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Methods to reverse engineer spare parts

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Abstract

The introduction of additive manufacturing allows to picture a new supply chain for spare parts. In this new model the concept of digital spare parts is defined. The only information needed to reproduce a part using additive manufacturing technology is a ready-to-be-produced 3D model, that already contains manufacturing instructions.

The scope of this work is to present reverse engineering methodologies to obtain a ready-to-be-produced 3D model from each of the possible single and combined input data available of a spare part: 2D paper drawing, 2D digital drawing, the physical spare part or the physical mold/tool used to produce it and nominal 3D model and their combinations of interest. The pieces of equipment used in this work are three different CAD modeling software (SolidWorks 2018, PTC Creo 3.0 and Siemens NX 11), a structured light-stereovision 3D scanner and two specific reverse engineering software (Scan2CAD v10 and Geomagic Design X 2018). The reverse engineering methodologies are defined after a research on the scientific literature is accomplished. For each of the inputs aforementioned one or more procedures to obtain the final 3D model are proposed. In the experimental phase, different versions of a recoil starter were used as spare parts to be reversed engineered. The methods defined for single input cases were tested to acquire real-life results and to define their effectiveness. The results obtained were time needed to perform the reverse engineering task, advantages and disadvantages of the procedure tested. These are discussed in order to propose further developments and to evidence where the processes can be enhanced. All the methodologies defined and tested demonstrated to be operational to accomplish reverse engineering of spare parts, aside from vector image-aided CAD modeling, where the conversion from 2D paper drawing to 2D digital drawing was proved not sufficiently accurate.

In conclusion, this thesis work defined a standardization of the methods to obtain a ready-to-be-produced 3D model of a spare part from every possible starting piece of information available.

Keywords reverse engineering; digital spare parts; 3D model; spare parts supply; part on-demand production; additive manufacturing; manufacturing information.

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Table of contents

Acknowledgements	III
Table of contents	V
List of figures	VII
List of tables	IX
Abbreviations	XI
1 Introduction	1
1.1 Background	1
1.2 Research problem	1
1.3 Objectives	1
1.4 Limits	2
2 Literature review	3
2.1 Digital spare parts (DSP)	3
2.2 3D scanning technologies	3
2.2.1 Non-contact active techniques	4
2.2.2 Non-contact passive techniques	7
2.2.3 Contact techniques	8
2.2.4 Case studies and applications	9
2.2.5 Summary	10
2.3 Computer-aided-design (CAD).....	15
2.3.1 Scan-to-CAD software and tools	15
2.3.2 Drawing-to-CAD software and tools	15
2.3.3 Discrete model vs. analytical model	16
3 Methods	17
3.1 Materials	17
3.2 Reverse engineering from 2D paper drawings	18
3.2.1 Direct 3D modeling	18
3.2.2 Vectorial image aided 3D modeling	19
3.3 Reverse engineering from 2D digital drawings	20
3.4 Reverse engineering from physical spare part	22
3.4.1 Traditional measurement and 3D modeling.....	22
3.4.2 3D scanning and 3D model refinement	23
3.5 Reverse engineering from 3D model	24
3.5.1 3D model.....	24
3.5.2 3D model with PMI	24

3.6	Combined inputs	25
3.6.1	3D model and 2D drawing	25
3.6.2	Physical spare part and 2D drawing (digital or paper).....	25
3.7	Process validation	26
4	Results.....	29
4.1	Experiment 1. Direct 3D modeling	29
4.1.1	Experiment 1.1. Simple spare part	29
4.1.2	Experiment 1.2. Complex spare part.....	30
4.2	Experiment 2. 2D paper drawing conversion to DWG.....	32
4.2.1	Experiment 2.1. Simple spare part	32
4.2.2	Experiment 2.2. Basic geometry	33
4.3	Experiment 3. 2D digital drawing imported and 3D modeled.....	35
4.3.1	Experiment 3.1. SolidWorks 2018	35
4.3.2	Experiment 3.2. PTC Creo 3.0.....	37
4.3.3	Experiment 3.3. Siemens NX 11	38
4.4	Experiment 4. Physical spare part 3D scanned to CAD	38
4.4.1	Experiment 4.1. Spare part scanned without coating.....	39
4.4.2	Experiment 4.2. Spare part scanned with coating.....	41
4.5	Experiment 5. Process validation by inspection	45
4.6	Results summary	48
5	Discussion	53
5.1	Reverse engineering from 2D paper drawings.....	53
5.2	Reverse engineering from 2D digital drawings	53
5.3	Reverse engineering from physical spare part	54
5.4	Reverse engineering from 3D model	56
5.5	Process validation by inspection	56
5.6	Possible developments	57
6	Conclusion	59
	References	61
	Appendix	67

List of figures

Figure 3.1 Reverse engineering from 2D paper drawings process scheme	18
Figure 3.2 Reverse engineering from 2D digital drawing process scheme	20
Figure 3.3 Reverse engineering from physical spare part process scheme	22
Figure 3.4 Reverse engineering from 3D model process scheme.....	24
Figure 3.5 3D model and 2D drawing combined input process scheme	25
Figure 3.6 Physical spare part and 2D drawing combined input process scheme	25
Figure 3.7 Physical spare part and 3D model combined input process scheme	26
Figure 4.1 2D paper drawing input of simple recoil starter, scanned with high contrast ...	29
Figure 4.2 Simple recoil starter final 3D model isometric view and section view	30
Figure 4.3 2D paper drawing input of complex recoil starter, scanned with high contrast .	31
Figure 4.4 Complex recoil starter final 3D model	31
Figure 4.5 Comparison between DWG converted file (left) and post-processed 2D drawing (right)	32
Figure 4.6 Original basic geometry drawing	34
Figure 4.7 Basic geometry drawing after PDF to DWG conversion in Scan2CAD.....	34
Figure 4.8 Drawing after conversion in SLDDRW format	35
Figure 4.9 Top, front and bottom drawing views inserted as sketches in the appropriate plane in SolidWorks part file.....	36
Figure 4.10 Recoil starter (third version) obtained after 3D modeling	36
Figure 4.11 2D to 3D conversion with PTC Creo AutobuildZ tool result.....	37
Figure 4.12 Spare part to be 3D scanned after reference marks application	38
Figure 4.13 Overview of scanned spare part before application of corrective algorithms ..	40
Figure 4.14 Detail (a) and lateral overview (b) of scanned spare part before application of corrective algorithms	40
Figure 4.15 Overview of scanned spare part after application of corrective algorithms....	41
Figure 4.16 Overview of scanned spare part with coating	42
Figure 4.17 Details of scanned result of the coated part. (a) series of holes left in semi-obstructed surface; (b) detail n°1 reference mark elimination, detail n°2 scanning noise...	43
Figure 4.18 Automatic mesh subdivision into different regions	44
Figure 4.19 CAD model obtained with deviation analysis in respect to STL data.....	44
Figure 4.20 Surface comparison after pre-alignment with average, maximum, minimum and sigma deviation computed for the whole spare part	45
Figure 4.21 Local-best fit n°1. Top cylinder with teeth surface comparison	46
Figure 4.22 Local-best fit n°2. Bottom cut cylinder surface comparison.....	47
Figure 4.23 Times comparison of the performed experiments (results shown in hours)	50

