Mobile inventory system for hydrotechnical objects using data from multiple sensors operating simultaneously

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The knowledge of the location, shape and other characteristics of spatial objects in the coastal areas has a significant impact on the functioning of ports, shipyards, and other water-infrastructure facilities, both offshore and inland. Therefore, measurements are taken of the underwater part of the waterside zone, which means the bottom of water and other underwater objects (e.g. breakwaters, docks, etc.), and objects above the water, such as the above-water part of the waterside, breakwaters, hydraulic constructions, and other objects of the waterside infrastructure.

In this paper, a project of a mobile inventory system for hydrotechnical objects using data from multiple sensors operating simultaneously will be presented. The aim of the project is to elaborate a mobile underwater scanning system which could be applied in various works requiring precise, detailed and coherent, underwater and above-water measurement, especially in areas associated with surveying, inspection and monitoring of objects in coastal areas.

To elaborate the concept of the system, analysis concerning existing methods of precise underwater and above-water measurement, as well as the measuring equipment available, was carried out. The results of the research were used to develop the concept of a mobile system equipped with underwater laser scanning and acoustic positioning. The technology demonstration was developed using a specially-built laboratory environment that simulates hydrotechnical infrastructure with access to GPS data. The final stage of the project will consist of testing the system in open waters.

Keywords: ROV, IMU, underwater laser scanner, acoustic positioning system

1. Introduction

Knowledge of the location, shape, and other characteristics of spatial objects in the coastal areas has a significant impact on the functioning of ports, shipyards, and other water-infrastructure facilities, both offshore and inland. Therefore, measurements are taken of the underwater part of the waterside zone, which means the bottom and other underwater objects (eg. breakwaters, docks, etc.), and objects above the water, such as the above-water part of the waterside, breakwaters, hydraulic constructions, and other objects of waterside infrastructure [1, 2].

For a port to operate, it is necessary to provide a water channel of the necessary depth, berths providing protection from winds, waves, and currents, access to other means of transport (trains, trucks, pipelines), storage space for transshipment of goods (warehouses, tanks, silos). All these elements of infrastructure must not only be inventoried and measured, but also regularly monitored, to ensure smooth functioning.

The same applies to other coastal infrastructure facilities such as shipyards, for which maintenance of the shipyard's basin and docks, devices such as ramps, cranes and overhead cranes, is essential to their functioning.

In addition to industrial facilities in the coastal zone, there are also other objects - tourism (piers, bridges, and marinas), archaeological - requiring measurement of both the topside, and underwater. It is also important to monitor the natural coastline, beaches and cliffs, to prevent, and inventory, damage done by the winds, storms, and harmful human activity.

A separate issue is the inland waters, in an area where there are a lot of hydro-technical facilities, that require precise measurements of both above-water and underwater elements. These are objects such as weirs, locks, aquatic power stations, dikes. Keeping these objects in good condition is essential for the safety of the population.

Besides objects of coastal infrastructure, it is also important to ensure the smooth operation of vessels. Keeping ships in a proper condition is essential to ensure safety in the maritime area and inland, as well as for the environment. Cargo ships are required to measure the underwater portion of the hull twice within every 5 year period [8]. Detailed inspection is performed in a dry dock, when and where it is possible, to perform an accurate measurement of the hull (eg. Using a terrestrial laser scanner) as well as to detect any defects and perform the repairs deemed necessary. According to the regulations, one of the two mandatory surveys may be performed under water. The measurement of a ship's hull under water is a difficult undertaking, but if we are able to provide the technology to perform the underwater part of the work related to the inspection of the hull, we can avoid putting the ship in a dry dock, which can save a lot of time and money.

To achieve these objectives it is necessary to use techniques to measure underwater. Underwater measurements can be divided into the following categories depending on the order in which they are performed, related:

- to mapping underwater areas (area surveys), in particular maps of the bottom, seismic maps, maps of the density of water, its salinity and temperature, maps of zooplankton and phytoplankton, maps of fish habitats, maps of raw materials and mineral deposits,
- to the inspection of underwater objects floating, submerged, or embedded at the bottom (eg. Drilling platforms rigs, quays, submerged cables and pipelines),

- positioning, eg. Drilling platform service using underwater vehicles ROV (Remotely Operated Vehicle), UUV (Unmanned Underwater Vehicle) and AUV (Automated Underwater Vehicle)),
- to static measurements, and other human activities underwater.

