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New Approach to Calibration of Vertical Fuel Tanks

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Abstract—**Recalibration of the vertical fuel tanks must be done once in 5 years. Fuel tank during its usage can be affected by geological or other reasons (for example it may be damaged during installation or repair). So Volume chart of the tank can be corrupted. For calibration of vertical fuel tanks in Lithuania and in all EU, mix of geometrical and liquid filled methods is used.**

In this article a new approach to calibration of vertical fuel tanks, based on 3D laser scanning and data processing, will be presented.

Index Terms—**3D laser scanning, fuel tank calibration.**

I. INTRODUCTION

Nowadays, when innovation is spreading into the business world we need to take a new look at some metrological procedures. The calibration of the vertical fuel tank and volume chart of the tank can be made using various methods [1]. There is big competition between companies which make calibrations. The ones which choose to invest in innovative new methods for calibration of vertical fuel tanks may win this competition. In previous paper [2] authors presented a new approach to the calibration of horizontal fuel tanks which is based on the 3D laser scans. Main idea was that the tank can be scanned using accurate laser and volume of the tank can be calculated using 3D point clouds.

The aim of this article is to show how previously described method with some adaptation can be used for calibration and recalibration of vertical fuel tanks.

The main advantages of the 3D laser scanning method are:

1) Time saving;
2) Water waste problems;
3) Lowest measurement temperature limit;
4) Only 1 person is needed for calibration.

Laboratories and companies which perform calibration of fuel tanks using liquid fill methods states that calibration procedure takes around 3-4 hours for calibration of 30-40 m^3 fuel tank. Same time must be spent for filling bottom of vertical fuel tank, because only bottom of vertical fuel tank is filled with water. When using 3D laser scanning method at least 4-5 inside scans from different positions of the tank must be made. This takes around 45-60 minutes. Data processing of the scans takes another 10-15 minutes. So using 3D laser scanning method we can save 2-3 working hours. For this method we don't need any water so we save on it, too.

Normal operating temperature of the equipment needed for volumetric calibration must be positive ($+5^0$ to $+35^0$ by Celsius). This means that calibration can't be done 3-4 months per year. With 3D scanner we can work at lowest temperature -10^0 by Celsius.

And finally calibration can be done by one person, when for liquid fill + geometrical methods at least two, sometimes three persons are needed.

II. CALIBRATION OF VERTICAL FUEL TANKS

Calibration of vertical fuel tanks is followed by simple steps:

- inspection of the fuel tank,
- preparation of measurement gear and fuel tank for verification,
- fuel tank test,
- primary verification of fuel tank,
- volumetric/geometric calibration,
- preparation of graduation table.

Geometrical calibration of vertical fuel tank can be done using various geometrical methods. In EU three main methods are used [3], [4]:

1. Fuel tanks strapping;
2. Optical reference line measurement;
3. Optical triangulation measurement.

In Lithuania mostly mix of the methods are used. For the bottom of the fuel tank volumetric method and for the upper part one of the methods mentioned above is used. Volumetric calibration procedure is similar as for horizontal fuel tanks. It was described in previous paper [2].

A. *Fuel tanks strapping*

The oldest method for measurement of the tanks volume is fuel tanks strapping method [3]. The main idea of manual tank strapping method is that tank is strapped at some height points using a strapping tape. The tape must be calibrated using master tape. Master tape is never used for the strapping procedure. The procedure of strapping is simple. The strapping tape is laid around the vertical walls of the tank, parallel to and a measured distance from a particular

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ring. The position of the tape can be adjusted either by using jointed poles with a special fitting on the top or by use of a slotted ring. The tape is read after sliding to distribute surface tension and applying the predetermined pull at the tape ends using a spring balance. It depends on the size of the tank how much strapping has to be taken on each tanks ring. After measurements volume is calculated at measurement points. This method needs at least 2 persons and it has problems with accuracy when calculating the volume of the bottom of the fuel tank.

