GEOMETRIC INSPECTION USING LINE SCANNING

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Abstract

As part of a growing interest in implementing ideas from Industry 4.0, a larger need for quality control systems has arisen. In this article, established methods used for geometric inspection are applied on point clouds. The alignment methods used in this article are Iterative Closest Point and Principal Component Analysis, which are augmented by Random Sample Consensus and Density-Based Spatial Clustering of Applications with Noise. When the point clouds are symmetric, planar and have a non-uniform density distribution, these methods cause misalignment to occur. These attributes are exhibited when line scanning a planar workpiece, which have symmetric features. By using an assumption of the workpiece's general position and orientation being known, it is possible to apply the registration methods without causing misalignments. This is validated by using laser line scanning on the workpiece. The results reveal a particular sensitivity to transformations that cause the assumption to be untrue, as well as a need for a high resolution, when evaluating tolerances of the workpiece.

Keywords: Geometric inspection, CAD reference model, Symmetric and planar non-uniform point clouds

1. Introduction

The transformation from Industry 3.0 to Industry 4.0 has created an increased need for quality control systems. This is due to the higher concern of reducing waste in production, which is present in all manufacturing processes [1]. This article explores an aspect of these quality control systems, namely geometric inspection of manufactured workpieces. The overall goal for the geometric inspection in the context of this article, is to evaluate whether the manufactured workpieces meet the tolerances set by CAD reference models, or working drawings created from those models.

In the industry, the current methods used for geometric inspection are mechanical probing and scanning technologies, such as optical and laser line scanning. Using line scanning on a workpiece produces a data-set, which is commonly represented as Point Clouds (PCs). However, evaluating whether tolerances are upheld using PCs is not standardised in the industry. The process of making this evaluation, in the context of this work, is therefore presented in Figure 1 to clarify the steps taken to make the evaluation. The general approach involves an alignment of the PCs, similar to the illustration in Figure 2.

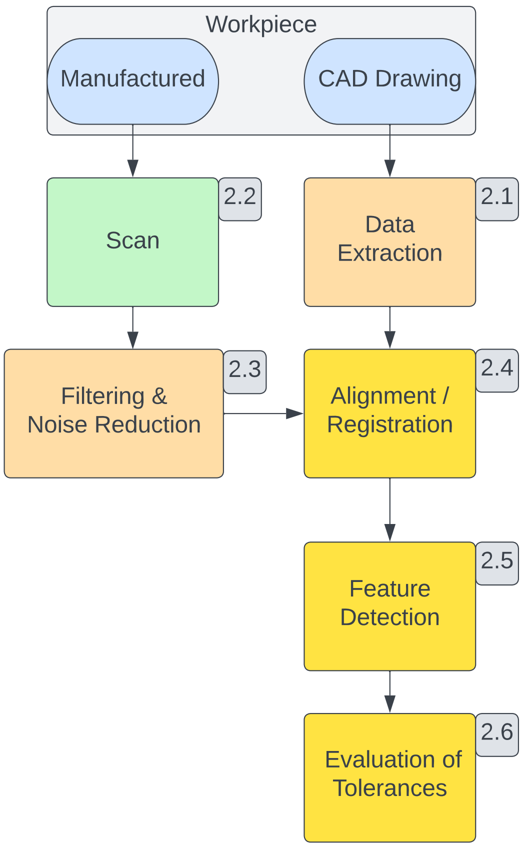

Figure 1 Flow diagram of evaluating tolerances. Blue is the input, green signifies a physical action, orange is a non-geometric software action, and yellow is a geometric software action. The numbers serve as references to Section 2.

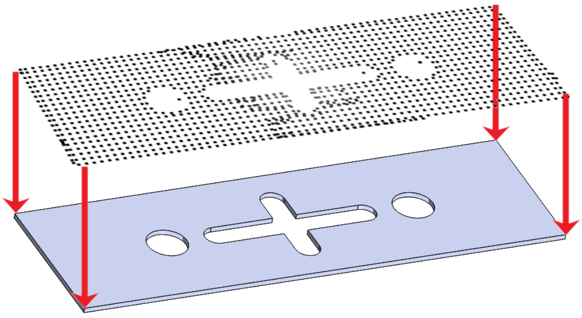

Figure 2 An alignment of a scan's PC to a CAD drawing.

