Materials Today: Proceedings 45 (2021) 5255–5262

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

A case study on use of 3D scanning for reverse engineering and quality control

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ARTICLE INFO

Article history:
Received 25 December 2020
Accepted 26 January 2021
Available online 3 March 2021

Keywords:
Reverse engineering
3D scanning
Point cloud
Surface reconstruction
Product quality control

ABSTRACT

Reverse engineering is needed to acquire knowledge of design that is lost, obsolete or withheld. Techniques have evolved from manual measurements, to utilizing the possibilities that lie within 3D scanning technologies. This paper surveys literature to map the possibilities and challenges connected to methodologies and technologies using 3D scanning for reverse engineering and production control. A case study on reverse engineering using a handheld 3D laser scanner is conducted to compare with the findings in literature. In the case study, a 3D printed component with complex internal features is 3D scanned and the point cloud is optimized before two different surface modelling techniques are tested. The dimensional errors of the output CAD design are mapped before the process and results are compared with the findings in literature. The findings of this paper show that using 3D scanning technologies for RE and PC is possible but significant challenges exists in developing accurate surface reconstruction algorithms that deals with point cloud imperfections like i.e., noise and holes. Using 3D scanning for RE purposes is found to be most suitable for components with complex geometry like free-form surfaces that are hard to measure manually.

1. Introduction

The field of engineering involves the processes needed to design, manufacture, assemble and maintain products and systems [1]. While the traditional forward engineering uses logical, mathematical and abstract ideas and transforms them into physical products or systems, the concept of Reverse Engineering (RE) is the opposite where it goes from a physical product or system, to a digital model convertible to computer-aided design (CAD) file. In many situations, there may be physical products without any technical details or data where RE duplicates the product, study its features, or acquire as-built models. According to Eilam [2], RE has similarity with scientific research, the main difference being that RE investigates man-made artifacts. As stated by Colin et al. [3], new technologies and research in image processing, computer graphics, advanced manufacturing and virtual reality have advanced the creation of computer-based representation of physical objects. There exist several reasons to employ RE including in the cases where the manufacturer of a given product or machine part no longer exists, nor produces the product, the original product documentation maybe lost or never existed, the production quality control needs a digital (CAD) model, improvements are needed to existing product, the CAD model is needed to make modification on the product, etc. [1,4].

Though RE methods differ from field to field, all evolved with the innovations taking place in computer technology and digital control over the past century. Manual measurements and deconstruction of existing products have been traditionally utilized using manual measuring devices to measure diameters, depths, etc., and manual creation of the design [4,5]. This process is efficient and accurate for simple cases but becomes more difficult when applied to increasingly complex geometries like non-planar free-form surfaces. The approach enjoyed better accuracy of acquired digital data with the development of new technologies particularly to address the needs for increasingly complex, more non-linear and free-form product designs. The same traditional methods and modern trends are accurate for product quality control (QC), where manual measurements are being replaced by new technologies of measurement.

The advancement in the coordinate measuring machines (CMM's), which first appeared in the 1960′s, enabled point measurements on surfaces using computer controlled machines consisting of a probe supported by 3 perpendicular (x,y,z) axes with

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https://doi.org/10.1016/j.matpr.2021.01.828
2214-7853/

built-in reference standards to characterize free-form surfaces [6]. This technology developed from manually manoeuvring the probe, to programming the path, to finally uploading a CAD model that the CMM uses for path planning. The largest constraint is that the probe must physically touch the measurement locations [6]. The aim of this study is to demonstrate the methodologies and technologies used for RE & QC of products and investigate what possibilities, limitations, and challenges exists when applying 3D scanning technologies.

2. 3D scanning technologies applied in reversed engineering

As illustrated in Fig. 1, application of 3D scanning in RE process involves three main steps: (1) scanning, (2) point processing, and (3) application specific geometric model development. These steps shown in the figure illustrate the different phases the engineer takes the object from physical state to a point cloud and transforms it into a CAD model.

The scanning phase consist of choosing scanning techniques, preparing the part, and performing the actual scanning. The output is a point cloud. This is usually a file consisting of the (x, y, z) coordinates often complimented by a black/white intensity or a colour for each measurement point [7].

3D scanning devices are divided into two categories: (1) contact and (2) non-contact scanners. Contact devices use probes that follow the physical surface, similar to CMM method. The accuracy of contact devices is good, though they can be slow because points are registered sequentially at the probe. Another problem is that contact pressure is used, meaning soft materials cannot accurately be measured [1]. Non-contact scanners such as lasers and optics, computer vision, photogrammetry, light detection and ranging (LiDAR), and imaged based techniques [8], on the other hand, capture geometry without physical contact. These devices can capture large amounts of data in short time, though they suffer several issues including poor accuracy compared with contact devices [1,4]. The challenge with non-contact scanners is when scanning surfaces parallel to laser axis. Since light is used in scanning, non-contact devices have problems with shiny surfaces, resulting in a need for temporary coating. Although these problems limit the use of non-contact scanners to cases where speed and magnitude of data capture is more important than accuracy, the technological developments in the area are constantly improving [1]. Geng et al. [4] proposed a hybrid method where non-contact methods are used for path planning for CMMs, yielding a combination of high speed and high accuracy.

