AN AUTOMATED SYSTEM FOR CALIBRATION TABLE CALCULATION OF CYLINDRICAL HORIZONTAL TANKS

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Abstract. *The article presents the results of the development and implementation of the software "Automated Calculation of Calibration Table" for the calibration of steel cylindrical horizontal tanks obtained using 3D laser scanning. The proposed system automates the processing of 3D point clouds using a hybrid segmentation method (RANSAC and DBSCAN) and improved geometric formulas for calculating a per-millilitre capacity table. The results of calculating volumes and capacity coefficients are compared with alternative enterprise software, which demonstrates an increase in accuracy by 5–15% and a reduction in processing time by 70–80%. The developed software adapts to tank deformations, ensuring reliability in industrial conditions, which is confirmed by data analysis for 10 tanks with a cloud density of 5–15 million points.*

Keywords: calibration, 3D analysis, point cloud, control system, automation system, computer-integrated technologies

AUTOMATYCZNY SYSTEM DO OBLICZANIA TABELI KALIBRACYJNEJ CYLINDRYCZNYCH ZBIORNIKÓW POZIOMYCH

Streszczenie. *Artykuł przedstawia wyniki opracowania i wdrożenia oprogramowania "Automatyczne obliczanie tabeli kalibracji" do kalibracji stalowych cylindrycznych zbiorników poziomych uzyskanych za pomocą skanowania laserowego 3D. Proponowany system automatyzuje przetwarzanie chmur punktów 3D przy użyciu hybrydowej metody segmentacji (RANSAC i DBSCAN) oraz ulepszonych wzorów geometrycznych do obliczania tabeli pojemności w mililitrach. Wyniki obliczeń objętości i współczynników pojemności porównano z alternatywnym oprogramowaniem przedsiębiorstwa, co wykazało wzrost dokładności o 5–15% i skrócenie czasu przetwarzania o 70–80%. Opracowane oprogramowanie dostosowuje się do deformacji zbiorników, zapewniając niezawodność w warunkach przemysłowych, co potwierdza analiza danych dla 10 zbiorników o gęstości chmury wynoszącej 5–15 milionów punktów.*

Słowa kluczowe: kalibracja, analiza 3D, chmura punktów, system sterowania, system automatyki, technologie zintegrowane z komputerem

Introduction

Oil is an important energy for the sustainable development of society. In many countries, an oil reserve system has been established to ensure security. Large cylindrical tanks are used to store oil because they are economical and take up little space. These tanks are the main equipment for storing oil. Optimizing the frequency of metrological supervision, taking into account the type, volume of tanks and maintenance schedules, allows you to reduce costs and increase the accuracy of control [13]. This contributes to ensuring economic efficiency and environmental responsibility. The lack of universal criteria for determining the frequency of tank calibration makes it difficult to ensure their effective metrological supervision. It is necessary to adapt the calibration frequency according to the type of tank, its volume and operating conditions. This will allow synchronizing metrological control with maintenance, minimizing costs and environmental impact [16]. This approach contributes to increasing the accuracy of measurements and supports global standards for trade and environmental safety.

Large deviations in tank volumes are often associated with theft or sabotage, but research [1] shows that they are mainly caused by inaccuracies in tank calibration. Analysis of two sets of calibration data revealed significant discrepancies due to deformations caused by uneven roads, accidents and other physical factors that affect the accuracy of inventory records in the supply chain. This highlights the importance of regular calibration to improve the accuracy of inventory management and minimize economic losses.

Calibration of steel cylindrical tanks is a key process that ensures accurate determination of the volume of liquid during its storage. Correct accounting of products and effective inventory management depend on this. There are several calibration methods, among which the most common are hydrostatic and geometric methods:

1) Hydrostatic method.

This method involves filling a tank with water and determining the volume based on the liquid level and its density [8]. Although the hydrostatic method is quite simple and widely used, its main disadvantage is its high labor intensity and dependence on the measurement conditions. Humidity, temperature and other external factors can affect the accuracy of measurements.

In addition, the method requires significant water and time. However, in cases where it is not possible to use more modern approaches, the hydrostatic method remains the main tool, especially for small-volume tanks.

2) Geometric method.

