Solid Volume Calculator
An Approach to Glass Molds In-line Inspection

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Abstract

This dissertation consists in the study of the possibility of implementing a solution to perform quality inspection of molds' inner cavities for the glass mold industry.

The intended solution requires a series of specifications from the company that provided the problem that led to the exploration of 3D scanning commercial solutions as a tool to simplify and make the process of inspecting the molds faster to the operator.

Three approaches are proposed and explored, the first one working with simple geometric shapes that allow the identification along the part determining the parameters that define the shape, with this information the volume is analytically computed. The second method intends to go further and account for complex shapes and engravings in the mold, by going through each section iteratively, polynomials are fitted into the curves that will allow the computation of the volume of each cavity by means of integration. The last method presented took a step back and computes the volume based on the revolution of the profile of the mold.

For the first two methods tests were performed in simulation as well as with real data, while for the last one only real data tests were effected. Promising and consistent results were obtained that indicate the viability of the solution.

The third method goes far beyond volume computation itself, it illustrates the difficulties encountered during the search for a solution allowing to define unambiguously relevant parameters in what concerns specifications.

Considering the work developed, guidelines for further work are discussed.
Keywords: Volume, Mold, Point Cloud, Metrology, 3D Scanner.

1. Introduction

The purpose of this dissertation is to evaluate methods for measuring the volume of mold cavities. The glass mold industry is searching for a solution to test its production with precision and in a functional way, as in the production line it is not possible to ensure that no errors occur.

ISO 2859 standard defines inspection as "The process of measuring, examining, testing, gauging or otherwise comparing the unit of product with the applicable requirements".

The need for quality inspection is required, according to the Industrial Partner, by the costumer. Some require the volume of each mold individually.

The value in scope here is the volume rather than a specific length. So this procedure does not directly allow to find where the problem is located, it only detects the existence of a non-compliance with the tolerance. Although it can be extended if required.

Indirect improvement on the production can mean a cost reduction as nonconformity is expected to reduce once the problem in the production line is known and corrected.

The objective is to develop a general solution for volume inspection for industries, taking into account some specifications suggested by the company in the glass mold industry.

Several techniques were considered and studied in what concerns the data acquisition and processing as well as in terms of physical implementation solutions.

The approach to design and develop in this dissertation distinguishes itself from known applications since the volume to measure is a cavity and not the actual object. This implies different requirements and constraints to be further explored.

1.1. Quality Challenges

The problem arose at Intermolde, a Portuguese company based at Marinha Grande, a region internationally known for its glass industry.

This company accepts a wide-range of types of projects producing different forms and sizes of molds in several materials.

This will cause a high variability of tolerances and shapes to check.

1.2. Mold Description

The scope is glass molds and their inner cavity. That is a complex surface, curved, defining the shape of the bottle with the particularity of being made of polished metal, making the surface extremely shinny. Thus, it is challenging to fit a geometric shape to the mold outline. Also shinny surfaces are very difficult to scan.

Dimensions of molds can vary depending on the bottle to produce, even for the same mold dimensions there are slight variations leading to different volumes.

A mold consists of three parts: two cavities, one male and one female, and the bottom part. The material is either cast iron as shown in Figure 1 or bronze.

Figure 1: Cast Iron Blow Mold - Example of a mold produced at Intermolde.

For the purpose of this project only the two cavities will be used since it was considered that bottom parts are not so concerning and susceptible to production errors. One relevant characteristic of parts is their curvature at the top. The apparent planes have in fact a curvature of approximately 0.1% of the total longitudinal length.

This feature will be studied along the development of a solution, as it is relevant to the total volume. It will be researched if it is precisely detectable and relevant.

2. Statement of the Problem

The techniques and technologies already in place and approaches related to volume measuring allowed to acquire experience and learn advantages and disadvantages of each approach and where difficulties can arise from. Although few references are found in the subject it is not possible to determine *a priori* which will be the way forward towards the desired goal. Despite that, all of the mentioned before need to be taken into account developing a new concept or solution.

2.1. Solid Volume Measuring Solutions

The first method studied focuses on finding the inliers of the planes of a scene and, subsequently, the vertices that connect adjacent planes of the object, so that it is possible to determine each edge length.

It was decided to implement a method similar to the one in [2] with higher resolution cameras as a learning process and a test to cameras that were considered for point cloud acquisition.

The work developed in [1], [3] and [6] was analyzed. The method in [7] was the base to the Slicing Algorithm presented in next sections.