The point processing phase consists of importing the raw point cloud data, reducing the noise, and reducing the number of points using filter algorithms. The point cloud data can be merged in cases when the whole part is captured in multiple scans. Different software providers have different solutions for merging files.

The application specific geometric model development phase is the most complex activity in RE [1]. The main reason is the need for advanced surface fitting algorithms to generate accurate surfaces. Since most CAD software are not designed for the large amount of data in point clouds, separate software is needed for the complex and heavily researched process of transforming point clouds into surfaces that can be used in CAD software [4].

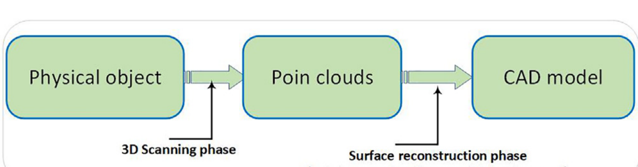

Fig. 1. Generic RE process using 3D scanning technology.

2.1. Surface reconstruction

In short, surface reconstruction is the process of inferring a 3D object from a collection of discrete points that sample the shape [9]. Earlier works of surface reconstruction focused on reconstructing piece-wise smooth surfaces, while recent works have focused on addressing the significantly challenging data imperfections. The properties of the point cloud effect the behaviour of the reconstruction algorithms. As listed in Table 1, a survey by Berger et al. [9] categorizes the point cloud properties according to their impact on reconstruction algorithms.

In the same study, it is stated that the minimum requirement for input data in surface reconstruction algorithms are points that sample the surface. This alone, may fail in the reconstruction of certain types of point clouds. As depicted in Fig. 2, other data such as surface normal, scanner related information and RGB (Red, Green, Blue) imagery data may be helpful in surface reconstruction.

The surface normal is extremely useful for surface reconstruction algorithms because disoriented normals, which are pointing either in the inside or the outside of the surface, are often computed directly from the point cloud using the local neighbourhood of the given point. Oriented normals, having consistent direction either in the inside or the outside of the surface, are useful in surface reconstruction as they provide knowledge of the exterior and interior of the surface. The scanner information provides useful information for surface reconstruction. Knowledge about its 2D lattice structure enables estimation of sampling density which can be used to detect outliers. It can also be used to define the "confidence" of a point with respect to being noise or not by the information about the reflectivity measured at the points.

Table 1
Imperfection properties of point clouds.

Sr .No	Parameter
Sampling density	The distribution of the points sampling the surface, important for defining a neighborhood in a surface reconstruction. A neighborhood being a set of points close to a given point that captures the local geometry. The neighborhood needs to be large enough to describe the geometry but small enough that local features are not lost. The sampling density usually varies spatially, meaning it is non-uniform. This can be due to the geometric features of the shape or the scanners position and orientation.
Noise	Points randomly distributed near the surface. The noise distribution is usually due to sensor noise, depth quantization and distance or orientation of the surface with respect to the scanner. Noise can also be impacted by surface interaction like scattering. In surface reconstruction, this is usually compensated by producing surfaces that pass near the points without overfitting the surface to the noise.
Outliers	Points far from the true surface. Outliers often have density smaller than the density of the points that sample the surface. Outliers should not be used in surface reconstruction, unlike noise. This is often fixed through detection methods.
Misalignment	The imperfect registration of scans to each other. These effects are less dominant for smaller objects, as it is common to rotate the object in-place with respect to the scanner between different scans, making it easier to account for the known rotation. For bigger scans, the effects of misalignment become more dominant. When misalignment accumulates between sequential scans, this is called drift. Misalignment can be fixed by algorithms composing the point clouds of planar primitives aligned along three axes and then "snapping" erroneously rotated scans onto one of the axes.
Missing data	This is due to limited sensor range, high light absorption and occlusions in the scanning process. This is not the same as non-uniform sampling, as the sampling density is zero in such regions.

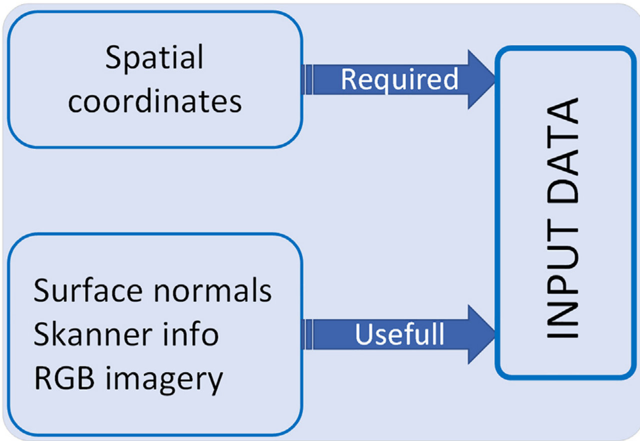

Fig. 2. Input Data for Surface Reconstruction.