The geometric method [9, 10, 19] is based on measuring the physical parameters of the tank, such as diameter, length, wall curvature, and subsequent volume calculations based on these parameters. This method is one of the most accurate, since it eliminates the influence of external factors, such as temperature and liquid density. It allows you to calculate the volume based only on the geometric data of the tank. The main disadvantages of this approach are the complexity and duration of calculations, which makes it less attractive in cases where it is necessary to obtain a result quickly. The geometric method is divided into the manual-strapping method (MSM) [10] and electro-optical methods (Electro-Optical Distance Ranging (EODR)) [9, 19]. The manual measurement method is outdated and is mainly used to improve the calculation results of other methods. Electro-optical calibration methods use specialized devices that measure the liquid level or pressure in the tank with subsequent automatic calculation of the volume. This approach provides speed and accuracy, but requires high costs for equipment and its maintenance. In addition, electronic methods require high technical knowledge to work with the equipment and software.

In the article [15], a comprehensive analysis of methods for quality control of the volume of tanks for storing liquids, such as petroleum products and chemicals, was conducted. The main results of the study are that geometric methods are effective for tanks with a clear geometry, while hydrostatic methods are more suitable for tanks with complex shapes or small capacities. 3D laser scanning was recognized as a promising method due to its accuracy and the ability to take into account tank deformations. The need for standards to harmonize this method with international standards was noted. The results of the article can be used to improve tank quality control processes in the industry, as well as for the further development of technologies and standards in this field.

In the study [2], a comparative analysis of tank calibration methods was conducted: manual measurement (MSM) and electro-optical remote measurement (EODR). The EODR method provides higher accuracy, speed and safety, but is more

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expensive to use, while MSM is more economical, but requires more time and effort. Both methods meet international standards, but EODR is recommended for use in cases where accuracy and speed of calibration are important. Another study [3] evaluated geometric calibration methods for liquid storage tanks using the Fuzzy TOPSIS (F-TOPSIS) approach. Four main calibration methods were considered, including their strengths and weaknesses, according to the following criteria: accuracy, risk, execution time, physical effort, cost. The electro-optical method was recognized as the best with a proximity coefficient of 0.974, while the manual measurement method showed the worst result – 0.197. Another technique, the Fuzzy Analytic Hierarchy Process (FAHP), was used to confirm the results, which also recognized the electro-optical method as the most effective method.

The paper [14] investigates the advantages of 3D laser and photo-scanning for metrological control of tanks. Both methods provide high measurement accuracy (up to ±0.5%), the ability to create 3D models and detect deformations. Photo-scanning is more convenient to use, but its effectiveness decreases in low-light conditions. These technologies are recommended to improve the accuracy and speed of tank inspection in industry.

Also, studies suggest modern calibration methods, such as 3D laser scanning and process automation through Monte Carlo simulations. Knyva et al. [11, 12] proposed the use of laser scanning to create high-precision point clouds that allow accurate determination of the volume of tanks even under conditions of deformation of their geometry. This approach provides high accuracy and detailed analysis of errors, but requires significant financial resources and specialized equipment. In contrast, Zhou and Zhang [21] considered the use of Monte Carlo simulations to automate calibration. This method is more accessible and versatile for different types of tanks, although its accuracy depends on the quality of the mathematical model and input data. The study by Samoilenko & Zaets [18] considers an improved laser scanning method that allows calibrating tanks taking into account their real deformations. Unlike Knyva et al., this approach provides a more detailed analysis of geometric parameters, such as radius, surface area, and volume. In addition, the work of Samoilenko & Zaets pays special attention to the assessment of errors due to operating conditions, which makes the method more versatile compared to previous approaches. The approaches have their advantages and limitations: laser scanning is ideal for complex tank geometries, while Monte Carlo [4] simulations are more effective for mass application. Another innovative approach is photogrammetric methods that allow non-contact measurement of tank geometric parameters and detection of their deformations [6]. These methods provide high accuracy and significantly simplify the control process. In addition, data processing techniques based on VAB and OLE described by Wan et al. [20], contribute to the automation of the creation of calibration tables and provide flexibility for working with tanks of different types. At the same time, the development of sensor systems for tanks with variable orientation, as noted by Segura et al. [5], allows for effective control of liquid volumes even under difficult operating conditions. The integration of these modern methods into the practice of metrological control will not only increase accuracy, but also adapt the calibration process to various industrial conditions, which is critical for ensuring efficiency and economic feasibility [7].

The presented geometric methods can provide high accuracy, but require a lot of time, which leads to errors in calculations. In this context, automation of the calibration process becomes of great importance. It allows you to avoid errors, speed up the calculation process and increase the reliability of the results. The development of software for automated calculation of the calibration table is a step towards optimizing this process, which allows you to combine the accuracy of the geometric method with the speed and convenience of modern technologies.