2.2. Current Procedures in the Mold Industry

The task is currently performed by an operator, the mold is joined filling the gaps with an appropriate paste. Having the mold closed it is filled with water, determine the mass of water and its temperature in order to theoretically determine the water density using tables.

The accuracy of this method considering the uncertainty of the whole process is $\pm 0,1ml$ for molds with volume of approximately 100ml and $\pm 0,25ml$ for molds with volume around 1000ml.

Another method to measure molds inner volume is Sonicam S3 [8]. It is a system designed to fill a balloon and determine the volume from the water used.

Sonicam S3's measures [8] have an uncertainty of $\pm 0.05ml$ for molds of around 100ml and $\pm 0.09ml$ for molds with approximately 1000ml.

The device has limitations in what concerns the maximum volume, some diameters of the mold as well as its height, this implies that S3 can't be used for the all types of molds produced.

2.3. Problem Statement

Molds' inner cavities have complex shapes and engravings as illustrated by Figures 1 and 2 and the series are short, 12 to 90 units [5], with a typical value being 30 molds. This means that the molds to inspect are very different from each other, thus a generalized method is desired.

Both bronze and cast iron are very bright and reflective, presenting a diffuse reflection as it is possible to observe in Figure 2. According to the Industrial Partner's requirements the method to develop is intended to be a solution with the following characteristics:

- The inspection can't be destructive or some-how damage the part, scratches on the surfaces can lead to and accelerate undesired oxidation;

- Use commercial scanning solutions;
- No surface aids are allowed, such as powders or sprays to overcome issues caused by brightness;
- No stickers with glue such as targets to overcome alignment problems caused by symmetries in the part can be used;
- The solution must be fast enough to be applied in-line, the time indicated by the Industrial Partner is around 20 minutes, but this depends on the type of mold and its production time.

The usage of stickers, powders or sprays would not decrease task time. As molds have to be delivered clean, as it would be a risk to clog the narrow pores existing in the part, cleaning time should be accounted.

Figure 2: Example of engravings and light diffuse reflection in a bronze mold - Ref. 2283 female

3. Methods

3.1. Mathematical Tools

Several approaches were considered, among them it was assessed the usefulness of several mathematical tools to develop in the implementation phase to converge to a method of obtaining the volume of solids from simple to complex shapes and in particular mold cavities.

Iterative Closest Point, an algorithm to register two point clouds resulting in a transformation matrix that minimizes the distance between each source point to its match. It is used by the majority of the scanning devices. It reveled very use full when dealing with cameras with no processing software and for some approaches to find desired shapes.

The least squares approximation is a criteria to find the best-fitting curve to a given set of points by minimizing the sum of the squares of the offsets, the so called "residuals" of the points from the curve. It is the base of the Slicing Approach.

Another approach is the Random Sample Consensus Algorithm, it is of particular interest combined with other estimation methods. As it was not used in the approaches it will not be further developed.

3.2. Estimation Architecture

This Algorithm was developed to include three phases: the data acquisition, the pre-processing and the actual volume computation.

For the volume computation four solutions were developed. The first one designed to measure the volume of boxes, the second to measure volume of geometric shapes with a known model. The remaining two were designed specifically for molds even though they can have different applications, one assumes the mold is a revolution of a profile and thus circular, the last solution is a general solution in which the model is completely unknown and it is intended to work for any kind of mold produced.

3.2.1. Box Volume Calculator

The first method tested was similar to the one proposed in [2] with some simplifications.

The simplification can be briefly described. A point cloud of the floor is taken for calibration and the equation of the floor plane is computed. Then for each box to measure a top view point cloud is acquired.

The geometric center of the top plane is computed, knowing the center point (marked with letter "o" in Figure 3) the most distant point in the plane to the center will be assumed as one of the corners (marked with the letter C on Figure 3).

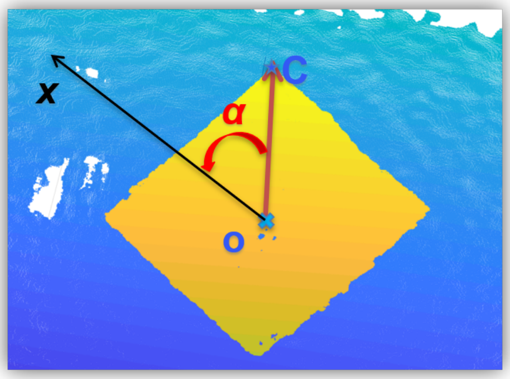

Figure 3: Schematic representation of the method to find the first corner C

The point cloud is rotated an angle α in z, such that the vector $\overrightarrow{oC}$ is aligned with the x axis. With this rotation, corners do now correspond to the maximum and minimum points in each direction as shown in Figure 4.