The output produced by reconstruction algorithms can be affected by different algorithm priors, i.e. algorithm assumptions to combat imperfections in the point cloud and eventually focus what information about the shape is reconstructed, based on the type of shapes that are acquired and the type of faults that are associated with the data [9]. The main categories of these prior types are surface smoothness (local, global or piecewise) that can ensure that the surface fits the point data, volume smoothness, visibility, geometric primitives, global regularity, being data-driven and user-driven.

2.2. Surface reconstruction techniques

An important phase of surface reconstruction is to transform raw point cloud data into CAD useable information. As shown in Fig. 3; according to Geng et al. [4], there are three major techniques commonly used: Wire-frame modelling, surface modelling, and solid modelling. This subchapter will focus on the two first, as they are the most applied. Wire-frame modelling is the most basic method which stores data as a collection of points, lines, and some types of curves. The benefit of wire-frame modelling is that it requires low data storage, but it cannot satisfy requirements for modern complex designs with free-form surfaces.

There are a variety of surface modelling techniques. Surface modelling in algebraic form assume surface representation using implicit equation of the form $f(x,y,z) = 0$ and fits coefficients by algorithms like least squares fitting. Algebraic methods are efficient in computation, but any modification of data will refit the whole surface and leads to the so-called global modification of the geometry. The parametric forms include Bèzier's surfaces, B-spline surfaces, and non-uniform rational basis spline (NURBS) surfaces. Bèzier surfaces use Bernstein polynomials, B-spline surfaces uses polynomials defined over a knot-vector, and NURBS surfaces use rational polynomials. The parametric forms are easy to modify but are extensive in computation.

2.3. Dimensional accuracy

Several factors influence the dimensional accuracy of a design. When conducting forward engineering, the original design is sent to manufacturing with a dimensional tolerance. This is done because it is impossible to manufacture any component without errors. In RE process, three types of errors are observed [4]: (1) manufacturing error related to the tolerance given in the initial design for manufacturing, (2) RE error related to the measurements of the object, i.e. the accuracy of the 3D-scanning technology and (3) new manufacturing error when RE design is used for manufacturing. As RE is conducted when the original design is lost, the

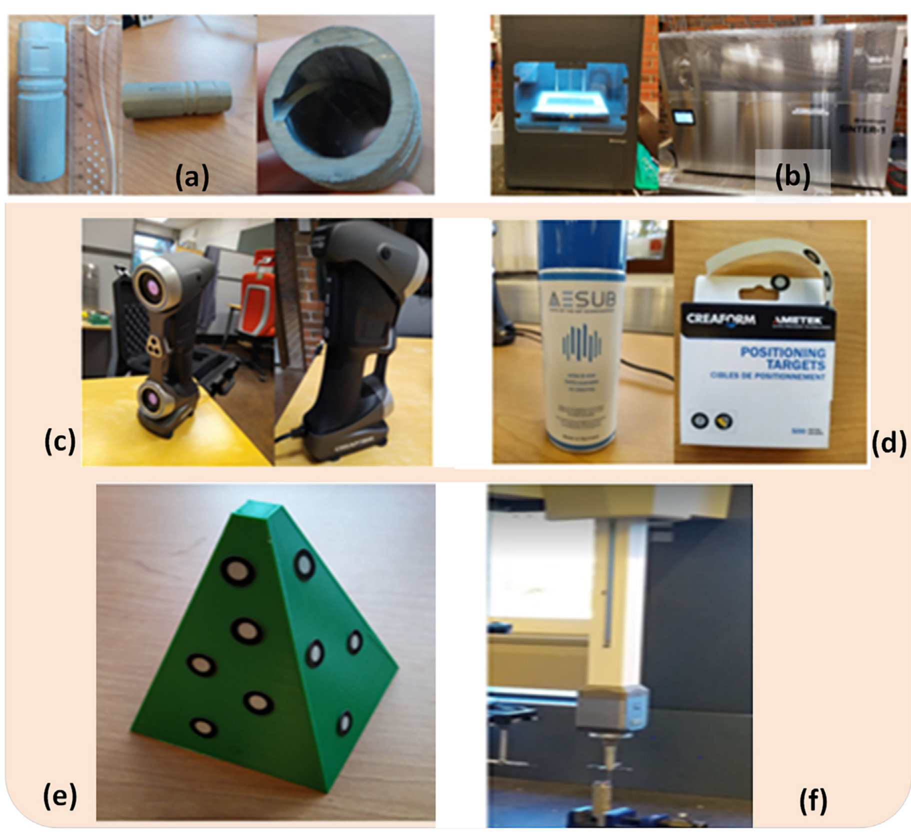

Fig. 3. Equipment used in the experiment (a) Test objects for RE, (b)Metal X 3D printer with sintering facility, (c) Handheld 3D scanner, (d) Coating spray and positioning target, (e) Plastic support pyramid and (f) CMM probe.

