Method of Modelling a Tank with Ribbing using a Spatial Scanner for Optimized Control of Volume Characteristics

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Abstract. Increasing requirements for product quality, whether from the side of technical standards or customers, generate demands on the optimization of measurement and data evaluation processes, which include also dimensional characteristics. The paper deals with determining the volume of the tank of a railway wagon with ribbing. In practice, volume flow meters are usually used to measure the internal volumes of manufactured tanks, which measure the volume of water when filled with water. The method is not only time-consuming but also energy-consuming and generates a large amount of wastewater. Therefore, these obsolete methods are gradually being replaced by those that allow effective inspection of tank wagon dimensions according to the technical documentation. The topic of the paper is a description and verification of the design of a progressive method of determining the internal volume of the tank using a spatial 3D scanner Faro Focus and software processing of measured data. At the same time, verification of compliance with the requirements for the accuracy of determining the internal volume of the tank is presented. The aforementioned methods are therefore compared in terms of accuracy, complexity and time consumption.

1. Introduction
Minimizing the negative impact of passenger and cargo transport on the environment and thus on its quality and sustainability is becoming one of the priority topics on a global scale. Transport accounts for about one-third of the energy consumption and the total CO2 emissions in the EU. The efficient use of more sustainable modes of transport, such as rail or inland waterway transport, can help reduce Europe’s level of dependence on imported fossil fuels and the associated pollution. According to the European Environment Agency, CO2 emissions from rail transport are 3.5 times lower per ton-kilometer than from road transport [1].

An integral part of the transport of goods by rail is also the transport of dangerous and chemical gaseous and liquid substances. These are transported in tanks designed exclusively for this purpose, which must comply with the transported hydrostatic pressure of the medium acting on the tank walls and withstand the transported chemicals by their properties. From a mechanical point of view, it is important that the transported substance can be safely filled in and exhausted without risk of damage or deformation such as the tank implosion. Therefore, the customers demand increasing accuracy of manufactured wagons, which must be documented by measuring outputs from the relevant measuring systems, through which measurements of tank wagon components are performed according to the drawing documentation - measuring sheets or metrological drawing documentation. Not only the
dimensions but also the prescribed geometrical tolerances are checked. Therefore, effective quality assurance of the production and its control is a challenge for continuous improvement by producers.

Up to now, the volumetric method of filling water and simultaneously measuring its volume with flow meters is still used in many production plants to control the volume of the tank [2], which is a time-consuming method requiring a special workplace with powerful pumps. During the measurement, there is a large consumption of water, which is being contaminated with impurities from production after the measurement and it is necessary to ensure waste management for it. Energy is used to drive the pumps during filling and draining and also to dry the tank after measurement. Therefore, an alternative optical scanning procedure has been used to reduce the environmental burden [3] - [8] in recent years.

This paper is aimed at comparing the traditional method of measuring the internal volume of a tank by filling with water, the volume of which is measured by flow meters, with a progressive method of evaluating volume characteristics using 3D scanning measurement. The application of 3D scanning to the measurement of object volumes is a relatively well-established methodology, but it is usually described for simple surfaces [9], [10], [11]. Therefore, this paper presents the unique methodology of measuring and evaluating the volume comprising the comparison of both methods.

2. Experimental part
A Zagns 85 m³ tank wagon belonging to the production portfolio of Tatragónka Poprad was chosen for the measurement of volume characteristics.

Since a huge amount of data accumulates when scanning objects, these can only be processed with powerful hardware and software. Experimental data were processed on an HP Z840 Workstation Desktop - IGSSEQ4 with a pair of Intel® Xeon® CPUs E5-2630 v4 @ 2.2 GHz, 128 GB of RAM, a pair of 4 TB LSI Logical Volume SCSI Disk Devices and a pair of NVIDIA Quadro P4000 64 GB graphic cards.

Programs used: FaroScene for processing scanned data points and Polyworks Metrology Suite 2019 IR4 for performing calculations and creating spatial models.