Scanning a symmetric and planar workpiece produces a PC, which is also symmetric and planar. Additionally, due to noise and the surface of the workpiece, this PC also has a non-uniform point distribution. Each attribute poses a unique problem when established methods are applied in the steps of the flow diagram in Figure 1. A common shortcoming is found due to most methods' reliance on the uniformity of the PCs. This reliance is seen for methods such as Iterative Closest Point (ICP)[2] and Principal Component Analysis (PCA)-based methods[3][4], which are commonly used for alignment. These apply to step 2.4 in Figure 1. The non-uniformity of a PC shifts the location of the Centre of Mass (COM) towards the denser regions of the PC, causing an in-plane rotational misalignment. ICP is also limited by symmetry, as no unique geometric features exist in a symmetric PC. This impact is also seen in the planarity attribute, as the PC is reduced to 2D. This further limits the amount of geometric features by removing the third dimension. These problems have been identified in other publications, seeking to develop the alignment methods to allow their application on PCs with one of the aforementioned attributes[5][6][7]. However, a gap is found in the current methodology, when applied on PCs exhibiting all three attributes simultaneously.

This work presents the methods used in each step of the flow diagram in Figure 1. These methods are needed to make the geometric inspection of a workpiece, which produces a symmetric, planar, and non-uniform PC when scanned. To combat the problems exhibited by the previously mentioned alignment methods, an assumption surrounding the context of the geometric inspection must be made. The assumption used in this work is the general position and orientation of the workpiece being known in the global coordinate system. The implications of using such an assumption is discussed in Section 5. By knowing the general position and orientation, it is possible to restrict the already existing alignment methods, allowing their use. It is also possible to distinguish between the identified manufacturing features without the need for feature detection. The geometric inspection is validated in Section 3. As the implementation of the methods used in each step of the flow diagram in Figure 1 vary. As the variation depends on the geometry of the workpiece, a case description of the geometry used in this work is presented.

1.1 Case presentation

This work is centred around a rectangular object with symmetrically placed features, which when scanned will produce a non-uniform, symmetric, and planar PC. The general position and orientation of the workpiece are known. The rectangular shape is chosen to ensure consistency, though any non-circular cross-section works, which is discussed in Section 5. The workpiece's CAD drawing is shown in Figure 3.

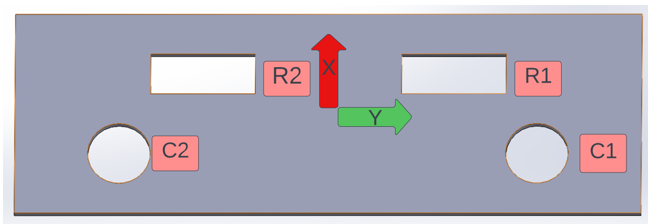

Figure 3 The CAD drawing of the workpiece in the global coordinate system. C1 and C2 serves as identification for the circles, the same applies to the rectangles, R1 and R2. This identification is used throughout the article.

2. Methodology

The general procedure for the geometric inspection of a manufactured workpiece is to scan it, filter the scan and remove noise, and compare it with geometric data stemming from a CAD reference model. The workpiece is assumed to be manufactured based on a working drawing stemming from the CAD reference model. The comparison between the workpiece and CAD reference is done by representing all data as PCs and making an alignment between those PCs. The manufactured features' location and properties are known from the CAD reference model, which makes their detection unnecessary when the alignment has occurred. An evaluation is then made of whether the tolerances are met. This section will present these steps in the order presented in Figure 1, starting with the CAD data extraction.

2.1 CAD data extraction

In order to use a CAD drawing as a reference to a scanned object, it is necessary to have an equivalency between the information presented by the drawing and the scan. Independent of which software is used to create the CAD drawing, it is possible to extract geometric information from the Standard for the Exchange of Product model data (STEP)-file format[8][9]. While many techniques of automatically extracting geometric information from STEP-files exist, such as using an Extensible Markup Language (XML) conversion[10], the extraction of the information is only necessary once.

2.2 Scan of workpiece

To find the dimensions of the produced workpiece, a scanner is needed for creating a PC of the workpiece. A scan is presented on Figure 4. For any tolerance evaluation to occur, the resolution of this scan must be larger than the tolerances themselves. Essentially, the tolerances must not be smaller than the distance between the points in the PC.

