Integrated acoustical-optical system for inventory of hydrotechnical objects

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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 of the underwater part of the waterside zone are taken, which means the bottom of the 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, project results of an integrated acoustical-optical system for inventory of hydrotechnical objects are presented. The aim of the project was to elaborate a mobile underwater scanning system which could be applied in various works that require precise, detailed and coherent, underwater and above-water measurement, especially in areas associated with surveying, inspection and monitoring of objects in coastal areas.

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

1. Introduction

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. So that a port could operate properly, it is necessary to provide a water channel for ships of the necessary depth, berths which can protect against winds, waves, and currents, access to other means of transport, like trains, trucks, pipelines and storage space for transshipment of goods. 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.

Besides industrial facilities in the coastal zone, there are also other objects, like touristic (piers, bridges, and marinas), archaeological, that require measurement of both the above-water, and underwater parts. It is also important to monitor the coastline, beaches and cliffs, to prevent, and inventory damage done by the winds, storms, and harmful human activity. No less important are inland waters, in the area where there are a lot of hydro-technical facilities, that require precise measurements of both above 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 living in nearby areas.

Therefore, the purpose of the project was to implement an innovative demonstration of a mobile metering system that provides integrated above-water and underwater data with uniform georeference using multiple sensors simultaneously. This solution makes it possible to optimize the measurement process, provide new product categories, and improve the safety of water infrastructure measurements and other coastal facilities. In order to meet the project assumptions, a number of industrial studies were carried out to verify existing sensors for their ability to be used in the mobile system and to work in a simultaneous mode, thus reducing the impact of single sensor limitations on the final measurement result. The preliminary results of the project were presented in [1].

2. Sensors for above-water and underwater measurements

The purpose of the project was to develop a solution enabling the use of remote methods for above-water and underwater measurements. By definition, remote measurement takes place without physical contact with the surface being measured. For information about the location, shape and dimensions of objects without contact with them, it is necessary to use the emitted and reflected signals of the examined areas. The vast majority of remote sensing methods use electromagnetic waves. Acoustic waves can be also used for this purpose. A key issue in this type of measurement is the medium in which the measurement is performed. This is a determining factor for the effectiveness of a given measurement method under certain conditions.

The effectiveness of the propagation of electromagnetic radiation in the Earth's atmosphere is dependent on the wavelength. Some of the electromagnetic radiation is completely absorbed by the atmosphere, the part is more or less scattered and the part is propagated without major obstacles. The electromagnetic waves that are freely propagated in the atmosphere are called atmospheric windows. Such atmospheric windows are primarily visible radiation, near infrared, medium infrared, thermal infrared, and microwave radiation. These electromagnetic radiation ranges can be used for remote measurements in the Earth's atmosphere. Among the above-water measurement techniques most suitable for the intended applications are photogrammetry [2] and time-of-flight (TOF) laser scanning [3]. Both techniques are well established and widely used for short-range ground-based measurements. Both photogrammetry and laser scanning allow measurements from one millimeter to single centimeters. The scope of measurement using photogrammetric techniques is limited only by the transparency of the air. In the case of laser scanners, the range of measurement depends on the laser signal strength, and the method used to measure the distance (pulse or phase).

In the aquatic environment, electromagnetic waves are absorbed to a much greater extent than in the air. Most of the spectrum of electromagnetic waves is completely absorbed. Exceptions are visible waves that are somewhat propagated in water. The extent of their propagation is, however, incomparably smaller than in the air. It depends on the transparency of the water and reaches, in extreme cases, several dozen meters. However, in Polish conditions the transparency of water does not exceed a few meters.. In the case of more polluted inland waters, water transparency sometimes drops below 1 meter. Unlike electromagnetic waves, good sound propagation in the aquatic environment is characterized by acoustic waves. Sound in the aquatic environment is not as damped as it is in the air, and spreads several times faster. Despite the constraints associated with the water environment, which makes it difficult to carry out any measurements, acoustic wave methods are the most commonly used method of underwater measurement. This applies in particular to large area measurements and measurements at large depths. For submarine measurements, the use of side scan sonar (SSS) and multi-beam echo sounder (MBES) is most appropriate. The use of side scan sonar allows for the most detailed search of the bottom shape. The range of measurement depends on the frequency of the sound waves used, and varies from several dozen to several hundred meters. Side scan sonar provides limited information about the location and shape of underwater objects, as their measurement result is a two-dimensional image [4]. Unlike later side scan sonar, the multi-beam echo sounder is a cloud of points representing the bottom and all of the underwater objects encountered by the acoustic signals. Measurement range varies from several hundred to several thousand meters. The limitation of this measurement technique is the resolution and accuracy of the measurement of distance. For short-range measurements that are of interest to this project, you can achieve a resolution and a cloud point accuracy of about 0.1 meter [5].