List of tables

Table 2.1 Analysis of the 3D scanners available in the market (February 2019).....	12
Table 4.1 Simple recoil starter direct modeling time.....	30
Table 4.2 Complex recoil starter direct modeling time	31
Table 4.3 Simple recoil starter paper to digital drawing conversion time	33
Table 4.4 Basic geometry paper to digital drawing conversion time	33
Table 4.5 Geometric error analysis of the converted DWG quotes after scaling	35
Table 4.6 2D digital drawing to 3D model conversion time with SolidWorks	37
Table 4.7 2D digital drawing to 3D model conversion time with PTC Creo	38
Table 4.8 Physical spare part without coating experiment time	39
Table 4.9 Physical spare part with coating experiment time	42

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
ABS	Acrylonitrile butadiene styrene
AI	Artificial intelligence
AM	Additive manufacturing
CAD	Computer aided design
CMM	Coordinate measuring machine
CT	Computed tomography
DFP	Digital fringe projection
DSP	Digital spare parts
DWG	AutoCAD drawing database format
DXF	Drawing exchange format
FOV	Field-of-view
FPP	Fringe projection profilometry
HDR	High dynamic range
IGES	Initial graphics exchange specification
OEM	Original equipment manufacturer
PCD	Point cloud data
PDF	Portable document format
PMI	Product and manufacturing information
PRT	PTC Creo part file
SLDDRW	SolidWorks drawing file
STEP	Standard for the exchange of product data
STL	Stereolithography file format

1 Introduction

1.1 Background

Additive manufacturing technology allows to produce objects layer-by-layer based on digital three-dimensional files. With its introduction, a new model for the supply chain of spare parts can be conceived: spare parts can be directly manufactured on-demand where and when needed. This new approach can lead to the elimination of warehouses and all the related storage and obsolescence costs, in favor of a digital storage of ready-to-be-produced 3D models. This can be possible with an adequate telecommunication infrastructure that is able to transmit the ready-to-be-produced 3D models, coming directly from the original equipment manufacturer (OEM), to the repair shops.

This new supply chain model has generated the concept of digital spare part (DSP). It can be defined as a spare produced with additive manufacturing technology close to the place where it is needed using a ready-to-be-produced 3D model.

Not always the spare parts are available as three-dimensional models, so a solution needs to be found in order to digitalize the spares that need to be distributed as DSP. Based on the inputs available, five different cases can be described:

- The data is available as 2D paper drawings
- The data is available as 2D digital drawings.
- Only the physical part or tool/mold is/are available
- Only the 3D model is available.
- No data is available.

It is also possible that the inputs available are more than one. In these cases, the optimal solution can differ from single input solutions by taking advantage of the multiple inputs.

1.2 Research problem

All the spare parts that can get an economic advantage with the development of digital spare parts infrastructure need a ready-to-be-produced 3D model to be additively manufactured. In order to minimize the time needed when such model is not available and thus to reduce the extra-costs of the replacement, the definition of standard methods to reverse engineer spare parts is needed.

1.3 Objectives

This research aims to define the reverse engineering processes from each of the available input (2D paper drawing, 2D digital drawing, physical spare part, 3D model) and their combinations, to become a general guide for reverse engineering purpose. The work done tries to determine which method paths are not sufficiently effective to be used and which are good for industrial application. The analysis is performed considering the time needed to reverse engineer a part in function of the method used, to determine where it is possible to enhance the methods with a consequent time reduction while maintaining a sufficient accuracy. Also, the currently available tools and technologies to perform reverse engineering are investigated. The final result of each method is always a ready-to-be-produced 3D model.

1.4 Limitations

The limitations of this thesis work are:

- The software products used were limited to the educational ones and only a selection of the available software has been considered.
- In the reverse engineering of a physical spare part only one scanner technology was available, e.g. combined structured light and stereovision technology, and the other technologies have not been tested.
- The research conducted tried to give a general definition of the reverse engineering methods, but the focus has always been on the spare parts case.
- The part tested was one, even if in slightly different versions, and with fixed features.

2 Literature review

2.1 Digital spare parts

Spare parts are a common need for customer products aftermarket servicing. For example, manufacturing plants need them to continue the production when a machine encounters a failure. Generally, customers want their products to be repaired as fast as possible, with the lowest servicing time, in order to minimize the money loss.

An optimal customer service has to be offered to keep high the quality of the product sold: if a problem arises during warranty, it has to be solved rapidly and it has to create the least distress to the customer. The supply chain of spare parts is of vital importance for the product life cycle. When spares are difficult to source, the consequence is increased service time and decreased customer satisfaction, if a repair shop is considered.

Additive manufacturing (AM) technology, that uses computer-aided design to build objects layer by layer, could become a great advantage in term of reduced downtimes of manufacturing plants: by allowing the production of spare parts where those are truly needed, at the repair shop or at the spare parts distributor (1), the delivery time of the spare part can be minimized. This can be achieved with the introduction of a telecommunication network that allows the exchange of digital spare parts. These parts are in the form of data, they can be downloaded from a server to be directly additive manufactured.

The perceived value of additively manufactured digital spare parts has been investigated by Chekurov et al. (2). They have interviewed a total amount of 46 manufacturing experts coming from different industrial branches. The results showed multiple potential applications; moreover, with the adoption of DSP and AM in the spare parts supply chain, it is possible to eliminate a portion of warehouse dedicated to spare parts that meet the requisites for being additively manufactured, leading to lower storage costs, avoidance of obsolescence costs and elimination of unavailability risk.

The main disadvantages of this system are the high AM machine acquisition price, personnel intensiveness and the slow production rate; that could be partially covered by a sharp decline in transportation costs, and the already cited decreased inventory, obsolescence and downtime costs. (3)

The current non-employment of DSP is imputable to a non-readiness of AM processes, that needs further developments in terms of available materials, accuracy levels, tolerances, and building chamber volumes; nonetheless the digital storage of spare parts is considered a great opportunity to reduce companies' costs. (4)

2.2 3D scanning technologies

The purpose of this review is to understand the state-of-the-art regarding three-dimensional measurement techniques for reverse engineering of spare parts. 3D scanning technology can be a great tool in the digitalization of parts, especially for those that contain no technical drawings nor 3D models but just the physical part. This theoretical chapter will underline which are the currently available scanning technique and which are the most suitable for reverse engineering of spare parts, considering both technical specifications and costs.

The research is focused on literature, in particular scientific papers, that present methods with practical examples and analyze their accuracies and speeds of execution. Moreover, a research on the scanners currently available on the market is performed to compare the technical specification and to be able to perform an economic analysis of 3D scanning.

