

Device for measuring barrel volume using a digital method

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Abstract

The production of wooden barrels represents a specific segment of the wood-processing industry with high added value, especially in the aging of wine and spirits. Accurate determination of the internal volume of barrels is crucial for quality control, inventory management, production process optimization, and for the beverages themselves during aging. The aim of this study was to design and test a device that enables the measurement of barrel internal volume using a dry digital method. The device eliminates the disadvantages of traditional measurement methods (wet and calculated) and allows rapid, precise, and contactless volume determination. The prototype was tested on a set of new and used oak barrels of various volumes. The results confirmed high measurement accuracy and significant time savings compared to conventional methods.

Key words: oak barrels; volume; laser measurement; digitalization; Industry 4.0

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1. Introduction

The history of aging wine in oak barrels is a fascinating story that began over 2000 years ago and today represents a refined tradition. The first mentions of barrel usage come from Pliny the Elder (Genty & Vicard 2024). In the Middle Ages, barrels began to be used not only for storage but also for aging spirits, including cognac, when it was discovered that long-term storage in barrels could improve the taste and quality of the beverage (Carpena et al. 2020).

The quality, aroma, and taste of a beverage are influenced not only by storage duration, fermentation processes, and production technologies, but also by numerous other factors such as the chemical and physical properties of the wood, including: elasticity; durability; low fluid permeability; straightness of the wood grain; defect-free wood that prevents leaks or the release of undesirable flavors into the beverage; thermoplasticity, which is crucial in barrel production; wood porosity affecting the “angel’s share” process; wood species, which influences the beverage’s flavor and aroma through compounds like tannins or coumarins; and, last but not least, the shape of the barrel itself (Lindsay & Chalk 1954; Mosedale 1995; Díaz-Maroto et al. 2008; Alamo-Sanza & Nevares 2017; Martínez-Gil et al. 2017, 2018; Hic et al. 2021).

Accurate quantification of the volume of oak barrels is of crucial importance both in winemaking and in the

production of spirits such as cognac and whisky. Precise determination of barrel volume is a key factor in production, since it influences the extent of interactions between the beverage and the wood, ultimately shaping the taste, aroma, and quality of the final product. It is also essential for ensuring efficiency in inventory and production management – detecting leaks, damage, and beverage contamination, as well as evaporation and absorption by the wood, etc. (Zhang et al. 2024).

The geometric properties of barrels, including their internal surface area and volume, affect the intensity of tannin exchange and micro-oxygenation, the added value of wine, production processes, storage, and even the cost of the barrel itself (Conde-Fernández et al. 2020). An experiment on the extraction of phenolic compounds from wood during the first three years of aging confirmed the importance and influence of barrel size, in this specific case for brandy aged in 250-liter and 650-liter barrels (Canas et al. 2008).

Determining the precise volume of a barrel is essential for maintaining quality standards. For example, in the Burgundy region, barrels with a volume of 228 liters are commonly used, while in Bordeaux the most frequently used barrel volume is 225 liters, in accordance with traditional requirements.

Additionally, the need to measure barrel volume arose from purely practical reasons related to storage and trade of alcoholic beverages. The barrel was a basic and variable

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commercial unit – its volume was not always precisely defined, as each barrel was handcrafted and could vary slightly in shape and capacity. For sellers, producers, and buyers, it was therefore important to know the actual liquid content of a barrel. Customs and tax policy was also a key factor. Since the 18th century, alcoholic beverages were among the most important taxed consumer goods in some countries. To prevent tax evasion and ensure fair collection of duties, authorities began requiring accurate measurement of barrel volumes. In the USA, an official position of “gauger” was even established – a customs officer responsible for measuring barrels and verifying alcohol content directly with producers and merchants (Sechrist 2022).

As a result, standardized measurement methods gradually developed, enabling uniform volume calculations regardless of artisanal differences between individual barrels. Barrel measurement thus became a bridge between traditional cooperage and a technical approach based on precise measurement, standards, and mathematics.

In wooden barrel production, strict rules apply to the internal volume. To guarantee the minimum barrel volume, manufacturers produce barrels with an extra allowance of 2.5 to 4 liters per barrel depending on its size. Some of the common barrel sizes include 225 L, 228 L, 250 L, 300 L, 350 L, 400 L, 500 L and 600 L.

Historically, barrel volume was measured using tools such as the *velte*, a graduated rod that approximately determined volume based on the barrel’s diagonal (Lavaud 2013; Mille et al. 2019). Although widely used, this method was sensitive to several factors: the number and quality of staves, hoop tension, and storage conditions such as humidity and temperature. Pioneers like Johannes Kepler (1615, 2018) formalized these measurements mathematically, and later mathematicians and inventors further refined stereometric formulas for barrels (Oughtred 1633; Camus 1741; Detz 1776; Taransaud 1976; Jongmans 2010).