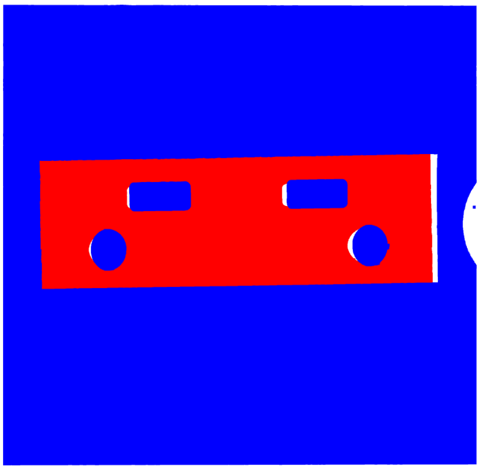

Figure 4 A raw PC made from an untouched scan.

2.3 Filtering and noise reduction

To ensure that only the workpiece is represented in the PC, it is necessary to separate it from the surroundings in the scan, as well as remove noise. The methods used for this purpose are Density-Based Spatial Clustering of Applications with Noise (DBSCAN) and plane segmentation using RANSAC. DBSCAN is used to make clusters in the overall PC of points that are close together.

The same workpiece, or equivalently manufactured workpieces, is scanned every time. It can therefore be assumed that the number of points used to represent the workpiece is consistent between scans. This number of points can be found by making a scan and isolating the workpiece manually. This enables the use of DBSCAN for filtering noise and other objects from a scan of the workpiece. This is done by using DBSCAN to make clusters and removing the clusters, that does not contain a similar number of points as the workpiece. This results in a single cluster that only contains the points that describe the workpiece. However, it is possible that some noise persists depending on the parameters used for DBSCAN. To remove out-of-plane noise and prepare the alignment in Section 2.4, RANSAC plane segmentation is used. As RANSAC utilises random sampling, and therefore sampling outliers may occur, a strict convergence criteria is applied while allowing for many iterations. This effectively removes out-of-plane noise.

2.4 Alignment of PCs

By utilising the plane parameters from Section 2.3, it is possible to align the plane orientation to the global xy-plane. By applying this rotation to all points in the workpiece and projecting the PC surface of the global xy-plane, the third dimension is removed. This utilises the planar attribute to make the alignment purely in 2D, making the computational requirement lower.

While the attributes of the scanned PC cause alignment using ICP to be inaccurate, the scanned PC can be modified to remedy those inaccuracies. This modification is made from geometric information extracted from the scanned PC. By identifying the four edges of the rectangle in the workpiece's PC, and representing these with a line, the intersection points of those four lines yields an approximation of the workpiece's four corner points. These four corner points form a uniform PC, and due to the low number of points ICP does not suffer from a lack of unique geometric features.

To find the edges of the rectangle, these edges must first be separated from the surface. A K-Nearest Neighbours (K-NN) algorithm is used to identify the points with a large average distance to their nearest neighbours. Depending on the number of neighbours sampled, this average distance increases when the points are on a physical edge of the geometry. This is illustrated in Figure 5. The points with a small average distance are removed from the overall PC and DBSCAN is used to create clusters of the resulting points. This results in clusters of each physical edge in the workpiece, which is illustrated in Figure 6. The cluster with the most points is the outer edge of the geometry, which is used to find the corner points.

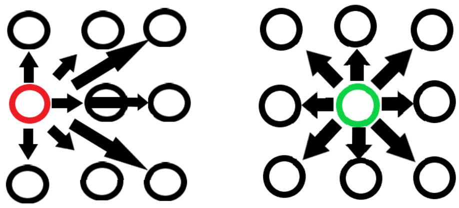

Figure 5 The average distance between the points on a physical edge (red) is larger than those not on an edge (green).

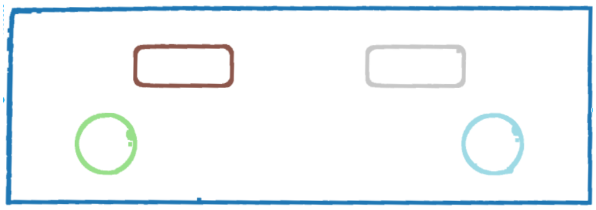

Figure 6 Clusters of the workpiece, where each colour is a unique cluster.

To ensure minimal influence from noisy edge points, RANSAC is used to identify the straight lines with the most inliers. Due to the presence of vertical lines in the xy-plane, it is necessary to express these lines implicitly on the form: $ax + by + c = 0$. This is due to the slope of the explicit line function goes towards infinity, the more vertical the line is. This makes consistent results from RANSAC difficult to achieve during implementation, as most algorithms have a built-in ceiling for the slope of the lines. Applying RANSAC to find the line with most inliers, and then separating these inliers from the PC of the outer edge, it is possible to loop the RANSAC function. This is done four times providing four explicit functions, that describe the outer edges of the rectangle. Using linear algebra, it is possible to find the intersection points. As the longest sides are identified first, the first two lines' intersection with the last two are found for a total of four points. The result is illustrated in Figure 7.