Table 2
Dimensional Accuracy of 3D Scanning Technologies.

Technology	Accuracy (mm)	Source
Contact	0.03–0.39	Mitra [11]
Traditional contact	0.01–0.02	Raja [1]
Modern contact	0.00005–0.005	Geng et al. [4]
Non-contact	0.025	Geng et al. [4]
	0.025–0.2	Raja [1]
	0.73–1.5	Lee et al. [12]
	0.07–0.55	Yao [13]
	0.06–1.28	Azlan et al. [14]
Non-contact: Structured Light Scanning	2	Salehi et al. [8]
	0.16–0.48	Yu et al. [15]
Non-contact: Handheld Laser Scanner	0.05	Ghahremani et al. [16]

most important source of dimensional accuracy is the second source of error. The accuracy of 3D scanning technologies and processes have been surveyed in the literature and are presented in Table 2. The 3D scanning errors, in particular, can be as a result of [10] wrong reference points, out of field view, improper aligning of the measurements, improper calibration of the scanner, temperature difference and software problems.

3. Case study on reverse engineering of a 3D printed metal cylinder with complex internal geometry

This section presents the methodology and results from the physical experiment on a 3D printed metal cylinder with complex internal geometry, which was reverse engineered using a handheld non-contact 3D laser scanner. A smaller test of product quality control using a CMM was also conducted and is presented.

3.1. Experimental equipment and procedure

The experimental study was conducted in the 3D printing laboratory of the University of Stavanger. The goal of the experiment is to study the possibilities that 3D scanning technology can provide in RE process and product quality control purposes. Fig. 3 shows the equipment used in the experiment. In addition, software tools such as VX Scan and Model, and Autodesk Inventor were used.

The components, shown in Fig. 3(a) were modelled in Autodesk Inventor® and transferred to STL file format for 3D printing and sintering (Fig. 3(b)). To imitate RE of a degraded part having rough surface due to corrosion and wear, as well as to avoid the effects of shiny surfaces, the test sample was covered in a white coating spray (Fig. 4).

Position markers were then placed on the surface of the component and the pattern of the markers are used to recognize the spatial location of each scanning point as the scanner is moved around. While scanning, it is observed that the scanner could not properly capture the geometry even though the test sample was covered in coating spray and position targets. A plastic pyramid covered with position markers was therefore used as a base for the scanner to find some known geometry to initiate the scanning process**.** This enabled the scanner to find the component properly. The component was first scanned as shown in Fig. 4 (R) before it was turned 180° and scanned again.

Once the physical scanning was completed, the scanned data was transferred into VX Model data and merged into one point cloud using a "best-fit" algorithm for matching points and geometry and some manual adjustments. The point cloud was then optimized and transformed into surfaces using different surface

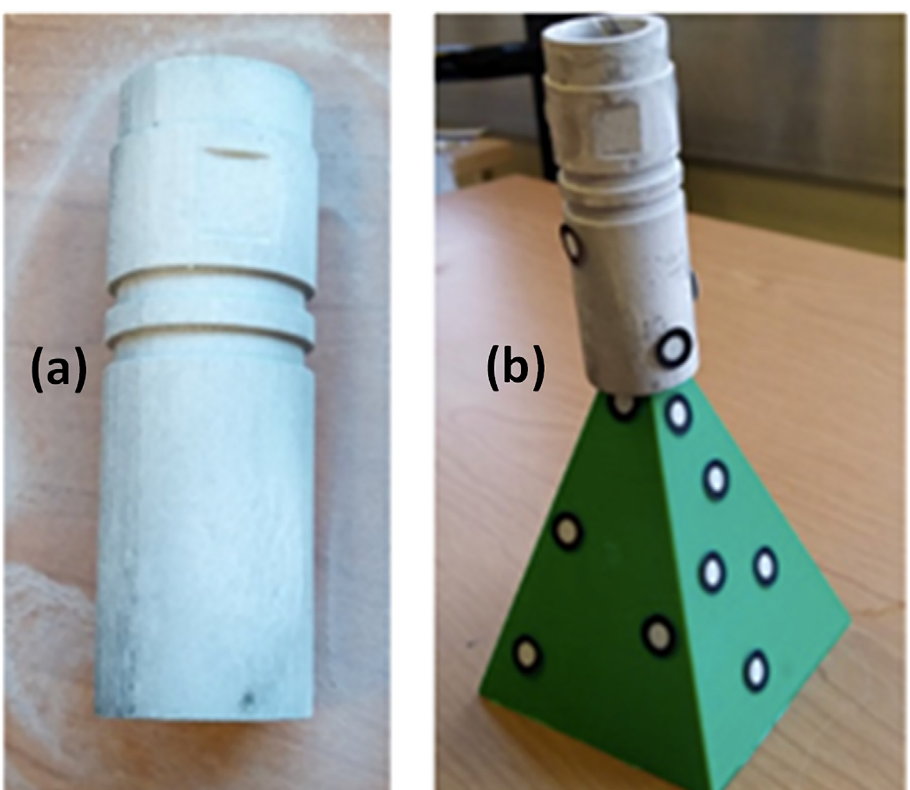

Fig. 4. Component (a) with coating, and (b) scan setup on support pyramid.