The purpose of this article is to present the results of our own calculations of the calibration of various horizontal tanks, as well as to compare the obtained results with the calculations of the enterprise. The work will calculate the capacity of the tanks and perform a comparative analysis of the accuracy and efficiency of the calculations.

1. Software description

In response to the need to optimize the tank calibration process, the "Automated Calibration Table Calculation" software was developed based on the Python programming language using libraries for 3D data processing. This software integrates the processes of importing a point cloud, segmentation, estimating geometric parameters, calculating filling volumes, and generating output documents. The software's algorithm is based on the geometric calibration method, improved by automating the stages of laser scanning data processing, which allows taking into account tank deformations and ensuring millilitre accuracy of the capacity table.

The block diagram of the automated system on which the software is built is presented in Fig. 1, which illustrates the sequence of steps from scanning the tank to forming a calibration table. The process begins with laser scanning of the tank (internal or external) using a FARO Laser Scanner Focus3D X130 scanner, followed by obtaining a point cloud in the text format *.xyz. For external scanning, an ultrasonic thickness gauge is used to correct the wall thickness, which ensures adaptation to real operating conditions.
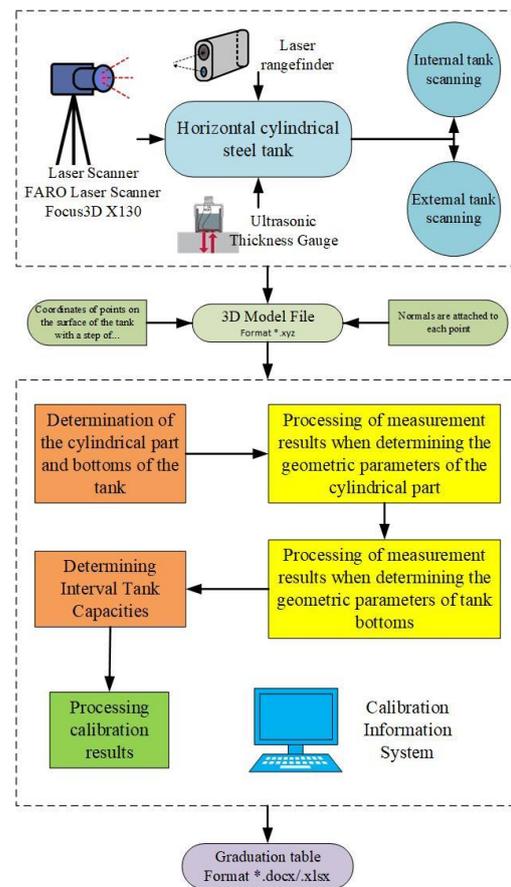

Fig. 1. Block diagram of an automated system

To improve clarity and reproducibility, the complete processing pipeline, from point cloud import to calibration table generation, is described below as a structured algorithm. Mathematical models used at individual stages are introduced after the algorithm and explicitly referenced by step numbers.

Algorithm 1. Calculating a calibration table deformation-aware from a 3D point cloud

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Input: 3D point cloud $P=\{(x_i, y_i, z_i, n_i)\}_{i=1}^{N}$, scan metadata (optional).

Output: Calibration table $V(h)$, capacity factor $K(h)$.

Parameters:

RANSAC threshold τ (2–3 mm, corresponds to scanner noise), number of iterations I (500–1000, fixed for all tanks); DBSCAN parameters ε (2–5 mm, fixed, density-independent), $minPts$ (30–50, fixed); axial window length Δx (0.5–1.0 m, depends on tank length); numerical integration step δx (0.01 m, simpson's rule); fill-level step $\delta h = 1$ mm; Monte Carlo sample size M (1000–5000, stable σ(V) convergence).

1. Import and preprocessing
   Load the point cloud, remove outliers, and verify or estimate surface normals.
2. Segmentation of tank geometry
   Extract the cylindrical surface using RANSAC and cluster the remaining points into front and rear bottoms using DBSCAN, followed by boundary refinement based on local geometric features.
3. Geometric parameter estimation
   Estimate the cylinder axis, length L, and spatially varying radius $R(x)$; fit geometric models to the segmented bottoms.
4. Volume computation for each filling level
   For $h=0$ to $2R$ with step δh:
   4.1 Compute the cylindrical-part volume $V_{cyl}(h)$.
   4.2 Compute bottom volumes $V_{b1}(h)$ and $V_{b2}(h)$.
   4.3 Obtain total volume $V(h)$.
5. Capacity factor computation
   Compute the capacity factor $K(h)$.
6. Report generation
   Export results to .xlsx and .docx formats.

