, using visual fiducial markers will be unfeasible in such scenario due to the high sensitivity of such markers to visibility conditions. Alternatively, we will validate the capability of estimating the position of the diver according to the following scenario. First, a fixed position will be marked on the ground where a diver can stand over, and the GPS coordinates of this point will be measured. Then, by having the vehicle's GPS antenna above the water surface, the position of the AUV can be measured and thus a ground truth relative position between the diver and the AUV can be produced to evaluate the position estimation capabilities of the algorithm.

4.2. Field Validation - EagleEye for Collision Avoidance

Following successful results in the Stonefish simulated environment, sea trials will be conducted with the UH SPARUS II AUV and possibly with the BlueRobotics ROV.

The algorithm will be tested in the Mediterranean at the Achziv Nature Reserve in an underwater canyon with steep walls that is difficult to navigate without good obstacle avoidance in the Shikmona nature reserve, home to a rocky reef, close to the UH campus in Haifa, and in Nachsholim reef, that has interesting rocky formations. The final validation will be performed in the Red Sea in a coral reef near Eilat. Figure 6 shows the location of these places on the map and examples of obstacles in Nachsholim and in the Red Sea.

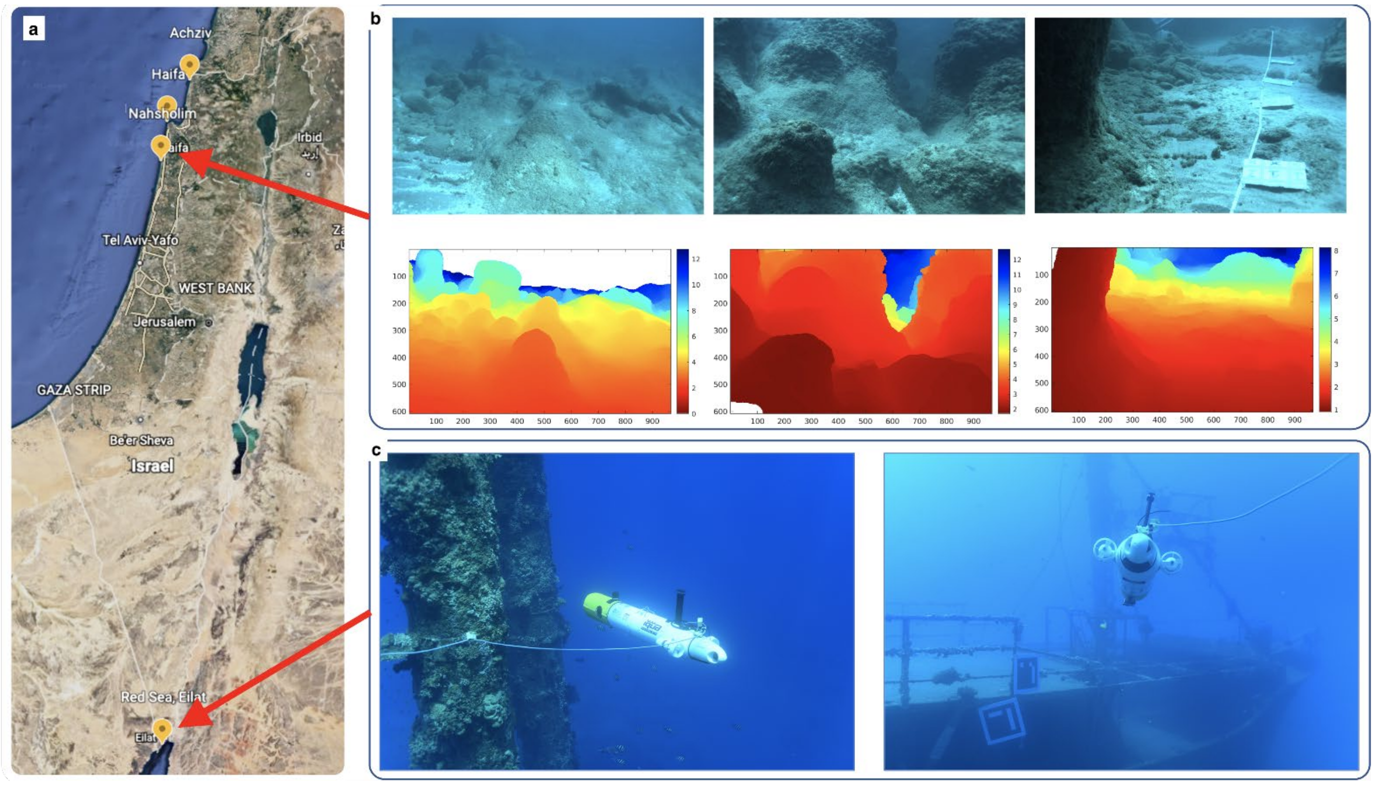

Figure 6 Experiment locations for UC2 in Israel. a) Map with the 3 locations in the Mediterranean Sea: Haifa hosts our lab and the test pool, as well as a rocky reef nearby. Achziv has an impressive canyon at depths around 20m. Nachsholim has interesting rocky formations as can be seen in (b). Our fourth location is in the Red Sea in Eilat, that has both coral reefs and man made structures as can be seen in c).