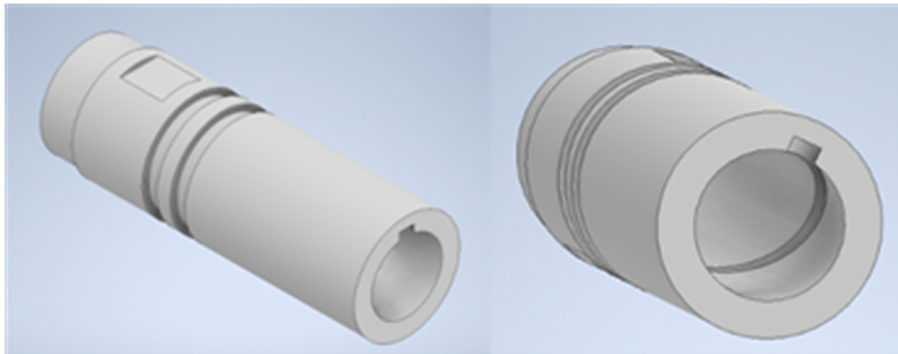

Fig. 5. 3D model of the original design of test object.

modelling techniques before being transformed into CAD model format in Inventor®. After the process of merging, optimizing, surface reconstruction, and CAD modelling in Inventor® the product QC with a contact device (CMM) was done by measuring the roundness of the cylinder at its thickest radius (Fig. 5, main view 20 mm from the right edge).

The CMM was used to make QC by measuring along a predetermined path and to determine the roundness deviation from the CAD model. The results are presented in Fig. 6, where the nominal value is presented as the black circles and the two red circles are the given design tolerances (±0.05 mm). The results show that the roundness exceeds the tolerances at most measurement points and additional surface treatment would be needed in a real-life production process. The maximum deviation measured was 0.214 mm.

3.2. Reverse engineering

The output of the physical scanning was saved as two raw point cloud files, one from each side of the test object. These are shown side by side in Fig. 7. The raw files contain unwanted information like i.e., the pyramid and table geometry. The original point clouds also included features like holes, spikes, noise, and outliers. The pyramid and floor points were then removed by removing all points located below a defined plane (Fig. 8). Large outliers were also removed manually by selecting points within a specified rectangle.

Upon removing the unwanted points of the two separate scans of the component, i.e. point clouds captured from both sides, it is observed that both scans have missing data on different locations. However, scanning the component from two opposite direction

