

Integration of multi-source point clouds for bridge inventory – case study

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Abstract

The accurate inventory of hydro-technical infrastructure, such as bridge structures, requires the seamless integration of data capturing both above-water and submerged geometries. This study presents a comprehensive workflow for the fusion of multi-source point clouds acquired using an integrated Norbit iLidar and Winghead i77h multibeam echosounder (MBES) system. A primary focus is placed on the challenges of data acquisition in demanding environmental conditions, specifically under-bridge areas characterized by degraded GNSS reception and multipath interference. To ensure survey-grade accuracy and geometric consistency, a rigorous field calibration procedure, including a specialized LiDAR and MBES Patch Test, was implemented. The results demonstrate that precise determination of boresight angles — specifically a Roll correction of -0.3° for the LiDAR sensor—is critical to eliminating systematic offsets and "ghosting" effects in the fused model. Furthermore, the study accounts for environmental factors such as sound velocity variability (1486.5–1487.6 m/s) and beam refraction at the air-water interface. The resulting integrated point cloud, with resolutions of 1 cm (LiDAR) and 2 cm (MBES), served as the foundation for structural 3D modeling using Building Information Modeling (BIM) and Constructive Solid Geometry (CSG) approaches. The findings confirm that the proposed diagnostic and correction workflow significantly enhances the reliability of digital twins for bridge health monitoring and hydro-morphological analysis in complex engineering environments.

1. Introduction

The modern measurement techniques enable increasingly accurate mapping of engineering infrastructure elements in the hydro environment. In recent years, there has been a dynamic increase in the use of integrated data from Multibeam Echo sounders (MBES) and Laser Scanning Systems (LiDAR) for three-dimensional modeling of bridge structures and analysis of hydro-morphological processes. As emphasized by Yin et al. (2020), the shift towards point cloud-based bridge health monitoring represents a significant advancement over traditional inspection methods, offering a more comprehensive and objective digital representation of the structure's condition.

Specht (2024) presented a methodology for comprehensive bathymetric and photogrammetric measurements using UAV and USV platforms, pointing to the need to integrate various observation techniques in the coastal zone. Rowley et al. (2020) compared the accuracy of data from LiDAR, SfM, and MBES systems in the context of geomorphological analyses, confirming the complementarity of these methods in underwater and above-water environments. Li et al. (2022) proposed methods for recording point clouds from bathymetric LiDAR and multibeam echo sounders, emphasizing the importance of precise data matching in 3D models. Furthermore, Michałowska and Gocał (2021) demonstrated that the effective integration of MLS (Mobile Laser Scanning) and MBES data is crucial for the technical inventory of hydrotechnical structures, where the continuity of the model between the submerged and emerged parts determines the quality of the final engineering documentation. In turn, Włodarczyk-Sielicka and Damaševičius (2025) drew attention to the potential of using artificial intelligence methods in the automation of hydroacoustic and LiDAR data processing.

Despite the availability of integrated surveying systems, standard manufacturer procedures often prove insufficient in demanding environmental conditions, such as under-bridge areas with degraded GNSS reception. This necessitates the development of specialized verification and data correction workflows. Even for advanced solutions like the Norbit system, which offer native time-synchronization between GNSS/INS, MBES, and LiDAR sensors, achieving survey-grade accuracy requires a rigorous field calibration. In practice, sensor installation on the survey vessel (e.g., via the Portus mounting system) is rarely ideal, leading to discrepancies in extrinsic parameters—specifically regarding spatial offsets and boresight angles between the sonar, LiDAR, and GNSS antennas. Furthermore, geometric errors resulting from platform dynamics—roll, pitch, and yaw—along with potential GNSS latency, must be systematically corrected through a patch test to ensure the spatial integrity of the fused multi-medium point cloud.