In addition to the *velte* and diagonal rods, several physical measuring instruments were historically used to obtain more accurate barrel volume estimates. The most common included head calipers, which measured the thickness of the barrel heads through the bung hole, and long calipers, which measured the distance between heads externally with correction for wood thickness. Cross calipers were used to measure the external barrel diameter, often at multiple heights to account for the barrel shape. Another instrument was the gauging rod, a square rod calibrated in volume units (e.g., gallons) to measure the barrel diagonal through the bung hole. Although geometrically approximate, this method provided sufficiently accurate estimates for trade and tax purposes, as handcrafted barrels had relatively consistent proportions. Wall thickness was measured with a stave gauge, while a head rod or gauging slide rule allowed measuring head diameters and directly estimating volume or liquid content. To check liquid levels in filled barrels, dipping

rules adapted to standard barrel types, and excise rules used by customs authorities, were employed to determine volume and alcohol content. These historical methods demonstrate that accurate barrel volume determination was always challenging due to variability in handcrafted barrels (Ham 1996).

Currently, two main methods are predominantly used for measuring the internal volume of wooden barrels:

- *Wet method*
- *Calculated method*

The volume of a wooden barrel using the calculated method is determined based on the geometric parameters of the barrel. This method relies on mathematical formulas that work with the internal dimensions – primarily the length between the barrel heads and various diameters of the barrel (at the base and at its widest point). However, the accuracy of the result strongly depends on the precision of these measurements.

For traditional barrels, the so-called historical *barème de jaugeage* is often used – a procedure that involves averaging measured diameters and converting them to volume. This method was widely used in practice for many years, but its drawback is that after the barrel is assembled, it is very difficult to measure internal dimensions precisely, such as the true diameter of the base or the exact internal length. Therefore, results can be inaccurate. In cases where internal dimensions are unavailable – which is common for already filled or sealed barrels – alternative calculation methods are used. The most common is measuring the so-called barrel diagonal, i.e. the distance from the center of the bung hole to the farthest point on the barrel surface. Based on this single value, the *formule des Douanes* can be applied, estimating the total volume using the formula:

$$V = 0.625 \times C^3 \quad [1]$$

where C represents the measured diagonal. This is a practical method as it requires only one measurement. For smaller barrels, it even provides results very close to the actual capacity. An alternative is the so-called *jauge cognaçaise*, a special measuring tool with engraved conversion scales, primarily used in the Cognac region. While calculation-based methods offer rapid volume determination, their accuracy can be affected by barrel shape, condition, and measurement quality (Chanson 2023).

The second, more precise method of determining barrel volume is direct filling with liquid, i.e. measuring volume using the wet method. This measurement is based on a simple principle: the barrel is filled to the bung, and the exact amount of liquid it contains is measured. Measurement is performed either using a volumetric device or by weighing the full barrel and calculating the volume based on the known liquid density. When filling with water, the method is very reliable, as the density of water changes minimally at standard temperatures. If measurements

are conducted between 15–25 °C, volume deviation is small, even for large barrels. However, handling water is a drawback – it must be chlorine-free to avoid unwanted odors affecting the wood, and the used water (already enriched with tannins from the barrel) requires proper disposal. When filling with spirits (e.g., eau-de-vie), more precise corrections are necessary, as alcohol density varies with temperature and alcohol content. If these factors are not properly accounted for, the result can be biased in terms of volume. Épalement (the French term for the process of filling and emptying a barrel with water for volume measurement) is relatively time-consuming and requires organization, but if measuring instruments are properly calibrated, it remains one of the most accurate methods for determining barrel volume – with an accuracy of up to one liter, which corresponds to a range of 0.29% to 0.44%, depending on the size of the barrel, which is still a significant improvement in measurement accuracy. A practical drawback of this method is the need for regular calibration of the measuring device, which is both time-consuming and costly (Chanson 2023).

The main disadvantage of both commonly used methods is the time requirement. For the calculated method, all internal dimensions must be measured, which is complicated and highly imprecise due to uneven surfaces. For the wet method, inaccuracies and significant delays arise due to wet barrels, as some water almost always remains in the barrel after pouring. Water absorption by wood is another factor which influences the accuracy and varies significantly depending on the wood properties. The wet method may also introduce further errors as water is absorbed into the wood during measurement, causing the wood to swell and affecting the originally measured value. For this reason, the wet method incurs a significant delay even immediately after measurement, as barrel drying takes a minimum of seven days.