B. Optical reference line measurement

The optical reference line measurement is currently dependent upon the reference circumference determined by manual strapping of the first course, 20-30% below the top of the course horizontal weld seam. This point of measurement is the first vertical station. After positioning the optical device, the moving trolley is placed on the first vertical station and the reference offset is recorded. Then the trolley is moved up vertically to each previously assigned vertical station. Readings must be recorded sequentially. After reading the uppermost station, the trolley is lowered back to the first one to verify that the latest reading is correct. This verifies that there have been no physical changes in the trolley or scale. The procedure is then performed in the same manner at each horizontal station. The measurements are taken at two vertical stations per ring. This determines three radiuses per course. The mean radius of these three is used for the calculations of the volume. This method requires 2-3 persons to perform and has same problems with measurements of bottom.

C. Optical triangulation measurements

Optical triangulation measurements procedure uses the measurement of tank angles to determine the tank diameter at certain heights. This method provides a means for calibrating vertical cylindrical tanks using external measurement of angles with a laser theodolite. The theodolite being used must have an angular graduation and inaccuracy equal to or less than 0.022 degrees to ensure the required accuracy of measurement is achieved.

The base length is determined by manually strapping the bottom course circumference, 20% below the horizontal weld seam. This measurement is the reference circumference. The tank is then sighted from the first horizontal station using a laser theodolite. Two sightings must be made, on the left and right from each station, to the tank. The angle subtended between the two sightings must be recorded. From measured data radius of the tank (it has cylindrical form) at certain levels can be calculated. And finally volume of the tank at can be calculated. This method needs at least 2 people and has problems with accuracy when measuring bottom of the tank.

III. Inside 3D Scan of Vertical Fuel Tank

We want to present a new approach to calibration of vertical fuel tanks which is based on 3D scanning and data processing of the fuel tank. Unwrapped figure of the scanned vertical fuel tank presented at Fig. 1. To receive such as figure, combination of 4-5 laser scans is required.

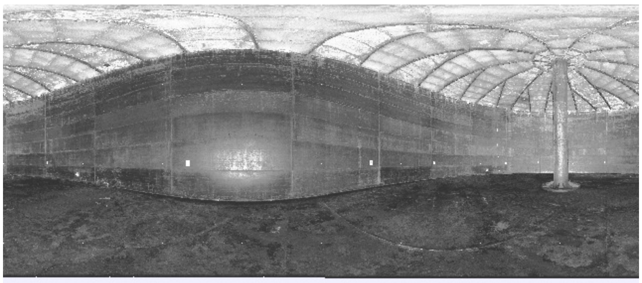

Fig. 1. Unwrapped 3D scan of the fuel tank.

Volume calculations of such as tank can be made using two stages:

1. Calculation of the bottom volume of fuel tank, or calculations until 0 point (when the z plane forms solid figure).
2. Calculation of volume of the upper part of fuel tank.

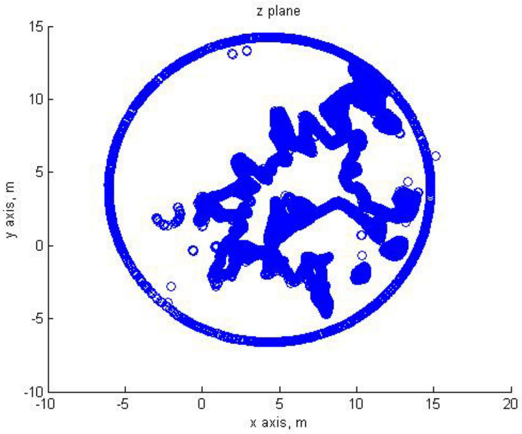

Fig. 2. 3D scan of the fuel tank. Z plane.

For the volume calculation of whole fuel tank two stages must be used because bottom of tank must be calculated using different methodic.

As example, Fig. 2–Fig. 4 can be analyzed. All figures showing scanned same data from different points of view.