A critical challenge in the integration of MBES and LiDAR data for bridge inventory is the degradation of positioning quality in GNSS-denied or multipath-prone environments. Under-bridge sectors frequently suffer from signal shadowing and poor satellite geometry, which directly impacts the precision of the Inertial Navigation System (INS) trajectory. In such conditions, even minor misalignments in the extrinsic orientation of the sensors—commonly referred to as boresight errors—are significantly amplified, leading to 'ghosting' effects or vertical offsets in the fused point cloud. Rigorous determination of these angular offsets is a fundamental requirement in laser scanning systems to ensure geometric consistency (Skaloud and Lichti, 2006). While modern systems like Norbit iLidar provide high-frequency synchronization, they remain sensitive to the initial lever-arm and angular offset values. Without a rigorous patch test procedure to decouple mounting misalignments from trajectory-induced errors, the resulting 3D model may fail to

meet the stringent accuracy requirements for structural health monitoring and hydro-morphological assessment. The aim of the study was to propose a procedure for the diagnostics and correction of calibration errors in integrated MBES–LiDAR systems, with a particular focus on the iLidar system performance in GNSS-constrained environments.

2. Materials

The object of the study was a road bridge located approximately 30 km north of Warsaw, Poland. The bridge is 332 m long and 13.5 m wide. The bridge is located over Lake Zegrze, which is a retention reservoir on the Narew River (Figure 1).



Figure 1. Bridge over Lake Zegrze a) orthophoto (GSD = 5 cm), www.geoportal.gov.pl; b) bottom view; c) side view

A mobile topographic Norbit iLiDAR system was used to measure the bridge structure above the water surface. Velodyne VLP-16 sensor is widely used in scientific research due to its characteristics and availability. The most important parameters of the topographic Norbit iLiDAR scanner are presented in Table 1.

Parameter	Value
Infrared Laser module:	1-20 Hz Time of Flight with dual returns
Wave Length	905 nm
Field of View:	360° horizontal, 30° vertical
Range:	100 m
Scan speed:	up to 300 000 points per sec
Dimensions:	103 mm x 130 mm x 150 mm
Weight:	2,4 kg

Table 1. Norbit iLiDAR parameters

Bridge pillars measurement and the shape of the bottom of the water reservoir in the immediate vicinity of the bridge were performed using a Norbit Winghead i77h multibeam echo sounder.

The NORBIT WINGHEAD i77h is a compact ultra-high resolution curved array broadband multibeam sonar offering tight integration with GNSS/INS (Applanix OceanMaster) that is designed for use in the most demanding operational environments, such as under bridges or in rough sea conditions.

The main parameters of the NORBIT WINGHEAD i77h echo sounder are listed in Table 2.

Parameter	Value
Swath coverage:	5-210°
Number of Beams	256, 512, 1024
Range Resolution	< 10 mm
Depth Range	0.2 m to 400 m
Operating Frequency	nominal 400 kHz, 200-700 kHz
Ping Rate	Up to 60 Hz, Adaptive
Position Accuracy:	
- Horizontal	± (8mm + 1ppm x distance from RTK station)
- Vertical	± (15mm + 1ppm x distance from RTK station)
Heading	0.02°
Pitch/Roll	0.008°
Heave	5 cm

Table 2. Parameters of the NORBIT WINGHEAD i77h MBES

The control unit integrates data from the MBES, GNSS antennas, and LiDAR, then transmits it to a computer equipped with hydrographic software. The antennas, echosounder, and lidar were mounted using the Portus mounting system. For hydroacoustic measurements, it is important to account for the speed of sound propagation in water. The AML SV Profiler was used to measure the sound velocity profile in water.

The vessel is prone to tilting, which are measured continuously using GNSS/INS devices. Nevertheless, in the process of processing LiDAR and MBES data, it is necessary to correct the data in order to reduce geometric errors related to platform movement: Roll, Pitch, Yaw and GPS Latency.

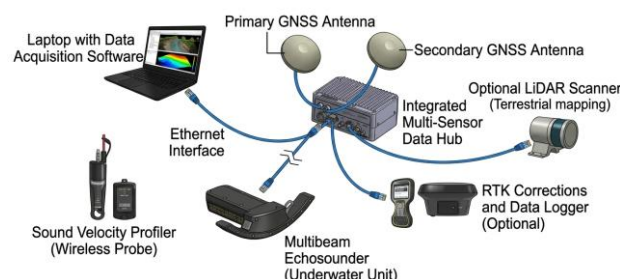


Figure 2. Integrated measurement system Norbit Winghead i77h with iLiDAR

In order to bridge point clouds integration, a workflow has been proposed: LiDAR and MBES data filtering, consideration of the speed of sound in water, LiDAR and MBES data calibration including Patch Test and MBES cross check (Figure 2). The MBES cross check refers to a quality control method used in multi-beam echo sounder (MBES) surveys to verify the accuracy of bathymetric data.