Where required underwater measurements exceed the accuracy of acoustic measurements, it is possible to use underwater triangular laser scanners. Instruments of this type allow for very precise measurement (even under 1 millimeter) but their range is limited by the transparency of water. It is also possible to use photogrammetric techniques for underwater measurements. Underwater images allow for very precise measurements (even at millimeter). Photogrammetry is a fairly popular technique for measuring and documenting underwater archaeological objects. However, as with triangulation scanners, the measurement range is limited by the transparency of the water.

The differences in acoustic and laser measurements are shown in Fig. 1. The points represented by green were obtained by a mechanically rotating 3D scanning sonar with an angular resolution of 1 degree and frequency 2.25 MHz. The black and red points were obtained mechanically by the ULS-100 triangular triangulation scanner [6].

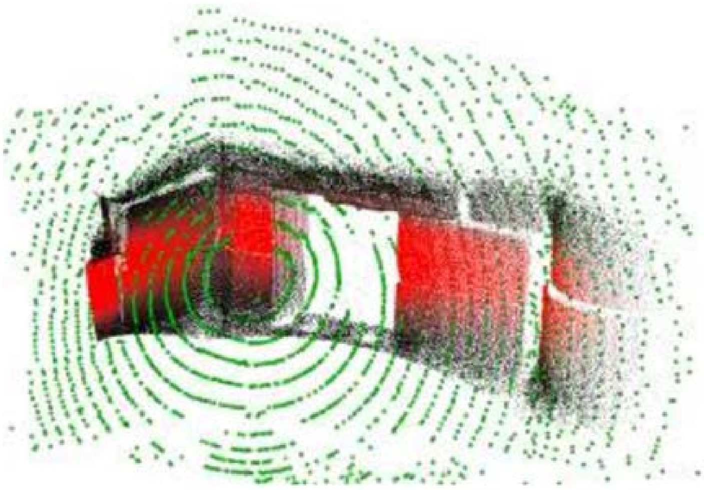

Fig.1. The differences in acoustic and laser measurements
(green points - acoustic, black and red - laser) [6]

It was planned for the project to purchase an underwater laser scanner with an underwater locating system. Currently available solutions of this type have some limitations that do not allow for full use of the potential of triangulation scanners to the planned precision measurements of underwater infrastructure. These limitations are related to the accuracy of georeference measurements. As a result, it was decided to begin work on creating an innovative triangulation scanner using multiple laser lines projected onto a measured object. Such a solution would make it possible to obtain from each photograph a cloud of points representing a part of the surface to be measured. Point clouds derived from a sequence of images could be used to improve the accuracy of the trajectory of the scanner's movement and consequently lead to a coherent model with high detail. As a result of the work, it was found that it is possible to construct a triangular laser scanner on the basis of low-cost, universally available components that allow the measurement of very detailed surface. The scanner's test model grew as a laser module and camera mounted on a photo rail, which collected the first point cloud data according to the target principle of the triangulation scanner (Fig. 2).

