Development of low-cost Unmanned Surface Vehicle system for bathymetric measurements

J. Wajs¹,∗ and D. Kasza¹

¹Wrocław University of Science and Technology, 27 Wyb. Wyspiańskiego St., 50-370 Wrocław, Poland

*Corresponding author: jaroslaw.wajs@pwr.edu.pl

Abstract. Bathymetric measurements are a significant branch of geodesy. They provide information required for the modeling of terrain topography below the water level for both running (lotic) and standing (lentic) waters. The existing technology allows the development of autonomous bathymetric systems which integrate Global Navigation Satellite Systems (GNSS) sensors, an echosounder/sonar and a floating platform. Such a solution has been designed at Wroclaw University of Science and Technology. BATDRON – an integrated bathymetric system – is a low-cost solution. The hull is in the form of a catamaran, which ensures high stability during measurements. The navigation module was based on the Ardupilot APM platform and was integrated with a propulsion system consisting of two T200 thrusters manufactured by Bluerobotics. The main sensor set uses a Satlab SLD-200 single beam echosounder synchronized with a Trimble R6 GNSS antenna for both navigation and recording the position of the echosounder pole.

1. Introduction

The rapid pace of technological progress intensifies research related to the development and implementation of remote measurement techniques. In various engineering projects, an increasingly extensive use is being made of minimally or entirely non-invasive measurement technologies and instruments which provide data required in further processing and analyses. This fact applies also to bathymetric measurements.

An Unmanned Surface Vehicle (USV), such as the one focused on in this article, is a measurement platform comprising a boat and remote or autonomous propulsion, navigation and measurement systems. Although prototypes of USVs have been used for military purposes since the Second World War [1], they were significantly improved and employed on a wide scale in the 1990s [2]. Their applications include collecting and analyzing samples of water, gas and organic matter, as well as mapping lotic and lentic waters [3-7].

2. Design and technical setup

Based on the reviewed literature and on analyses of various types of structures, the authors of this article decided to design a double-hull boat, i.e. a catamaran. This decision was motivated primarily by the high transverse stability of such structures [2, 8-13]. In theory, this design solution will minimize the offset from the vertical of the pole equipped with the sensor set – the GPS antenna and the echosounder.
1.1 Hull – design and development

The float of the catamaran was designed in the SketchUp environment. The design concept was to ensure that the boat has high stability during measurements in both running and standing waters, while preserving its manoeuvrability and minimum dimensions. The size and shape of the float are shown in Fig. 1A. During the design phase, a decision was made not to provide the boat with a keel/skeg in order to enable it to move on shallow waters. Stability is provided to the boat by two floats in a parallel, catamaran-type arrangement.

The physical model of the float was built of expanded polystyrene (EPS) with the use of a 5-axis CNC milling machine. The results of this step are shown in Fig. 1B. In the next step, the milled model was covered with a laminate consisting of fiberglass and polyester resin. The boat was finished with polyester putty reinforced with micro fiberglass (Fig. 1C).

The chosen CNC milling technology allowed the boat model to be precisely built, preserving the design dimensions and shapes. The surface of the hull was subsequently covered with acrylic lacquer (Fig. 1D). The typically final step, consisting in the extraction of the filler material, was not necessary due to the planned installation of the thrusters. Moreover, if a hull structure filled with EPS becomes discontinued in an emergency situation, such as a collision, it can preserve its displacement properties.

The floats were connected with a custom-designed, H-shaped frame made of V-slot 20x20 mm Open Builds aluminum profiles. The frame was connected with the use of joining plates. The Open Builds technology allows the frame to be easily configured, or provided with additional elements and sensors in order to further modify the floating platform.

![Figure 1](image.png)

**Figure 1.** Four modeling and development steps of the BATDRON catamaran: A – conceptual model; B – physical model made with the CNC milling machine; C – painting of the hull; D – boat joined with the aluminum H frame.