3. Methods

3.1. Data acquisition

The bridge measurements were taken on August 22, 2025, at an average water level of 5 m. The air temperature was 20 °C, with an average wind speed of 8.5 km/h. LiDAR and MBES measurements were taken from the deck of a manned RIB boat (Figure 3).



Figure 3. RIB boat with integrated Norbit Portus measurement system

The average speed of the boat was 4 knots. The frequency of the hydroacoustic beam was 400 KHz. As a result, 7 measurement lines around the bridge and 4 measurement lines for the MBES data calibration were acquired (Figure 4).

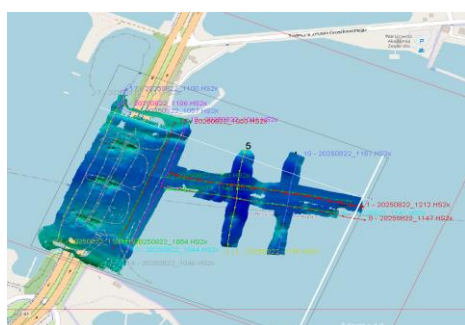


Figure 4. Acquired MBES data with measurement lines

The table below shows the measurement parameters of the MBES multibeam echosounder (Table 3).

Parameter	Value
Sweep Time	200 μ s
Frequency	400 KHz
Bandwidth	80 KHz
Swath	90°
Direction	90°

Table 3. MBES parameters during bridge pillars measurement

To ensure reliable measurement results, it is necessary to measure the speed of sound in water each time data is acquired with a multibeam echosounder. The speed of sound propagation is proportional to water temperature, water pressure, and salinity (Figure 5).

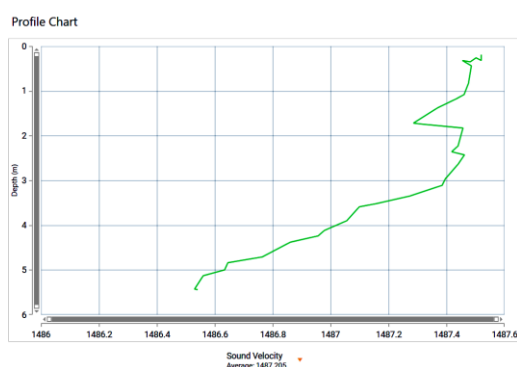


Figure 5 . Graph of the velocity of sound propagation in water, Lake Zegrzyskie, 22/08/2025

Lake Zegrze is a large freshwater reservoir with no salinity. Sound velocity measurements were taken using a profilometer. The sound velocity in the water ranged from 1486.5 m/s to 1487.6 m/s.

3.2. Data Processing

Data processing included sound velocity compensation, noise filtration (median and adaptive filters), and GNSS/INS error correction through LiDAR calibration and a patch test. Although the LiDAR orientation is specified by the manufacturer (NORBIT, 2024), precise mounting angles must be determined for hydrographic software. The MBES Patch Test was performed to determine precise angular corrections and time delays between the transducer, IMU and GNSS system.

Measurement data acquired with the multibeam echosounder are also subjected to a calibration procedure, the MBES Patch Test. The purpose of the MBES Patch Test is to determine precise angular corrections and time delays between three key systems on the vessel: the echosounder (transducer), the inertial measurement unit (IMU), and the positioning system (GNSS).

After taking into account corrections for roll, pitch, yaw, and GPS latency, two point clouds are obtained from different measurement systems (Lidar and MBES), reduced to a single, common reference system. The workflow of LIDAR and MBES data integration is illustrated below (Figure 6).