First, an artificial obstacle range (same like in the pool, barrels like in Figure 2, buoys) will be positioned, preferably in a coastal lagoon in the Mediterranean with several objects simulating obstacles at different distances and altitudes from each other (distance between obstacles in the range of 5m). The goal for the AUV is to navigate from his initial position to a target position (an object or a predefined location) while avoiding the obstacles, preferably though performing avoidance in the horizontal plane. Successful goal achievement is defined by arriving the target location without surfacing (mission abort) or colliding into obstacles.

Second, the AUV will attempt to navigate between two defined points in an unknown environment (underwater wrecks\vehicles, pier) or a coral reef (potentially), without crashing into parts of the reef. In these trials the AUV will be attended by scuba divers or connected to a wifi buoy to protect the reef and the AUV in case of an imminent crash hazard.

The field validations will involve the safe navigation of our Alice AUV through 3-dimensional artificial (in the Mediterranean) and natural (in the Red Sea) obstacle courses. The latter will be a real coral reef (following successful previous trials). The validation of EagleEye will be successful when it is able to guide the AUV through the obstacle course.

4.3. Field Validation - SmartSeafloorScan for Seabed Mapping

The field validation and demonstration will be conducted in two stages.

The first stage will focus on the testing of the real-time classification algorithms during a standard boat survey conducted by TA. The goal is to validate the real-time performance in a marine survey scenario that is of high interest for end-users. Suitable locations for the demonstration are currently being identified as part of an extended coastal survey that TA is currently undertaking. An example of such is provided in Figure 7.

In a separate validation effort, the AUV set-up, consisting of the Girona1000 AUV equipped with the side scan sonar and optical cameras, will be used to acquire data. This data is intended to be used offline as preparation for the final demonstrations, which will be conducted using the same hardware, but without the use of the optical camera. Testing sites, suitable for the final demonstration, will be defined during this period.