The mathematical formulation used in the software directly corresponds to the steps outlined in Algorithm 1.

The first step is to import the point cloud and segment it into the cylindrical part and the bottoms. A detailed description of the hybrid segmentation method, which combines the RANSAC algorithms for estimating the parameters of the cylindrical surface, DBSCAN for clustering and refinement of boundaries based on local geometric characteristics, is given in a separate paper [17]. The segmentation approach itself is not claimed as novel in this manuscript and is described in detail in [17]. In this software, segmentation is performed automatically with reference to the mentioned methodology, which allows reducing the error by 2–5%. The segmentation parameters are optimized depending on the density of the cloud (from 1 million to 18 million points), ensuring noise resistance (~12% of the total number of points, as shown in [17]).

After segmentation, the software estimates the geometric parameters: the radius R of the cylindrical part (using the least squares method on the selected points), the length L (projection onto the cylinder axis) and the bottom parameters (radius of curvature for different shapes). The calculation improvement consists in integrating the correction for deformations: for the cylindrical part, an ellipsoid approximation is used (if a deviation from an ideal cylinder >0.5%) which reduces the error of volume estimates at low filling levels ($h < 10\%$ of the diameter) by 1–3% compared to alternative software, as confirmed by the results in the "Calculations and Results" section. For the bottoms, surface fitting (flat or curved) is used taking into account the point normals, which increases the accuracy of accounting for volumes at the edges of the tank.

The calculation of the filling volumes is performed iteratively for each level h (from 0 to $2R$ with a step of 1 mm for a millilitre table). In Step 4.1 of Algorithm 1, the basic formula for the volume of a horizontal cylindrical segment without taking into account the bottoms and deformations, as in the DSTU 7475:2016 standard [19], has the form:

$$V_{cyl,\,std}(h) = L\left[R^2 \cos^{-1}\left(\frac{R-h}{R} \right) - (R-h)\sqrt{2Rh-h^2} \right] \quad (1)$$

where L is the length of the cylindrical part, R is the radius, h is the filling level. However, this formula provides an ideal geometry, which leads to a loss of up to 5–10% in real tanks with deformations (e.g. due to wear or irregularities, as shown in [3]). To improve it, we modified the formula by integrating from a point cloud: the radius R is replaced by the locally averaged $R(h)$, calculated as a function of the filling level using a polynomial approximation (degree 2–3) at the segmented points of the cylindrical part. This takes into account the ellipticity of the cross section, where $R(h) = R0 + ah + bh2$, with coefficients a, b determined by least squares (fitting error (fit – fit, adaptation) < 0.1%). Modified formula:

$$V_{cyl,\,imp}(h) =$$

$$\int_0^L \left[R(x)^2 \cos^{-1}\left(\frac{R(x)-h}{R(x)} \right) - (R(x)-h)\sqrt{2R(x)h-h^2} \right] dx \quad (2)$$

where $R(x)$ is the variation of the radius along the length L (approximated from the cloud using PCA for local segments of length 0.5–1 m). This integration is performed numerically (Simpson's method with a step of 0.01 m), which reduces the error by 3–7% for deformed tanks and provides smoother volume dynamics.

In Step 4.1 of Algorithm 1, for bottoms, the standard formula for an elliptical segment is:

$$V_{ell,std}(h) = \frac{\pi R^2 c}{3}\left[3\left(\frac{h}{c} \right)^2 - 2\left(\frac{h}{c} \right)^3 \right] \quad (3)$$

where R is the radius of the head base (equal to the cylinder radius), m; c is the nominal semi-minor axis (head depth from documentation), m; h is the liquid segment height in the head ($0 \le h \le c$). This expression assumes an ideal ellipsoidal shape without accounting for real deviations.

Improved formula accounting for actual geometry from point cloud data:

$$V_{ell,imp}(h) = \frac{\pi R^2 c}{3}\left[3\left(\frac{h}{c} \right)^2 - 2\left(\frac{h}{c} \right)^3 \right] \cdot (1 + k_{def}) \quad (4)$$

where R is the effective base radius, determined as the weighted average distance from the cylinder axis to points in the transition zone after boundary refinement; c is the effective semi-minor axis, obtained via least-squares ellipsoid fitting to the head point cluster; k_{def} is the shape deviation correction coefficient:

$$k_{def} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\|\mathbf{p}_i - \mathbf{o}\| - d_{ideal}(\mathbf{p}_i)}{d_{ideal}(\mathbf{p}_i)} \right)^2 \quad (5)$$

with p_i the i-th point in the head cluster, o the fitted ellipsoid center, d_{ideal} the theoretical distance for the ideal shape, and N the number of points. Typical k_{def} values range from –0.012 to +0.028.