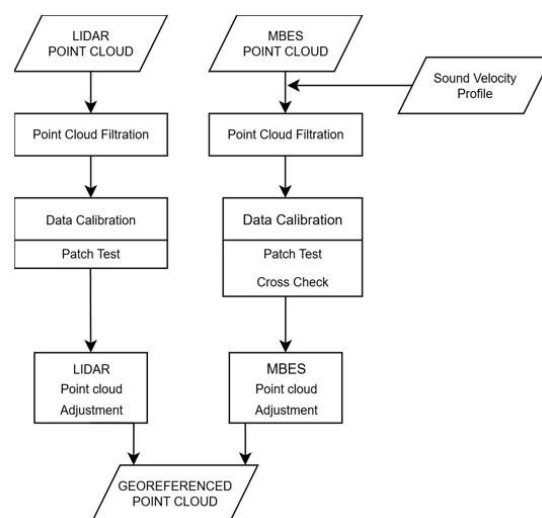


Figure 6. Integration of LiDAR and MBES data – workflow

The obtained georeferenced point cloud can be the basis for developing a 3D model of the bridge.

4. Results and Discussion

As a result of data acquisition, two point clouds were obtained: above water (LiDAR point cloud) and under water (MBES point cloud). Then data calibration was necessary. LiDAR data calibration was performed based on measurement lines parallel to the bridge. The MBES patch test and cross check were performed on four measurement lines intersecting each other, running over the deepening.

4.1. LiDAR Data Calibration

The iLidar orientation must be specified in the acquisition software. The HYPACK 2024 Hardware software was used to acquire data, for which the applying mounting angles according to the iLidar User and Technical Manual (NORBIT, 2024) are: roll: 0°; pitch 0°; yaw (heading): 180°. Above mounting angles are initial value only. A Lidar calibration must be performed, similar to the multibeam patch test, to determine the precise mounting angles.

The iLidar system calibration integrated with the RIB Boat required determining angular corrections to ensure geometric consistency of point clouds recorded from different directions and with varying vessel dynamics. Using the structure of the bridge pillars as reference objects allowed for precise minimization of residuals in three planes (Figure 7).

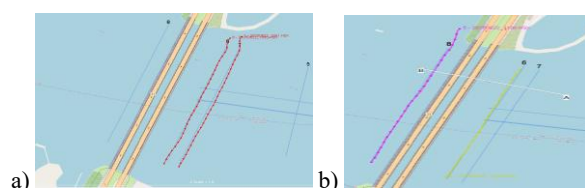


Figure 7. Measurement lines used for data calibration LiDAR
a) roll, yaw (red lines), b) pitch (pink and yellow lines)

To compensate roll angle, a cross-sectional profile was drawn through two measurement lines, located on the same side of the bridge, in the same direction, but at different distances from the object. Compensation for pitch deviations was performed using a cross-sectional profile drawn through two measurement lines, located on opposite sides of the object, in opposite directions. The last angle to be calibrated is the yaw (heading) angle. The same measurement lines were used to calibrate the data for yaw as for the roll angle, but this time the profile line was drawn along the measurement lines (to process the yaw, the profile is taken along the structure).

Before calibration, point clouds from different measurement lines do not overlap. During the calibration process, virtually changing the mounting angle (roll, pitch, or yaw) results in the clouds overlapping. (Figure 8).

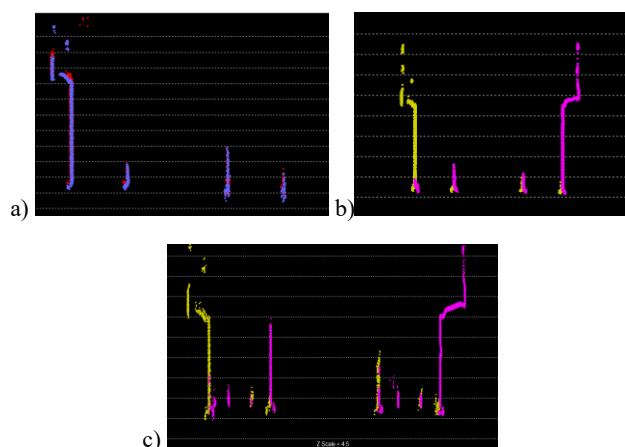


Figure 8. Cross-section of the point cloud from different measurement lines after the calibration process: a) for the roll angle, b) for the pitch angle, c) for the yaw angle

In addition to cross-sections representing overlapping point clouds, Depth Error plots are used to assess calibration accuracy (Figure 9). The V-shaped residual plot illustrates the process of finding the minimum of the error function. The sharper the lower peak, the more unambiguous the geometric fit of the point clouds, which directly translates to the accuracy of the resulting point cloud.