Figure 2 contains scanned data from z plane point of view. It consists of two parts – outer circle which is outer wall of the fuel tank and inside “chaotic” figure – which is bottom of fuel tank. For the calculations of the upper part of fuel tank such as combination of the data is good. We can filter all unnecessary points inside the circle and calculated volume of the tank integrating data millimeter after millimeter until top of the tank. Accuracy comparing to other methods will be very good because we calculate each millimeter of the tank not only few basic strapped levels.

But for volume calculations of the bottom other point of view is needed. Calculation of the volume of inside figure is very complex, because you never know the shape of the fuel tanks bottom. Figure 3 and Fig. 4 shows same 3D point clouds viewing from x and y planes. As can be seen from figures shape of the bottom is clear and now calculations of the volume can be done without risk of the faults. For better results mean value of volumes of x and y planes can be calculated.

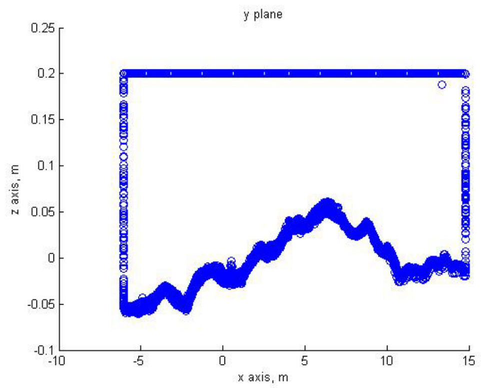

Fig. 3. 3D scan of the fuel tank. Y plane.

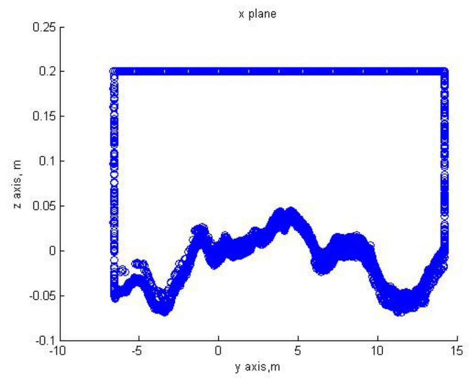

Fig. 4. 3D scan of the fuel tank. X plane.

IV. VOLUME CALCULATIONS OF 3D SCANNED FUEL TANK

Basic volume calculation algorithm can be described in

$$A_j = \frac{1}{2}\sum_{i=0}^{N-1}(x_{i,j}y_{i+1,j} - x_{i+1,j}y_{i,j}), \quad [\mathrm{m}^2], \tag{1}$$

where A_j – area of j layer, $j = 1,\ldots H_{\max}/\Delta h$, $H = 1,\ldots H_{\max}$ (cm) fuel tanks filling level, $H_{\max}$ – maximal filling level, Δh – scanning step (mm), x_i and y_i – j perimeter points coordinates of j layer (m), N - j layer's point number of perimeter.

For the bottom part of the tank (1) is changed to (1a) or (1b):

$$A_j = \frac{1}{2}\sum_{i=0}^{N-1}(z_{i,j}y_{i+1,j} - z_{i+1,j}y_{i,j}) = \\ = \frac{1}{2}\sum_{i=0}^{N-1}(x_{i,j}z_{i+1,j} - x_{i+1,j}z_{i,j}), \quad [\mathrm{m}^2]. \tag{1}$$

Then volume of the fuel tank can be calculated as sum of all 2D layers

$$V_H = V_{H-1} + \sum_{j=(H-1)\cdot M+1}^{H\cdot M} A_j\cdot\Delta h + \Sigma K_H + \Omega_H, \quad [\mathrm{dm}^3], \tag{2}$$

where M – number of layers in 1 cm ($M = \frac{10}{\Delta h}$,); ΣK_H – sum of volumes of all inside construction elements; Ω_H – hydrostatic pressure correction.