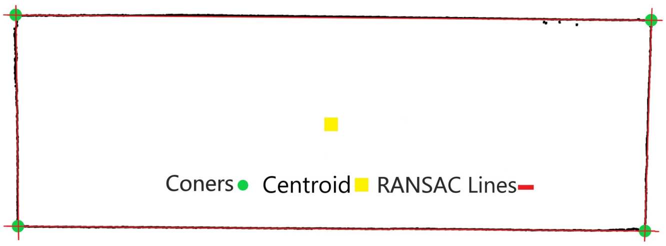

Figure 7 Illustration of the scanned workpiece's corners being found using RANSAC.

Averaging the corner points' coordinates results in the COM of the corner points' PC. As the corner points are symmetric around the centroid of the workpiece, the COM of the corners will coincide with the centroid. Translating all points by the COM's coordinates towards the origin of the global coordinate system guarantees that the symmetry-axes of the workpiece intersects at the global origin. The reason the COM is used for translation instead of any individual corner point is to combat interference from the randomness inherent in RANSAC. As RANSAC uses random sampling, the intersection points move slightly between different scans. Using the COM reduces this movement between the scans. Utilising this method, the non-uniform density's influence on the COM position is negated. To ensure consistent results and minimal influence from noise, a strict convergence criteria is needed. This also reduces the movement between the scans.

With the centroid of the geometry being placed in the global origin, only the orientation needs to be aligned. Due to the low number of points in the corner-point PC, it is possible to utilise ICP as mentioned previously. The implementation of ICP in this work identifies the closest points by using a brute force algorithm, possible due to the low number of points. Extracting the corner points from the STEP-file, and creating a PC from these, an equivalent PC of the scan's corners is made. Applying ICP afterwards results in a rotation-matrix, which serves as the final alignment of between the scan and CAD reference model.

Applying the translation from the COM and rotation from ICP to the whole of the scanned workpiece, the PCs of the CAD and workpiece are aligned. This is illustrated in Figure 8. It must be noted, that this transformation must only be applied after the orientation of the plane segment from RANSAC is made, as the scanned PC must be aligned to the xy-plane to apply the translations and rotations. With the PCs aligned, it is now possible to detect and evaluate the tolerances of the manufacturing features.

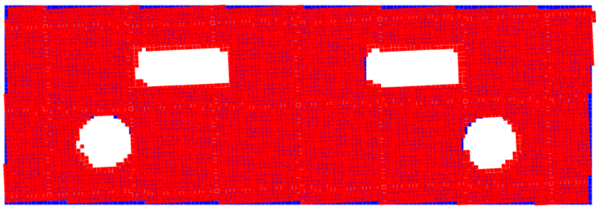

Figure 8 Alignment of the scanned workpiece to the CAD reference model using the method in Section 2.4. The red points are of the scanned workpiece, and the blue points are from the CAD drawing.

2.5 Detection of manufacturing features

In order to find the manufacturing features, the edge clusters presented in Figure 6 are used. By removing the cluster with most points, the outer edge, only the clusters of the manufacturing features remain. After aligning the scan and CAD reference model the clusters can be paired to the manufacturing feature they represent. This is done by pairing the coordinates of the COM of each manufacturing feature to its closest manufacturing feature in the CAD reference model. This makes it possible to automatically identify the shape of the manufacturing feature in the scan. Depending on the shape of the manufacturing features, different variations of RANSAC are utilised to find the centres of the manufacturing features.

The workpiece in the case from Section 1.1 has four holes, a circular and rectangular pair. These manufacturing features form the basis of the evaluated tolerances in this work, though it is acknowledged, that the methods for detecting the properties of these manufacturing features might not be applicable to other types of features. For rectangular manufacturing features, the same approach is used as the corner point identification of the workpiece. A variation of RANSAC is used for the circles, which returns both the center position and radius[11]. An illustration showing all RANSAC-lines, corner intersections, and centres are presented in Figure 9.