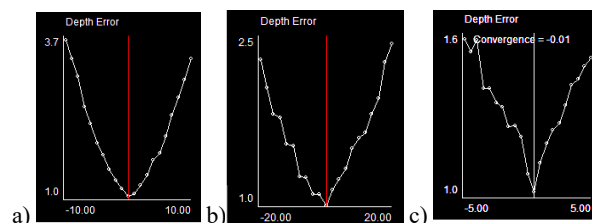


Figure 9. Depth Error plots for LiDAR offsets
a) Roll b) Pitch, c) Yaw

As a result of calibration, corrections were made to the data due to the following angles: Roll, Pitch, Yaw (Table 4).

	HYPACK 2024	LIDAR Patch Test
Roll	0 °	-0.3°
Pitch	0 °	0.00°
Yaw	180 °	180.05°

Table 4. LIDAR patch test results

As a result of calibration, the roll value changed from -0.3° to -0.3°. This means that the LIDAR head is physically tilted 0.3° to the left relative to the longitudinal axis of the IMU reference system. This is the most significant correction, as the error in the roll axis increases linearly with distance from the scanner, causing "undulations" in the terrain at the edges of the scan strip. The pitch angle value remained at 0°. This suggests perfect alignment of the sensor's longitudinal axis with the reference system. The yaw angle value changed from the standard 180° to 180.05°. The difference indicates minimal horizontal rotation of the head relative to the platform's axis of symmetry. This error would manifest itself as vertical objects "spreading out" when scanning in opposite directions. As a result, the Lidar point cloud was aligned. The figures below show the bridge pillar before and after Lidar data calibration (Figure 10).

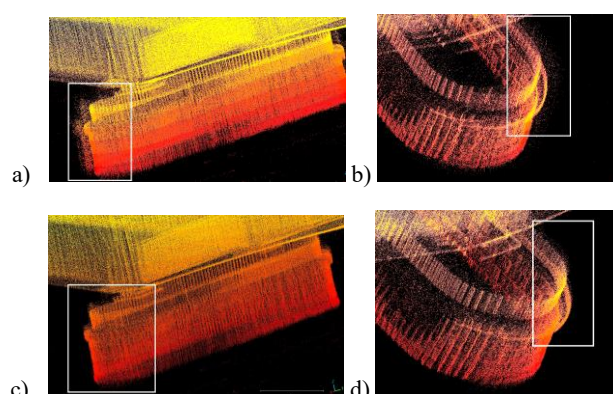


Figure 10. Lidar point clouds of a bridge pillars above the water surface. a) and b) before calibration; c) and d) after calibration.

4.2. MBES Data Calibration

The calibration of the point cloud with MBES consisted of two stages: patch test and cross check.

4.2.1. MBES Patch Test - data acquired from measurement lines are considered to correct for GPS latency roll and pitch. In the integrated Norbit Portus system, GNSS antennas are mounted on a dedicated antenna bracket integrated with the echosounder head. This ensures that the base vector (the line between the GNSS antennas) is parallel to the MBES head axis, so the angular error between the GNSS heading and the echosounder axis (yaw) is 0° .

GPS Latency: two lines in the same direction, over a point object, at different speeds; **Pitch:** two lines in opposite directions, over a point object or slope (constant speed); **Roll:** two lines in opposite directions over a flat bottom (Figure 11).

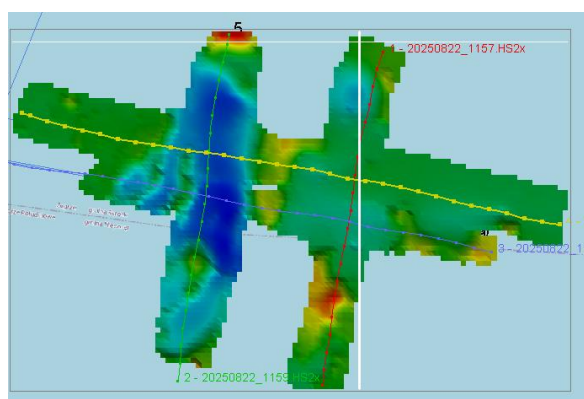


Figure 11. Measurement lines used to calibrate the MBES data

Patch Test was conducted using HYPACK 2024 software (HYSWEEP Calibration module). Calibration of multibeam systems is based on the Profile Matching method. The process involves iteratively determining angular corrections by eliminating geometric discrepancies in the point cloud.