The catamaran, designed and built in the low-cost approach, was equipped with two Peli on-board cases. One of them contains a power module, a computer and control electronics as well as a thruster commander. The second case contains the bathymetric data-acquisition module and a Bluetooth module for communication with the controller.
1.2 Propulsion system, communication and control
The catamaran is equipped with the Graupner radio communication device provided with telemetry services for transmitting data from the on-board computer. The navigation module was based on the Ardupilot APM platform, which was integrated with a propulsion system consisting of two thrusters. The thrusters are T200 engines manufactured by Bluerobotics. The T200 is the smallest underwater thruster for ROVs, AUVs and surface vessels and is compatible with Bluerobotics Thruster Commander and fully integrated with Ardupilot software. The main idea of the navigation mode was to apply the ArduRover 2.43 firmware. The Ardupilot was integrated with GPS positioning to navigate the boat. As a result, the vehicle can be not only controlled manually, but also set in automatic navigation mode. The system is provided with radio-frequency live transmission of telemetric and location data, based on free QGroundControl software. The operator can use a background map to plan a mission or trace the current position of the vehicle in live mode. The mission is planned on the basis of the defined Area of Interest (AOI) and of the automatic definition of the itinerary in order to record its measurements in the form of e.g. a regular grid.

1.3 Measurement system
The bathymetric measurement system comprises a Satlab SLD-200 single beam echosounder. At the current stage of the USV development project, the depth sounding is performed independently from the navigation (Fig. 2). The system uses a Trimble R6 receiver installed on a measurement pole integrated with the head of the echosounder. The measurement is an integration of the GNSS signal with the synchronized single beam echosounder signal in time T via Bluetooth using the NMEA 0183 standard. The Satlab SLD-200 echosounder has a measurement range starting at 40 cm and reaching a maximum depth of 120 m. The measurement resolution is 0.01 m. The specification of the single beam echosounder is presented in Table 1.

![Figure 2. BATDRON RC boat equipped with SATLAB SLD200 echosounder.](image-url)
Table 1. Technical specification of the Satlab SLD-200 echosounder Sonar Transducer Specification.

| Specification                        | Value                  |
|--------------------------------------|------------------------|
| Beamwidth                            | 9°                     |
| Depth Range                          | 0.4 m to 100 m         |
| Resolution in Depth                  | 0.01 m                 |
| Ping Frequency                       | 200 kHz                |
| Data Output Rate                     | 1 Hz                   |
| Serial Interfaces                    | BlueTooth, Mini USB    |
| Data Format (both USB and BlueTooth) | 4800 baud, 8 bits, 1 stop bit, no parity. NMEA 0183 Standard |
| Measurements (WxHxL)                 | 60 mm x 34 mm x 165 mm |
| Environmental resistance             | IP67                   |

The spatial coordinates of a measurement point in a selected flat coordinate system are based on the position recorded by the GNSS receiver as a 3D coordinate \((X,Y,h_A)\) of the antenna, with the \((h_A)\) component reduced by the height of the pole \((s)\) and by the distance measured by the echosounder \((e)\), which consequently equals the elevation of the floor of the waterbody \((h_B)\), in accordance with (1):

\[
h_B = h_A - (s + e)\]

The above relationship is graphically represented in the figure below (Fig. 3A). The catamaran-type design of the USV allows the pole to maintain its vertical position and thus ensures that the measurement of the pole height \((h_A)\) is collinear. The bathymetric measurements were preceded by measurements of the elevation of the water level \(-h_{WL}\) (2). With the known draft of the echosounder mounted on the boat, these data may be used to calculate the relative depths in the analyzed reservoir. The horizontal position is recorded by the GNSS RTK receiver, while the elevation of the waterbody floor is calculated from the following equation (3):

\[
h_{WL} = h_A - s\]
\[
h_B = h_{WL} - (d + e)\]

The above method for calculating the elevation below the water level is valid on condition that the boat has a constant draft during the bathymetric mission. In this research, independent identification of the XY position and of the relative depth based on the elevation of the water level (Fig. 3B) was not used for 3D underwater digital terrain modeling.

**Figure 3.** Schematic diagram of depth measurements based on the integration of the single beam echosounder with the GNSS receiver (A) direct measurement of the position and of the elevation in real time, (B) relative floor elevation measurement based on the water level.
3. First test and results
A quarry located in the vicinity of the Gross-Rosen Nazi camp in Rogoznica (Lower Silesia in southwestern Poland) was selected as the site for the first test of the measurement platform. The site is a currently closed granite quarry, known for the slave labor of prisoners from the neighboring Gross-Rosen concentration camp. Difficult working conditions and accidents limited the average life length of the people working in the quarry to not more than five weeks. Currently, the quarry is flooded, and the water level in the deepest spot of the excavation was estimated at approximately 25 m [14].