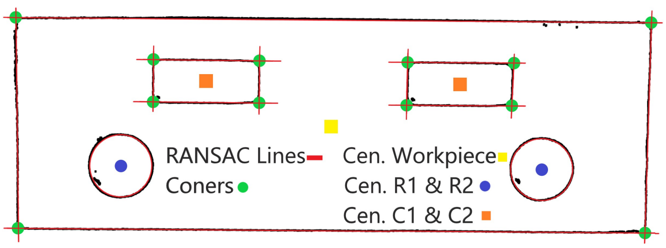

Figure 9 Illustration of detection of manufacturing features. All features are detected using RANSAC.

2.6 Evaluation of tolerances

With the manufacturing features detected and paired to the CAD reference model, it is possible to evaluate the distance between these in the global coordinate system. This is used to evaluate how well the alignment performs. The list of tolerances that can be evaluated from the detection in Section 2.5 is presented below:

- Size of workpiece edges
- Placement and size of rectangular features
- Placement and radius of circular features

2.6.1 Size of workpiece edges

By using the corner points of the workpiece, the width and height of the workpiece are evaluated. As the lengths of the sides are defined in the CAD reference model, the difference in height and width is comparable to the sum of differences in the coordinates of the corner points. For example, using the two corner points at the top of Figure 9 the difference between the scan's top side and the CAD's top side is found. By finding the distance of the scan's corner points to their associated corners in the CAD reference model, and summing these in the workpiece's y-direction (as defined in Figure 3), the difference in the side length between the scan and CAD reference model is found. Additionally, though not necessary for the purposes of this work, the parallelism of the sides of the workpiece can also be evaluated using the corner points.

2.6.2 Rectangular features

Reusing the centres from Figure 9, the difference between this centre and the one defined in the CAD reference model is found. This centre is similarly preferred over the individual corners due to the slight movements possible in RANSAC, as also mentioned in Section 2.4. The difference in x and y-coordinates of this centre is used for the validation presented in Section 3. For evaluating the size and parallelism of the rectangular features' edges, the same approach as the evaluation of these tolerances for the workpiece edges can be utilised.

2.6.3 Circular features

The circles' centres and radii are directly comparable to the CAD reference model's circles. It is also possible to evaluate the circularity of the scanned circles by evaluating the individual points' distances to the circle model from RANSAC, this is not relevant for the purposes of this work, however.

3. Validation

To validate the methods outlined in Section 2, a physical setup is utilised. The setup is presented in Figure 10. The setup consists of a Wenglor MLWL 153 laser line scanner, which is mounted on a KUKA KR 120 R2700. The parameters of the line scanner are presented in Table I.

Table I Parameters set for the Wenglor line scanner.

Exposure time	$150\,\mu\mathrm{s}$
Scan speed	$15\,\frac{\mathrm{mm}}{\mathrm{s}}$
Line distance	$0.1\,\mathrm{mm}$
Point distance	$0.09\,\mathrm{mm}$

The line scanner outputs the scan as a text file, which represents a PC.

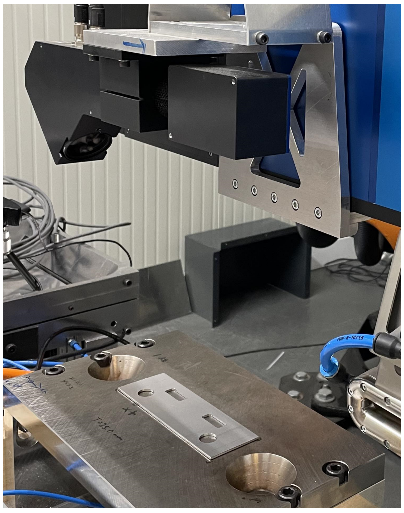

Figure 10 The setup used for scanning the workpiece.

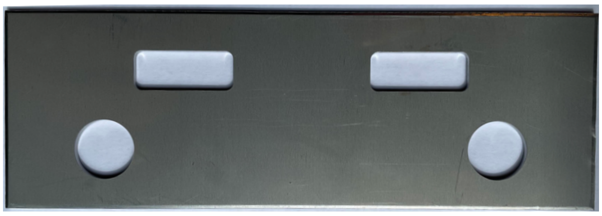

Figure 11 The workpiece that was used to validate the methods used in Section 2.

To evaluate the influence of the setup and used methods on the tolerances, the workpiece is scanned ten times without changing position and orientation. The workpiece was produced using a CNC-milling machine with every geometric tolerance being $\pm 0.1\,\mathrm{mm}$. The manufactured workpiece is presented in Figure 11. Additionally, the workpiece is moved rotationally and translationally between some of the scans, to identify these factors' influence as well. In Table II an overview of the scans and their transformation can be seen.