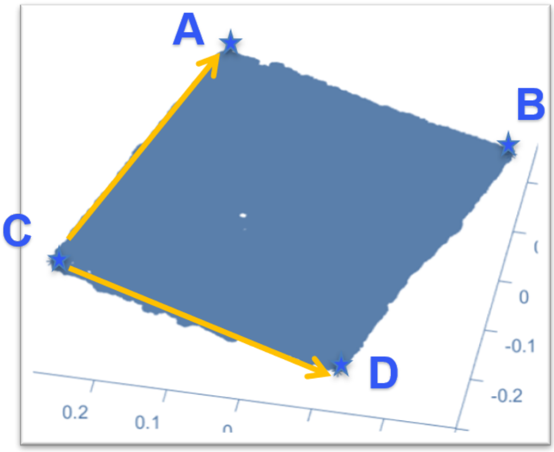

Figure 4: Schematic representation of the method to find the remaining corners

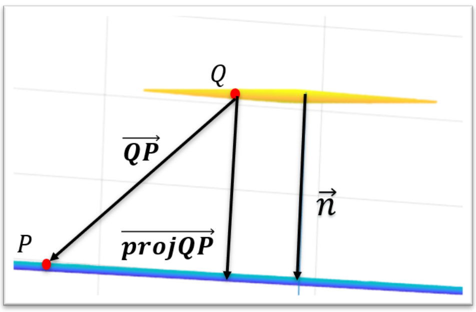

Figure 5: Schematic representation of the relevant vector

The dimensions of the box can now be determined by norms of vectors represented in Figures 4 and 5 using Equations 1 to 5.

$$Width = ||\overrightarrow{CD}|| \tag{1}$$

$$Depth = ||\overrightarrow{CA}|| \tag{2}$$

$$TOPArea = ||\overrightarrow{CA} \times \overrightarrow{CD}|| \tag{3}$$

$$\overrightarrow{projQP} = \frac{\overrightarrow{QP} \cdot \overrightarrow{n}}{||\overrightarrow{n}||^2} \tag{4}$$

$$Height = ||\overrightarrow{projQP}|| \tag{5}$$

3.2.2. Feature Recognition Approach

The method implies total knowledge of the 3D shapes to be evaluated and its sequence through the longitudinal axis, although none of its dimensions needs to be known.

The principle is to segment each geometric form along the longitudinal axis by fitting the 3D shapes by the predefined order and determine the best fit of shapes that reduces the error when the parameters are computed by the Least Squares Method for 3D Shapes.

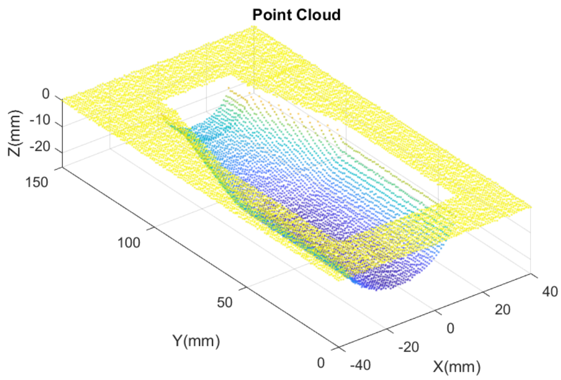

Figure 6: Generated Point Cloud

In Figure 7 one can observe the identification of one cylinder in the point cloud in Figure 6 whose parameters are to be computed by the least squares method (colors and lines are represented for clarity).

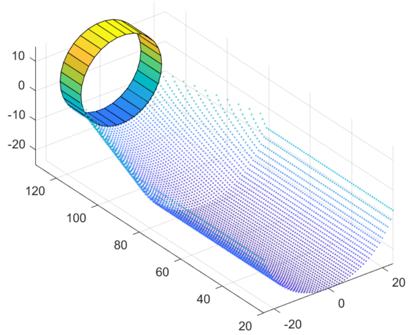

Figure 7: Segmentation of the second cylinder in the longitudinal axis

3.3. The Profile Revolution Approach

The Profile Revolution intends to meet the specifications in terms of time by taking the assumption that mold shapes are the revolution of a profile. This implies that only the profile will be taken into account. In this method, the remaining internal surface will not be considered.