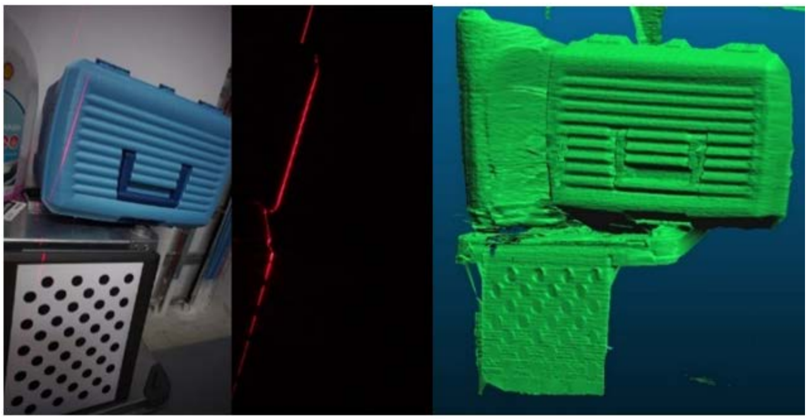

Fig.2. Measurement of objects using a model of a laser-scanner set on a photo rail

In parallel with the analysis of the properties of the triangulation scanner, the properties of complementary sensors were determined to decide the location and orientation of the scanner during the measurements. In the inertial sensor (IMU) test, four sensors were tested: KVH1750, VectorNav 100, Xsens MTi30 and STIM300. The possibility of integrating sensors with a submarine navigation system has been verified. A laboratory experiment was performed to verify the applicability of the sensors and a multi-criteria comparison of sensors was made. Program interfaces have been developed to integrate sensors with the operating system of an onboard submarine computer. Xsens MTi30 sensor was selected for further design work. The choice was dictated primarily by the maturity of Xsens technology (4th generation sensor) and better algorithm setting capabilities.

Because of the problems associated with the drift of inertial sensors, it has also become necessary to provide an additional source of location information. Therefore, the possibility of determining distance using hydroacoustic sensors was analyzed. The concepts and technical design of the underwater hydroacoustic system for underwater positioning have been developed. It is based on the acoustic wave propagation properties in water, which allows one to convert the time difference between the acoustic signal and its reception by hydrophones mounted on telemetry distances to the transmitter. The principle of operation of the system is based on communication with four floating telemetry buoys, which determine the distance from the pinger and send the signal to the receiver at the operator's computer. The software based on the received information calculates the position of the object.

3. Data georeferening and fusing from different sources

For the purpose of obtaining a submarine point cloud, a georeferencing system based on tags around the object was developed. The authors' layout of the markers was arranged in the form of five well-coordinated wheels. Also, a tag layout detection algorithm has been developed that automatically identifies each tag on each image captured. On this basis, it was possible to determine the location and orientation of the camera-laser system during the measurement. These works provided the first cloud of points representing the underwater object (Fig. 3).

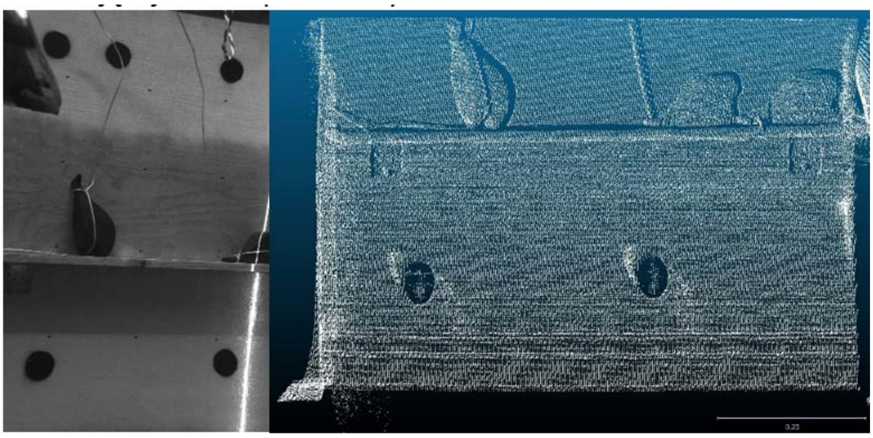

Fig.3. Photo of underwater object with visible marker system (left)
and image of the object using underwater cloud of points (right)

The developed georeference measurement system provided the positioning of the scanner, but the frequency of positioning obtainable by acoustic waves was approximately 1Hz, which was insufficient in relation to the intended operating frequency of the triangulation scanner camera (15Hz). In addition, the system would not provide system orientation information that is necessary for georeference. In connection with this, it was necessary to use the merging of acoustic sensor data with data from the inductive sensor type MEMS (Micro-Electro-Mechanical System).