These measurements are performed from the air, ground, and underwater. The following are the conventional techniques used to measure underwater:

- Direct methods, based on the work of divers:
  - Video documentation, photographs and sketches.
  - Direct surveying - measuring the azimuth and distance of the object relative to a known point, offsets rectangular and indent, from the known base trilateration.
- Remote methods [3-6]:
  - Underwater photogrammetry - allows for precise measurement within water transparency.
  - Sonar systems - enable measurements to a depth of several hundred, or even several thousand meters, depending on the used frequency of the sound wave.
  - Aerial photogrammetry - allows for the measurement to a depth of several meters with very clear waters (not in Poland).
  - Airborne laser scanning - allows the measurement to a depth of several meters with transparent waters.
  - Magnetometers - can detect underwater objects and their approximate location.

Direct methods based on the divers require extraordinary security measures. For the work of people under the water to be safe, it is necessary to use reliable equipment, and have personnel assisting the divers. In addition, direct measurements are very time-consuming. These factors make this method of measurement not very effective. That is why, for a long time (more than a hundred years), methods for remote measurement, of the bottom waters and objects under water, have be developed. A key aspect in this field are the physical properties of the water, associated with the propagation of various types of signals used for remote measurements.

Most of the spectrum of electromagnetic waves is significantly absorbed by water, relatively good propagation in the water is characterized by visible light, and in particular the lower range of the spectrum, so blue and green light. The degree of turbidity has a key effect on the propagation of light in the water. Polish waters' transparency is usually from tens of centimeters to several meters, and is variable depending on the season. Due to poor propagation of electromagnetic waves in the water, acoustic waves are commonly used for underwater remote measurements.

Over the last decade, the scale and scope of application, of systems based on multi-beam sonar has expanded. Such sonar, through the multiple wide-angle observation of the bottom, while maintaining high (relatively) angular resolution, allow for conducting high resolution imaging and bathymetric measurement of the basin, as well as other underwater objects. The creation of this type of measurement system was the result of the integration of multi-beam sonar technology, a new generation of multi-dimensional digital signal processing, and geographic information systems GIS.

A sonar transducer provides reception of echoes from different directions, and the coverage area of the searched area is divided into quasi-parallel stripes consisting of a large number of measured points. The distance of the observed object is determined based on the return time (delay) of the echo signal for a given beam. The result is a discrete (point cloud) picture bathymetric bottom surface or underwater object with a relatively high resolution, mainly dependent on the depth of observation in the vertical (nadir) and the number of beams.

For some applications, hydroacoustic measurement accuracy may not be satisfactory. For applications requiring very accurate and detailed measurements (at the level of millimeters), it is necessary to use more precise measuring instruments. An alternative may be the use of underwater laser scanners. These instruments are based on the principle of triangulation. They give very dense underwater measurements of submillimeter accuracy. Their primary limitation is a relatively small range (about 10 m) determined mainly by the clarity of the water.

2. Work concept

The aim of the *Hydromonitor* project is to build a technical demonstrator of an innovative mobile measuring system, providing integrated data waterside and underwater. This solution will enable the optimization of the measurement process, providing new product categories and increase the security of measurements of water infrastructure and other facilities offshore. The project is co-financed by the Polish National Center For Research and Development (NCBiR), in the scope of *III edition* of *Applied research programme*.

During the project development, a few visions of the mobile system were analyzed. The first vision of the system, was focused on integrating a multibeam echo sounder with laser scanning to produce a seamless and georeferenced dataset above, and below water. The concept of the analyzed solution is shown in Fig.1.

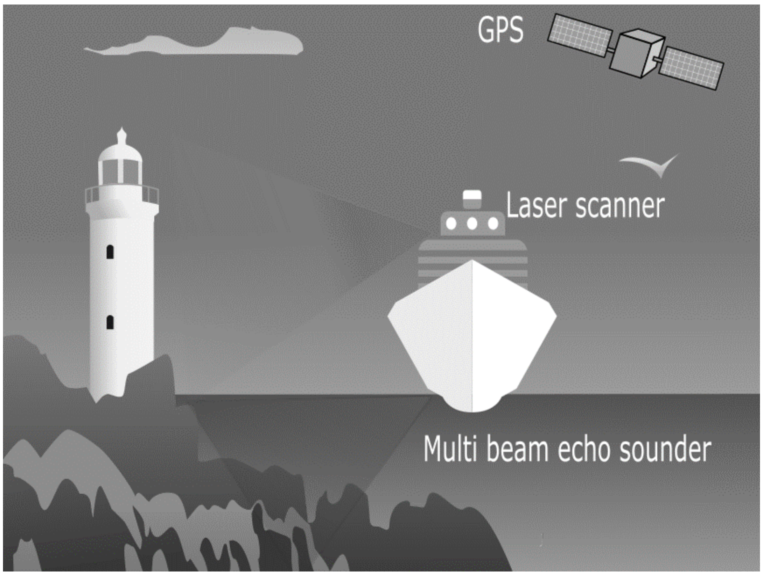

Fig. 1. Draft of the 1st vision for the mobile scanning solution (source: www.vectoropenstock.com).