The rotational and translational modifications are made separately to ensure that any error from either does not influence the other. The translational modification is made by moving the workpiece by increments of $2\,\mathrm{mm}$ in the workpiece's y-axis, which are presented in Figure 3. The rotations are made within the interval of $\pm 25°$ with $5°$ increments.

Table II Overview of the experiment made.

Number of scans	Transformation
10	Untouched
5	Rotated to the left
5	Rotated to the right
5	Translation

4. Results and analysis

Before presenting the results from the transformations of the scans, the standard deviation of the differences for the same scan, which is evaluated ten times, is calculated. This is done using the corners and manufacturing features' centres. Evaluating the same scan ten times reveals the implementation's own influence on the results. One of the untouched scans was chosen, and the results are shown in Table III.

Table III Standard deviation of the tolerance evaluations for the same scan ten times. The table values are given in mm.

Tolerance	Std
Corners [x,y]	$[0.32, 0.55]$
C1 Cen. [x,y]	$[0.10, 0.17]$
C2 Cen. [x,y]	$[0.04, 0.17]$
R1 Cen. [x,y]	$[0.09, 0.16]$
R2 Cen. [x,y]	$[0.05, 0.16]$

These results indicate, that the procedure implementation itself has an influence on the results presented in this section. Speculations on why this is the case can be made, such as the inherent randomness used in RANSAC, it is not possible to identify the individual factor that creates this deviation. The difference between the standard deviation of the manufacturing features and the corners may stem from the definition of the manufacturing features' centres. The corners of the workpiece are found directly by using RANSAC, while the centres of the manufacturing features are found by using both RANSAC and the COM of the feature clusters. Additionally, the difference between the standard deviations' size in the x and y-axes is intriguing. This may stem from the slightly smaller distance between the points in the x-axis, presented as "point distance" in Table I, compared to the y-axis, presented as "line distance". It could also stem from the workpiece's geometry being longer in the y-axis. Further experimentation is necessary to pinpoint which method in the procedure creates the presented deviations, which also applies to the geometry's own influence on the results.

Having the standard deviations from Table III in mind, the different transformations' influence on the results is also presented. As mentioned in Section 3, ten scans were made without changing the location or orientation of the workpiece. The resulting tolerance evaluations are seen in Table IV.

Table IV Standard deviation, mean values and maximum values for different tolerances of untouched scans. The table values are given in mm.

Tolerance	Std	Mean	Max
Corners [x,y]	$[0.36, 0.37]$	$[0.00, 0.00]$	$[0.56, 0.81]$
C1 Cen. [x,y]	$[0.09, 0.08]$	$[0.10, 0.12]$	$[0.30, 0.26]$
C2 Cen. [x,y]	$[0.09, 0.07]$	$[0.15, 0.09]$	$[0.34, 0.21]$
R1 Cen. [x,y]	$[0.09, 0.11]$	$[0.07, 0.00]$	$[0.27, -0.19]$
R2 Cen. [x,y]	$[0.05, 0.11]$	$[0.17, -0.07]$	$[0.27, -0.24]$

The standard deviations of the untouched scan are close to the ones presented in Table III, it must be noted that a smaller deviation is seen in the y-direction, however. The maximum tolerances of the features are larger than their associated mean values. This is especially evident for the workpiece's corners. The centroid of the CAD reference model's PC is located in the origin of the global coordinate system. When evaluating the difference between the coordinates of the centroid and the mean difference of the corners, the result will always be zero, as this form the basis for the alignment. The maximum values of the corners correspond to the individual corner point's positional tolerance to its CAD drawing counterpart. The rectangular features do not share this attribute.

While the assumption for this work presented in Section 1 establishes the general position and orientation of the workpiece being known, it is important to evaluate the influence of slightly changing both the position and orientation. This is done by evaluating the tolerances of the translated and rotated scans presented in Table II. The standard deviation, mean values, and maximum values of the translated workpiece are presented in Table V.

Table V Standard deviation, mean values and maximum values for different tolerances of translated scans. The table values are given in mm.