Standard formula for spherical segment:

$$V_{sph,std}(h) = \pi h^2\left(R_{sph} - \frac{h}{3} \right) \quad (6)$$

where R_{sph} is the nominal sphere radius (from documentation); h is the segment height.

Improved formula:

$$V_{sph,imp}(h) = \pi h^2\left(R_{sph} - \frac{h}{3} \right) \cdot (1 + k_{def}) \quad (7)$$

where R_{sph} is the effective sphere radius obtained by least-squares sphere fitting to the head points; k_{def} is calculated analogously using spherical distance metrics.

Standard formula for a conical segment:

$$V_{con,std}(h) = \frac{\pi h}{3}\left(R^2 + R^2\left(1 - \frac{h}{H_{con}} \right) + \left(R\left(1 - \frac{h}{H_{con}} \right) \right)^2 \right) \quad (8)$$

where R is the base radius (cylinder radius); H_{con} is the nominal cone height.

Improved formula:

$$V_{con,imp}(h) =$$

$$= \frac{\pi h}{3}\left(R^2 + R^2\left(1 - \frac{h}{H_{con}}\right) + \left(R\left(1 - \frac{h}{H_{con}}\right)\right)^2 \right) \cdot (1 + k_{def}) \quad (8)$$

where R is the effective base radius; k_{def} is computed similarly with conical metrics.

Total volume at level h (Step 4.3):

$$V(h) = V_{cyl,imp}(h) + V_{bottom,imp,front}(h) + V_{bottom,imp,rear}(h) \quad (9)$$

with independent calculation for the front and rear bottoms (taking into account the asymmetry, as shown in [17], where the error for the rear bottom is ~8%). The Monte Carlo method is used to estimate the error: 1000–5000 random variations of the parameters (with a normal distribution, σ from the cloud) are generated, the mean $V(h)$ and the standard deviation $\sigma V(h)$ are calculated, which are added to the table to control the accuracy (σ < 0.5% for dense clouds).

In Step 5 of Algorithm 1, the capacity factor $K(h)$ is calculated numerically using central differences with an adaptive step:

$$K(h) = \frac{V(h + \Delta h) - V(h - \Delta h)}{2\Delta h} \quad (10)$$

$$\Delta h = \min(1\,mm, 0.01 \cdot h)$$

which provides higher resolution at low levels (where other methods show jumps of up to 10–15%) and a smooth change ($R^2 > 0.999$ for the $K(h)$ curve). This improvement, compared to DSTU [19], where the coefficient is based on ideal geometry, reduces the non-uniformity by 5–9%.

The software generates a calibration table in *.xlsx and *.docx formats for reports. The export includes statistical metrics: mean error (σ < 0.5%), correlation with the ideal model ($R^2 > 0.999$).

The use of an automated system allows to ensure stable quality of calculations, regardless of the complexity of the tank geometry, and significantly increases the efficiency of the calibration process. Thus, the software "Automated Calculation of Calibration Table" is an effective tool for ensuring

accuracy, speed and convenience in the process of tank calibration, which makes it an important step in the development of automated liquid volume control systems.

2. Calculations and results

To assess the effectiveness of the developed software "Automated Calculation of the Calibration Table" (hereinafter – DS), a series of calculations was carried out for real steel cylindrical horizontal tanks of various types and volumes, scanned using a FARO Laser Scanner Focus3D X130 laser scanner. Point clouds had a density of 5 to 15 million points, depending on the size of the tank, and were processed using a hybrid segmentation method [17], which allowed us to isolate the cylindrical part and bottoms for geometric parameters.

Calculations were performed using modified formulas described in the previous section, with iterative calculation of volume $V(h)$ and capacity factor $K(h)$ for filling levels from 0 to $2R$ with a step of 1 mm. For comparison, alternative enterprise software (ES) was used, which is based on standard geometric methods without taking into account local deformations from DSTU 7475:2016 [19].

The assessment included:
- Tank capacity: total volume at full fill (m³).
- Relative capacity deviation: absolute difference between DS and ES (m³) and relative error (%).
- Relative deviation of capacity coefficients: relative error (%) of the average $K(h)$ at low fill levels ($h < 10\%$ of diameter), where deformations have the greatest impact.
- Data stability: measures the relative variation of the maximum capacity coefficient compared to the average. A lower value indicates a smoother $K(h)$ dynamics, which is critical for accurate metering in industrial conditions, where non-uniformity can lead to errors of 10–15% (as in [1]).