Unfortunately, using a multibeam echo sounder has its drawbacks, when used in detailed inventory tasks. Fig. 2 shows a comparison of laser and sonar data done by Jason Gillgam from 2G Robotics. The sparse dots, that form circular patterns, are points collected by a 3D sonar using a 2.25 Mhz sonar head, with an average angular point spacing of one degree. Triangular laser scanner data is in the middle of the object, showing a very dense 3D point cloud.

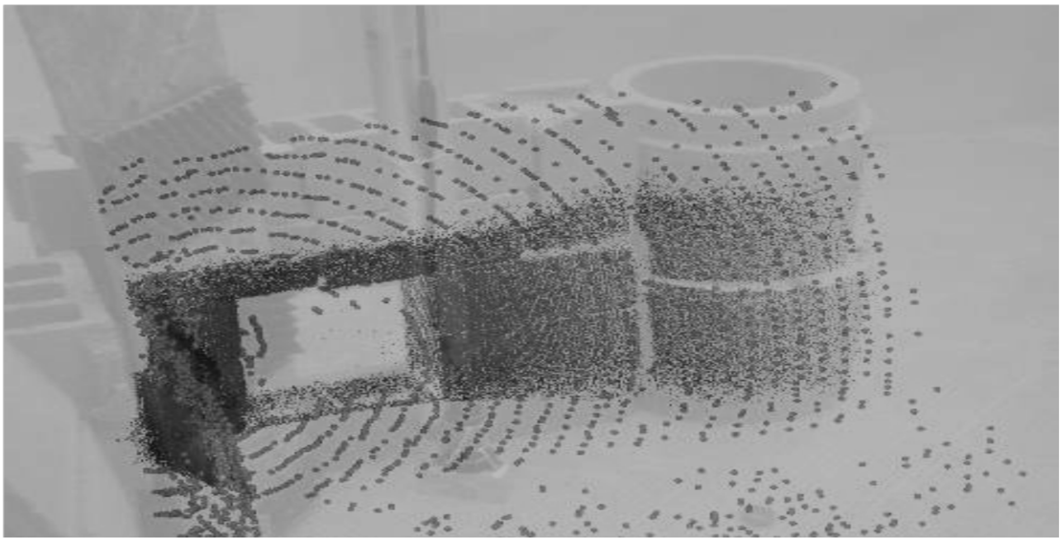

Fig. 2. Underwater sonar and laser measuring an experimental comparison [7].

The measurement resolution of the laser system is multiple orders of magnitude higher, enabling very dense point clouds. Measurements made from dense laser point clouds will, in general, be much more accurate than those taken from relatively sparse sonar point clouds. Additionally, laser systems are not affected by confined spaces prone to acoustic echoes. Sonar data does not provide a precise understanding of the edges, and an accurate position and size for the hole cannot be determined. This inaccuracy, or you can call it also an ambiguity, is due to the size of the sonar system's footprint [7].

Talking into the account the characteristics of sonar and multibeam echo sounder data, the project team decided to focus on using a triangulation laser system as the main underwater sensor. Such systems use an internal laser diode to emit the light signal, the light is reflected off the target surface and collected using an offset sensor. Based on the known offset between the laser and the sensor, and the angle of the reflection measured from the offset sensor, the distance to the target is calculated [7]. Using a triangulation technique is ideal for underwater measurements: however, the downside of this technique is that the performance of the system degrades with increasing distance. Talking into account the range limitations of underwater laser scanners, the project team decided to mount it on an underwater ROV. The ROV, as a mobile platform, overcomes the limitations of laser range underwater. The vison of the system is shown in Fig. 3.

The main problem in the new approach is georeferencing the data collected under water without direct access to a GPS signal. In any mobile measurements system, having an accurate trajectory is needed to merge separate scans captured during the movement of the platform. To provide global georeferencing for the Hydromonitor system, an acoustic positioning system was constructed. The system uses 4 buoys, two of them floating on the water with a GPS antenna, two of them fixed to the infrastructure, with their position derived from the tachymeter, to increase positioning accuracy. The pinger on the ROV will emit an acoustic signal which will be received by the buoys. From the signal time of travel, distance to each of the boys will be calculated, and from it the position of the pinger. The data will be coupled with a depth sensor and IMU data, to provide the precise trajectory of the sensor. A detailed schema of the Hydromonitor system is shown in Fig. 4. The camera and a laser diode will serve as the basis for the triangulation scanning system. To capture data above the water, a puck laser scanner with a GPS antenna will be mounted on the top of the ROV.