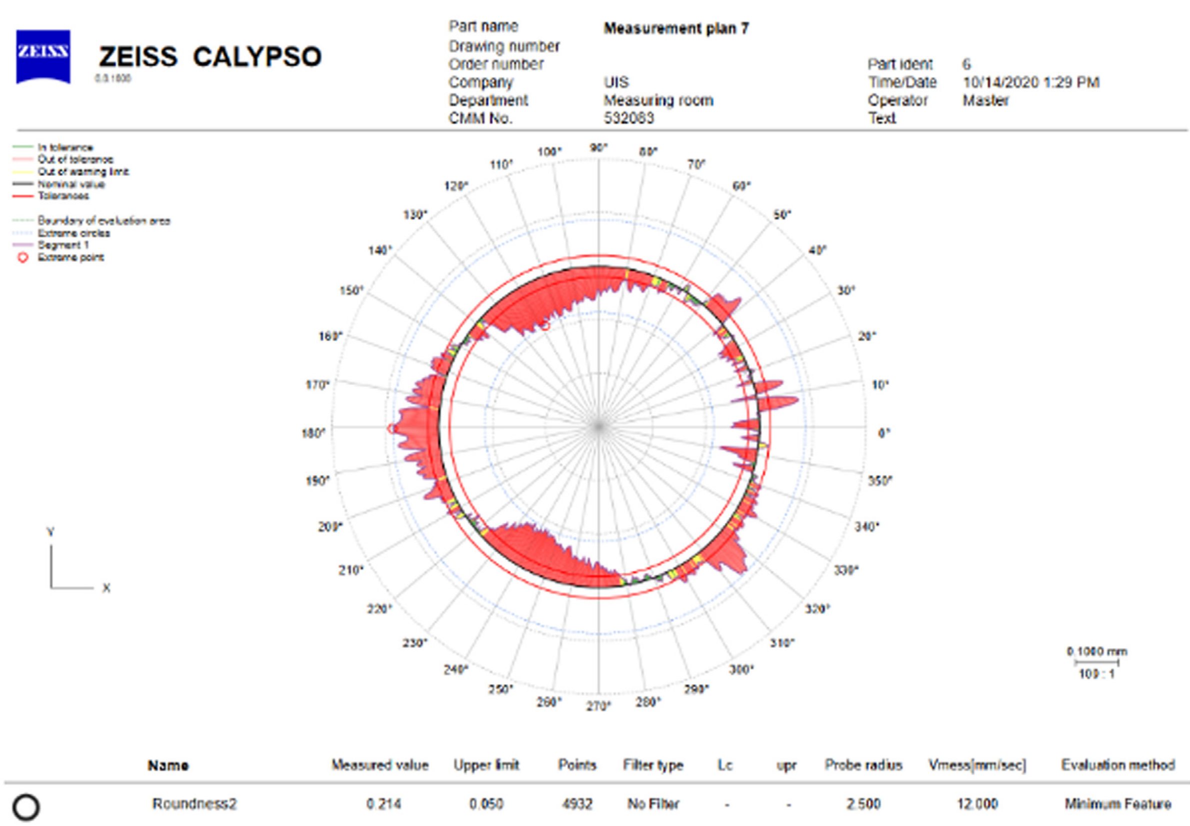

Fig. 6. Roundness measurement results from CMM.

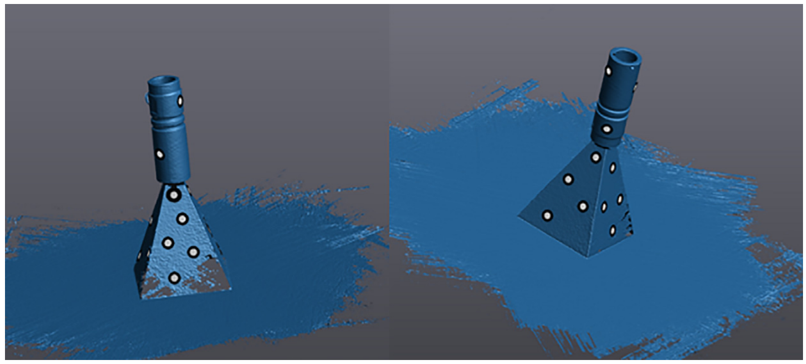

Fig. 7. Raw point clouds of the scanned sample.

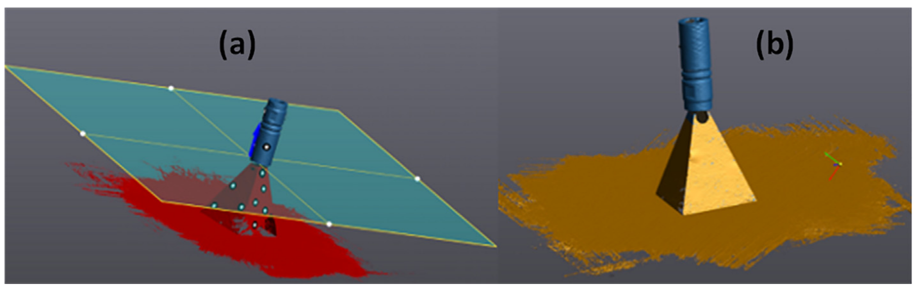

Fig. 8. Removing irrelevant point clouds by cutting plane (L) and removing outliers by manual selection (R).

(rotated 180°) is that the missing data in one scan will be complimented by the other. Some of the visually observed missing data visible in Fig. 9(a - c)**,** where the 1–2 cm internal scan range is also shown.

The next part of the process was to align the separate scans to each other, and this was done by manually translating and rotating the scans to approximately fit and then using the "best-fit" tool in VX model. This fits the scans to each other by shared geometry within a set tolerance of 1 mm (Fig. 9(d) – (f)). As can be observed from these figures, some of the missing data shown in Fig. 9(c) were filled. The file was then converted into a mesh of triangles with vertices on each point.

Some point cloud optimization steps were done before starting the surface reconstruction steps (Fig. 10). First, the "clean-mesh" algorithm was applied, removing isolated patches, spikes, small holes, and singular vertices. Then, holes were filled using the "fill