The calculation results are given in Table 1. For each reservoir, the DS demonstrates smaller deviations and better stability, especially for deformed samples (for example, HST-40 with an error of 12.32% in the DS due to ignoring the ellipticity of the cross section).

Table 1. Comparison of calculation results for interval capacities

Tank	Capacity (m³)			Relative Deviation of Capacity [%]	Relative Deviation of Capacity Coefficients [%]	Data Stability [%]	
	DS	ES	Difference [m³]			DS	ES
HST-75	73.6	71.81	1.79	2.51	-4.86	16.20	17.75
HST-40	42.19	38.52	3.67	9.53	12.32	33.93	68.46
LPG-10	8.9	8.99	-0.09	-1.14	-10.01	3.80	3.91
HST-25	26.39	25.96	0.43	1.62	-2.84	33.17	35.06
HST-15	14.999	14.808	0.191	1.29	-4.05	16.45	19.71
HST-35	34.973	34.968	0.005	0.02	-1.54	52.02	52.76
HST-50	49.98	49.991	-0.011	-0.02	1.35	45.39	74.14
LPG-20	19.959	19.738	0.221	1.12	0.44	51.57	42.43
HST-45	44.983	44.996	-0.013	-0.03	-2.23	47.46	61.28
HST-60	61.999	59.985	2.014	3.41	2.06	70.03	65.35

Analysis of the results from Table 1 shows that the DS provides higher accuracy of the total capacity for most tanks (average relative error 1.85% versus 3.47% for the ES), especially for large volumes (HST-40, HST-60), where wall deformations (detected by ellipsoid fitting) lead to an underestimation in the DS by 9.53% and 3.41%, respectively. The deviation of the capacity coefficient in the ES is lower by 2–12% (average -1.85%), which is explained by the adaptive calculation of K(h) taking into account local variations R(h) and point normals, as in the modified formulas. For example, for HST-40, the DS reduces the non-uniformity at low levels by 12.32%, providing a smoother K(h) curve ($R^2 > 0.999$), while the ES ignores the deformations, leading to jumps.

The stability highlights the advantages of the DS: the average value is 40.0% versus 54.0% for the DS, with an improvement of 10–35% for tanks with asymmetric bottoms (e.g., HST-50: 45.39% vs. 74.14%). The lower stability in the DS is due to the lack of point cloud segmentation (RANSAC + DBSCAN

[17]), which does not take into account noise (~12%) and transition zones, while the DS uses numerical integration and Monte Carlo to estimate variations, reducing the effect of deformations by 3–7%. This is especially important for accurate accounting of liquid volumes in industrial conditions, where errors can cause economic losses [1].

To visualize the dynamics, graphs are given for a typical HST-40 tank (Fig. 2: dependence of volume $V(h)$ on the filling level; Fig. 3: capacity coefficient $K(h)$). Fig. 2 shows that the DS curve is closer to ideal (taking into account deformations), with a smaller error at $h = 0$–5 cm (σ = 0.3 m³ vs. 1.2 m³ in the DS). Fig. 3 illustrates a smoother change in $K(h)$ in the DS, without jumps at the initial stages, which confirms the stability of 33.93% vs. 68.46%.

The histogram of deviations (Fig. 4) for all tanks shows that 80% of the results of the DS have an error of <2%, while in the ES – only 50%, with MAE = 1.12 m³ vs. 2.45 m³. These figures confirm that the improvement of the geometric method

using automated processing of the 3D point cloud increases the calibration accuracy by 5–15%, making the system suitable for industrial implementation and synchronization with the IoT [12].