Existing commercial devices based on LiDAR, sonar, photogrammetry, or other technologies cannot fit inside

the barrel through the bung hole due to their physical size. Therefore, our goal was to design and test a digital device created for measuring the internal volume of barrels. The device is specific due to its unique design and principle of determining the actual volume of the tested barrel. The device design also had to meet other essential requirements, such as mobility, ease of operation, repeatability, measurement time, measurement accuracy, and the ability to measure both new and used barrels, ensuring the device is practical and effective in real-world use.

2. Material and methods

The primary objective of this research activity was to develop an original digital method for determining the internal volume of barrels. To achieve this goal, the following specific objectives were established:

- selection of the most suitable sensors for the prototype device based on available technical datasheets;
- deployment of the chosen sensors and testing during measurements on a pre-selected sample of barrels with varying properties and parameters;
- optimization of the measurement process both at software and hardware level;
- achieving a maximum allowable measurement deviation of 0.29%;
- completing the entire measurement process within 3 minutes per barrel;
- testing the device in real operational conditions.

For measuring the internal volume of barrels, a prototype measuring device was designed, developed, and constructed, utilizing an array of intelligent optical sensors integrated into a mechanically guided measuring system. As schematically illustrated in Figure 1, the device consists of a rigid frame (3) mounted on a stable base (1) equipped with adjustable locking legs (2), allowing pre-

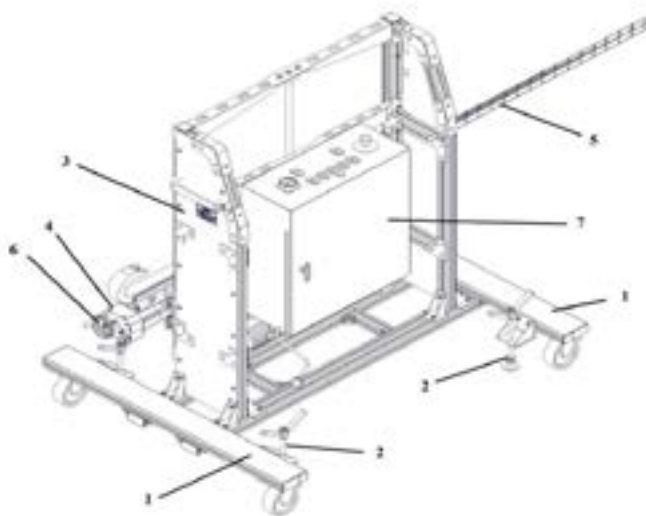


Fig. 1. Technical schematic of the barrel volume measuring device.

cise positioning on a flat surface. An electrical cabinet (7) mounted on the frame houses the electronics and computing unit responsible for sensor control, data acquisition, and processing.

The frame (3) supports a height-adjustable arm (4) carrying a retractable elongated measuring probe (5). The measuring probe (5) is mechanically connected via a movement mechanism to a manually operated rotating wheel (6), which enables controlled extension and retraction of the probe during positioning. Along the length of the measuring probe (5), one or more optical distance sensors are arranged in sequence and electrically connected to the computing unit located in the electrical cabinet (7).

During operation, the barrel to be measured is positioned such that its filling opening is aligned with the measuring probe (5). The probe is inserted through the barrel opening until contact with the internal wall is detected and is then slightly retracted to ensure unobstructed movement during measurement. Once the probe (5) is freely positioned inside the barrel, the measurement process is initiated. The measuring probe (5) is automatically rotated around the axis of the adjustable arm (4), while the sensors continuously record distance values from the rotation axis to the internal barrel surface at discrete angular positions.

The collected distance data form a spatial point cloud representing the internal geometry of the barrel. Based on this point cloud, a three-dimensional model of the internal barrel shape is generated using dedicated software developed for this purpose. The internal volume of the barrel is subsequently calculated from the reconstructed 3D model.

2.1. Measurement principle and data processing workflow

The measurement process is based on the acquisition of a spatial point cloud representing the internal geometry of the barrel. Optical sensors mounted on the measuring probe record the distance from the rotation axis to the internal barrel surface at discrete angular positions. The measurement process proceeds as follows:

- Initialization – the probe is inserted through the filling opening into the barrel interior and positioned freely to allow rotation without contact with the walls.
- Data acquisition – the probe performs a controlled rotation about its longitudinal axis, while optical sensors measure the distance to the internal barrel surface at regular angular increments (5° or 3° depending on device configuration).
- Point cloud generation – measured distances are converted into three-dimensional coordinates and stored as a point cloud in a Cartesian coordinate system.
- 3D modeling – from the point cloud, a three-dimensional

model of the internal barrel shape is generated using a surface approximation algorithm. For this purpose, custom software was developed that compensates for asymmetries and undetected regions through interpolation based on neighboring data points.