FaroFocus is a scanner that uses laser technology for detailed scanning of objects in a radius from 0.6 m to 150 m with three-dimensional point cloud output. When scanning, it emits an infrared laser beam into the center of a rotating mirror, which further deflects it into space in the 360˚ x 300˚ field of view and bounces back into the scanner when in contact with an object. The distance from the scanner is determined by measuring the phase shifts of the infrared radiation [3], [13]. The XYZ coordinates of each scanned point are calculated using angle sensors to measure the rotation of the mirror and the

![Figure 1. Basic dimensions of the wagon Zagns 85 m³][12]
horizontal rotation of the laser scanner body. Each point is coded together with the coordinates of position, length and spherical angle. In this way, its exact position in space is determined.

2.1. Preparing for measurement
Before the measurement, it is necessary to clean the inside of the tank so that there are no grinding residues or slag from welding, or other objects. Glossy mirroring surfaces are unsuitable for scanning because rays are reflected of them in an inappropriate manner and such a false shape can be generated. That kind of surfaces should be treated with a suitable composition, e.g. dimmed using a spray consisting of chalk that is easy to clean after scanning. If the object surface is wet, it must be dried before the measurement. It is also necessary to close all openings before scanning.

Before scanning, the operator must determine the number of relocations of the scanning device that are necessary in order that the entire surface (100%) to be scanned. Sometimes one position is enough, other times several dozen positions and relocations are necessary. In this case, after the scans are loaded, they need to be registered, which is the process of aligning all scans into one overall scan according to position, direction, and height data. This can be done in one of the following ways:

- Registration using the reference balls;
- Registration using the targets;
- Planar registration;
- Registration at any symmetric objects;
- Automatic registration.

![Figure 2. The inside of the tank with distributed reference balls](image)

The most accurate way is to register by means of reference balls, which are suitably distributed in space (Fig. 2). When selecting the above procedure, it is necessary that reference balls, which contain a clamping magnet, are placed in the measuring space before the measurement, facilitating their attachment to the steel parts. They have a precise spherical surface of white color with ø 145 mm. For proper alignment of scans, they must be arranged in such a way that the instrument has at least three balls visible in the field of view from each scanning position in space. They must not be on a moving surface. Each ball must be named the same on each scan because the software joins and overlaps the scans based on the same designation and orientation of the reference balls in space. After each scan, the scanner must be moved between the other internal reinforcement ribs so that they are scanned from all sides.
Thus, 6 reference balls were arranged in the measured tank along the entire length of the tank at different heights. The entire tank was scanned in 6 positions, i.e. five shifts of the scanner. The first position was at the entrance and the last at the opposite end of the tank (Fig. 3). After activating scanning, it takes the scanner about 20 seconds to initialize and start scanning, so the operator has enough time to leave the measurement area.

Fig. 4 shows 100% scan of the tank consisting of 265 million dots. Then, it is necessary to activate the PreprocessScans module, which fine-tunes the registration process in such a way that the module filters out very dark and wandering points generated e.g. by mirroring; coloring the scans; creates and saves panoramic images for all scans.

The data processing process in the FaroScene software is accomplished and the data have to be saved to a .fls file via Export ScansOrdered so that the points are saved with the normal. Each point stored in this way contains six data: the coordinates x, y, z [mm] and the normal directions i, j, k [°].

Data processing in PolyWorks

PolyWorks is metrological software from the Canadian company Innovmetric for processing measured data from 3D measuring systems from single-point inspection - probing to data scanning and their comparison with CAD models. It does not contain a Plug-In that would allow the processing of measured data directly from the FaroFocus® 150 outdoor scanner.

PolyWorks software works on two levels: WorkSpace Manager for basic project organization, where work modules are selected that are already part of the basic version or can be purchased, and Inspector Manager (IM), which already contains the 3D space for working with CAD models and
measured data. To work in IM, there is necessary to create a new work project to import point clouds into, select that from a saved file and import into a 3D scene.