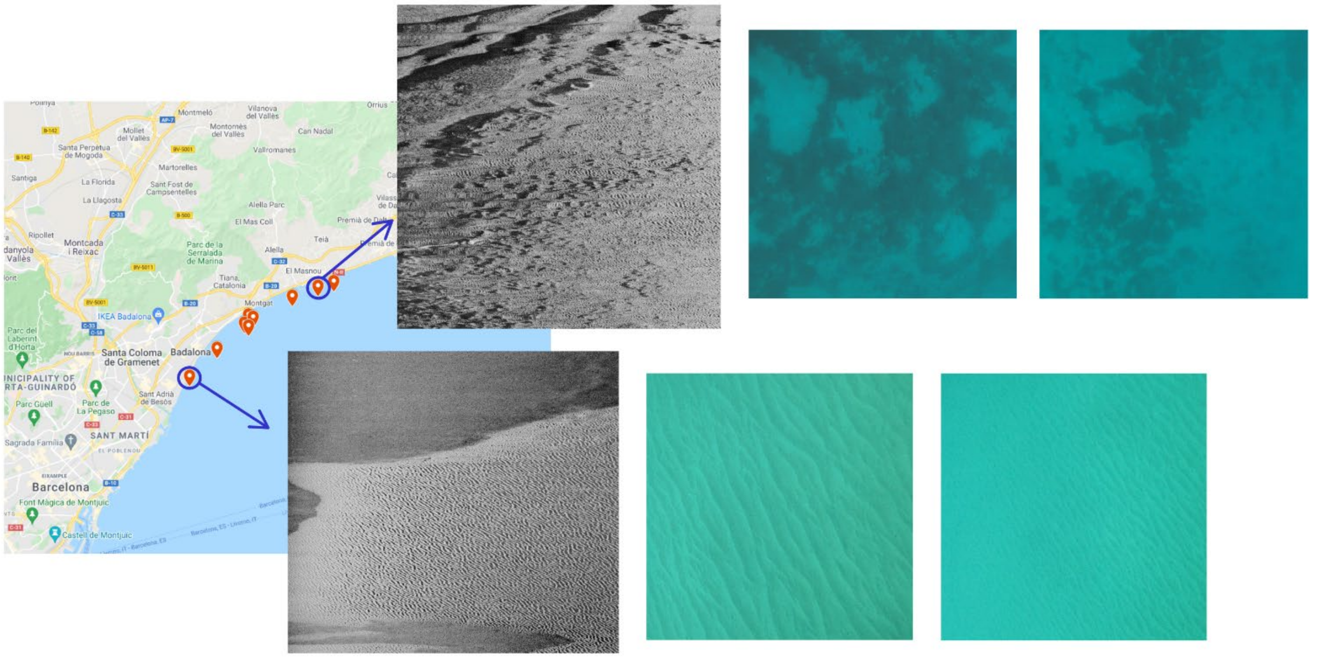

Figure 7 Map of some of the locations, in the coastal area north of Barcelona, where TA is conducting mapping surveys using side scan sonar (left). Preliminary data, acquired with the Klein 3000 sidescan sonar (center), along with video for some of the sites (right) will allow to identify suitable locations for filed validation and demonstration. The above examples of rocky seafloor (upper row of images) and sand with ripples (lower row of images) were collected during September 2021, in an ongoing extended coastal survey.

5. Final Joint Field Demonstration

5.1. Objectives & Goals

A joint final demonstration is planned as an event to reach out to the robotics community and the stakeholder communities addressed by the DeeperSense use cases, but also to potential stakeholders in application areas. The event will bring together the three integrated robotic systems that were used for the validation of the DeeperSense algorithms and demonstrate the advantages of the elaborated technologies.

5.2. Location & Setting

The Starnberger See (Figure 8), a lake in southern Germany, was selected as location for the final demonstration event.