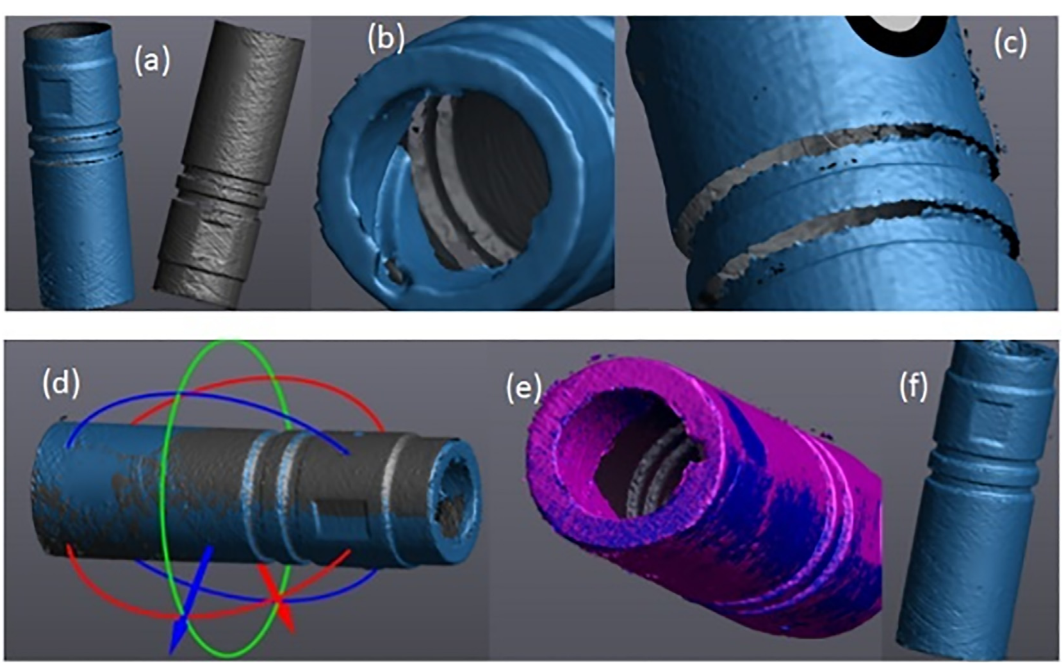

Fig. 9. Results of scanned object (a) Separate Scans, (b) Internal Scan, (c) Scanned surface with missing data, (d) manual aligned scanned model, (e) "Best-fit" model and (f) Merged scan.

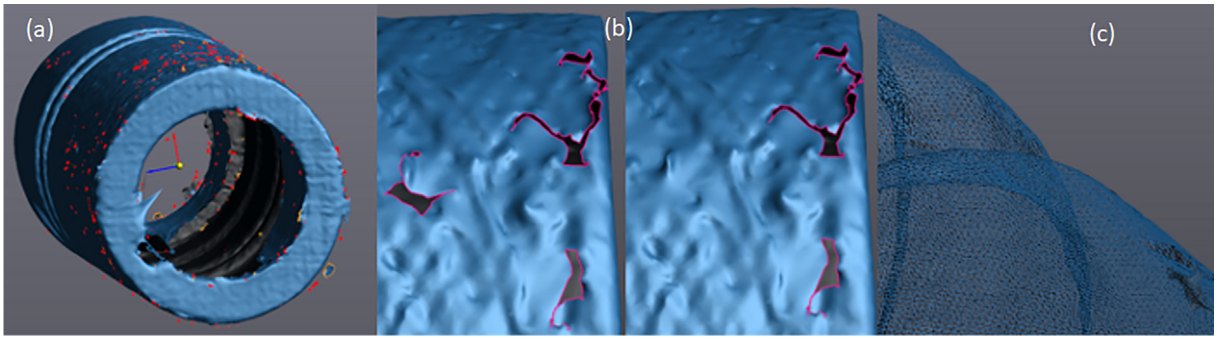

Fig. 10. Pre-surface construction of scanned object (a) «Clean-mesh», (b) Holes before and after fill, and (c) Mesh of triangles.

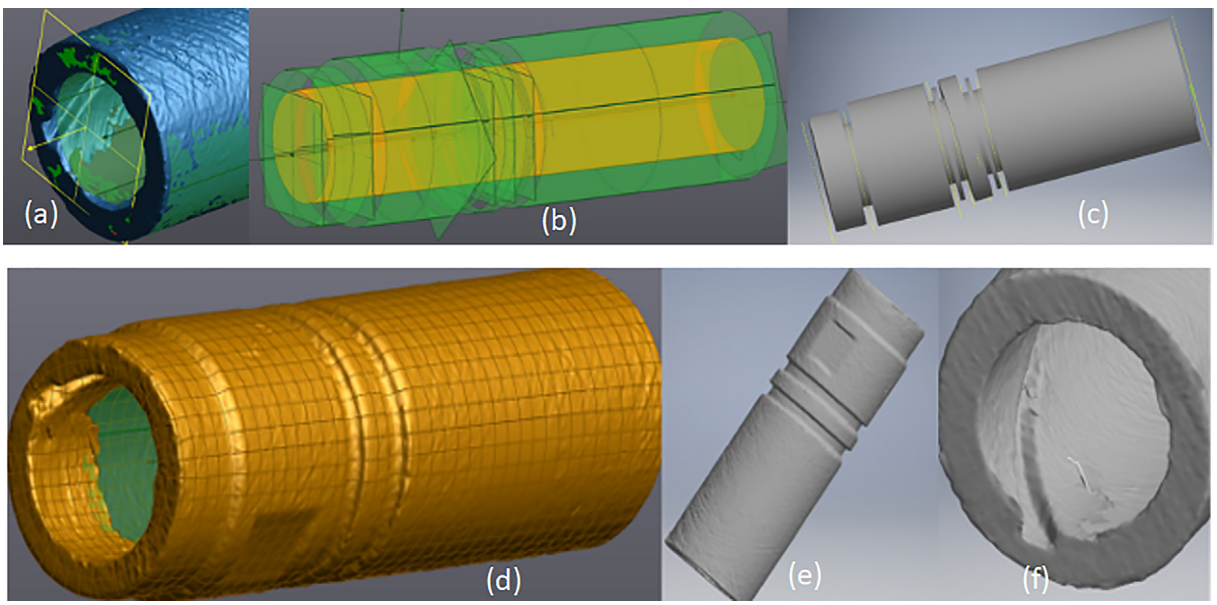

Fig. 11. Surface reconstruction phase (a) Extraction of primitives, (b) View of primitives, (c) Primitives as solids, (d) NURBS surface, (e) Surface in CAD environment, and (f) Internal surface of the model.