For the purpose of selecting the fuzzy data algorithm and determining its parameters, a laboratory environment equipped with a positioning system simulator was used to enable the model pool to be used. The simulator fulfilled the functional assumptions corresponding to the planned parameters of the acoustic positioning system (position accuracy 0.5 m, time for positioning 1 s). The simulator's work is based on tag tracking technology, using the ARUCO library, which can track several tags on-line even when using energy-efficient ARM processors. An ROS (Robot Operation System, Indigo) compatible interface emulating the positioning system has been developed, so position information is processed to the appropriate format supported by the corresponding Kalman filter that also integrates the IMU data. Because the underwater positioning system does not provide as high a precision as the GPS system, there is a need to develop a concept of georeference measurement supported by providing additional data to improve the accuracy of the trajectory of the scanner. Hence, the concept of using multiple laser lines has emerged; so that from each image you can obtain a fragment of a surface model that could be used to improve the accuracy of the trajectory.

The underwater test data was obtained using a laser module and a diffraction grating that splits the laser beam into 25 parallel lines. The first challenge was to develop an algorithm that automatically detects the laser lines in the image. The goal was to bring the image to a binary form where black represents no laser line, while white corresponds to laser lines in the image. Many algorithms in the field of image processing and computer vision, such as local threshold, fast Fourier transform, Laplace filter, cumulative histogram, Canny edge detection, Sobel filter, image match, are implemented in the process of detecting the laser line. Finally, optimal results are obtained by applying the following sequence of operations: Gaussian filtering, global threshold, search for local maxima in each line of the image, scaling using the Gaussian pyramid.

The next step after receiving a binary image was to develop a laser line indexing algorithm. Each group of pixels representing the laser line should be given a laser line number to be able to correctly determine the field coordinates for those pixels. As part of the work carried out, an algorithm was developed to index the laser lines in an iterative way. In the first place, the algorithm assigns a unique identifier to each pixel group representing the laser line fragment. Then, for each line of the image, the sequence of identifiers is counted. The sequence of 25 identifiers that is most often considered to be the most likely sequence corresponding to laser lines in order from 1 to 25. According to this sequence, groups of pixels are assigned numbers 1 to 25. This is the point of departure for successive iterations that seek to assign line numbers. Groups of pixels are not uninfected in the first iteration. In subsequent iterations, recurring sequences are searched again. In case no repetitive sequence of identifiers is present, shorter sequences are sought. Each iteration generates line numbers according to the most common sequence of identifiers. The algorithm aborts at a time when there are no repeating sequences of identifiers.

Having obtained several underwater data sets, and testing the algorithm, it has been found that with more complex objects, a significant number of indexing errors appear. Correctly assigning a laser line number in the case where overlapping by complex objects has made it difficult for the observer. It was assumed that the cause was too close to the occurrence of the line, which leads in many situations to ambiguity and consequently to errors in line indexing. It was decided to replace the diffraction grating projection line with a projection grid of 11 lines. The surface model obtained on the basis of 11 lines is less detailed but more reliable (Fig. 4.). The developed algorithms based on 25 laser lines turn to 11 laser lines. Because the 11-line indexing results were still not error-free, further work has been done on creating an algorithm to detect errors in indexing results based on image sequences. Eliminating erroneously indexed lines is an important issue as they bring to the resulting cloud a noise point that can significantly hinder its further use.

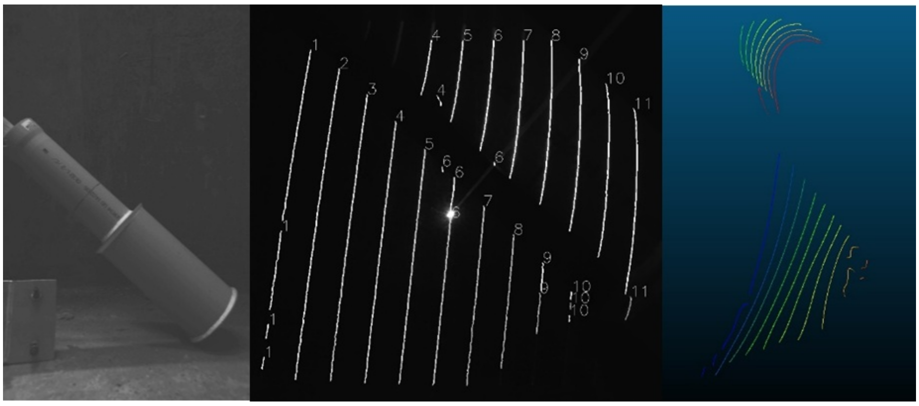

Fig.4. Photo of the underwater object (left), detected and indexed laser lines projected on the object (center), object point cloud formed on 11 laser lines (right)