Tolerance	Std	Mean	Max
Corners [x,y]	$[0.31, 0.53]$	$[0.00, 0.00]$	$[0.47, 1.12]$
C1 Cen. [x,y]	$[0.04, 0.12]$	$[0.24, 0.39]$	$[0.28, 0.50]$
C2 Cen. [x,y]	$[0.06, 0.11]$	$[0.10, 0.48]$	$[0.17, 0.60]$
R1 Cen. [x,y]	$[0.01, 0.10]$	$[-0.20, -0.29]$	$[-0.22, -0.39]$
R2 Cen. [x,y]	$[0.06, 0.10]$	$[-0.02, -0.33]$	$[-0.12, -0.43]$

Translating the workpiece reveals an influence on the mean and maximum values of the features. While both the x and y values are influenced by the translation, the influence on the y-values of the deviations are larger, when looking at the mean and maximum values. This is expected, since the translation was only made in the y-axis. This shows that translations between different scan has an influence on the accuracy of the result, and therefore necessitates that the assumption of this work is upheld when implementing the method for any scanning setup.

The rotational transformations similarly necessitate this assumption. Due to the influence of the rotation being high compared to the other transformations, a graph showing the center coordinates of one of the features, R1, is presented to illustrate this point. The graph is shown in Figure 12.

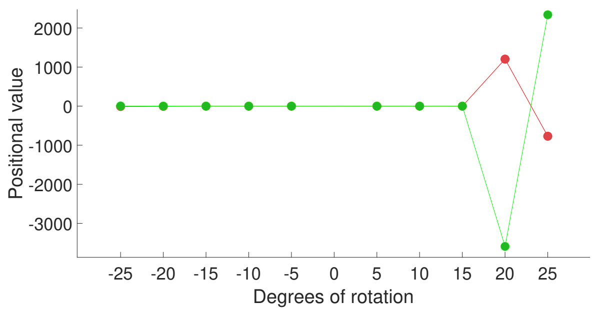

Figure 12 A graph showing R1's x and y coordinate deviations between the scan and the CAD drawing. The red is the x-values, and the green is the y-values.

While it is difficult to visualise, due to the large deviations above 20°, the tolerances of all features have significant deviations when rotated outside ±10°. The four data points within this interval are tabulated in Table VI.

Table VI Standard deviation, mean values and maximum values for different tolerances of rotated scans within $\pm 10°$. The table values are given in mm.

Tolerance	Std	Mean	Max
Corners [x,y]	$[0.37, 1.17]$	$[0.00, 0.00]$	$[0.69, 2.58]$
C1 Cen. [x,y]	$[0.13, 0.12]$	$[0.17, 0.26]$	$[0.31, 0.41]$
C2 Cen. [x,y]	$[0.10, 0.17]$	$[0.11, 0.30]$	$[0.21, 0.52]$
R1 Cen. [x,y]	$[0.03, 0.13]$	$[-0.18, -0.19]$	$[-0.22, -0.32]$
R2 Cen. [x,y]	$[0.13, 0.15]$	$[-0.13, -0.21]$	$[-0.25, -0.38]$

The standard deviations of the corner points of the workpiece are significantly larger than the other experiments, which primarily come from the data points rotated the furthest from $0°$, in this case $\pm 10°$. While the manufacturing features' tolerance evaluations are not as influenced as the corners, they also exhibit a difference to the untouched scan, in line with the translated scans. It is evident, that the rotation of the workpiece impacts the results from the scan. This, like the translation, further necessitates that the assumption made in Section 1 must be upheld, if the procedure is to be used.

5. Discussion

In this section, the considerations made throughout the work will be presented and the choice of the used methods is clarified. The impact of these choices are discussed, together with an overall evaluation of the method stemming from the results and analysis in Section 4.

5.1 Overall evaluation

Though this procedure is able to visually align the scans, assuming the general position and orientation are known. However, the results indicate that the methods used in the procedure have error factors. Pinpointing which methods contribute to the errors requires further experimentation. The results indicate that the transformations influence the accuracy of the procedure. The results are based on 15 scans, and therefore more scans are needed to give a clear indication of the magnitude of the influence. Similarly, the data sample only includes the influence of moving the workpiece, while other factors might also impact these scans, such as lighting or measurement errors when applying the transformations in Table II.

5.2 Alternative alignment methods

The alignment made in Section 2.4 utilises the creation of a uniform PC. However, when using a uniform PC as input, other methods are available for the purpose of alignment. An alternative is using PCA to obtain the same rotation matrix as provided by ICP. Using PCA as either an alternative or in addition to ICP is generally beneficial. Since ICP works best for small rotations, PCA can be used to make the larger rotations[12]. The results in Section 4 indicate that the maximum deviation of the manufacturing features are different from the average. Additionally, the corner points of the workpiece having a higher standard deviation than the manufacturing features. This is the case for all scans. This indicates that ICP suffers from a lack of accuracy, which might be caused by the lack of 3D positional information, or the lack of distinct geometric features.