When importing a point cloud or polygon models, the surface normal is calculated for each point (except for specific point cloud file formats). These normals are used for various operations, such as rendering, primitive fitting, and reference deviation operations. Cloud points in workspaces can also be imported into the module depending on their format. In this step, it is very important to set the sampling factor so that unnecessarily number of points is not imported into PolyWorks. Of course, with increasing number of points, the processing time also increases, which can reach a duration of several hours, depending on the computing resources.

After importing a point cloud, it is possible to see all six scans, each in a different color, combined into one entity (Fig. 5), still with the erroneous points that were generated by reflections from the object.

![Figure 5. Point cloud after import into PolyWorks](image)

Creating a polygonal model

When creating a polygonal model from a point cloud, the software always connects the two nearest points into a vector, while it is necessary to set the source data objects, networking method, data type, resolution, merging the scanning step, smoothing and reduction (Fig. 6). When three vectors are connected, a triangle - a polygon is created, and when all polygons are connected, a polygonal model is created. The denser the points are, the more readable and dimensionally descriptive is the model.

![Figure 6. Step of the triangles number reduction: A – before, B - after [14]](image)

2.2. Comparison to CAD model

This is an important operation for the correct evaluation of the dimensions along with the insertion of the coordinate system. This operation must be consulted and agreed with the design and production technology department, taking into account the following design or technological assembly,
production on CNC coordinate or machine tools, as well as the customer and his input 3D check, because different alignments also cause different dimensional outputs [15], [16].

By activating the Create Color Map function, all scanned points in the perpendicular direction of the normal to the CAD model are displayed in color resolution according to their distance from the nominal elements (Fig. 7). The intensity of colors can be changed by a range of tolerances. In general, the smaller the set tolerance, the more colorful the model and the better the resolution of the deviations. On the right side, a color scale is automatically generated to show deviations in mm. It should be noted here that the data measured by the scanner correspond to the inner surfaces of the tank and the nominal data represent the outer dimensions of the tank. Therefore, in order to obtain the correct result, it is necessary to take into account the thickness of the casing and the lid in the calculation.

![Figure 7. Color Map of deviations of nominal and measured dimensions](image)

Preparation of data for volume calculation
Before the calculation of the volume itself, it is necessary to clean the object from unwanted and auxiliary elements that influence the overall result of the volume. In this case, there are six reference balls inside the tank, which would take their volume from the actual volume of the tank, and a central spacer bar, which serves to pump the gas out of the tank and at the same time prevent deformations of the tank in the middle part. Since it is hollow and also serves as a pipe, there are two options to regard it in the calculation. The first option: keep it, calculate its internal volume and add it to the total volume of the tank, the second option: delete it and do not modify the calculation, because its thin wall will affect the volume calculation negligibly. The second method is preferable to choose as faster and more practical.

In the next step, it is necessary to insert the Cartesian coordinate system into the data model. Since the basic elements for the insertion of the coordinate system are not specified, namely: plane, vector and point, it is necessary to define them. The vector will also be the axis of the cylinder.

To calculate the volume, it is necessary to identify four more entities, namely: reference plane, contour, direction and sampling step.

2.3. Calculation of the actual volume of the tank
When calculating tank volume, PolyWorks software enables a calculation method through a definite integral. The accuracy of such a calculation is limited by the selected sampling step. Since the outline of the tank in the section is a curve, the challenging problem is to calculate the content of the area just below the curve. In order for the software to calculate and evaluate this accurately, it would have to use a given continuous function f(x), along the entire contour of the geometric shape of the tank. Since
the tank is not an ideal rotational body, such an exact description of individual continuous functions at certain intervals would be extremely laborious and unusable in common practice from a time point of view [17]. The total volume is the sum of the positive and negative volume in mm³. Both values are not the same because the tank is unevenly deformed and also depends on the position of the reference plane, which does not pass through the exact central axis X (Fig. 8). Ultimately, this does not affect the accuracy of the tank volume calculation.