Many different methods can be used to acquire the shape of an object, and each of them has their own pro and cons. These are mainly divided into three categories, in function of the medium used to accomplish the measurement:

- *Non-contact active techniques*, if the measurement system uses a source that emits a signal (electromagnetic radiation, x-rays and ultrasounds are the most common).
- *Non-contact passive techniques*, if the measurement system uses a signal that is naturally available (natural electromagnetic radiation).
- *Contact techniques*, if it involves a physical interaction between a probe and the piece or part to be measured.

After having considered the state-of-the-art of the scientific literature, a market analysis (results shown in Table 2.1) is conducted to understand which products are available for the mentioned technique. The main parameters considered in the analysis will be:

- *Range*: the working range of the scanning system, that defines the working distance from the scanned part.
- *FOV near*: the minimum dimension of the field-of-view that a scanner can scan with a single shot, expressed in square millimeters.
- *FOV far*: the maximum dimension of the field-of-view that a scanner can scan with a single shot, expressed in square millimeters.
- *Maximum scan volume*: used only for CT scanners, is the maximum volume that can be scanned without having trouble with one of the dimensions, is expressed in cubic millimeters as diameter multiplied per height (the π necessary to compute the scan volume is omitted in the literature).
- *Accuracy*: defined as the difference between the observed reference value and the reference standard value, expressed in millimeters.
- *Resolution*: the smallest increment measured by the system, expressed in millimeters.

2.2.1 Non-contact active techniques

2.2.1.1 Time-of-flight

The first method analyzed is 3D scanning using *time-of-flight* of an ultrasonic wave (5) or a laser pulse (6). The measurement of distance is computed multiplying the speed of the signal (for the laser pulse is the speed of light, $c = 3 \times 10^8$ m/s) and the time recorded between the emission and the reception of the reflected signal divided by half. It is good for long range measurement but not for the short range: due to the high speed of light, it is difficult to measure short distances with a high precision, because the time interval that has to be measured is really small (pico-seconds). The previous assumption is generally valid, but also confocal chromatic microscopy has to be mentioned as it is a highly accurate technique that uses the time-of-flight principle (7); this has anyway not been taken into consideration because it allows only the measurement of too small lengths.

Some research has been done to improve time-of-flight technique, and the results showed a greater noise coming together with improved accuracy (8).

So, time-of-flight technique is commonly used for long-range scanners, used for the three-dimensional acquisition of buildings, large/natural environments, or for reverse engineering of large product, e.g. the body of a boat or an entire aircraft, as will be seen in 2.2.4. In the market research summarized in Table 2.1 the available scanners using time-of-flight method, or more precisely phase shift method, show good accuracies ranging from $\pm 0.3 \text{ mm}$ to $\pm 1 \text{ mm}$ considering the wide ranges up to 110 m. The prices of these scanners are generally high, spreading from 30.000,00 € to more than 100.000,00 €. These types of scanners are suitable for aeronautical and naval spare part reverse engineering, that can be very large.

2.2.1.2 Structured light

More interesting is 3D shape measurement with *structured light* technique, where an active pattern is projected on the part to be scanned to simplify the correspondence problem, that is established analyzing the pattern distortion of the image captured. The system consists of a camera and a projector positioned at a certain distance from each other, by knowing the reciprocal positions it is possible to triangulate to get the position of the point being scanned. The projected fringes carry a coding inside and the coding method adopted highly influences both scanning accuracy and speed. Some examples of coding methods have been evidenced by Zhang et al. (9).

The method of using a digital video-projector to project sinusoidal fringe patterns for retrieving the phase is called digital fringe projection (or DFP) and the related technique is called fringe projection profilometry (or FPP). The accuracy of this technique with a static object to scan is comparable to the one of a CMM (10). The challenge for FPP is to measure shiny surfaces, common in manufacturing, that leads to reflection and inaccuracies of the standard process. This can be achieved using a sprayed layer of non-reflective powder, if it does not affect the dimensional accuracy too much; or better with a high dynamic range (HDR) fringe projection technique. A detailed research on the HDR 3D measurements with fringe projection profilometry has been done by Feng et al. (11). In the review six different techniques that allow to detect shiny surfaces have been tested:

- Camera-based techniques (12)
- Projector-based techniques (13)
- Additional equipment-based techniques (14)
- Hybrid techniques (15) (16)
- Algorithm-based techniques (17)

These techniques are usually combined together in scanners analyzed in Table 2.1.

Structured light scanners available in the market use more than one of the techniques mentioned combined together to achieve optimal results. These scanners, together with triangulation scanners, are the most flexible in terms of accuracy, resolution and price. The

accuracy of the scanners currently available in the market covers a wide range, from $\pm 0.04 \text{ mm}$ to $\pm 1 \text{ mm}$. Such a wide spread in accuracy gives the chance to buy a 3D scanner starting from only 434 € (Table 2.1, 3D Systems Sense 2). While operating reverse engineering on a spare-part, tolerances have to be taken into account during the selection of the accuracy needed: when those are not strict, having a cheaper solution can be a benefit. The prices of a professional/industrial 3D scanner based on structured light principle are usually around 50.000,00 to 100.000,00 €. However, the price range is well covered in the market that presents a scanner for every pocket, as can be seen in Table 2.1.

2.2.1.3 Laser triangulation

A common configuration, used in laser triangulation displacement probe, is to have the laser perpendicular to the surface and a receiver lens plus a charge-coupled device (CCD) positioned inclined of a certain angle. The CCD detects the laser dot (or line) position. By knowing the tilt angle θ of the CCD and the distance ΔD between the laser dot projection in the reference plane and in the normal surface, the height can be easily computed using a basic triangle equation ($H = \Delta D * \tan\theta$). With this configuration a great accuracy has been achieved removing the laser dithering angle, that can span from -1° to $+1^\circ$ creating a certain noise in the signal and strongly affect the measurement, with the aid of a corrective algorithm and a laser pointing control. The achievable accuracy in height measurement with this method can be lowered from $\pm 7 \text{ mm}$ to $\pm 5 \mu\text{m}$ (18). Selami et al. (19) proposed a new scheme for the laser triangulation technique, composed by four laser emitters instead of only one. The three additional lasers are used to perform a calibration of the accuracy of the system, detecting the inaccuracy of each of them. The centroid algorithm (20) is used for sub-pixel curve fitting, to better detect the laser spot center.

In Table 2.1 are presented the sets of data collected from some of the laser triangulation scanners currently available on the market. These scanners accuracy compared to the structured light scanners one is typically higher for products of the same price range. The maximum accuracy achieved is $\pm 0.007 \text{ mm}$ (Table 2.1, Nikon Metrology H120). A very good compromise is presented by Nextengine with their 3D Scanner, that is the cheapest scanner of this category. The working range is usually under 1 m, but it is not limiting because with the software aid multiple scan can be fused together to obtain a single wide 3D reconstruction.