- Volume calculation – the internal barrel volume is calculated by numerical integration of the 3D model. The software automatically applies calibration offsets and correction factors specific to the size category of the measured barrel.

The accuracy of the resulting volume is directly dependent on point cloud density (determined by angular measurement step), optical sensor quality (their ability to capture distances on contaminated or uneven surfaces), and device calibration precision. The entire process from probe insertion to volume calculation takes less than 3 minutes.

The angular measurement step used during data acquisition directly influences the density of the resulting point cloud and, consequently, the accuracy of the reconstructed 3D model. In the initial phase of device testing, two angular step configurations were evaluated: 5° and 3°. The 3° step produces a denser point cloud and was expected to yield higher accuracy; however, testing revealed that under certain conditions – particularly in internally contaminated barrels – the increased number of measurement points also amplified the effect of erroneous or missing readings caused by sensor limitations, leading to distorted 3D models. The 5° step configuration proved more robust across varying barrel conditions and was therefore adopted as the standard configuration in the optimized version of the device. This selection was further supported by the fact that the resulting point cloud density at 5° angular increments remained sufficient for accurate volume calculation within the defined tolerance of 0.29%.

2.2. Configuration of measurement parameters

Measurements were conducted on both used and new oak barrels of various volumes. To ensure consistent and reproducible volume determination across barrels of different sizes, a calibration procedure was implemented at the software level. Prior to the measurement, an operator selects the appropriate barrel size category, for which predefined calibration offset values are automatically applied by the software. The calibration offset is a correction factor derived from reference measurements on a certified stainless steel barrel (INOX) with a precisely known volume, and it compensates for systematic deviations arising from the geometry of the measuring probe, sensor positioning tolerances, and slight asymmetries in the internal barrel shape. The offset

is not adjusted mechanically on the device hardware but is configured exclusively through the measurement software, ensuring repeatability and eliminating operator-dependent variability in the calibration process. In total, seven oak barrels were evaluated, specifically barrels with capacities of 227.20 L, 227.80 L, 272.07 L, 228.51 L, 400.64 L, 415.26 L, and 496.96 L.

At the initial stage of device development, a stainless steel barrel was secured and its volume was determined by calibrated measurement. The very first tests were performed on this stainless steel barrel while the device was being developed and adjusted. Only after this development phase was the device prepared for testing new and used oak barrels obtained from real production conditions.

The oak barrels came directly from a French production facility and were therefore barrels used in practice for aging wine, cognac, and other spirits. Their current volume was determined using the wet method – by measuring the difference between the weight of the empty barrel and the full barrel after filling with pure water. This wet method process was repeated over time, as the wood of empty barrels dried during long-term storage, altering their internal volume.

The choice of measurement parameters – including angular step and calibration offset values – was determined empirically during the development phase based on repeated measurements on the INOX reference barrel. Parameters were selected to minimize systematic deviation while maintaining measurement cycle duration within the 3-minute operational limit.

3. Results

During the development and testing of the device, more than 1,000 measurements were performed on barrels with the previously mentioned volumes and various properties, as well as on barrels of different volumes directly in the production facility in France. Measurements were conducted in various ways, ranging from repeated measurements of the same barrel to alternating barrels after each measurement.

In the initial measurements (Tables 1 and 2), two barrels used for aging cognac were found to have contamination in the form of sediment deposits on the walls and bottom of the barrels. The two smallest barrels were new, unused, and directly from production. Including barrels with diverse characteristics was necessary to provide a realistic representation of measurements, as in practice, the volume of both new and used barrels is determined.

Initial barrel measurements after calibrating the prototype device were conducted with calibration offset settings and at 5° and 3° measurement angles. The measurements are presented in Tables 1 and 2. The initial version of the prototype was equipped with the first generation of selected distance-measuring sensors, which during testing showed significantly higher deviations compared to reference values obtained using the wet method. The limitations were primarily due to the technical parameters of the sensors, which performed poorly on contaminated barrels and distorted the measurements; some points in the distance point cloud were completely missed.

A significant deviation was recorded when measuring at a 3° angle for the barrel with a volume of 228.51 liters, where the largest measured deviation reached 6.72 liters, as shown in Table 2. For measurements taken at a 5°

Table 1. Results of the first measurement with 5- and 3-degree angles compared with the water-measured volumes of the individual barrels.