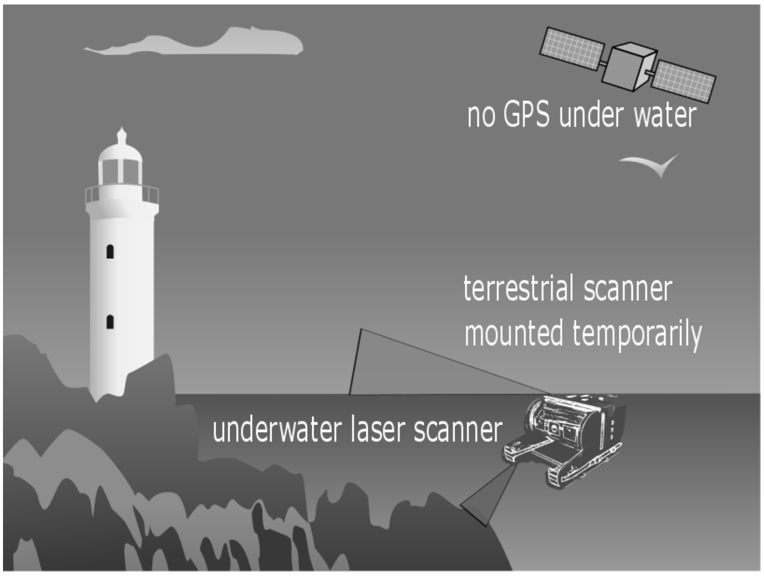

Fig. 3. Draft of the 1st vision for the mobile scanning solution (source: www.vectoropenstock.com).

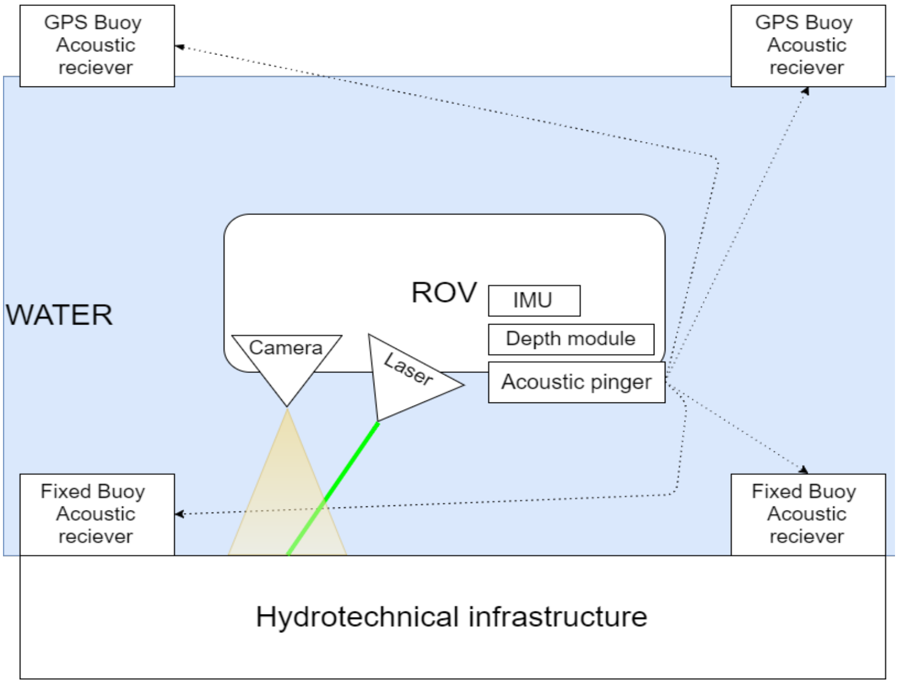

Fig. 4. Hydromonitor system diagram.

3. Experiments

Construction of the Hydromonitor system started with building a triangulation laser scanner proof-of-concept. Using a camera and a line projected on the surface, a 3D point cloud of the scanned objects was generated.

The camera and laser setup was calibrated using 15 images of the calibration field "checkerboard" (Fig. 5) at different positions of the calibration field in relation to the camera. In each position of the calibration field, two photos were taken, with the projected line, and without it. Thanks to detections of the squares, the equation of the calibration field plane was calculated in different positions, in the camera coordinate system. Similarly, equations of the projected lines were calculated. By fitting the least squares method, the plane was determined from the lines equation. This plane is an approximation of a plane projected by the projector.