Based on the results obtained, a decision was made to target the triangulation scanner consisting of a camera, a laser beam projector 1, and a second laser projection module 11 of parallel lines (Fig. 5).

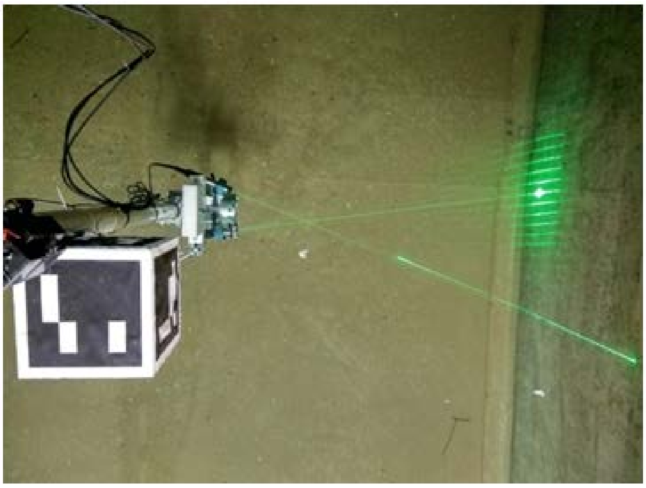

Fig.5. The final configuration of the triangulation scanner

4. Results

The direct result of the measurement carried out using the constructed scanner is the point cloud. Point cloud is a set of points with XYZ spatial coordinates. Point coordinates are derived from a high density surface measurement that allows you to reproduce the shape of the surface objects.

The reproducibility of objects depends on the density of the measurements, and on their accuracy. It was assumed that, based on the point cloud obtained by the constructed scanner, it would be possible to generate derivative products that would be the source of information on the underwater infrastructure, which could largely replace information from a visual inspection performed by a diver.

Two measurement campaigns were conducted during which 8 data sets were acquired to generate a point cloud. In the first campaign 2 measurements were taken, in the second campaign 6 measurements. Clouds of points were generated on this basis. Each time in the pool, the same objects whose dimensions were measured were placed. The visual analysis of the point clouds and the object models generated on them were first performed (Fig. 6 and Fig. 7). The accuracy of cloud points was then analyzed.

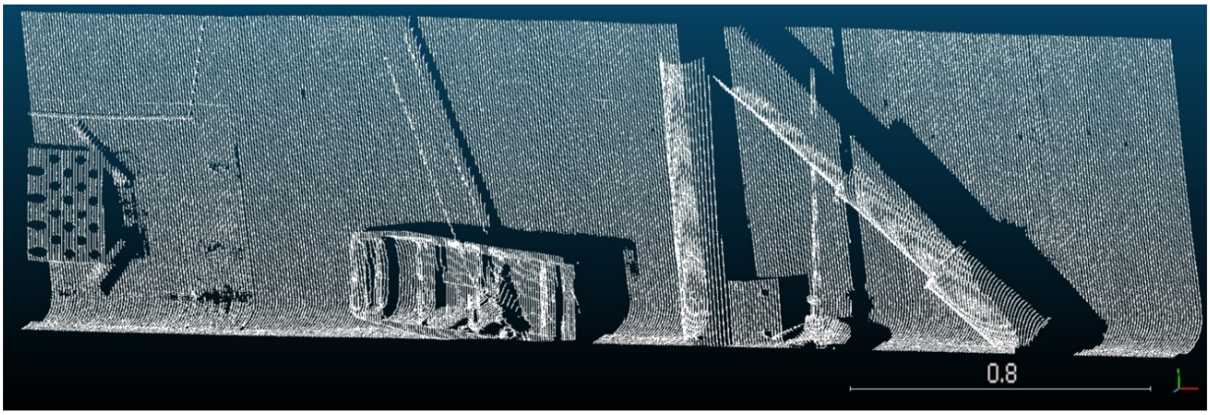

Fig.5. Point cloud showing the model pool wall and placed some objects at its bottom