Correction for hydrostatic pressure Ω_H (dm^3) can be calculated:

For the first course ($0 < H \le h_1$)

$$\Omega_H = \frac{0{,}8\cdot K\cdot H^2}{t_1}, \tag{3}$$

for second ($h_1 < H \le h_2$)

$$\Omega_H = 0{,}8\cdot K\cdot\left[\frac{\Delta h_1^2}{t_1} + \frac{2\cdot\Delta h_1(H-h_1)}{t_1}\right] + \\ + K\cdot\left[\frac{(H-h_1)}{t_2}\right], \tag{4}$$

for the third course ($h_2 < H \le h_3$)

$$\Omega_H = 0{,}8\cdot K\cdot\left[\frac{\Delta h_1^2}{t_1} + \frac{2\cdot\Delta h_1(H-h_1)}{t_1}\right] + \\ + K\cdot\left[\frac{\Delta h_2^2}{t_2} + \frac{2\cdot\Delta h_2(H-h_1)}{t_2}\right] + \\ + K\cdot\left[\frac{(H-h_2)}{t_3}\right]. \tag{5}$$

For n-th course ($h_{n-1} < H \le h_n$)

$$\Omega_H = 0{,}8\cdot K\cdot\left[\frac{\Delta h_1^2}{t_1} + \frac{2\cdot\Delta h_1(H-h_1)}{t_1}\right] + \\ + K\cdot\left[\frac{\Delta h_2^2}{t_2} + \frac{2\cdot\Delta h_2(H-h_1)}{t_2}\right] + \cdots + K\cdot\left[\frac{(H-h_{n-1})}{t_n}\right], \tag{6}$$

where H – filling level of fuel tank, mm; $t_1, t_2, t_3, \ldots, t_n$ – thickness wall at first second, third, n-th ring, mm; $h_1, h_2, h_3, \ldots, h_n$ – measured height at first second, third, n-th ring, mm; K – fuel tanks constant. It can be calculated using

$$K = \frac{\pi\cdot g\cdot D_j^3\cdot(\rho_S - 1{,}2)}{8\cdot E\cdot 10^9}, \tag{7}$$

where ρ_S – density of liquid in the tank, kg/m^3; D_j – fuel tanks diameter at the j measuring point (C_j/π), mm; g – free-fall acceleration, m/s^2; E – Jung module, N/m^2.

V. UNCERTAINTY ESTIMATION

Standard uncertainty of the fuel tanks calibration using geometrical and liquid fill methods must be less or equal $\pm 0.2\%$ as described in standard [5]. The uncertainty of the 3D scanning method can be calculated using expressions described in [2]. In this paper we will present specific components of uncertainty of vertical fuel tank.

Uncertainty of vertical fuel tanks bottom measurement. With this component measurement of the bottom of the vertical fuel tank can be estimated. Uncertainty uV_d is calculated until H_d filling level when fuel tanks section plane forms solid figure. It is accepted that uncertainty of bottom level is equal to $\pm 0.25\%\ V_H$

$$uV_d = 0{,}0025 \cdot V_H \text{, [dm}^3\text{].} \tag{8}$$

Uncertainty of the hydrostatic pressure Ω_H can be estimated:

$$u\Omega_H = \Omega_H \cdot \sqrt{(3 \cdot uR_j / R_j)^2 + (uE/E)^2 + (ut_j / t_j)^2}\text{, [dm}^3\text{],} \tag{9}$$

where uR_i – uncertainty of fuel tanks radius estimation at the j measuring point R_j ($R_j = C_j / 2\pi$), It can be expressed: $uR_j = uC_j / 2\pi$, m; E – Jung module (typical uncertainty $uE = 5 \cdot 10^9 / \sqrt{3}$, N/m^2; ut_j – uncertainty of thickness wall estimation at first second, third, n-th ring, mm; $ut_j = 0{,}001 / (2 \cdot \sqrt{3})$, m.