In HYPACK software, the process follows a strictly defined sequence because errors are interdependent: **GPS Latency correction:** Time synchronization between the navigation system and the echo sounder. The time offset corrects the position of the object on the profile. **Pitch correction:** Elimination of longitudinal errors. Correction is applied until the object profiles recorded from opposite courses perfectly overlap. **Roll correction:** A key step in eliminating lateral error. The correction aims to achieve a horizontal plane and eliminate the "smile" or "sad" effect (V-shape) in the lateral profile. The table below shows corrections for GPS latency, roll and pitch for MBES data (Table 5).

Parameter	Initial Offset	MBES Patch test
GPS Latency	0.00 s	0.10 s
Pitch	-0.05°	0.45°
Roll	0.34°	0.14°

Table 5. MBES calibration results

The accuracy analysis of the MBES patch test is provided by the Depth Error plots (Figure 12). The values on the horizontal axis represent the tested parameter values, while the values on the vertical axis represent the sum of the squared differences

(residuals) between the two measurement lines. The point at the very bottom of the "V" is the minimum of the error function.

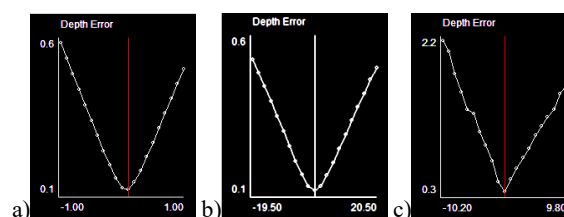


Figure 12. Depth Error plots for MBES offsets
a) GPS Latency, b) Pitch, c) Roll

The GPS Latency test showed a minimum time offset of 0.1s. This result confirms the correct configuration of the time synchronization protocols (PPS/NMEA) between the positioning system and the echosounder's central unit. This is a very small value, typical of modern integrated systems. The Pitch parameter calibration was performed over a bottom with diverse morphology, ensuring high sensitivity of the profile matching algorithm. The determined correction of $+0.45^\circ$ eliminated the longitudinal offset of the bathymetric data. The Depth Error plot is characterized by a sharp and unambiguous minimum, confirming the correct time and geometric synchronization of the system in the longitudinal axis. Roll angle calibration also shows a clear minimum of the error function (which allowed for the precise determination of the Roll offset at 0.14°). The small correction value (-0.20°) relative to the initial settings demonstrates high measurement repeatability and the stability of the echosounder head's mounting on the vessel.

4.2.2. MBES Cross Check - in order to confirm the reliability of the determined corrections, a comparative analysis of the control line with the reference surface was performed, the so-called Beam Angle Test (Figure 13).

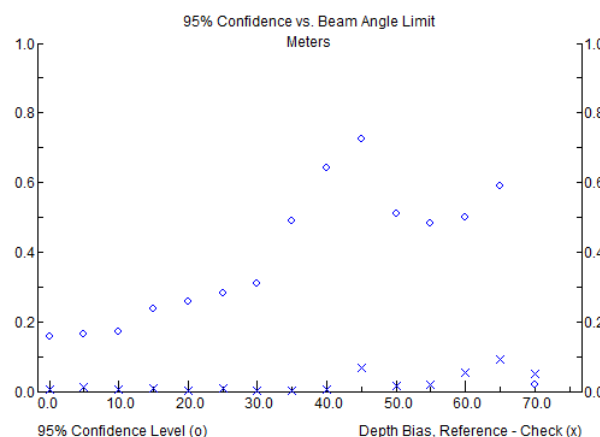


Figure 13. Vertical TPU (Total Propagated Uncertainty) at 95% confidence level vs. beam angle.

Detailed analysis of residuals in the beam angle test showed:

High nadir stability: In the angular range from the probe axis, the confidence error does not exceed $\pm 0.30^\circ$, which allows the data to be classified to the highest order of accuracy IHO Special Order.