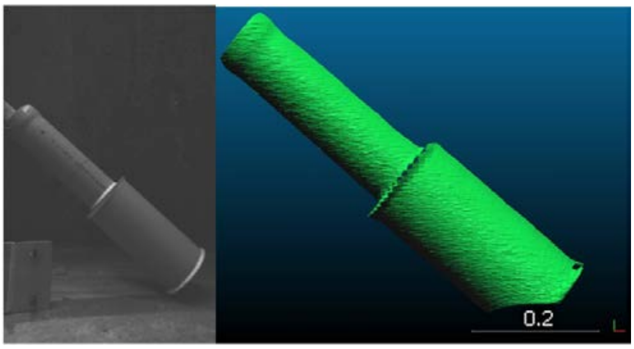

Fig.6. An image of a camera showing the object placed at the bottom of the pool (left) a model of this object generated on the basis of the measured cloud point (right)

The visual assessment of the obtained measurements showed that on the basis of the cloud point scanner model tested, it is possible to generate very detailed surface models that allow the identification of objects and damage with very high precision.

The accuracy of the point cloud was then assessed on the basis of the reference measurements. Five actual values (tube diameters, ship model dimensions) were measured and compared with point cloud measurements (Tab. 1).

Tab. 1. A summary of measurements made on the obtained points clouds with reference measurements

[m]	measuring campaign 1		measuring campaign 2								
	measurement										
	1	2	3	4	5	6	7	8	RM	SE	SD
Object 1	0,156	0,153	0,155	0,155	0,156	0,155	0,156	0,156	0,162	0,007	0,001
Object 2	0,104	0,107	0,107	0,106	0,107	0,106	0,106	0,107	0,111	0,005	0,001
Object 3	0,706	0,705	0,690	0,699	0,699	0,698	0,698	0,698	0,722	0,023	0,005
Object 4	0,284	0,283	0,276	0,282	0,276	0,275	0,274	0,275	0,287	0,009	0,004
Object 5	0,262	0,261	0,251	0,252	0,250	0,252	0,250	0,250	0,253	-0,001	0,005
									average	0,009	0,003

RM - Reference Measurement, SE - Systematic Error, SD - Standard Deviation

As can be seen from the table, the point cloud obtained using the laser scanner model allows the measurement of the size of the identified objects or phenomena (cracks, dents) to less than 1 cm. This fulfills all the requirements for underwater measurements, and their derived products, that the project team encountered during the project.

Another result of the project is the technology demonstrator presented in Fig. 7.

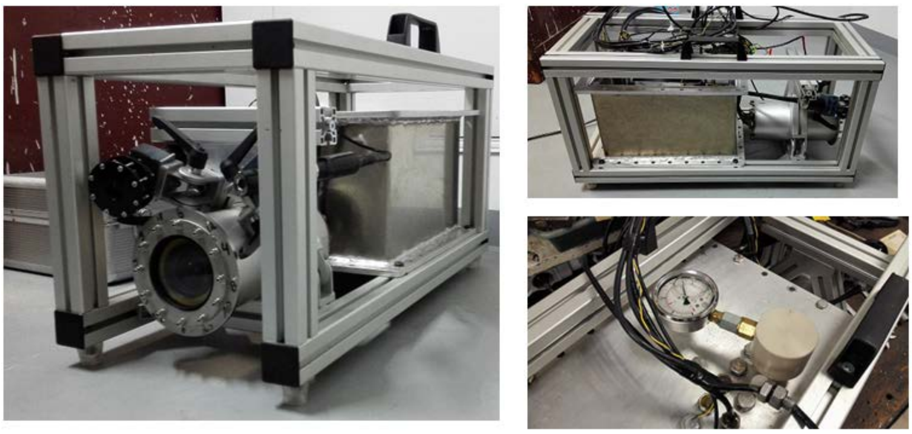

Fig.7. Technology demonstrator

Integration and management of the technology demonstrator sensors required designing a development environment. For the purposes of data fusion, a previously known ROS was used. Measurement data processing algorithms have been implemented in the Python programming language using OpenCV and PCL libraries. There is also a graphical user interface (GUI) that allows you to run previously developed scripts. The GUI allows for visualization of algorithmic results, which is more accessible to a user who is not routinely involved in programming.