Barrel	Water volume (l)	First series of measurements_Measured values – Angle 5			Second series of measurements_Measured values – Angle 3		
		M1	M2	M3	M1	M2	M3
S1	227.20	227.19	228.18	227.30	228.22	228.46	228.01
S2	227.80	228.92	228.30	228.69	229.56	228.80	228.76
S4	272.07	271.85	271.60	271.83	272.14	272.77	272.20
S5	228.51	231.52	231.71	231.69	231.88	232.08	231.84
S6	415.26	416.43	416.87	416.77	417.29	417.65	417.43
S7	496.96	496.74	497.17	497.09	497.49	497.61	498.65
S8	400.64	400.92	400.36	398.95	400.73	400.33	398.89

Table 2. Results of the second measurement with 5- and 3-degree angles compared with the water-measured volumes of the individual barrels.

Barrel	Water volume (l)	Measurement no. 2_Measured values – Angle 5			Measurement no. 2_Measured values – Angle 3		
		M1	M2	M3	M1	M2	M3
S1	227.20	227.99	228.51	226.85	228.37	228.68	228.79
S2	227.80	228.53	228.94	229.20	229.60	229.83	229.87
S4	272.07	271.83	272.59	272.69	272.54	272.99	273.20
S5	228.51	231.41	232.17	232.40	235.23	232.81	232.50
S6	415.26	417.23	417.60	416.20	417.84	418.78	416.88
S7	496.96	497.15	496.92	496.47	497.81	497.86	497.06
S8	400.64	401.75	401.29	401.89	402.23	401.57	402.28

angle, the most significant deviation was again observed in the barrel with a volume of 228.51 liters, in this case amounting to 3.89 liters.

Based on these measurements, it was determined that the initially selected sensors were not sufficiently powerful to handle measurements in the case of contaminated barrels, as this particular barrel was the most internally contaminated of all those tested. As a result of this measurement inaccuracy, the 3D models were imperfect and distorted, leading ultimately to very large deviations in the measured volume and significant inconsistencies between repeated measurements of the same barrel. In addition to inaccuracies caused by the sensors, it was found necessary to adjust the calibration input data for different size categories of barrels.

Based on these findings, a hardware modification was performed, and the prototype was equipped with more powerful sensor units. Following their implementation, the measurement parameters were optimized, including the adjustment of measurement angles, calibration data, offsets, and improved modeling of the barrel's expected shape. Repeated measurements after this optimization, conducted directly in the production facility in France, demonstrated a significant improvement in accuracy.

During testing in the production environment, complications were observed regarding the simplicity and intuitiveness of device operation. For this reason, and to accelerate the measurement process, modifications were made to the prototype, simplifying the measurement procedure and automating certain steps. These modifications included, for example, replacing the manual insertion of sensors through the barrel bung into its interior with an automated process. Regarding software adjustments, the option to select measurement angles was removed, as tests indicated that a 5° angle was the optimal choice. Predefined intervals for barrel sizes based on volume were also created, with preset calibration data, to eliminate large measurement deviations caused by improperly executed calibration settings.

The current technical solution of the measurement device demonstrated exceptionally high accuracy and repeatability when compared to the standard wet reference method. In repeated measurements of a certified stainless steel calibration barrel (INOX) with a designated volume of 341.5 liters, an average deviation of only 0.1–0.2 L was achieved, while the industry practice requirement set the maximum tolerance at ± 0.5 L. These results confirm that the device significantly exceeds operational demands.

The results of individual measurements are presented in Table 3, comparing the volume values obtained using the developed measurement device with the reference wet method. The table also includes calculated deviations for each measurement, which were subsequently used to assess the accuracy, repeatability, and stability of the measurement process after the hardware and software modifications.

To provide a rigorous statistical characterization of measurement performance, both descriptive and inferential statistical analyses were conducted on the dataset obtained from repeated measurements of the INOX reference barrel ($n = 33$).

Prior to inferential analysis, the assumption of normality was assessed using the Shapiro–Wilk test ($W = 0.972$, $p = 0.522$), which did not indicate a significant deviation from normal distribution ($p > 0.05$). Homogeneity of variances was subsequently verified using Levene's test ($F = 1.115$, $p = 0.376$), confirming that the data met the assumptions required for parametric statistical testing.

To evaluate whether measurement performance varied significantly across different days, a one-way analysis of variance (ANOVA) was performed using the measurement day as the grouping factor (7 measurement sessions across 6 days, $n = 33$). The ANOVA results indicated no statistically significant differences between daily sessions ($F = 1.855$, $p = 0.136$), demonstrating that day-to-day variability – potentially caused by operator handling, environmental conditions, or sensor stabilization effects – did not significantly influence measurement accuracy.