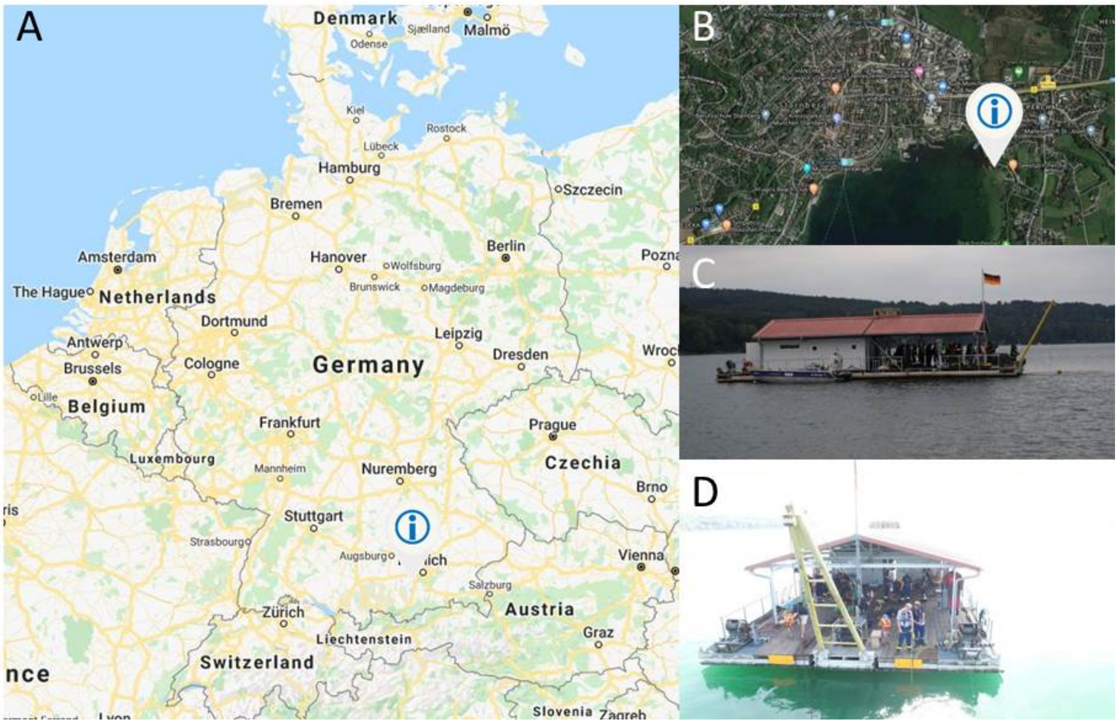

Figure 8 Location for final field demonstration (A), orthophoto of site (B), floating platform(C,D) (Sources: google maps, Maier/THW)

DeeperSense beneficiary THW has access to a facility that is frequently used by THW divers for training purposes. A large platform towed by boats is available for the deployment of the underwater vehicles and divers. On the platform there is also a mission control station and facilities for the crew and scientists managing the trials.

For UC1 THW will install a mock-up environment in the lake that allows to demonstrate the DeeperSense solutions in a real-world environment. Among others, underwater tasks like the emergency repair of underwater infrastructure or the removal of hazardous goods with divers will be simulated to demonstrate the diver surveillance system and the SONAVision algorithm.

For UC2, an artificial obstacle range will be positioned in the lake, and the goal for the AUV will be navigate from his initial position to a target position (an object or a predefined location) while avoiding the obstacles, preferably through performing avoidance in the horizontal plane.

The final field demonstration effort for UC3 will have to be conducted over an area that has distinct seafloor types, similar to those from which the algorithms were developed and trained. Given that such conditions do not exist in the lake in Starnberg, where the final demonstrators for UC1 and UC2 will take place, it was opted to conduct the field demonstrations for UC3 in a suitable area in the mediterranean sea. Those demonstrations will be carried out prior to the final joint field demonstration as a separate event, in order to show a presentation of the results in the final demonstration event.

In order to get an idea of how the Event will be organized a schedule draft is shown in Table 3:

Table 3 Demonstration schedule draft

Day 1	Installation of Equipment on the platform
Day 2	Installation of obstacle range and Workshop for Divers
Day 3	Dry rehearsal run
Day 4	Fixing Issues day
Day 5	Final Demonstration • Welcome presentation and display of the AUVs • SONAVision demonstration • Presentation of the SmartSeafloorScan demonstration (e.g. Video) • EagleEye demonstration • Discussion
Day 6	Disassembly and clean up

DeeperSense Consortium