\[
\text{The calculated volume of the tank Zagns 85 m}^3
\]

| Positive volume (green) | 42.49057 m³ |
| Negative volume (red)   | 42.52138 m³ |
| Total volume            | 85.01195 m³ |

The difference between the calculated value and that nominal is 0.01195 m³. Regarding the uncertainty of determining the result, it was calculated [18], [19] as ± 0.1 m³ which is an acceptable value from the point of view of tolerance ± 0.850 m³.

\[\text{Figure 8. Integral parts (green – positive, red – negative) of a Zagns 85 m}^3\text{ tank for the calculation of the measured volume}\]

2.4. Reference volume measurement by flow meters
In the production of Zagns 85 m³ wagon tanks, the technological process of production also includes the measurement of the internal volume. Two measuring flow meters are used simultaneously for this operation:

- MID 2-25/16-F/St-PT-MEL/HC-St M10AR with maximum flow 4.5 m³/hour
- MID 2-100/16-F/St-HG-ML/HC-St M20AM with maximum flow 70 m³/hour

According to the calibration sheets, the uncertainty of the MID 2-25/16 flowmeter is ± 0.05% of the measurement result and the uncertainty of the MID 2-10/16 flowmeter is ± 0.105% of the measurement result.

Measured volume of the water is 85.007 m³ ± 0.084 m³

2.5. Measurement time comparison
Regarding the time of measurement, the spatial scanner is more advantageous, because the measurement of the tank takes (altogether with the evaluation) approximately 36 minutes, i.e. it is 3x faster than the measurement with water flow meters (filling + emptying without drying takes 113.5 min). The procedure of scanning and evaluation can be optimized in order to save time or to obtain better accuracy (mainly by adjusting number of the points in the cloud and reduction factor of the triangles). Moreover, for the similar objects, regression models may help save time without loss of the accuracy. Time of the measurement including evaluation typically 15-20 min reported in the literature [3], [20] concerns conditions of the simpler objects (without ribbing). Thus, the obtained results may be rated as satisfactory. Finally, it was proven that regarding the accuracy, both methods fulfil conditions of tolerance limit.
3. Conclusion

Present work was focused on study of the measuring method of the internal volume of the railway tank with ribbing using a 3D scanner. Particular steps were presented and discussed. As a reference the currently used system of measuring volume using the flow meters was compared.

By comparing the two measurements in terms of accuracy, method of design and time, it can be stated that both methods are suitable for the volume measurement and their accuracy meets the technical requirements for tank volume tolerance. From the point of view of time consumption, the measurement with the FaroFocus® spatial scanner is more beneficiary, because the measurement of the tank (observing the prescribed deviation of the volume tolerance) takes altogether with the evaluation 36 minutes, i.e. it is approximately 3x faster than the present method of measurement using the flow meters (113.5 min.). Moreover, significant water and electricity savings and simpler working space requirements are also reached. Another benefit of measuring using a scanner is the acquisition of spatial data enabling the creation of an object model for other measurement possibilities including deviations of nominal and measured dimensions.

As for the possibilities of further streamlining of measurements, in the case of the volumetric method it is possible to use higher flows, but the total amount of water and energy consumed will not change. In the case of 3D scanning, alternative options to adjust the data processing can be tested. However, it must be considered that it may be related to the calculation accuracy and so the calculation procedure should be adjusted in proper way [21].

To conclude, the FaroFocus® scanner can be advantageously applied to measure the volume of objects with complex internal structure, such as tank with ribbing, in the production process in a practical way. It is therefore possible to recommend this method of measurement and incorporate it into the technological method of production, respectively control of tank volumes in practice.

Acknowledgment

The authors would like to thank the VEGA grant agency for supporting presented research work within the project VEGA 1/0205/19.

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