Increased uncertainty at the periphery: Above an angle of 45° , an increase in the 95% Confidence parameter to the level

was observed. This phenomenon is consistent with the error propagation theory of 0.6–0.7m in MBES systems (increase in beam spot size and the effect of refraction).

Correctness of Roll correction: A constant value of the Depth Bias parameter in the entire angular range (close to 0.0 m) finally confirms the correctness of the performed Patch Test.

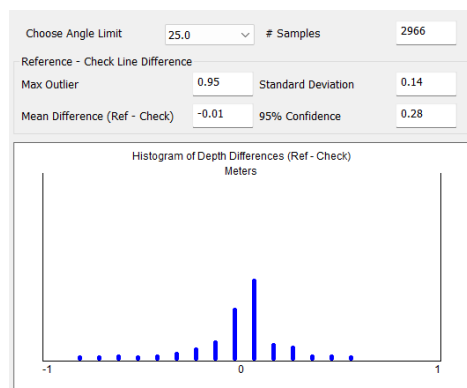


Figure 14. Histogram of depth differences between the check-line and the reference surface

Statistical analysis (Figure 14) showed that the mean depth error (Mean Difference) was only ± 0.01 m, demonstrating almost complete removal of systematic errors. The total vertical uncertainty at the 95% confidence level was ± 0.28 m.

4.3. Lidar and MBES point clouds integration

As a result, the integrated point cloud of the bridge was created (Figure 15). The LiDAR point cloud resolution was 1 cm and the MBES point cloud resolution was 0.02 m. Coordinate system was ETRS89/UTM zone 34N (EPSG:25834)

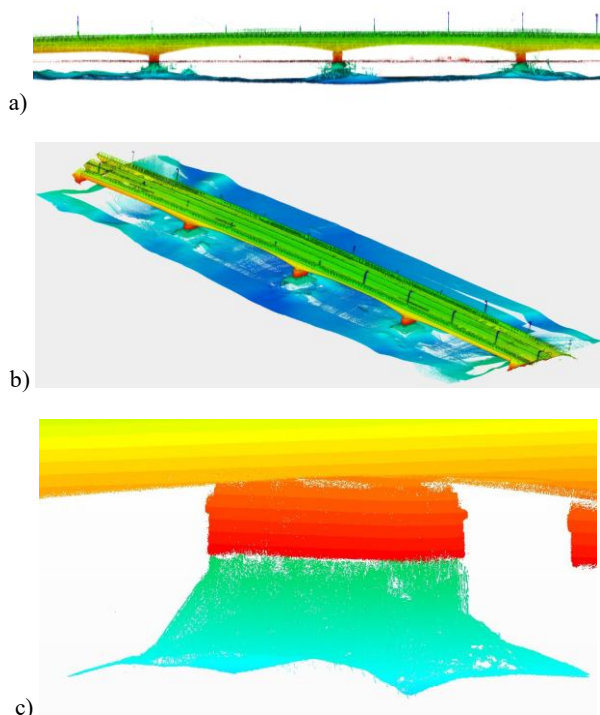


Figure 15. The integrated point cloud of Zegrze Bridge
a) side view b) oblique view c) a bridge pillar

A key challenge in integrating multi-source data is analysing the behaviour of measurement beams at the air and water environments. Ideally, the point clouds from the two sensors (LiDAR and MBES) should meet exactly at the water surface, representing the continuous surface of the bridge pillars. However, in practice, a small gap between the two point clouds is often observed.

This gap may be due to the following reasons:

1. LiDAR does not measure points from the wet surface of the pillar just above the water;
2. A multibeam echosounder may have difficulty measuring the surface in areas of high aeration near the water surface. The acoustic beam does not pass through the air for measurement. It terminates at the water surface or an object;

The opposite phenomenon can be observed, namely, overlap between two point clouds. This is because, in very clean water, the laser beam sent by the lidar can reflect 1 to 2 cm below the water surface. We typically consider such points as noise. This is because when the laser beam hits the water, it refracts according to Snell's law.