3.1 Mission planning
The catamaran is controlled by sending the telemetry data to a laptop with the Mission Planner software installed in it. The Mission Planner software ensures full flight control and mission planning for each drone compatible with Micro Air Vehicle Protocol – MAVLink. Its main objectives include providing easy operation and access using the Apache 2.0 and GPLv3 open license. The initial tests of communication with the catamaran and its configuration were performed with the use of the QGroundControl [15] and Mission Planner [16] software. Having access to the preview of the position of the boat in real time on the control panel, the operator can remotely control the boat and avoid potential collisions. Obstacles observed on the Gross Rosen reservoir during the tests caused the planned bathymetric mission to be performed in the manual VLOS (Visual Line of Sight) mode. Originally, the surveying mission of the bathymetric boat was planned in the form of a regular grid based on the Region of Interests (ROI; Fig. 4).

3.2 Data acquisition
The measurement data are recorded with the use of the Trimble TSC3 controller, in the GNSS RTK measurement profile and in reference to the ASGEUPOS network [17]. The trajectory of the bathymetric

Figure 4. Surveying grid planned with Mission Planner.
The recorded position of the boat was transformed into the Polish system of coordinates, i.e. PL-ETRF2000 (EPSG:2177). The elevation data measured in the ellipsoidal coordinate system were transformed with the use of a geoid model PL-geoid-2011, as part of the implementation of the global EGM08 geopotential model [18] for the area of Poland, and into the normal height system PL-KRON86-NH. The Trimble R6 receiver was installed in two points of the Polish geodetic control network. The bathymetric measurements were preceded by measurements of the elevation of the water level. With the known draft of the echosounder mounted on the boat, these data may be used to calculate the relative depths in the analyzed reservoir.

The bathymetric data acquisition was performed at 1 m distances, by integrating the Trimble R6 antenna with the SLD200 echosounder in the GNSS RTK measurement mode. The result was a set of 1546 measurement points. The measurement time was approximately 30 minutes. The boat speed was approximately 1.5 m/s. During the bathymetric data acquisition process, the tracked satellite signal was partially lost due to obstacles as the boat moved under the edge of the excavation. Because of this fact, the position of the boat could not be identified with a satisfactory precision in the GNSS RTN/RTK mode and thus the measurement was not performed.
3.3 Data processing

The tests of the BATDRON bathymetric boat in the Gross Rosen quarry included: elevation measurements of the water level, bathymetric data acquisition and laser scanning of the excavation in order to obtain the contour of the object. The bathymetric data acquisition provided a set of measurement points representing the position of the boat and the elevation of the waterbody floor, calculated from equation (1) and graphically represented in Fig. 3A. The positions of the boat and the echosounder measurements were recorded in the ASG-EUPOS RTN Fixed mode, with mean survey point errors shown in the following table. The positioning accuracy did not exceed 0.05 m and was obtained with the GNSS Trimble R6 receiver working in the ASGEUPOS RTK/RTN mode. The measurement error for the third dimension (h) is the sum of the GNSS RTK position accuracy and of the SATLAB SLD200 echosounder accuracy and did not exceed 0.10 m (Table 2).

| Label | X     | Y     | h    |
|-------|-------|-------|------|
| Error [m] | 0.046 | 0.045 | 0.076 |
| RMSE  | 0.022 | 0.021 | 0.030 |

The elevation of the water level was 273.55 m a.s.l. The maximum depth of the analyzed reservoir was 244.33 m a.s.l. The above survey data may serve to calculate the maximum measured depth, which was 29.22 m. Fig. 6A shows the surveying points recorded by the original BATDRON platform. For the purpose of this research, an additional laser scanning was also performed with the use of a RIEGL V400i scanner. The purpose was to obtain a contour of the analyzed Gross Rosen waterbody (Fig. 6B).

3.4 Bathymetric map of the reservoir

The numerical models of the Gross Rosen reservoir floor were reconstructed on the basis of the data acquired with the use of the Satlab SLD200 single beam echosounder and the contour surveyed with an independent geodetic technique. The contour of the reservoir is represented by a cloud of 109,494 points, which were linked to the set of bathymetric measurements (1546 points) to finally provide a total of 111,030 points. These points were processed with the use of four methods for developing numerical
terrain models in the GRID data structure. The underwater DTM (Digital Terrain Model) was visually represented using the Surfer software. For the purpose of this research, uDTM visualizations were prepared with the use of the most used algorithms [19]: Inverse Distance to a Power, Nearest Neighbor, Local Polynomial and Triangulation with linear interpolation (Fig. 7).

![Figure 7](image_url)

**Fig. 7.** The results of interpolation algorithms: A) Inverse Distance to a Power; B) Nearest Neighbor; C) Local Polynomial; D) Triangulation with linear interpolation.