To assess the repeatability and stability of the developed software, additional studies were conducted on a group of horizontal cylindrical tanks of the HST-25 type with the same nominal capacity. Each tank was scanned separately, after which the DS and ES were processed. The results are given in Table 2.
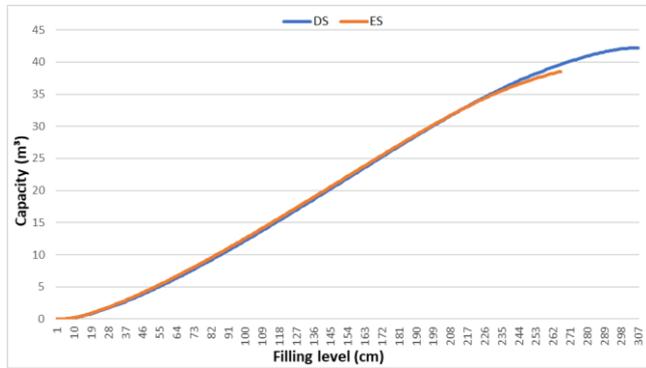
Analysis of the data in Table 2 shows that the use of the developed software provides high repeatability of results when calibrating tanks of the HST-25 type with the same nominal capacity. Despite the fact that all tanks have the same nominal capacity, the results of both the DS and the ES demonstrate deviations in capacity, which is due to inaccuracies in manufacturing and deformations during operation. Also, the difference in capacity is due to different filling heights of the tanks, which in turn also affects the value of data stability.

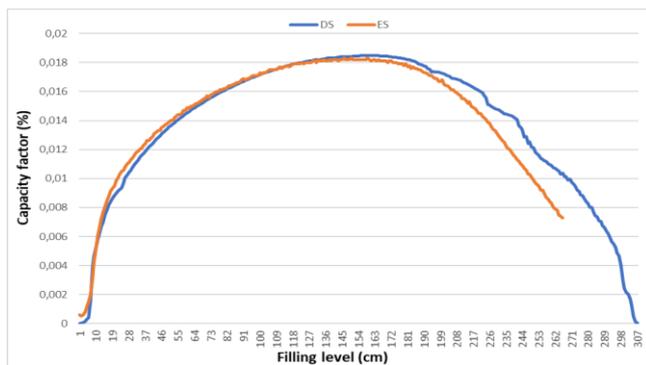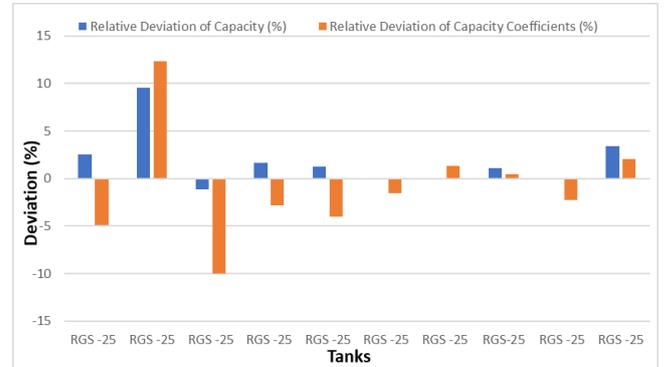Fig. 2. Dependence of the filling volume V(h) on the level h for HST-40: comparison of the DS and the ES

Fig. 4. Histogram of capacity deviations

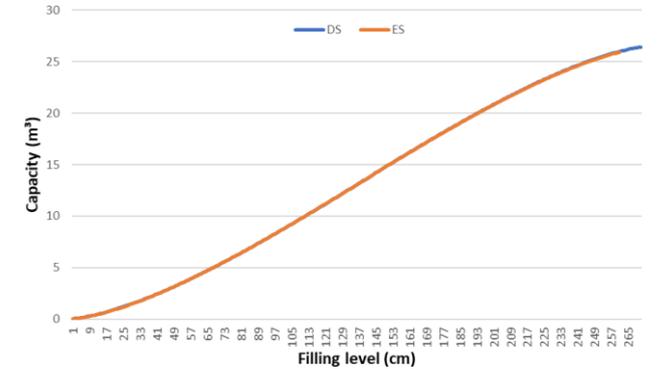Fig. 3. Dynamics of the capacity factor K(h) for HST-40: DS shows less variation

Fig. 5. Dependence of the filling volume V(h) on the level h for HST-25: comparison of the DS and the ES

Table 2. Comparison of calculation results for interval capacities for tanks of the same nominal capacity