Descriptive statistics were calculated for the complete dataset of repeated measurements ($n = 33$). The mean deviation from the reference volume of 341.5 L was -0.004 L, with a standard deviation of 0.254 L and a coefficient of variation (CV) of 0.074%, confirming a high degree of measurement consistency. All individual measurements remained within the range of -0.46 to $+0.62$ L relative to the reference value, with one measurement (0.62 L) marginally exceeding the required industrial tolerance of ± 0.5 L.

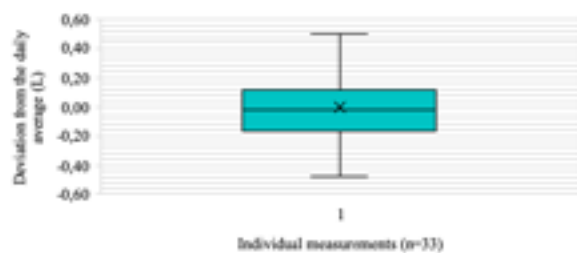
Figure 2 shows the distribution of individual measurements of the barrel's internal volume obtained under identical experimental conditions ($n = 33$). The boxplot illustrates the deviation of each measurement from the daily average, expressed in liters (L). The central line represents the median deviation, while the cross marker indicates the mean value. The results demonstrate that the mean deviation is close to zero, and the median lies within a narrow interval around the daily average, indicating a high level of repeatability. Most measurements fall within a deviation range of approximately -0.2 to $+0.1$ L, with only a small number of observations reaching the lower and upper limits. The absence of significant outliers further confirms the stability of the measurement process. These findings suggest that the developed digital method and the prototype measuring device provide consistent output with limited variability between repeated measurements, which is a key metric for validating the reliability of the proposed technology.

Figure 3 presents the distribution of daily average deviations from the reference barrel volume based on seven consecutive measurement days ($n = 7$). Each point represents the daily mean value obtained from repeated measurements conducted under identical conditions.

Table 3. Comparison of barrel volume measurements using the prototype and the reference wet method, including calculated deviations.

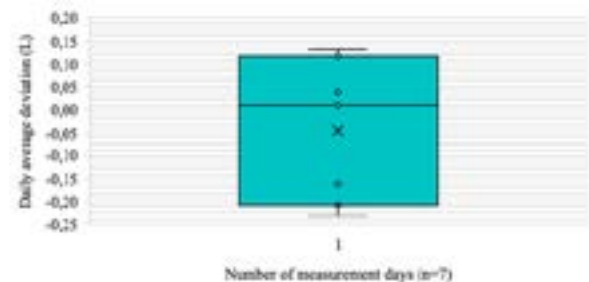
Barrel model	Date/Time	Volume	Number	Deviation	Average	Repeatability (Vol – Avg)	Gauge	Difference (Avg – Gauge)
INOX	10.09.25 / 12:19	341.8	Inox7	–0.2		0.3		
INOX	10.09.25 / 12:18	341.9	Inox7	–0.1		0.4		
INOX	10.09.25 / 12:08	341.4	Inox7	–19.2		–0.2		
INOX	10.09.25 / 12:06	341.1	Inox7	–17.5		–0.5		
INOX	10.09.25 / 12:03	341.5	Inox7	7.7		0.0		0.0
INOX	10.09.25 / 11:33	341.4	Inox6	–14.1		–0.2		
INOX	10.09.25 / 11:32	341.4	Inox6	–9.3		–0.3		
INOX	10.09.25 / 11:28	342.1	Inox6	7.7		0.5		
INOX	10.09.25 / 11:27	341.5	Inox6	5.6		–0.1		
INOX	10.09.25 / 11:25	341.7	Inox6	5.6		0.1		0.1
INOX	09.09.25 / 16:55	341.8	Inox5	–3.3		0.1		
INOX	09.09.25 / 16:53	341.5	Inox5	–20.5		–0.2		
INOX	09.09.25 / 16:46	341.7	Inox5	25.8		0.1		
INOX	09.09.25 / 16:45	341.6	Inox5	19.8		0.0		
INOX	09.09.25 / 16:43	341.7	Inox5	9.2		0.0		
INOX	09.09.25 / 16:40	341.7	Inox5	9.1		0.1		
INOX	09.09.25 / 16:30	341.5	Inox5	14.2		–0.2		0.1
INOX	03.09.25 / 10:52	341.3	Inox3	–1.9		0.0		
INOX	03.09.25 / 10:51	341.2	Inox3	18.7		0.0		–0.2
INOX	01.09.25 / 14:07	341.4	Inox2	0.3		0.1		
INOX	01.09.25 / 13:59	341.3	Inox2	0.0		0.0		
INOX	01.09.25 / 13:58	341.2	Inox2	0.1		–0.1		
INOX	01.09.25 / 13:56	341.2	Inox2	–0.2		–0.1		
INOX	01.09.25 / 13:55	341.5	Inox2	–0.6		0.1		–0.2
INOX	15.09.25 / 16:05	341.3	Inox calib	–8.4		–0.2		
INOX	15.09.25 / 15:55	341.8	Inox calib	2.5		0.2		
INOX	15.09.25 / 15:49	341.8	Inox calib	2.4		0.3		
INOX	15.09.25 / 15:47	341.5	Inox calib	–6.3		0.0		
INOX	15.09.25 / 15:45	341.3	Inox calib	–11.1		–0.2		
INOX	15.09.25 / 15:43	341.4	Inox calib	–11.2		–0.1		0.0
INOX	22.09.25 / 10:29	341.0	Inox 2209	–8.7		–0.2		
INOX	22.09.25 / 10:25	341.1	Inox 2209	13.1		–0.2		
INOX	22.09.25 / 10:19	341.8	Inox 2209	–4.4		0.5		–0.2