With additional absolute standard uncertainty component uncertainty of data combining (bigger vertical fuel tanks must be scanned from 4-5 different points) and error of zero point coordinates measurement, must be estimated and is equal $\pm 0.02\%\ V_H$

$$uV_{ad} = 0{,}0002 \cdot V_H \text{, [dm}^3\text{].} \tag{10}$$

Absolute standard uncertainty of fuel tanks volume at certain level can be estimated using

$$uV_H = \sqrt{\Big(\sum_{j=0}^{H \cdot M} uA_j \cdot \Delta h\Big)^2 + uV_d^2 + u\Omega_H^2 + uV_{ad}^2 + u(\Sigma K_H)^2}\text{,} \tag{11}$$

where $H = 1, \ldots H_{\max}$, cm; M – number of layers in 1 cm.; $u(\Sigma K_H)$ – absolute standard uncertainty of volume of fuel tanks constructional components.

Fuel tank expanded absolute uncertainty

$$UV_H = 2 \cdot uV_H \text{, [dm}^3\text{].} \tag{12}$$

VI. EXPERIMENTAL MEASUREMENT RESULTS

For experiments we used adapted version of previously created MATLAB mathematical model. Point cloud was formed from at least 4-5 scans from different angles of vertical fuel tank. Experimental verification of the algorithm was performed with 4 different fuel tanks with concentration on calculation of bottom volumes (levels from 0 to 60 cm). For all fuel tanks relational error stays around 0.2%. It goes up to 0.5 only at the bottom of fuel tank. This can be explained by scattering of the data merged from 4-5 scans.

As can be seen from Fig. 5 measurement expanded absolute standard uncertainty's of all fuel tanks stays around required level ±0.2% boundary. Uncertainty is a little bit bigger at the lowest levels, but when moving to upper part of the tank it stays around the boundary as required by standard [5] and Lithuania's verification methodic [6].

This article presented a new approach to calibration of vertical fuel tanks. This practice is very useful in solving time, water waste, working labor problems.

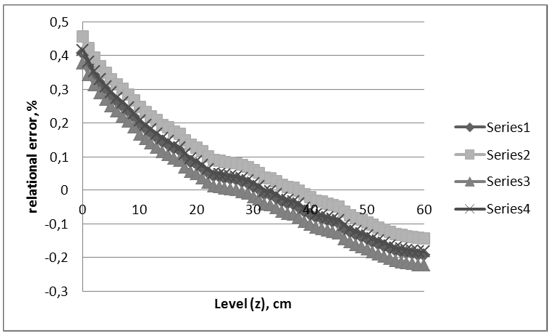

Fig. 5. 3D scanning vs. volumetric+geometric measurement relational error.

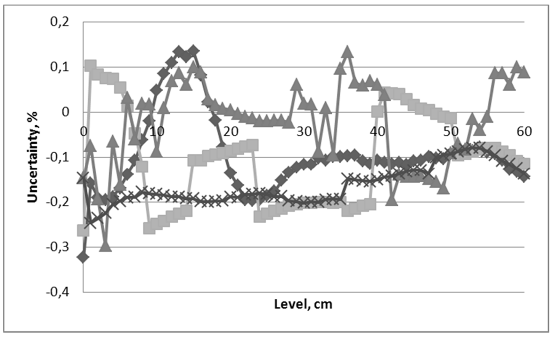

Fig. 6. Absolute standard uncertainties.

VII. CONCLUSIONS

1. New approach to calibration of vertical fuel tanks was presented. Main advantages of a new 3D laser scanning method are:
   - The time saving;
   - Water waste problems;
   - Lowest measurement temperature limit;
   - Only 1 person is needed for calibration.
2. Experiments with few vertical fuel tanks showed that for all fuel tanks relational error stays around ±0.2%. It goes up to ±0.5% only at the bottom of fuel tank.
3. As can be seen from Fig. 5, measurement expanded absolute standard uncertainty of all fuel tanks stays around required level ±0.2% boundary. Uncertainty is a little bit bigger at the lowest levels, but when moving to upper part of the tank it stays around the boundary as is required by the standard.

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