The method begins by registering the top plane of the mold using ICP. The top plane is rotated and aligned with the x,y plane. The profile lines in each side of the cavity are identified, allowing to compute the distance between them. In the case of a cylindrical shape this distance corresponds to its diameter.

Infinitesimal volumes are computed and summed to obtain a total volume. The operator has to select manually the limits of the cavity's region of interest, since no general criteria was reached.

The application of this method is shown to be useful, however it does not meet completely the purpose thus it is used as a comparison rather than for its results alone.

3.4. The Slicing Approach

The slicing method was developed with the goal of reducing the need of prior knowledge about the model.

The algorithm's underlined idea is to slice the scan in a longitudinal direction. The thickness of the slices is small enough to provide an almost continuous set of slices. Each slice is modeled as a 2D slice shape. For each slice shape, a polynomial can be fitted. The area of each 2D slice shape is computed.

The model to fit has to be carefully selected as it is not desired to obtain an over-fit of the model. Overfitting allows the possibility of taking into account non existing shapes caused by noise.

The slicing method will also allow the possibility of comparing slice by slice the produced mold with the CAD model, making evident where the defects are located with a precision as fine as the thickness of a single slice.

Let $f_z(x)$ be the line corresponding to the cut of the closing plane and $g_z(x)$ the cut of the cavity of the mold.

The area of a single slice located in z in a longitudinal axis is given by the area under $g_z(x)$ minus the area under the curve $f_z(x)$.

$$A(z) = \int_a^b g_z(x)dx - \int_a^b f_z(x)dx \tag{6}$$

$$V = \int_c^d A(z)dz \tag{7}$$

$$V = \sum_{z_{ROI}=c}^{d} A(z) \tag{8}$$

with $z_{ROI} \in [c, d]$

As in practice the limit of the cavity does not intersect the closing plane the volume computed will be of the shape closed by two vertical lines as shown in the schematization in Figure 8.

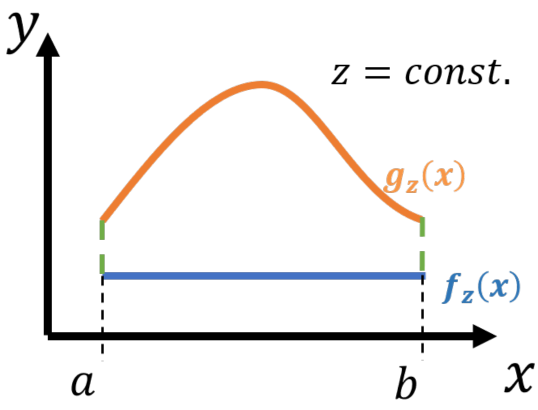

Figure 8: Schematization of a slice in a mold with concavity

To measure how well the polynomial fits the scanned curve the RMSE is used. It consists in the standard deviation of the residuals, which measure how far the data points are from the regression computed.

$$RMSE = [\frac{\sum_{i=1}^{N}(z_{scanner} - z_{regression})^2}{N}]^{\frac{1}{2}} \tag{9}$$

The idea of implementing an iterative solution to find the best fit intends to address computational efficiency and lower time of processing.

In the glass mold industry the most common shape will have the best fit at the second degree polynomial, so the iteration is not expected to take longer than assuming an order for the polynomial.

4. Implementation

4.1. Technological Solutions for 3D Scanning

A 3D scanner is a device capable of capturing digital three-dimensional information about the shape of an object. It can capture shapes from a small dent on a gear to a real size aircraft. Some can also acquire appearance data such as color.

Several technological solutions were considered to determine the best solution regardless of its cost, therefore it is important to understand the principles behind of each method to predict which ones will have an appropriate performance.

To meet the design specifications the choice is between a non-optical solutions such as acoustic and magnetic and a optical solutions whether active or passive. Several tests were performed with the collaboration of other laboratories.

4.1.1. *Laser* Scanner

A Laser scanners are non-contact, non-destructive, optical, active system. Lab2Prod at IST and their researchers allowed the opportunity to learn and use their ZScanner 700, shown in Figure 9.

Figure 9: Cast iron mold being scanned with ZScanner 700 with position targets at Lab2ProD

The results were promising when tested with cast iron molds although difficult in polished surfaces. Worse results were obtained for bronze molds.