It has to be considered that the laser triangulation technique needs to be optimized for a specific surface texture, for example lasers have lower performances with shiny surfaces and UV emitters work well with high temperature surfaces but could promote a degradation of the object under measurement.

The overall high accuracy and resolution of this method, an average optimal scanning range of 1,4 meters and the ability to deal with shiny surfaces (using blue light lasers) make laser triangulation-based scanners very good candidates for reverse engineering of spare parts.

2.2.1.4 Computed tomography

One big disadvantage of light-based techniques is the impossibility to detect the internal shape of an object. It can be a serious disadvantage if it is taken into consideration that with the newest manufacturing methods, e.g. additive manufacturing, more and more complex internal shapes can be made. This limitation can be overcome using *computed tomography* technique: it uses X-ray as source, and those are able to penetrate objects and thus to make achievable the detection of the whole 3D shape of a part. Moreover, it is possible to obtain

detailed information on surface roughness and porosity, by means of newer techniques that employ micro- and nano-focus X-ray sources, with an accuracy comparable to the one of a CMM machine (21).

Kruth et al. (22) has given a complete review on the CT application for dimensional metrology. The length computation can be done measuring the attenuation of the X-ray after the passage through the material: by knowing the attenuation coefficient, it is possible to derive the length traveled inside the material. The attenuation is measured through a 1D or 2D X-ray detector; the final accuracy of the measurement is affected by the pixel density. From 2D projected images taken from different point of view a mathematical reconstruction is performed leading to a 3D voxel model. Then a post-processing of the voxel data is needed to convert the data into a CAD or STL file. The attenuation coefficient setting is a limitation for CT process: it makes difficult to contemporarily detect with one single scan materials with different densities and to scan massive components. Furthermore, the accuracy can be improved by using data fusion technique: data from different energy levels or from different orientations/positions can be fused together; alternatively, it is possible to fuse data coming from contact or optical sensors to improve the accuracy to values below 5-10 μm . Villarraga-Gómez et al. (23) compared the measurement accuracy of the CT with a CMM; the results confirmed that some systematic large errors still happen.

A discussion about the current state of the standards regarding calibration and performance testing of CT scanners has been carried by Moroni and Petrò (24): they have proposed a procedure to test probing error, length measurement error and resolution.

Despite the optimism about the potential of computed tomography for 3D shape measurement, it still has some critical points to be solved, like the missing international standardization of a calibration process and the ability to be used even from non-expert operators.

The impossibility to determine the accuracy of a CT scanner makes the manufacturers declare only the resolution of the machine, that, referring to Table 2.1, can reach a really low value of just 0,35 μm .

So, in the case of spare-parts, computed tomography can become the most valid tool for 3D shape measurement in the near future, allowing to detect in one single passage the complete inner and outer geometry of a complex spare-part. The investment required nowadays is very high: these systems cost around 500.000,00 €.

2.2.2 Non-contact passive techniques

2.2.2.1 Stereoscopic vision

An intuitive technique of 3D scanning is the stereoscopic vision. It consists of two cameras placed at a certain distance one from each other, that measures the depth of an object using the principle of triangulation. Stereo-vision is a simple, cheap and fast method, having in calibration and stereo matching the most challenging tasks for an accurate 3D reconstruction (9). The basic principle of stereo vision works, but the correspondence problem is not easy to overcome. A hybrid model, using two telemetric cameras and a projector for 3D micro-shape measurement, has been introduced by Hu et al. (25): the projector is used to project active markers (as in the case of structured light) to improve the stereo-matching ability of the two calibrated cameras. The author suggests that this method can avoid the complex calibration needed for the projector used in combination with only one camera in standard

structured light techniques. By adding a single spherical mirror to the Hu et al. (25) configuration, Barone et al. (26) proposed a system able to measure inner surfaces of an object with full-field of view.

Thus, stereo-vision technique alone is not used for high accuracy shape measurement, but it can be used in combination with structured light to become a valid alternative solution, and if it is done, this hybrid technique is no-more part of the non-contact passive category, but it becomes part of the non-contact active one. These systems are taken into consideration in the structured light scanners for the market study, because pure stereoscopic vision scanners are not currently used.

2.2.3 Contact techniques

2.2.3.1 *Coordinate measuring machine*

Coordinate measuring machines (CMM) with contact probes are still the metrological accuracy reference level for every non-contact technique described since now in this review. These systems are commonly used for metrological applications in the manufacturing field and they are also employed in national metrology institute, mainly due to their great flexibility. The accuracy of coordinate measuring machine is high and traceable, with many proposed methods to certify the measurement uncertainty (27) and an ISO dedicated standard (28)(29). The basic configurations of these machines are: moving bridge type, fixed bridge type, cantilever type, column type or gantry type. Each of the configurations grants a certain level of damping and a certain working volume; the choice depends on the application.

The probes used for the measurement can be contact or non-contact probes, in this review the focus will be on the first ones. Two main scanning systems are common in contact probes: touch-trigger probes and continuous-path scanning probes. The former needs a point-by-point acquisition, making the measurement slow but accurate; the latter can keep the contact with the part and scan multiple points, making the measurement easier for free-form parts and enhancing the time-efficiency of the single-point acquisition.

Several methods have been proposed to accurately measure a part using a scanning probe, for example: He et al. (30) proposed a profile error evaluation method, using a pre-path planning related to the design profile, that is suitable for inspection. The main problem using a physical probe to reverse engineer a component is that a path has to be planned before the measurement is conducted in a standard CMM. To avoid the preliminary planning of the path, adaptive sampling methods have been implemented to make reverse engineering possible. An adaptive method has been introduced by Yu et al. employing a three-axis coordinate measuring machine with a touch-trigger probe (31). Starting from a predetermined amount of points, the adaptive method is able to iteratively add other points till the sampled points meet a certain stopping criterion. Duan et al. (32) improved the path prediction employing a laser sensor positioned in front of a touch trigger probe. The movement is accomplished going back and forth in the horizontal plane, granting the full scanning of the component, and using the laser sensor to detect the optimal vertical position. This method is suitable for free-form automatic scanning and seems that the same system could be mounted with a scanning probe instead of a touch trigger one, with opportune modifications. Adaptive methods are difficult to implement for scanning probes, because, even if those could have been the solution to get a faster measurement, the risk of breaking

the probe or damaging the part is high and the cost of the control could become too expensive.

In conclusion, even if the point detection speed is enhanced by the scanning probe, the danger of damaging the surface of the object being measured and the limited possibility to detect internal shapes are still inconvenient that have to be dealt with while using a CMM. The high accuracy with certified uncertainty is the absolute advantage of this technique, even though it needs longer measurement times than optical technologies.

Anyway, non-contact probes are available to combine the solidity of coordinate measuring machines and the advantages of an optical measurement device, a hybrid solution can be optimal for reverse engineering purpose. The limit of contact measurement is the high amount of time needed. For this reason, contact measurement will not be considered as an alternative for reverse engineering of spare parts.