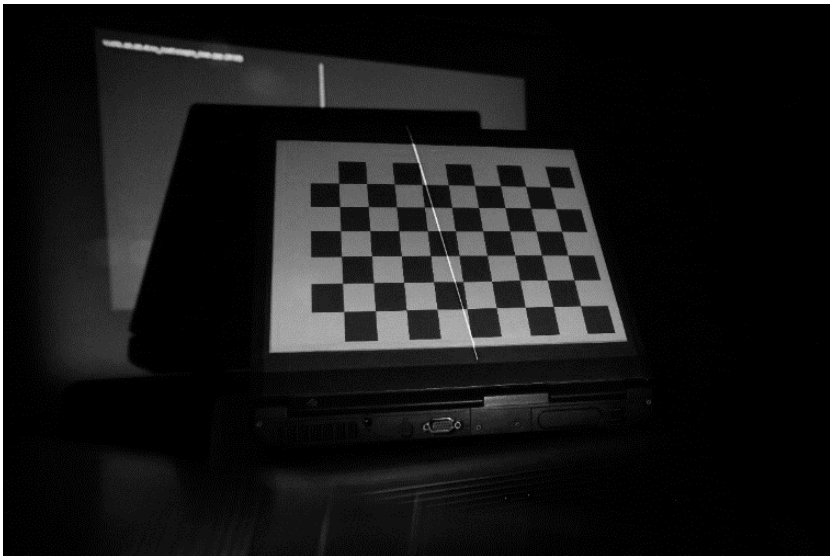

Fig. 5. One of the photos calibration field "checkerboard".

Based on the coordinates of the pixel lines projected on the object, and the equation of the plane determined previously, coordinates of the projected lines in the camera's coordinate system can be calculated. These coordinates represent the cross-section of the measuring surface area. A sample measurement result is presented in Fig. 6. On the left image an object on the projection that was the line. On the right, a "point cloud" representing a cross-section surface of the object being measured.

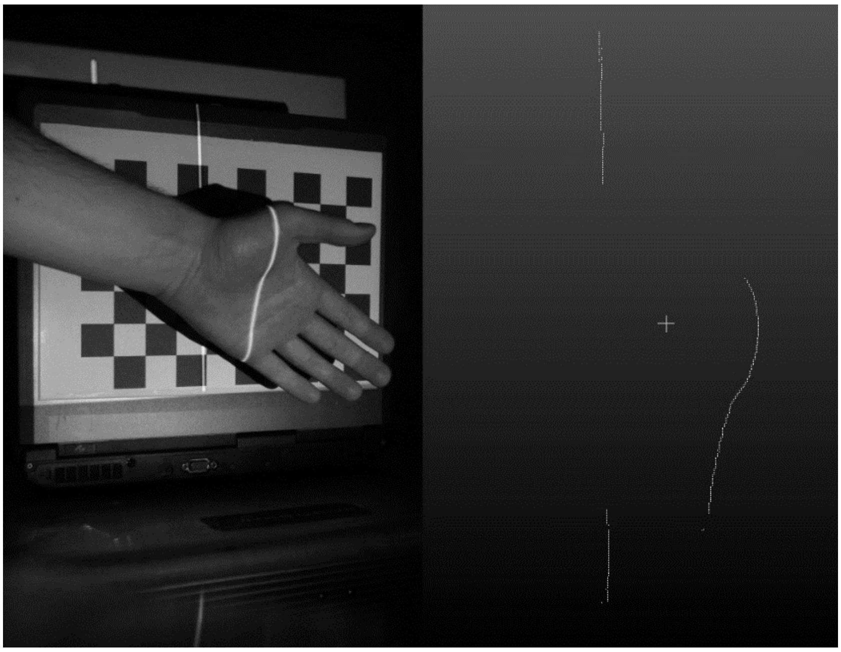

Fig. 6. A sample measurement result.

In order to enable simultaneous calculation of the calibration field plane, and detection of the laser line on the basis of the same image, different patterns of the calibration field were used (dots). As a result, it was not necessary to perform pairs of images (with, or without, the projected laser line) at the same position of the calibration field. This enabled the calibration of the laser-camera system based on video sequences. The position of the calibration was continuously changed to record images with different orientations of calibration field plane, which is necessary for subsequent fitting of the plane of the projected laser line.

The next phase of the experiments included moving the camera-laser setup, with the use of a time-lapse camera slider. To calculate the trajectory of the measuring system, calibration filed was put into the frame, shown in the Fig. 7 and Fig. 8).

Fig. 7. a) Sample images taken from the moving camera-laser system.