5.3 Line scanner parameters

As mentioned in Section 2.2, it is necessary for the line scanner to have a resolution, that ensures that the distance between the points is smaller than the smallest evaluated tolerance. The line and point distance parameters, presented in Table I, might also influence the results in Table III. This is best explained through an example. If the edge of a circle is scanned, the edge of the manufactured workpiece's circle might be shifted by $0.09 - 0.1\text{mm}$ in the scan due to the line scanner parameters. This influence is not guaranteed to happen between scans, which makes the quality of some scans better than others. Further experimentation should be made, to identify the resolution's influence on the standard deviations shown in Table III.

5.4 Shape of the workpiece

The workpiece presented in Section 1.1 is only symmetrical in one axis. While a workpiece, which is symmetric in both the x and y-axis is also possible to utilise, this is not needed, as the features are directly paired to the CAD reference model using clustering, as presented in Section 2.3. Detecting lines using RANSAC is only viable for square workpieces. It is possible to use the procedure on other methods, as long as the alignment procedure is modified. Using a circular workpiece as an example, would disallow the use of corner points. However, as long as the workpiece is not perfectly circular, it is possible to create four points and use a similar procedure to the one presented in this work. The four points on an oval workpiece, would be the points where the curvature is the highest and lowest.

5.5 RANSAC

In the results in Section 4, the deviation between the corners of the workpiece and the CAD drawing is significantly larger, than that of the manufacturing features' deviations. As mentioned in Section 4, using

RANSAC to identify the corner points has an inherent randomness, due to the nature of the method. While the experiments were not made to identify whether this impact also applies to the manufacturing features, the results indicate that this is not the case, as their standard deviation and maximum tolerance deviation were smaller than that of the corners. ICP returns the rotation matrix that cause the best alignment of the corners, no matter if their individual position is slightly shifted. This should cause slight changes to the rotation matrix between different scans, and experiments should be made to identify whether this influences to the deviation of the manufacturing features.

5.6 Implementation

As the goal of the procedure is to implement in manufacturing, as mentioned in Section 1, it is important to evaluate the performance of the implementation. It should be noted, that the implementation used to generate the results in Section 4 was not made with code optimisation in mind. The implementation was made in Python 3.8 primarily by using the NumPy [13] and Open3D [14] libraries.

Timing the code returns a run-time of 13 seconds, six of which are used for the initial identification of the workpiece (DBSCAN). This is without taking the data handling into account, that is, getting the text file output from the line scanner and inputting it in the code as a PLY-file. The six seconds used in the identification of the workpiece can be cut down by reducing the size of the scan. As shown in Figure 4, the scan is almost three times larger than the surface of the workpiece. Reducing the number of points in the PC to a third would speed up the initial identification significantly. The remaining seven seconds, used for everything else in the code, can be reduced by optimising the implementation. While 13 seconds is a long time in a mass-production setup, it can still be used periodically, as a means of sampling a larger production batch, or implementation in a smaller production setup.

6. Conclusion

The procedure from the flowchart in Figure 1 has in this work been created using already established methods, primarily DBSCAN, RANSAC and ICP. However, the tolerance evaluations in Section 4 reveal that several challenges are present, when seeking to make a real-world implementation of the procedure. As discussed in Section 5, it is crucial to consider the line scanning parameters' influence on the results. Two proposed solutions to this problem has been presented: increasing the resolution to reduce the distance between points in the PC or performing multiple scans of the same object and using the mean values of the tolerance evaluations. Furthermore, the results indicate that the procedure is sensitive to both translations and rotations of the workpiece compared to the expected position following the assumption in Section 1. The expected position is found using an initial scan. The overall accumulated error caused by the procedure itself also indicated that further experimentation and work must be made, in order to reduce the influence of the methods used.

The main objective of this study was evaluate whether geometric inspection could be done using established methods, while using the assumption presented in Section 1. This has succeeded, though the sensitivity to deviancy of the assumed position of the workpiece is larger than that of other procedures, where the workpiece does not have the aforementioned attributes. This work demonstrates the feasibility of using line scanning for tolerance evaluation of manufactured items, though this requires further experimentation, before a real-world implementation can be made.

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