The prices of CMM systems are ranging from 50.000,00 € to more than 100.000,00 €, making them very expensive. They are needed to assess the accuracy of the other scanners.

2.2.4 Case studies and applications

3D scanning technologies are widely used in reverse engineering applications, due to their high measurement speed and to their ability to directly produce a discrete 3D model. In this paragraph some examples of reverse engineering applications will be presented.

Stroklasek et al. (33) have performed a reverse engineering of bodywork and rear light-covers of an old pedal car from 1959, the scanner used has been a GOM TripleScan working with structured light principle. The reverse engineering was needed because no spare parts for the pedal car were available and a new pedal car model resembling the old one wanted to be manufactured. The scanned data have been post-processed and then converted from STL to parametric model with Geomagic Design X. Then, vacuum forming has been used to produce the parts. This is a standard example of reverse engineering process aided by structured light 3D scanning technology.

A good example of reverse engineering with 3D scanning and additive manufacturing of a spare part is given by Paulic et al. (34). They reverse engineered a car volume button performing, as the application presented before, 3D scanning and then mesh data (STL) manipulation to obtain a model ready to be produced. The obtained model has then been additive manufactured in PA2200 material by selective laser sintering. A similar procedure has been used by Sokół et al. (35) to reproduce a front fender for a motorbike 1:12 scale model, because the original part was damaged during the assembly. Furthermore, Wróbel (36) presented a case study where a worn stamping die punch has been reverse engineered to reproduce a new punch. The spare parts reverse engineered in the case studies presented before were all suitable for optical surface acquisition using structured light and laser triangulation scanning technologies: the parts analyzed presented complex shapes with free-form surfaces but no significant internal geometries.

In case of a more complex internal shape of the component, optical scanning is not sufficient. Gameros et al. (37) proposed a method to reverse engineer a turbine blade coming from aerospace sector that had inner cooling channels. They used a combination of technologies to obtain a precise 3D model, more precisely an optical scanner to obtain the external shape and a computed tomography scanner to obtain the internal shape of the blade. Moreover, to

assess the accuracy of the measurements accomplished a CMM has been used to obtain precise reference values. Then the reversed engineered blade is additive manufactured and used as a spare part. In this case study has to be evidenced that CT technology has not been used alone, because the uncertainty of this scanner was much higher than with the optical scanner.

Reverse engineering is especially needed in power production field: power plants are built to last for a long time and the ones produced before the computer era do not have any 3D model information. Zivkovic et al. (38) reverse engineered kaplan turbine blades coming from Iron Gate I Hydroelectric Power Station, the largest dam on Danube river. The blade looking in best condition has been selected to perform a 3D scan using a structured light scanner, but a correction of the blade profile was needed anyway due to wear of the blade edges. So, in this case a redesign was needed to achieve the original efficiency or even to obtain an enhanced one.

Reverse engineering application is needed especially in the fields where the engineering machinery are long-term assets. So, to the cited power plants sector aerospace (39) and military machinery (40) can be added.

2.2.5 Summary

Based on the collected information the techniques that can be used to reverse engineer spare parts are time-of-flight, structured light, laser triangulation and computed tomography. Excluding stereoscopic vision, that is just used as enhancement for the other scanning technologies, and coordinate measuring machines, that perform too slow measurements even if more accurate. The selected technologies are also the most diffused principles on which the scanners available on the market work.

A brief summary of each selected technique and its possible application related to reverse engineering of spare parts will be given:

- Time-of-flight technology is capable of scanning very large components: it can be used to scan entire boat and aircraft bodies. The limitation for these scanners is the near field accuracy. This is actually the only technique that is able to scan an object at more than 100 meters of distance with a very good accuracy. A great advantage in respect to the techniques that use triangulation as measuring principle is that with time-of-flight only one sensor is used to detect the distance, and so the view is less prone to be obstructed. Prices are generally higher than structured light and triangulation scanners.
- Structured light technology is very promising if the spare part to be scanned has small to medium dimensions; it is possible also to scan large parts with this principle, but the time needed to perform this operation could be excessive. The structured light scanners are susceptible to ambient light and to reflective surfaces: these limitations have to be taken into account while choosing this principle to perform a scan. This kind of 3D scanner is very diffused; a structured light scanner can be bought at a cheap price for amatorial use. In general, industrial structured light scanners are affordable.

- Laser triangulation technology can be used for small to medium sized parts, like structured light technology. These two principles are effectively using the same basic triangulation principle, that is just achieved in slightly different ways. Laser triangulation scanners are less susceptible to reflective surfaces, especially when equipped with blue lasers. The accuracy, from the information gathered in Table 2.1, is generally higher than structured light scanners as well as the prices. This method is very good in case of need to scan spare part on-site, because it can be transported easily and then a laser-line probe can be easily handled.
- Computed tomography is able to define the whole part, even its complex internal shapes and channels. This method could be the only choice available if a non-destructive scanning wants to be performed and the internal geometric information needs to be obtained. Two big disadvantages are present: there is still no standard defining the accuracy of these machines and these types of scanners are very expensive.

The choice of the scanner needs to be performed considering the case being studied and the features of the specific spare part to be reverse engineered. To obtain an optimal result is worth to combine more than one of the mentioned technologies, as demonstrated by Gamos et al. (37).

Table 2.1 Analysis of the 3D scanners available in the market (February 2019).

Structured light										
Manufacturer	Model	Range [m]	FOV near [mm2]	FOV far [mm2]	Acc. [mm]	Res. [mm]	Light source	Configuration	Price [€]	Application
3D Systems	Geomagic Capture	0,3	124x120	190x175	0,06	0,11	Blue light	Desktop	20.000-50.000	Reverse engineering small-size components
3D Systems	Sense 2	0,2 - 1,6	200x200	2000x2000	1	0,9	-	Handheld	434,00	3D scanning with low quality
Artec	Eva	0,4 - 1	214x148	536x371	0,1	0,5	Flash bulb	Handheld	13.700,00	Reverse engineering mid-size components
Artec	Eva Lite	0,4 - 1	214x148	536x371	0,1	0,5	Flash bulb	Handheld	6.700,00	(no color or texture capture respect Eva)
Artec	Space Spider	0,2 - 0,3	90x70	180x140	0,05	0,1	Blue LED	Handheld	19.700,00	High quality small-size components
Creaform	GO!SCAN 20	0,05 - 0,5	143x108*	143x108*	0,1	0,1	White LED	Handheld	20.000,00	Reverse engineering complex small-size comp.
Creaform	GO!SCAN 50	0,3 - 3,0	380x380*	380x380*	0,1	0,5	White LED	Handheld	20.000,00	Reverse engineering small to mid-size comp.
FARO	Cobalt	0,5	260x200	500x350	0,050	0,175	Blue LED	Tripod/Arm	20.000-50.000	Manufacturing automated process inspection
GOM	ATOS 5	-	170x130	1000x750	-	-	Blue LED	Tripod/Arm	150.000,00	High accuracy industrial metrology
GOM	ATOS CompactScan	-	40x30	1200x900	-	-	Blue LED	Tripod/Arm	40.000-80.000	3D digitizing of parts, tools and systems
GOM	ScanBox	0,5 - 6	-**	-**	-**	-**	Blue LED	Desktop	150.000-1mln	Reverse engineering mid to large-size comp.
Shining 3D	EinScan Pro 2X	0,4	135x100	225x170	0,04	0,16	LED	Handheld/Fixed	6.000,00	Reverse engineering small to mid-size comp.
Shining 3D	EinScan-SE	0,7	200x150*	200x150*	0,1	0,17	White light	Desktop	1.430,00	Reverse engineering small to mid-size comp.
ZEISS	COMET 8M	0,08 - 0,6	80x60	565x425	-	0,024	Blue LED	Tripod	50.000-100.000	Reverse engineering small to mid-size comp.
ZEISS	COMET LED 2 5M	0,04 - 0,5	45x38	481x404	-	0,018	Blue LED	Tripod	20.000-50.000	Reverse engineering small to mid-size comp.