With this device position targets were used in order to overcome the difficulties created by symmetry and talcum powder on the bright surfaces.

As the price range of laser scanners is above visible light scanners and its performance experimentally lead to worse results laser scanners were no further explored.

4.1.2. Structured Light Scanner

Structured light scanners are non-contact, non-destructive, optical, active systems. Structured light scanner systems, in particular the ones which use visible light, are expected to perform well in variable conditions as it is possible to vary the wavelength of the light source.

One Structured Light Scanner is the Einscan-Pro, *Laboratório de Biomecânica de Lisboa* at IST and their researchers kindly allowed some tests to be performed with it. It allows four scanning modes that were explored.

This Fixed Scan Mode is the one that guarantees the best resolution. The accuracy for this device in this mode is defined in its Start Guide [4] in the technical specifications as 0.05mm.

Figure 10: Einscan-Pro in fixed mode

The procedure consists in placing the scanner in a fixed position for each acquisition, the position of the object has well as the projector can be different at each time. Succinctly at each acquisition it projects a pattern as in Figure 11 and measures each point by the distortion of the lines in the pattern. The several point clouds are automatically aligned when their features allow it, the user can doubt that the fitting is correct and manually indicate 3 correspondent points in each cloud to better align it.

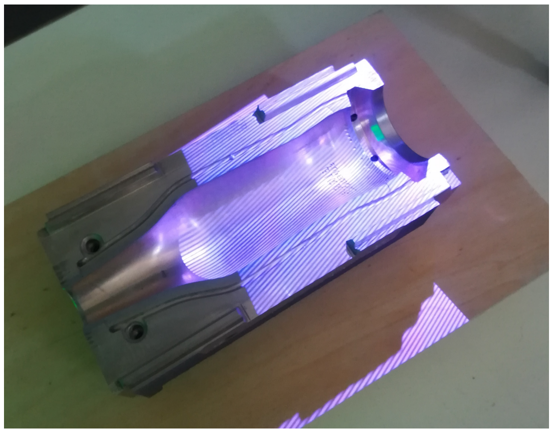

Figure 11: Einscan-Pro projected patter in a bronze mold

4.1.3. Stereo Vision - Intel Realsense D400 series

In order to scan the molds a stereo pair of RGBD cameras was used, these are a specific type of depth sensing devices that work in association with a RGB camera, that are able to augment the conventional image with depth in a per-pixel basis.

The model contains a considerable amount of noise in the acquired depth images since the map of infrared points is not as dense as desired.

4.2. Box Volume Calculator

The first approach implemented was the Box Volume Calculator. Initially the point clouds were obtained from two points of view and combined with ICP.

Later it was decided to simplify the process using only a top view as in Figure 12, using the process described before just for one plane, and determining the height by the length of the normal distance between the floor plane and the top plane of the box.

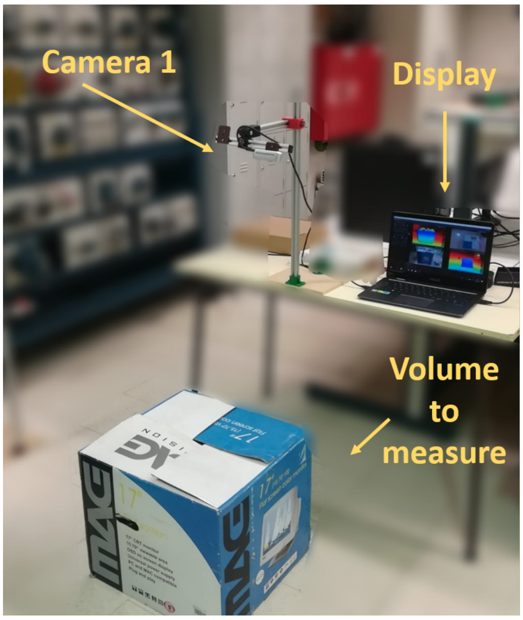

Figure 12: Experiment with one camera

4.3. The Feature Recognition Approach

In a first approach, in Figure 13, images were acquired in a closed dome specifically designed for visual quality control, although it reduces the external light influence, it also produces spurious reflections. The later revealing more importance than the former.