The median deviation is located close to 0.00 L, indicating a negligible systematic shift across days. The mean value, marked by the cross symbol, remains within a narrow interval around the median, confirming a consistent central tendency over the measurement period. The interquartile range spans approximately from –0.18 L to +0.08 L, suggesting moderate day-to-day variability, while the limit values cover the full observed range of deviations without indicating any extreme outliers.

**Fig. 2.** INOX barrel – measurement repeatability (Volume – Average).

The presence of individual points near the limit values reflects minor fluctuation attributable to environmental and operational factors, but not sufficient to compromise the overall measurement stability.

The observed distribution of daily average deviations demonstrates that the developed measurement system maintains its precision and repeatability over extended use. With a nominal reference volume of 341.5 L, the absolute variation observed between days remains signif-

**Fig. 3.** INOX barrel – daily average deviation from the reference volume (Average – 341.5 L).

icantly below the allowable deviation threshold of 0.29%, confirming that the system does not exhibit systematic drift or degradation in performance. The limited spread of the central quartiles suggests that any variability introduced by daily changes in operator handling, temperature conditions, or sensor warm-up effects is effectively minimized by the applied signal filtering and calibration procedures. When interpreted together with the results from the individual measurements (Figure 2.), the findings provide strong evidence for the robustness of the measurement method. The combination of low intra-day variability and controlled inter-day deviation indicates that the prototype device is suitable for repeated operational deployment without requiring frequent recalibration, thus supporting its practical applicability in real storage environments where measurement reliability is critical.

In addition to the achieved measurement precision and repeatability, the predefined operational time requirement was successfully met. The complete measurement cycle, including sensor initialization, data acquisition, and automated volume calculation, was consistently completed within the 3-minute limit per barrel. This confirms that the system fulfills not only the accuracy criteria, but also the practical constraints associated with real industrial workflows, where throughput and timing can be critical parameters. The low processing time further supports the suitability of the developed device for continuous use in operational environments without introducing delays into the existing handling procedures.

The industrial partner evaluated the achieved accuracy of 0.2 L as fully satisfactory, as the operational tolerance for barrel volume measurement under these conditions is set at ± 0.5 L. For further development, extended verification of accuracy is planned using a plastic barrel with a calibrated reference volume, which will allow precise long-term comparison between different versions of the device.

4. Discussion

The results showed that the accuracy of digital measurement of the internal volume of barrels is strongly influenced by the quality of the sensors used. The increased deviation observed in the initial configuration was caused by insufficient measurement precision of the sensors and their inability to capture distances in internally contaminated barrels, resulting in a point cloud density inadequate for creating a 3D model. This issue is also known in other 3D measurement fields, where data density is a critical factor for model quality.

After replacing the first-generation sensors with more powerful units and refining the measurement procedure, a clear and measurable improvement in accuracy was observed. The first-generation sensors

were characterized by limited measurement range and reduced sensitivity on contaminated or uneven surfaces, which resulted in incomplete point clouds and consequently distorted 3D models. The upgraded sensor units feature a significantly higher signal-to-noise ratio and improved performance on reflective and soiled surfaces, enabling reliable distance acquisition even in the presence of sediment deposits on barrel walls. This hardware modification, combined with software-level adjustments including revised calibration offsets and improved 3D shape modeling, reduced the maximum observed deviation from over 6 L to below 0.5 L. The proper configuration of calibration parameters was also essential, as it allowed compensation for slight geometric asymmetries inherent in handcrafted oak barrels.