* Only one FOV value declared by the manufacturer.
** In function of the scanner equipped.

Laser triangulation										
Manufacturer	Model	Range [m]	FOV near [mm2]	FOV far [mm2]	Acc. [mm]	Res. [mm]	Light source	Configuration	Price [€]	Application
3D Digital Corp	Optix 500L	0,85	600x550	675x625	0,05	0,125	R,G,B laser	Tripod	20.000-50.000	Reverse engineering mid-size components
3D Digital Corp	Escan 2.0	0,1 - 0,2	150x100*	150x100*	0,06	0,05	-	Tripod	6.800,00	Reverse engineering small-size components
Creaform	MetraSCAN 750	0,2 - 6	275x250*	275x250*	0,03	0,05	-	Handheld	50.000-100.000	Reverse engineering

Creaform	HandySCAN 700	0,1 - 0,5	275x250*	275x250*	0,03	0,05	Red laser	Handheld	57.000,00	Reverse eng. HQ small to mid-size comp.
Creaform	HandySCAN 300	0,1 - 0,4	225x250*	225x250*	0,04	0,1	Red laser	Handheld	43.000,00	Reverse eng. HQ small to mid-size comp.
FARO	Freestyle 3D	0,3 - 0,8	270x360	600x680	0,5	0,2	Flash LED	Handheld	10.000-20.000	Reverse engineering mid-size components
FARO	ScanArm Quantum E	4	80 (line)**	150 (line)**	0,13**	0,08**	Blu laser	Articulated arm	50.000-100.000	Reverse engineering small to large-size comp.
FARO	ScanArm Quantum S	2,5	80 (line)**	150 (line)**	0,048**	0,04**	Blu laser	Articulated arm	50.000-100.000	Reverse engineering small to large-size comp.
Konica Minolta	Vivid 910	0,6 - 1,2	111x83	1196x897	0,22	-	-	Portable box	8.000,00	Reverse engineering (old, 1999)
Kreon	Zephyr II Blue	-	75 (line)*	75 (line)*	0,01	0,05	Blue laser	Articulated arm	50.000-100.000	Reverse engineering (cost of arm included)
Kreon	Solano Blue	-	100 (line)*	100 (line)*	0,025	0,14	Blue laser	Articulated arm	50.000-100.000	Reverse engineering (cost of arm included)
Nextengine	3D scanner	1,5	130x96,5	343x256	0,1	0,1	Red laser	Portable box	3.000,00	3D shape acquisition
Nikon Met.	H120	2 - 4,5	120 (line)*	120 (line)*	0,007	0,035	Blue laser	Hanheld/Arm	20.000-50.000	Reverse eng. HQ small to mid-size comp.
Nikon Met.	MMDx200	2 - 4,5	200 (line)*	200 (line)*	0,016	0,115	Red laser	Hanheld/Arm	25.000,00	Reverse eng. HQ small to mid-size comp.
ZEISS	T-SCAN CS	2 - 4,0	125 (line)*	125 (line)*	0,04	0,075	Red laser	Handheld	20.000-50.000	Reverse engineering small to large-size comp.
ZEISS	T-SCAN LV	1,5 - 7,5	125 (line)*	125 (line)*	0,04	0,075	Red laser	Handheld	20.000-50.000	Reverse engineering small to large-size comp.

* Only one FOV value declared by the manufacturer.

** In function of the scanning probe equipped.

(line) The scanning system uses a projected laser line to scan, expressed in [mm].

Time-of-flight (or LIDAR or laser pulse)

Manufacturer	Model	Range [m]	Acc. [mm]	Res. [mm]	Light source	Configuration	Price [€]	Application
Artec	Ray	1 - 110	0,9	0,001	Laser	Tripod	50.000,00	Reverse engineering of large-size products
FARO	FOCUS 70	0.6 - 70	1	-	Laser	Tripod	30.000,00	Reverse engineering mid to large-size products
Surphaser	75USR	0.25 - 2.5	0,15	0,001	Laser	Tripod	50.000-100.000	Reverse engineering of mid-size products
Surphaser	SR_100HSX	1.0 - 7.0	0,3	0,001	Laser	Tripod	>100.000,00	Reverse engineering mid to large-size products

Computed tomography

Manufacturer	Model	Max scan vol. [mm ³]	Acc. [mm]	Res. [mm]	Source	Configuration	Price [€]	Application
GOM	CT	240x400 (øxH)	-	0,002	X-rays (225 kV)	Desktop/Fixed	450.000,00	Reverse eng. of complex small to mid-size parts
Nikon Met.	XT H 225	185x625 (øxH)	-	0,127	X-rays (225 kV)	Desktop/Fixed	-	Reverse eng. of complex small to mid-size parts
NSI	X50	300x300 (øxH)	-	0,5	X-rays (10-240 kV)	Desktop/Fixed	-	Reverse eng. of complex small to mid-size parts
NSI	X3000	500x610 (øxH)	-	0,5	X-rays (10-240 kV)	Desktop/Fixed	-	Reverse eng. of complex mid-size parts
NSI	X5000	810x1210 (øxH)	-	0,5	X-rays (10-450 kV)	Desktop/Fixed	-	Reverse eng. of complex mid to large-size parts
RX Solutions	DeskTom	180x250 (øxH)	-	0,004	X-rays (max 150 kV)	Desktop/Fixed	-	Reverse eng. of complex small-size parts
RX Solutions	EasyTom	320x420 (øxH)	-	0,00035	X-rays (max 230 kV)	Desktop/Fixed	-	Reverse eng. of complex mid-size parts (HQ)
ZEISS	VoluMax 800	155x430 (øxH)	-	0,0035	X-rays (130 kV)	Desktop/Fixed	-	Reverse eng. of complex small to mid-size parts
ZEISS	VoluMax 1500	430x800 (øxH)	-	0,4	X-rays (225 kV)	Desktop/Fixed	-	Reverse eng. of complex mid-size parts

2.3 Computer-aided-design (CAD)

Additive manufacturing is based on the models coming from computer-aided design software. There is multiple CAD software, but only those that allow a three-dimensional modeling are used to obtain 3D-printable models.