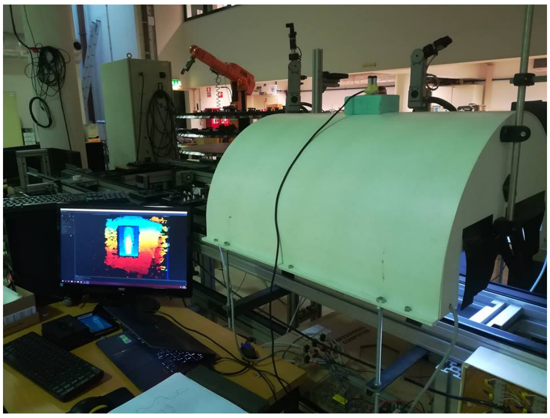

Figure 13: Initial setup

With the knowledge from the first setup several updated were made reaching the final one in Figure 14. This configuration allows the user to know the precise position of the mold, the height of the camera (with respect to the surface) and, most importantly, allow a stable and repetitive environment of data acquisition.

Noting that in this new solution the orientation of the mold must be constant (top of the mold facing the basis of the holder).

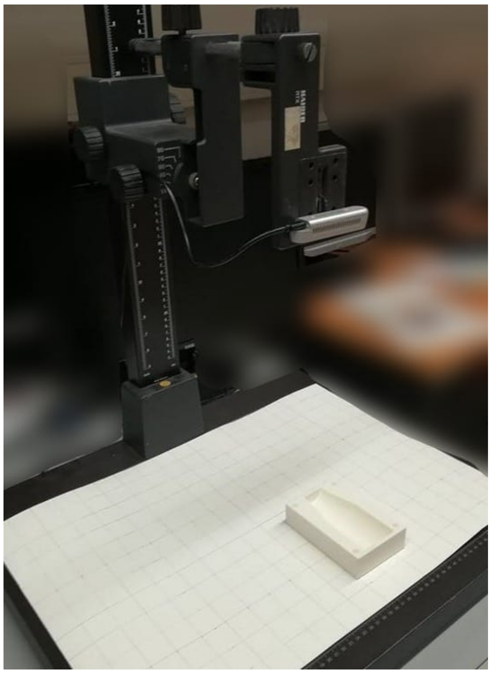

Figure 14: Final setup

4.4. The Profile Revolution Approach

The profile revolution approach was implemented by uploading a point cloud of the mold previously scanned. Resorting to ICP a plane is fitted to the top of the mold and the profile is determined. The distance between each two corresponding points in each side is computed and assumed to be the diameter of the circular section.

Obviously this only computes volumes of circular sections. There's also another issue since the diameter is smaller than the one of the rest of the section as it is required by mold designers for technical reasons. This method fails when used with Intel Realsense's scans since their problem is precisely in this top profile corner.

4.5. The Slicing Approach

The slicing method is the most general and further developed approach in the scope of this project. Several variants were developed before reaching a solution.

Two point clouds are uploaded to Maltab, one of the complete scan of the mold that must include the horizontal top of the mold and the same scan but this time only containing the cavity, in the same coordinate system, no new scan is required, only a manual removal of points with no relevance to the interior shape of the cavity.

The user must select at least three points, three is the desired number to define the plane, that defines the vertical top of mold to which the mold is considered to be filled when using water. These points are not arbitrary and require knowledge of the operator.

The mold is processed through a longitudinal direction in steps of 0.1mm, this value can be varied, and the 2D parameters of both the line defining the plane and the polynomial defining the cavity are determined, the integral under each line is computed and the difference times the thickness of the slice corresponds to the volume of a slice, in this case it corresponds to the volume of a 0.1mm thickness slice.

The slices volumes are then summed, only considering slices between the two manually selected horizontal planes that close the mold.

The user interaction was not completely eliminated but in an industrial implementation could be desirable depending on the company.

5. Results

This section presents the main results to consider from the experiments.

5.1. Box Volume Calculator

The detailed results for this experiment are presented in Table 1. The results would benefit if the camera was placed parallel to the background plane, in this case the floor.

Although the main goal was to return reference error values, some criteria to keep the solution industry oriented were considered, such as the goal to have fast results thus balanced computations between time and accuracy.

Table 1: Results for the box measure experiments

	Real Dimension (cm)	Test 1 (cm)	Test 2 (cm)	Percentage Error
Width	47.00	45.12	44.25	4.93%
Depth	49.50	49.22	49.34	0.45%
Height	41.50	43.31	43.04	4.09%

5.2. The Feature Recognition Method

In order to study the influence of increasing the number of points in the point cloud used in the computations experiments were performed with three different point clouds. The results are presented in Table 2.