4. Conclusions
A USV system developed at Wroclaw University of Science and Technology performs bathymetric surveys and allows a contact-free and fast acquisition of data on the waterbody depth. BATDRON, as a low-cost platform, allows the sensor to be transported to the required position and along a required trajectory based on the GNSS positioning of the boat. The thrusters used in the design offer a stable and fluent operation of the boat in the RC mode. The project is developed on the Ardupilot Pixhawk open navigation firmware and allows both integrating additional sensors and planning automatically performed missions. In the future, the BATDRON platform can be extended with additional sensors for detecting obstacles in order to perform autonomous bathymetric surveying missions. The Satlab SLD200 echosounder installed on the boat allows the waterbody depth to be recorded in real time. The
single beam measurement system provides highly accurate uDTM coordinates. Eventually, the position accuracy depends on the GNSS receiver and on the RTK/RTN positioning technique (0.05 m), while the measurement error for the third dimension (h) is the sum of the accuracies of the GNSS RTK position and of the SATLAB SLD200 data, and does not exceed 0.10 m. The waterbody elevation could be surveyed with greater accuracy by using relative measurements which would combine the draft of the echosounder with the echosounder measurement of the floor in a particular XY position.

The test measurements performed at the Gross Rosen reservoir demonstrated that the BATDRON platform enables bathymetric missions with data acquisition in the GNSS RTK mode. Missions in objects of this type had to be performed in the manual VLOS mode in order to avoid potential collisions with the banks of a reservoir. During the data acquisition process, the boat lost its fix position at the banks of the reservoir, as the GNSS antenna lost the tracked satellites due to obstacles. This limitation of precise positioning in the GNSS RTK/RTN mode rendered data acquisition impossible at a required RTK Fix accuracy level and therefore these measurements were discarded. The survey data comprise 1546 points measured during one mission over a time of 30 minutes. Remote bathymetric survey performed with the use of the RC BATDRON boat based on the GNSS positioning system allows mobile, fast and accurate uDTM modeling. In comparison to classic geodetic techniques of waterbody floor surveying, the use of a low-cost BATDRON boat provides time savings while the measurement accuracy is maintained at a level similar to classic manned bathymetric missions performed on a boat or a pontoon. Its design and the use of thrusters gives the BATDRON boat a potential to be used for bathymetric missions also on running waters (rivers).

References
[1] Corfield S J and Young J M 2006 Advances in Unmanned Marine Vehicles (Institution of Electrical Engineers) pp 311-328
[2] Manley J E 2008 Unmanned surface vehicles, 15 years of development OCEANS 2008 pp 1-4
[3] Lesser M P and Mobley C D 2007 Coral Reefs 26 819-829
[4] Caccia M, Bibuli M, Bono R, Bruzzzone Ga, Bruzzzone Gi, Spirandelli E. 2007 Marine Technology Society Journal 41 2 pp 62-71(10)
[5] Naeem W, Xu T, Sutton R, Tiano A 2008 Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment 222(2) pp 67-79
[6] Ferreira H, Almeida C, Martins A, Almeida J, Dias N, Dias A, Silva E 2009 OCEANS 2009 pp 1-6
[7] Seto M L and Crawford A 2015 OCEANS 2015 pp 1-5
[8] Qi J, Peng Y, Wang H, Han J 2007 International Conference on Information Acquisition pp 361-365
[9] von Ellenrieder K 2013 Journal of Marine Engineering & Technology 12:1 pp 3-11
[10] Sohn S, Oh J, Lee Y, Park D, Oh I 2015 IEEE Journal of Oceanic Engineering 40 2 pp 388-396
[11] Villa J L, Paez J, Quintero C, Yime E, Cabrera J 2016 IEEE Colombian Conference on Robotics and Automation (CCRA) pp 1-5
[12] Zhixiang L, Youmin Z, Xiang Y, Chi Y 2016 Annual Reviews in Control 41 pp 71-93
[13] Dobref V, Popa I, Popov P, Scurtu I C 2018 IOP Conference Series: Earth and Environmental Science 172
[14] https://www.gross-rosen.eu/
[15] http://www.qgroundcontrol.org/
[16] http://ardupilot.org/planner/
[17] Bosy J, Grasza W, Leonczyk M 2007 European Journal of Navigation 5 4 pp 2-6
[18] Pavlis N K, Holmes S A, Kenyon S C, Factor J K 2008 EGU General Assembly 2008
[19] Šiljeg A, Lozic S, Šiljeg S 2015 Hydrol. Earth Syst. Sci. 19 pp 3653-3666