When measuring bridge structures (pillars) underwater, refraction occurs in the water itself. This is primarily due to changes in water temperature and pressure and their impact on the speed of sound in water. Without an SVP (Sound Velocity Profile) measurement, the pillar will appear "bent" in the point cloud (recorded by the point cloud, below the water surface) (the so-called smile or sadness effect).

In addition to refraction, another factor that can influence the integration process of point clouds from two sensors is turbidity. In the case of the LiDAR system (905 nm), turbidity does not affect the geometry of waterside objects, as the beam is absorbed at the interface. In the case of MBES, high turbidity can generate acoustic noise, but with the 400 kHz frequency and short measurement range, this impact on geometric accuracy (point position) is negligible. This phenomenon did not affect the consistency of the integration of both point clouds and only required standard surface noise filtering.

4.4. 3D model bridge

The final stage of the workflow involved transitioning from the integrated point cloud to a structural 3D model using two distinct methodologies: Building Information Modeling (BIM) and Constructive Solid Geometry (CSG). The fused, georeferenced point cloud served as the high-resolution spatial backbone for both processes.

BIM Approach (Autodesk Revit): The bridge was reconstructed as a 3D BIM model to support comprehensive bridge inventory and asset management (Figure 16). Using the point cloud as a template, parametric families were developed for the pillars and spans. This allowed for the enrichment of the geometric model with semantic data, which is essential for creating a functional digital twin of the infrastructure.

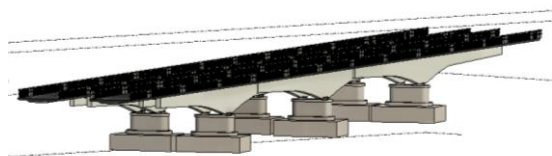


Figure 16. 3D BIM model of the bridge support developed in Autodesk Revit

CSG Approach (Blender): To achieve a highly detailed geometric representation, the Constructive Solid Geometry (CSG) method was employed (Figure 17). This technique involved using Boolean operations on geometric primitives to reconstruct the complex shapes of the pillars. This approach proved particularly effective in ensuring a seamless transition between the underwater sections (MBES) and above-water structures (LiDAR).

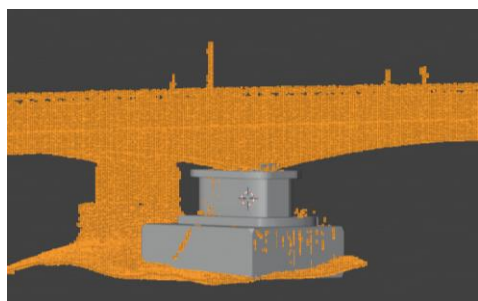


Figure 17. Geometric reconstruction of the pillar using Constructive Solid Geometry (CSG) in Blender.

The resulting 3D models provide a reliable basis for monitoring erosion and accumulation phenomena around the pillars, as well as for analysing the long-term stability of the bridge supports.

5. Conclusion

As a result of our work, we developed and verified a procedure that increases the reliability of data integration in specific engineering conditions, enabling the detection of errors that cannot be eliminated by standard manufacturer tools. The conducted research demonstrated that integrating multi-source point clouds from LiDAR and MBES systems enables the mapping of engineering structures in aquatic environments. Based on the obtained results, the following conclusions were drawn:

Calibration Efficiency: Performing a rigorous patch test procedure for both sensors is essential to achieving survey-grade accuracy, especially in challenging underwater conditions with limited visibility of GNSS satellites. This eliminated errors resulting from mounting angles and vessel dynamics (roll, pitch, yaw).

The role of the sound velocity profile (SVP): A key factor in ensuring the correct underwater geometry was the compensation of sound velocity changes (1486.5–1487.6 m/s), which prevented acoustic refraction errors resulting in pillar shape deformation.

Practical applications: The integrated 3D model provides a reliable basis for monitoring erosion processes around

supports, analysing structural stability, and verifying hydrodynamic models. The resolution of MBES (≈ 0.02 m) may be insufficient for detecting underwater structural cracks. However, the integrated 3D model can serve as a foundation for building digital twins of critical infrastructure.

Directions for further research: Future work will focus on the use of machine learning algorithms for automatic classification of structural elements and detection of geometric changes over time based on archived and current point clouds.

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