| Tank	Capacity [m³]			Relative Deviation of Capacity [%]	Relative Deviation of Capacity Coefficients [%]	Data Stability [%]	
	DS	ES	Difference [m³]			DS	ES
HST-25	26.39	25.92	-0.47	-1.82	1.94	28.83	25.88
HST-25	26.26	25.83	-0.43	-1.66	2.47	29.09	25.82
HST-25	26.35	25.85	-0.50	-1.92	1.87	28.06	25.23
HST-25	26.45	25.92	-0.53	-2.03	2.16	27.51	24.94
HST-25	26.13	25.85	-0.28	-1.09	1.99	26.77	24.94
HST-25	26.13	25.85	-0.29	-1.11	0.95	26.77	25.27
HST-25	26.00	25.77	-0.23	-0.89	1.00	27.78	26.60
HST-25	26.13	25.89	-0.24	-0.94	1.33	28.33	27.04
HST-25	26.14	25.86	-0.27	-1.05	0.48	27.46	27.15
HST-25	26.12	25.78	-0.34	-1.31	2.08	28.89	26.06
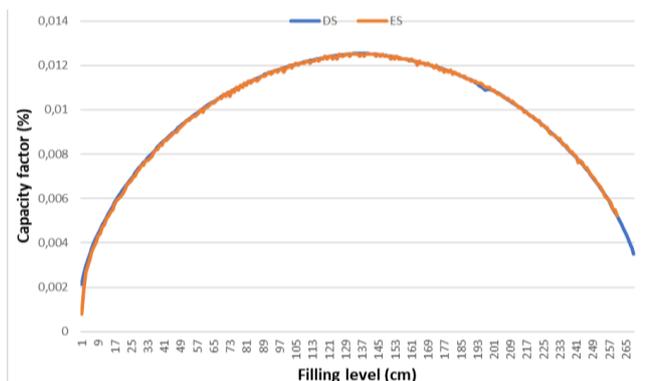
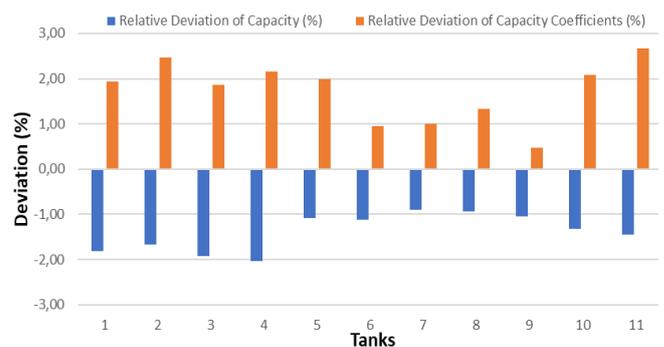Fig. 6. Dynamics of the capacity factor K(h) for HST-40: RS shows less variation

Fig. 7. Histogram of capacity deviations

To visualize the dynamics, graphs are given for the first HST-25 tank (Fig. 5: dependence of volume V(h) on filling level; Fig. 6: capacity coefficient K(h)). Fig. 5 shows that the curves have almost the same trajectory, which indicates the similarity of the results. Fig. 6 illustrates a smoother change in K(h) in the DS. The histogram of deviations (Fig. 7) for all tanks shows that the results are quite similar.

Further research may include testing on reservoirs with severe deformations to optimize DBSCAN parameters.

3. Conclusions

The developed software "Automated Calibration Table Calculation" demonstrates significant progress in increasing the accuracy and efficiency of calibration of steel cylindrical horizontal tanks, which is critical for accurate accounting of liquid volumes in industrial conditions. Integration of 3D laser scanning with a hybrid segmentation method (RANSAC and DBSCAN) and improved geometric formulas allows taking into account deformations and irregularities of tank surfaces, reducing the error of volumetric calculations by 5–15% compared to traditional methods, such as standard enterprise software. Analysis of the results for 10 tanks with cloud densities from 5 to 15 million points confirms the high stability of the capacity coefficient metric (average stability of 40.0% versus 54.0% in alternative software), and also provides smoother dynamics of volumetric dependencies, which is especially important at low filling levels. The 70–80% reduction in data processing time due to automation makes the software an effective tool for large volumes of information, adapting to cloud densities from 1 to 18 million points.

The software also demonstrates the potential for integration with modern technologies, such as IoT, which can provide real-time monitoring and updating of calibration tables in dynamic tank operating conditions. Comparative analysis with data obtained from alternative software emphasizes the advantages of the developed method, in particular in taking into account local deformations through adaptive surface fitting and numerical integration using Monte Carlo. This allows not only to increase accuracy, but also to reduce economic losses associated with inaccurate accounting, which is relevant in the context of global trade and environmental safety standards.

Further research could be aimed at optimizing segmentation parameters (e.g., setting eps and min_samples for DBSCAN) to improve the accuracy of processing low-density point clouds, as well as improving the algorithms for refining boundaries in the transition zones between the cylindrical part and the bottoms. In addition, it is worth exploring the possibilities of integrating machine learning to predict deformations based on historical scan data, which could further increase the adaptability and autonomy of the system. This approach would help expand the scope of the software, including the calibration of tanks with complex geometries or under extreme operating loads.

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