The first stage of the demonstrator's test was to calibrate the system by developing the measurement data from the calibration field. The next stage was to obtain test data at the Gdansk University of Technology modeling pool, which simulates actual underwater conditions. Then, the quality of the measurements was assessed. Research has shown that achieving satisfactory georeference is hampered by the curvature of the extreme lines of the diffraction grating of eleven laser lines. Unfortunately, these imperfections are hidden by manufacturers, and there is no way to spot product defects based on technical documentation. In Fig. 8 you can see the design of straight lines, where in real conditions the pattern deviates strongly from the assumed design assumptions.

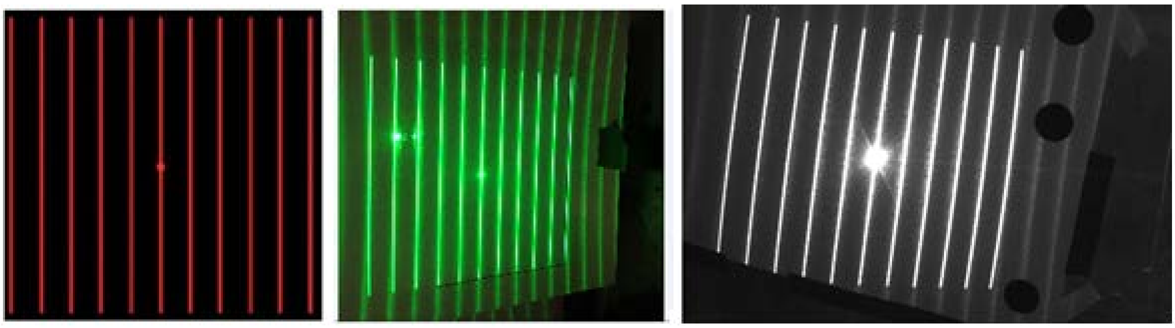

Fig.8. Grid pattern diffraction pattern 11, information provided by the manufacturer (left), behavior in the real world (center and right)

FastSLAM and Plain to Plain methods were used to compensate for point cloud alignment. However, they only brought a partial improvement. Detailed analysis of the trajectory obtained from Kalman filters indicated the possibility of unstable operation of the positioning system simulator.

The results of the demonstration tests in near-natural conditions (model pool along with the positioning system simulator) allowed us to draw conclusions and outline the future research work on the development of technology. The scanning system works very well if you have a good data georeference. Consider using visual feedback obtained from stereoscopic cameras, and verifying operation of the system with an acoustic positioning system. Improving the point cloud generation system from a single frame by eliminating the diffraction grating.

5. Summary

Underwater areas are the last areas on Earth that have not been mapped with high resolution (it is assumed that such maps exist for about 5% of their surface area). Changing this state of affairs is a unique technological and research challenge. The research and built-in technology demonstrator are a unique solution, which allows us to highly evaluate the feasibility of implementing / commercializing project results. Submarine mapping is dominated by acoustic systems that do not provide sufficiently high resolution data for inspection and metrology applications. At present, only 2 companies produce underwater laser systems (3D at Depth and 2G Robotics) on the world market. This indicates the high complexity of the problem and the potential market niche. At the same time, it is necessary to indicate the underwater conditions and wave propagation constraints introduced by this facility. The above challenges require further development work on the integration of new technologies (especially localization) and improvement of the developed system. In view of the high level of future technology implementation, it should be noted that this will require quite a long development phase.

The new knowledge gained during the project allowed for the construction of a unique mobile scanning system demonstrator. Continuing technological development, taking into account the conclusions of the demonstrator's tests, should allow further development of the system.

Acknowledgments

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