In the experimental phase only SolidWorks, Creo and Siemens NX software have been used.

2.3.1 Scan-to-CAD software and tools

In this paragraph some of the software available on the market to perform a scan-to-CAD operation are presented. This consists in converting the mesh or point cloud data into an analytic CAD model.

Geomagic Design X 2018. This is a software offered by 3D Systems made appositely to accomplish reverse engineering from 3D scanned data. With some supported 3D scanners, it is possible to gather the scan data directly, to create an STL file and then to convert it into a parametric model using the STL file as reference for the feature creation. It is able to export the parametric model into SolidWorks, Creo, NX and Inventor native files. (41)

Geomagic for SolidWorks 2019. Geomagic Design X tools and functions are also offered as add-on for SolidWorks CAD software. (42)

CATIA V5-6R2016. It offers a tool called Quick Surface Reconstruction that allows to recover digitized data that are imported using CATIA – Digitized Shape Editor, allowing to obtain a parametric model of a tessellated file automatically. It offers several approaches to recover surfaces depending on the type of shape: free form fitting, mechanical shape identification and primary surface extension. (43)

2.3.2 Drawing-to-CAD software and tools

In this paragraph some of the software available on the market to perform a drawing-to-CAD operation are presented. This consists in converting the 2D paper or digital drawing into an analytic CAD model.

Scan2CAD v10. Scan2CAD software is able to convert a raster image made of pixels into a vector image made of mathematical relations, e.g. drawing exchange format (DXF) files. It offers various functions: object recognition, which is able to recognize the features (e.g. layers); optical character recognition (OCR), which is able to convert image into text; raster effects, that allows to clean the raster image. It is a fully automated process after the conversion parameters have been set. (44)

VectorMagic v1.20. It allows to convert a raster image made of pixels into a vector file (DXF is of interest for this research). It offers three types of conversion: fully automated conversion, without any parameter settings; basic conversion, with some simple parameter settings; and advanced conversion, that needs the setting of all the parameters. (45)

SolidWorks 2018. The series of tool offered by SolidWorks 2018 and called “2D to 3D conversion” offer the possibility to use the views of the digital drawing as sketches. The

DWG/DXF drawing can be imported in the working environment being converted into a SolidWorks drawing file (SLDDRW), from this it is possible to copy and paste the useful geometries and use them as sketches in the wanted plane. It is also possible to just copy/paste the views from the SLDDRW file directly into the desired sketch. (46)

PTC Creo 3.0. In PTC Creo 3.0 two different options are offered: the former is a semi-automated tool called AutobuildZ, with which it is possible to clear the drawing from non-geometric entities, define the views as orthogonal, section or auxiliary and to create a 3D solid model in a new part file (PRT) connected to the 2D imported drawing; the latter is to import the drawing views directly into the sketches, similarly to what is done with SolidWorks software, with the 'File System' function that is directly in the sketch toolbar. (47)

2.3.3 Discrete model vs. analytical model

The main difference between a solid analytic-based CAD model and a STL discrete-based one are the resolution and the modification level permissible: the analytic-based solid model, by being built-up on mathematical functions (NURBS), keeps a very high resolution and the ability to be modified almost without limits; while the discrete-based mesh file has a fixed number of triangles used to define the geometry, and consequently has a lower resolution and a limited ability to be modified allowing only basic Boolean operations. Also, another disadvantage of the discrete model is that there is no topology information available to distinguish surfaces that in the analytic model are logically arranged and regrouped. (48)

Furthermore, if a reverse engineering of a worn spare part is considered, that consists in 3D scanning of the component and then refinement of the model, the missing material in the worn points needs to be added: this is an easy task to perform working with a parametric model, more difficult to be executed working on a discrete one.

The 3D scanning result is an STL file because it can be constructed at high speed: a mesh needs less computational power in its generation and it is of easier implementation with a point cloud data (PCD), in respect to an analytical model.

As aforementioned, if needed, the STL model can be directly manipulated, operating some basic functions like adding/removing geometries or adjusting the existing ones, with the aid of specific software (e.g. 3Data Expert, Netfabb, Magics or equivalent).

3 Methods

Reverse engineering of spare parts is needed when essential pieces of information, necessary to reproduce the part itself, are missing. Referring to the DSP case, the spare parts are manufactured by additive manufacturing and this means that the 3D models need to be available. Moreover, the nominal 3D model of a part that will be directly produced needs to be adjusted in function of the manufacturing instructions, for example to leave play or interference where required.

It is important to be able to reverse engineer a part in the shortest possible amount of time, either when the part needs to be immediately produced or in order to perform a digitalization of old spare parts documentations. The time is a key indicator on the efficiency of the process and a low amount of time spent retrieving all the information needed is important to reduce the overall cost of the DSP supply chain. This is the reason why the definition of optimal methods is required to perform reverse engineering on spare parts in function of the available inputs.

Reverse engineering of spare parts can start from different inputs. Listed below are all the single inputs commonly available:

- 2D paper drawing
- 2D digital drawing
- Physical spare part or tool/mold used to fabricate it
- 3D model
- No data (no focus in this study)

According to the available starting inputs and on the part complexity, different processes need to be defined in order to obtain a reversed engineered spare part. In Appendix I the full process diagram that summarizes all the processes described in this chapter is attached. In the following paragraphs each single input and their combinations will be analyzed separately, and one or more methods will be proposed for each of them.

Then, the proposed methods will be tested experimentally to assess their performance, efficiency and effectiveness.

3.1 Materials

The test parts used in this research come from Digital Spare Parts (DIVA) research project, managed and implemented by Aalto University and VTT Technical Research Centre of Finland (49). More specifically, different versions of a reversed engineered starter gear of a string trimmer, necessary to start the dual-stroke engine, have been used. Each version has been used as a different input for each of the possible methods. Only a single input of the recoil starters has been considered in each method, even if complete information was available.

All the recoil starters have the same basic shape and an internal cavity made to host a RFID sensor, only possible due to additive manufacturing production methods. They differ among each other because of their distinctive configurations of hole features, that can be very complex channels (Figure 4.4) or simple go-through holes (Figure 4.10). The physical parts tested have been manufactured in a Stratasys uPrint material extrusion 3D printer in ABS+

material with fused deposition modeling technology. The layer thickness parameter was set to 0.254 mm.