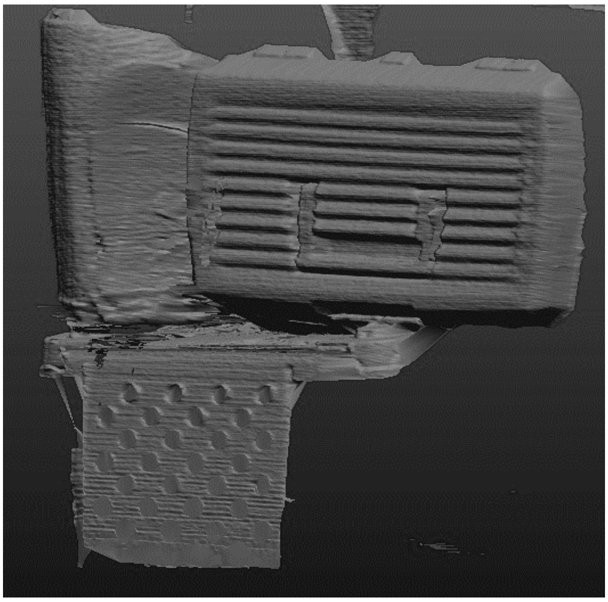

Fig. 8. 3D model created on the basis of measurements taken by camera-laser system mounted on a time-lapse camera slider.

After testing the proof of concept out of water, tests were moved under the water. Underwater experiments in the Hydromonitor project were carried out in the pool in the Hydromechanics Division of the Technical University of Gdansk. The laboratory is equipped with the necessary equipment to model tests in calm water and regular waves. Selected parameters towing pool:

- length [m] 30.00,
- width [m] 3.00,
- the maximum water depth [m] 1.60,
- adjustable depth of water Yes,
- max. speed of the tested objects [m / s] 3.00,

Model pool is equipped with two towing devices that enable the simulation to study the movement of models topside and underwater. In addition, the object has a regular wave generator. Towing equipment pool is presented in Fig. 9.

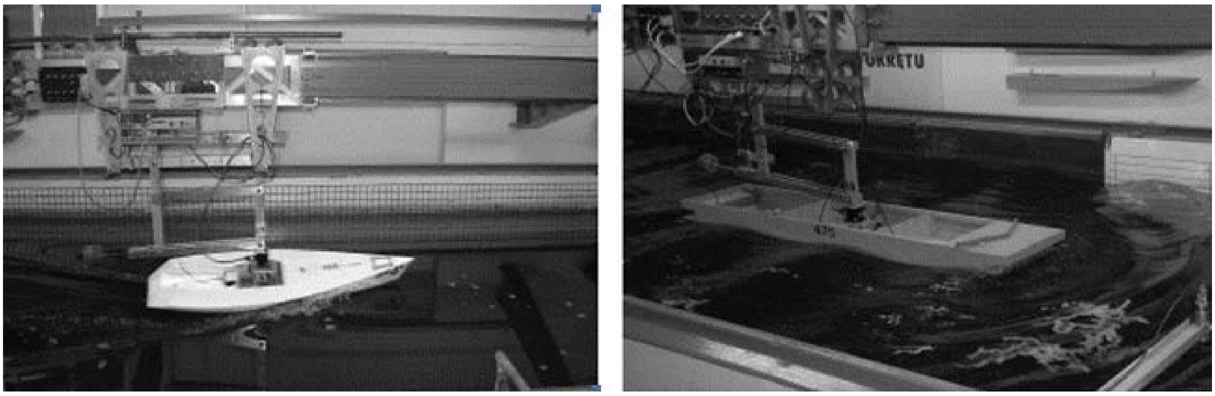

Fig. 9. Towing pool (source:http://oio.pg.edu.pl/katedra-hydromechaniki -i-hydroakustyki/informacje-ogolne1).

First experiments were performed with the use of a calibrated, filed to calculate the trajectory of the camera, scanner system. Additionally, an IMU sensor was put in the waterproof tube, to check their performance under water. Fig. 10 shows an image of the experimental set up on the trolley.