Table 2: Number of Points in the Cloud vs Computation Time.

Number of Points in the Cloud	12555	49105	194205
Computed Volume (mm^3)	87535.47	88076.37	88545.86
Percentage Error	0.640 %	0.021 %	0.51 %
Computation Time (s)	1.53	1.80	4.42

The performance in terms of precision of the algorithm is influenced by the random noise in the point cloud and not only by its dimension.

This method relied on the comparison to an estimated reference, in spite of this the absolute results were not considered so relevant as a comparison between them. As the method proceeds several graph are displayed to the user to control if the algorithm performed as desired.

The development and implementation of this method were analyzed. The idea showed to be promising for simple geometric shapes which is not the case of typical molds for the glass industry.

5.3. The Profile Revolution Approach

The Profile Revolution intends to meet the specifications in terms of time by taking the assumption that mold shapes are the revolution of a profile.

Table 3: Results for real point clouds using the Profile Revolution Approach

Ref.	Result (cm^3)	Nominal Volume (cm^3)	Absolute Error (cm^3)	Percentage Error
0561	414.60	417.00	2.40	0.60%
2283	416.76	418.10	1.34	0.32%
11937	163.49	166.19	2.70	1.60%

The main limitation of this method is that it does not take into account the entire cavity of the mold but only its profile, meaning it does not account for engravings or cavity defects. Also it depends on the operator action.

Testing this method allows relevant conclusions, not only about the method in particular but for general development of a solution. In an infinitesimal volume of $0.1mm^3$ and for a diameter of $6cm$ typical for a mold of a 33cl bottle, for Einscan Pro's mode with the smaller uncertainty $0.05mm$, assuming there is no error associated with registration of several point clouds, the error caused by this uncertainty is around $1mm^3$. In a entire mold of a 33cl bottle this would represent an error of $2cm^3$.

In order to obtain an uncertainty of $\pm 0.1ml$ for a 33cl (remember that mold filling has an uncertainty of $\pm 0.1ml$ for a 100ml mold) the solution would need a scanner with accuracy of 0.015mm which is the accuracy of the RobotScan E0505 from Shinning 3D, a solution that combines a robotic arm and a scanner from Shinning 3D, but is out of the price range of commercial scanners.

5.4. The Slicing Approach

Results were obtained for different scanning of molds. As, in general, only one scanning of each mold was available and from only one mold of each reference, there wasn't the possibility of checking for a tendency in the results, thus the focus is on absolute results. A comparative test is performed with only 3 molds that were available.

The results obtained by the slicing method are presented in Table 4. Although the percentage errors are just an indication and are not exact it illustrates the idea of how much does a better scanner influence our results.

Results presented in table 5 were obtained for the mold with Ref. 2283 for the Einscan Pro point clouds. They allow to conclude that Intel's cameras seem to create non-existing surfaces and reducing the volume.

Table 4: Results for real point clouds of an 1,5L bottle mold.

Scanner	Intel Realsense D415	ZScanner 700
Guess Volume (cm^3)	1017,5	1017,5
Computed Volume (cm^3)	951,2	1019,2
Percentage Error	6,5%	0.2%

Table 5: Results for real point clouds of Ref. 2283.

Ref.	2283
Real Volume (cm^3)	418,11
Computed Volume (cm^3)	209,77 (male) + 212,07 (female) = 421,84
Percentage Error	0,89%

The results in Table 5 were obtained with the method of automatic selection of the plane where the bottom part fits. This is done by finding the maximum of the second derivative.

Some testes were performed for the level of noise of Einscan-Pro in Handheld Rapid Scan mode which is $\pm 0.3mm$.

It was concluded that noise in this range does not affect volume measures, nevertheless it was taken into account that this range of uncertainty is for a single acquisition and one has also to account for the error in the fitting of the several acquisitions. The tests show that the method has repeatability for the same data, and for that data with rotations and translation applied. This didn't happen with real data.

A comparative test with three molds of the same reference, produced in same series, molds number 8, 21 and 29 of the reference TN-483 produced by the Industrial Partner which corresponds to a 70cl bottle mold made of bronze. The scan of this reference was performed by Microsense.