hole" algorithm by selecting edges of holes and the proper level of curvature by trial and error. Fig. 10(b) illustrates the process of the hole filling.

The final process was the surface reconstruction phase, which was done using two ways: (1) by creating primitives based on optimal fit to points, and (2) by creating NURBS surfaces that more accurately render the surface with its corresponding roughness. The primitives-based method uses the mesh to find best-fit cylinders, planes, triangles, etc. Fig. 11(a – c) shows the fitting of the primitives, the primitives themselves, and the solids exported to the CAD software. In the CAD environment, the solid cylinders were extended to go from plane to plane, the inside cylinder was used to extrude the hollow section, and the internal geometry was made using the "coil" function. The NURBS surface method, on the other hand, takes the mesh and transforms it to NURBS surfaces as shown in Fig. 11(d -f). The surface was then exported to Inventor as a surface model. The surface model itself only has 1–2 cm of internal geometry on each side, due to the limited scan range.

3.3. Dimensional accuracy

In this RE process, the dimensional inaccuracy is expected due to errors from three possible sources: (1) the manufacturing error on the original 3D printing part without surface treatment, particularly on relatively large parts, (2) the RE error from the equipment and (3) surface reconstruction algorithms. Length and diameter dimensions of the manufactured part were measured with a caliper and the average dimensional error obtained with respect to the dimensions given on the CAD design model was 0.113 mm, with a standard deviation of 0.386 mm for the primitives method and −0.035 mm, with a standard deviation of 0.473 mm for the NURBS method.

4. Discussion

The results of the case study correspond with much of the findings in the literature. The dimensional accuracy using a non-contact 3D scanner and the two surface reconstruction methods is within the intervals specified by Raja [1], Yao [13], Azlan et al. [14], and Javaid et al. [10]. The component needed coating due to its reflective metal surface and the sharp edges were to some extent rounded when scanned, which corresponds to the findings made by Raja [1]. The point clouds contained imperfections like holes, outliers and noise as explained in the study by Berger et al. [9]. The steps of physical scanning and point processing was relatively straight-forward and not time consuming. However, similar to what Raja [1] and Geng et al. [4] stated, the surface reconstruction phase was the most complicated and time consuming undertaking.

Although the software was quick at recognizing primitive shapes, it had troubles making cylinders extend to their real lengths, and since multiple cylinders were used, their central axes slightly deviated from each other. This leads to the need of manual changes and makes the process more susceptible to human error. The output of the primitives-based method was a solid with consistent dimensions and no surface roughness. The NURBS method yielded a smooth surface of the whole part where the scanned surface roughness was still present, but in this case; the central axis was not off. The primitives-based method was able to extend the internal geometry to make a watertight solid while the NURBS method was not able to extend any internal geometry further than the 1–2 cm internal scan range. The NURBS method more accurately resembles the actual point cloud, but for manufacturing purposes, the smooth surface roughness of the primitives-based method would be preferred. A combination of the two methods might be a solution to extend the internal geometry using primitives and use the external geometry from the NURBS method. It is also important to state that a different 3D scanner might be more efficient in capturing internal geometry.

Since the process was relatively time consuming compared to manual measurements, it is reasonable to state that using 3D scanning technology for RE is more suitable for complex parts with free-form surfaces that are hard to measure accurately with manual tools.

5. Conclusion

This article reported a case study conducted to investigate the possibilities and challenges of 3D scanning technology for reverse engineering and product quality control. The results of the case study are compared with the results reported in the literature. The technology, in general, provides possibilities to conduct RE by scanning the object and transforming it into CAD with different surface reconstruction techniques. Product quality control such as dimensional accuracy with 3D scanning technology can be done by deviation analysis between point clouds and the CAD design model. The accuracy of the product quality control and RE is largely down to the accuracy of the 3D scanning technology utilized in the process, and according to literature, this is constantly improving. The findings of the case study show that RE is possible using 3D scanning technology, but the process is not efficient enough for simpler components were manual measurement and design is faster than using 3D scans. Future research works in this direction will focus on investigation of automation of surface modelling techniques, and the possible combination of multiple techniques to improve the scanning efficiency and accuracy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge the technical support on 3D scanning provided by the laboratory engineer Jørgen Grønsund.

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