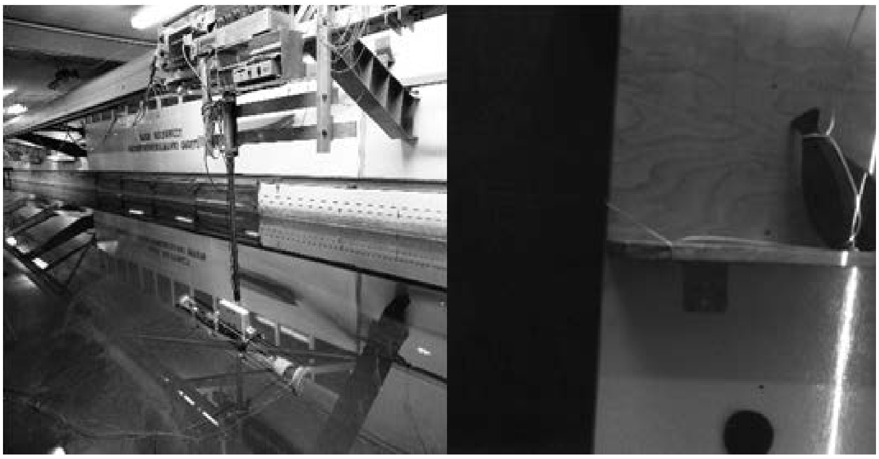

Fig. 10. Images from tests performed under water, on the left, and an underwater image taken with a laser line projected on the test platform.

From the data acquired, a point cloud of the scanned object was generated, shown in Fig. 11. Point cloud generated for the 0.4m x 0.4 m part of the calibration field shown in Fig. 11 consists of over 69000 points, which gives over 40 points per square centimeter. That density allows for precise modelling and scanning of any objects under the water surface, in a way comparable to terrestrial time-of-flight scanners.

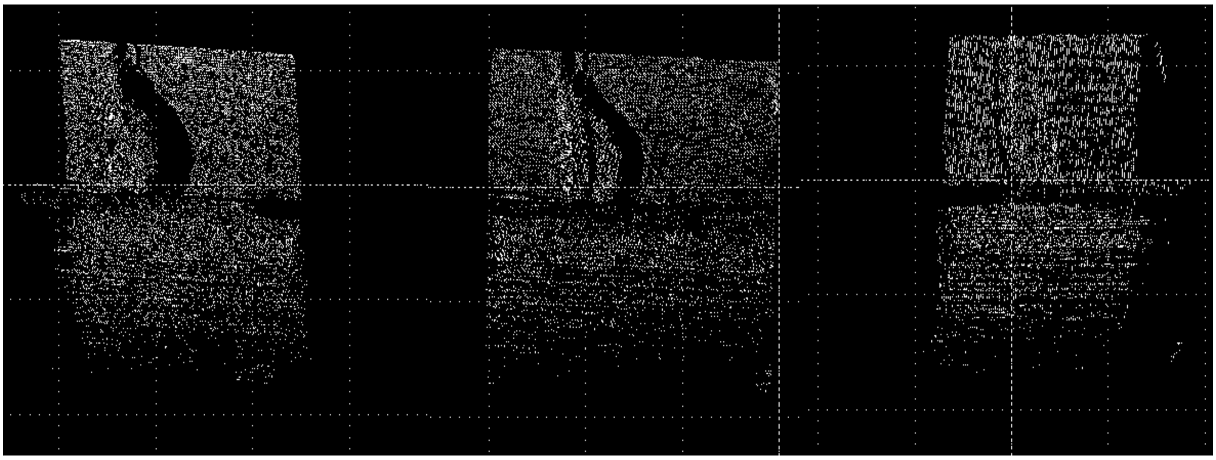

Fig. 11. Different views of the point cloud generated from the underwater measurements.

4. Conclusions

The essence of the concept presented in the article is the possibility of merging measurements above water, and underwater, to deliver a comprehensive inventory and analysis of embankments and hydraulic structures. The combination of both sources of measurement may enable the creation of a new type of product, in the form of complete object models covering both underwater and above-water. These types of models will enable the comprehensive analysis and monitoring of breakwaters, docks, and other facilities at the ports. They can also potentially support any decision-making processes that require precise, reliable, and timely measurements of matters transpiring underwater and above water.

The key advantages of the draft platform are comprehensive (measurements underwater and above-water) and flexible - to adapt to the measurements over large areas (water channels, riverbeds, lake bottoms), as well as the precise measurement of individual objects.

The main benefits of the measurement of underwater, and above the water, from one platform are:

- consistency of measurements underwater and above water,
- same-date data of underwater and above water,
- simultaneous measurement - important in the case of a variable water level, and the objects and effects of time-varying.

Future work in the Hydromonitor project includes:

- Point cloud noise reduction. Mostly thanks to applying image processing algorithms on the underwater data, and fitting lines better in the pixel detected on the image.
- Building visual tracking systems, to simulate GPS inside the buildings. The system works using cameras tracking a marker mounted on the platform. The data from the system is integrated with an XSENS MT30 IMU mounted inside the testing platform. Fig. 12 shows a working prototype of the tracking system using 3 connected cameras, the system is integrated in the Robot Operating System (ROS).