Table 6: Results for the comparative test with three molds of the ref. TN-483

Mold	test (cm^3)	Microsense (cm^3)	Manual water filling (cm^3)	Percentage Error w.r.t. Intermolde
8	819.24	820.56	820.80	0.190%
21	820.86	821.44	821.80	0.114%
29	821.84	822.00	821.85	0.001%

This section has shown the main result for the implemented methods. The next section presents the main conclusion withdrawn from this research.

6. Conclusions

The need behind this research and the methodologies to follow were described. Several approaches were pursued and tested.

The molds in scope are typically produced in bronze and cast iron, with complex features and engravings in the polished metal.

Several methods of data acquisition were used to acknowledge its advantages and disadvantages for the desired application. The ones considered the most promising and available were effectively tested in practice, performing a diversity of practical experiments in laboratory conditions.

Tests were carried out with IntelRealsense D415, Intel Realsense D435 and Kinect, cameras with no reconstruction algorithm relying in one acquisition only, that although showing promising results for applications of standard objects as boxes did not perform with sufficient precision and accuracy that would allow them to be considered for a mold volume measuring solution.

This cameras are designed to detect people or objects and its moves, meaning applications at a bigger scale. This devices have, for the purpose, low resolution, its perspective allows them to leave blind spots. This combined with bright surfaces cause the data to be incomplete. All this reasons motivated the search for a device closer to a metrological solution.

To obtain a higher level of precision and accuracy experiments were performed with visible light scanners from Shinning 3D, EinScan-SE and EinScan-Pro, in a price range considered low for industries but still around 6 times the price of the first cameras considered, as Intel Realsense. As stated, the search was oriented to metrological devices, thus two more technological solutions were tested. Zscanner 700, a laser scanner and also a FARO Dual Cronos was used by Microsense, this last one was not taken into account when choosing a solution since little information about it was available.

Shinning 3D solutions have shown great potential in this application. It is of great relevance to acknowledge that scanners in this price range usually require the use of sprays and powders to overcome polished surfaces reflection challenges. This problem is claimed to be solved in solutions from the same company especially designed for metrological applications, in a completely different price range, similar to the Zscanner 700 despite the fact that this one is still influenced by the bright surfaces.

The first approach implemented led to the conclusion that the method would benefit from a better positioning of the camera. Nevertheless the results were consistent and the method was able to approximate not only the box volume but also the 3 dimensions in detail.

The box solution was found to have several applications. Whether it is a matter of storage or transportation space optimization, the application is transverse to almost all the industries.

Two solutions were developed and tested focusing on actual glass mold industry molds. The Feature Recognition Approach was only tested in simulation and for a synthetic mold produced in the 3D printer. The time to return a result was below 20 seconds, way under the acceptable maximum time defined as 3 minutes. The maximum percentage error was defined as 10% and in practice it was always under 1%.

Although the results accomplished all the goals defined to the experiment the method is only adequate for simple shapes. In conclusion the Feature Recognition Approach is not suitable in practical terms for the main goal of measuring real data from molds.

A solution with the goal of being generalized for virtually every mold produced by the company was proposed, The Slicing Method. This solution was tested in simulation as well as with real data.

The simulation results were promising with the algorithm showing good precision and accuracy, as the percentage error was under 0.6%.

The biggest challenge dealing with real data from scanners was related with the approximation of the plane that should be considered for the volume measuring, referred to as the closing plane. The closing plane is influenced with a relevant amount of noise that causes the plane to be defined differently at each acquisition for the same mold. This introduces a random bias in the results.

In spite of the difficulties faced during the process, with limitations in hardware for not having a scanner dedicated to the project and in software as it was necessary to work only with software available with student access, satisfying results were achieved and most important a point was proven, that the solution has potential and it is crucial to learn from the limitations and invest in the project and further explore it, for that reason the next section defines guide lines for future development of this solution.

The industrial implementation problem persists and it will require automation and thus a repeatable protocol of image acquisition and processing has to be determined.

6.1. Future Work

It was acknowledged that for this type of industrial application the automation of the process of scanning benefit the solution. Attention should be paid to the developments in metal scanning technologies and also to the problem of missing data.

The industry remains searching for a practical solution that would aid or solve the quality inspection of its molds. The research techniques shown to be a feasible approach and a promising way forward to achieve this goal.

The problem still remains of great interest not only to mold producers but also to industries that order and use the molds as they desire to test the molds' wear and quality along time. Also the problem is extensible to several other industries that may see in this solution a way of optimizing its quality inspection and a way of assuring quality.

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