Nevertheless, there are limitations to the proposed solution. The number of sensors is restricted by their physical size and cost, limiting the possibility of creating an even denser point cloud, which could further increase accuracy. Another limitation is the need for manual operation, despite device modifications and partial automation of some measurement steps. The device must be carefully inserted through the barrel bung hole to prevent damage. While insertion and measurement are performed automatically, both processes still need to be initiated manually. Full automation could not only increase reliability but also eliminate the risk of errors caused by the operator. Moreover, removing the human factor and achieving full automation would not only enhance measurement accuracy but could also significantly reduce the overall measurement time. From a metrological perspective, the accuracy of the system is also influenced by environmental factors such as ambient temperature and humidity, which may affect both sensor performance and the dimensional stability of the barrel itself, particularly in the case of dry or recently emptied oak barrels. Although signal filtering and calibration procedures were shown to effectively minimize these effects under the tested conditions, their influence under extreme operational environments has not yet been fully characterized. Furthermore, the current validation dataset is based exclusively on measurements of a single certified INOX reference barrel and a limited set of oak barrels; broader validation across a wider range of barrel sizes, wood species, and aging conditions would further strengthen confidence in the system's general applicability.

From an industrial perspective, the developed device represents a significant step toward the digitalization of cooperage production. Barrel volume measurement has long relied on traditional techniques, and modern Industry 4.0 solutions are almost entirely absent in this segment. Although some innovative elements exist, such as IoT barrel stoppers monitoring the internal environment, technologies aimed at precise volume determination are not utilized in practice. The integration of optical sensors with digital data processing thus represents a unique and

innovative solution with the potential to significantly improve both production efficiency and quality control.

5. Conclusion

The developed device for digital measurement of the internal volume of barrels demonstrated high accuracy and practical usability after hardware and software optimization. The achieved mean deviation was -0.004 L, with a standard deviation of 0.254 L ($CV=0.074\%$). No statistically significant day-to-day variability was detected (one-way ANOVA, $F=1.855$, $p=0.136$), confirming the stability and robustness of the measurement system. The device enables fast, dry, and repeatable measurements without handling liquids, thereby eliminating time losses and risks associated with the wet method. Key limitations of the current prototype include its dependence on manual operation initiation, sensitivity to severe internal barrel contamination when using lower-grade sensors, and the need for size-category-specific calibration. The system has been validated primarily on a stainless steel reference barrel and a set of French oak barrels; further validation across a broader range of barrel types and operational environments is recommended before full-scale industrial deployment.

The prototype represents a significant innovation in the cooperage industry, which is technologically lagging in terms of Industry 4.0. The results confirm that digital measurement of the internal volume of barrels can be performed with high precision even within the physically constrained space provided by the barrel bung hole.

For future development, testing on a plastic calibration barrel with a precisely known and dimensionally stable volume is recommended as an immediate next step, enabling direct long-term comparison between successive device versions under controlled conditions. Further improvements should focus on three areas: first, increasing the number and angular coverage of sensors to achieve higher point cloud density, which would reduce the dependence on interpolation in regions with sparse data; second, fully automating the probe insertion and measurement initiation process to eliminate operator-dependent variability identified as a current limitation; and third, extending validation to a wider range of barrel sizes, wood species, and internal contamination levels – including heavily soiled barrels from active production – to provide a comprehensive characterization of system performance boundaries. These steps would support the transition of the prototype from a research instrument to a robust industrial measurement tool deployable across the cooperage sector.

The integration of science and industry brings mutual benefits. From the perspective of manufacturing companies in the cooperage sector, this research activity will optimize and streamline production processes, enable

more dynamic process management, and in the long term, optimize costs. It will also provide not only a competitive advantage, strengthening market position, but also enhance the company's reputation as a 21st century enterprise. Implementation of this solution in practice signifies progress, process efficiency, sustainability, and transformation of the labor market, creating opportunities for higher value-added jobs.

From a research institution perspective, this activity creates space for further knowledge development, generating new data that can serve as a basis for new analyses of factors affecting internal barrel volume measurement, followed by the design and development of new technologies. Ultimately, this will contribute to the advancement of automation and digitalization. Moreover, this research activity generates a significant synergistic effect by strengthening the scientific capacities of the institution, enhancing technical R&D infrastructure, and supporting global networking between research institutions and industry. By seeking solutions for optimizing and gradually transforming the woodworking industry into an innovative, fully automated, and digitalized sector with smart solutions, the development of both society and individual enterprises will be ensured.

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