- Data adjustment – adjustment of scanned data between different strips of data acquired at different depths, in a way similar to aerial laser scanning data processing.
- Integrating the system with the ROV system and open water tests.

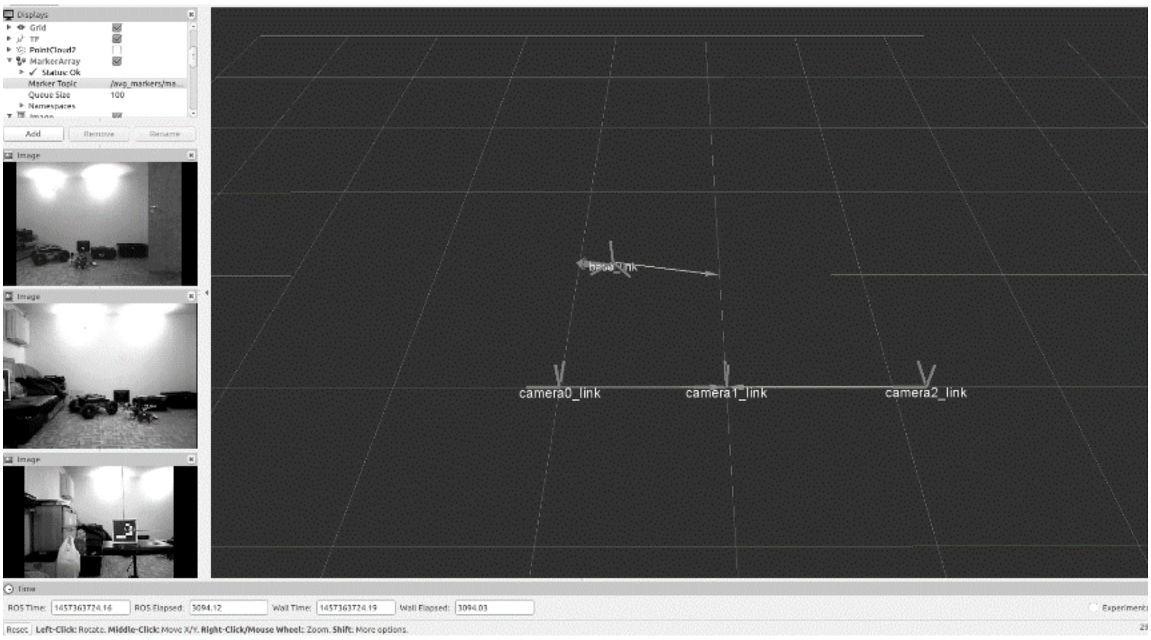

Fig. 12. ROS window, showing visual tracking solution.

Acknowledgments

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References

[1] N. Brahim, S. Daniel, D. Guerot, Potential of underwater sonar systems for port infrastructure inspection, Proceedings of the OCEANS 2008 conference, Quebec, Canada, 2008.
[2] N. Kishi, A. Asada, K. Abukawa, K. Fujisawa, Inspection methods for underwater structures of ports and harbors, Proceedings of 2015 IEEE Conference on the Underwater Technology (UT), Chennai, Japan, 2015.
[3] A. Mahiddine, J. Seinturier, D. Pelaso, J. M. Boi, P. Drap, D. Merad, L. Long, Underwater image preprocessing for autmoated photogrammetry in high turbidity water, Proceedings of the 18th International Conference on Virtual Systems and Multimedia (VSMM), Milan, Italy, 2012.
[4] J. Demkowicz, K. Bikonis, Combined spline wavelet decomposition for 3D seafloor imaging from multibeam sonar echoes, Acta Acustica united with Acustica, 2006, Vol. 92, No. 1, pp. 168-170.
[5] L. Yan, L. Zhe, S. Ying, The particularity of aerial photogrammetry for Architectural heritages by UAV, Proceedings of the 2nd International Conference on Remote Sensing, Environment and Transportation Engineering (RSETE), Nanjing, China, 2012.

[6] W. A. Wan Aziz, M. Z. Syahmi, A. Anuar, T. Khairuk Nizam, Terrian slope analyses between terrestrial laser scanner and airborne laser scanning, Proceedings of the 2012 IEEE conference on Control and System Graduate Research Colloquium (ICSGRC), Shan Alam, Selangor, 2012.
[7] J. Gillham, Underwater sonar and laser measuring an experimental comparison, G Robotics Inc. February, 2011.
[8] Regulation of the Minister of Maritime Economy on the technical conditions of use and the detailed scope of control of hydrotechnical objects, 2006.