3.2 Reverse engineering from 2D paper drawings

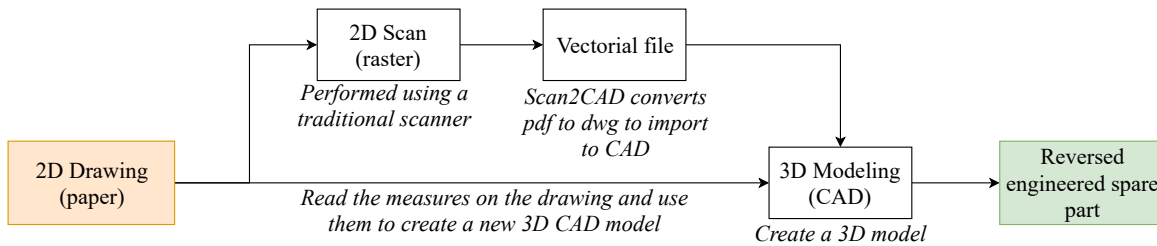


Figure 3.1 Reverse engineering from 2D paper drawings process scheme

Reverse engineering starting from a 2D paper drawing can be accomplished, as represented in Figure 3.1, following two different paths:

- Direct 3D modeling of the spare part in a CAD software,
- Vector graphic aided 3D modeling, that consists in scanning the 2D paper drawing, converting it into a 2D digital drawing in DWG/DXF format and then importing it into a CAD software.

3.2.1 Direct 3D modeling

If the spare part to reverse engineer has a simple shape, for example a square cover, it can be very efficient to just create a new 3D model and to start drawing it from zero. Also, if the part is really complex it can be convenient to model it directly to avoid any type of conversion error that could lead to a waste of time. To do that it is sufficient to use a 3D CAD software (e.g. SolidWorks, PTC Creo, Inventor, Siemens NX, Catia...) and the spare part drawing. A technical drawer is able to interpret the drawing and transfer the measures into the three-dimensional software space, adding also all the tolerance specifications, that are found in the original drawing. In this case the reversed engineered spare part has the exact values and it already contains the production tolerances, thus it is ready to be manufactured. Therefore, this method ensures the dimensional quality of the three-dimensional model.

The sequence of the operations is the following:

1. *Understanding.* In this phase the operator needs to understand the geometries of the drawing to have an idea of what he will have to model. It is also useful to choose where to start with the modeling. Multiple choices can be made, based on the operators experience and their ability with the CAD software.
2. *Modeling.* A standard modeling is performed with the aid of a CAD software.

Two experiments have been run to establish the advantages and disadvantages of this method:

- Experiment 1.1. Simple spare part
It has been conducted starting from a 2D drawing, paper version, of a simple spare part. The reversed engineered part is a simple recoil starter. The 3D modeling has been done using SolidWorks 2018 CAD software. The time has been recorded subdividing it into drawing comprehension time and modeling time.
- Experiment 1.2. Complex spare part
It has been conducted starting from a 2D drawing, paper version, of a complex spare part. The part was a recoil starter optimized for additive manufacturing, presenting complex internal channels and a helicoidal shape. The 3D modeling has been done using SolidWorks 2018 CAD software. The time recorded has been subdivided into drawing comprehension time, modeling time and function comprehension time (that can be avoided with an expert operator). The experiment has been run starting from the simple part 3D model, because the complex part was almost equal to the simple part, then the complex channels have been added. The total time has been computed considering the time needed to add the complex features plus the time needed to run Experiment 1.1.

3.2.2 Vectorial image aided 3D modeling

The alternative to the direct modeling is to perform a 2D scan of the drawing, by means of a traditional scanner, and convert it into a 2D digital drawing. The scanner just needs to have a scanning area of adequate dimensions. With the 2D raster image obtained it is possible, using specific software like Scan2CAD or Vector Magic, to generate a vector file in the DWG/DXF format: this specific type of file is not pixel-based but it uses vectors to define the geometries; in this way it is possible to just scale a single length to obtain a perfectly proportional result in the other dimensions. This file can be opened in a 3D CAD software and used as a reference for the three-dimensional modeling. For example, by importing the view from the horizontal plane it is possible, if the geometry of the spare part is simple enough, to just use the extrusion command and to give the third-dimension to the part. This method can sharply decrease the time needed to reverse engineer a part complex in only two out of three dimensions, like a gear with straight teeth.

The method proposed will consist the following steps:

1. *2D scanning.* The 2D drawing (paper) is scanned in a 2D standard scanner and saved as a PDF or PNG raster file. A definition of at least 400 dpi for an A3 paper drawing is recommended.
2. *Conversion.* The raster image with the aid of a specialized software (for example Scan2CAD or Vector Magic) can be converted from a raster file to a vector file. The converted result is saved as a DWG or DXF file.
3. *Scaling.* After having opened the digital drawing in DWG format in AutoCAD, it has to be scaled: it is sufficient to measure a non-scaled reference dimension and divide it for the nominal value wanted to get the scaling factor.
4. *Correction.* The conversion is computationally very difficult, so the drawing will need some post-processing to correct the mistaken geometries. The dimensional values of the geometries will show a certain error that has to be checked. If the error

found is exceeding the tolerance, it needs to be corrected. This phase is performed in AutoCAD.

5. *Importing and modeling.* Every 3D CAD is able to import a DWG or a whatsoever 2D digital drawing in his environment to use it as a starting point for the modeling. Then, in some software the modeling has to be performed manually, while in others an automatic function is offered.

Two experiments have been run to verify the capability, advantages, disadvantages of the process proposed:

- Experiment 2.1. Simple spare part
It has been conducted starting from a 2D drawing, paper version, of a simple spare part. The part reversed engineered is a simple recoil starter, the same of Experiment 1.1. The 2D drawing has been scanned using an EPSON Expression 11000XL scanner, as setting for the kind of document ‘Text’ has been selected, the resolution set at 300 dpi and PDF as output file. The conversion from raster image to DWG digital drawing file has been performed using Scan2CAD v10 software. In the conversion software the image has been optimized enhancing the contrast and removing speckles and holes larger than 10 pixels. The experiment has been repeated also using an image with a resolution of 600 dpi.
- Experiment 2.2. Basic geometry
To further analyze the potentialities of the method, a basic geometry has been drawn on AutoCAD 2018, it has been printed in A3 format in scale 1:1, and the process has been repeated. The scan has been performed using an EPSON Expression 11000XL scanner, setting as kind of document ‘Text’ with a resolution of 600 dpi and PDF as output file. Afterwards, the image has been opened in Scan2CAD v10 software, where the image contrast has been improved and speckles and holes with the size of 10 pixels have been removed. Then, the DWG file has been opened in AutoCAD software, where it has been scaled and corrected. Moreover, a geometric error analysis has been performed, considering the nominal values from the drawing and the dimensional values of the converted drawing.

The time recorded has been subdivided into scanning time, conversion time and adjusting time. The last is comprising all the operations done in AutoCAD software, e.g. scaling and correction.

The experiments stopped at the end of the conversion phase. After this point the 2D paper drawing has become a 2D digital drawing. Thus, the step 5. *Importing and modeling* will be considered in Chapter 3.3.

3.3 Reverse engineering from 2D digital drawings

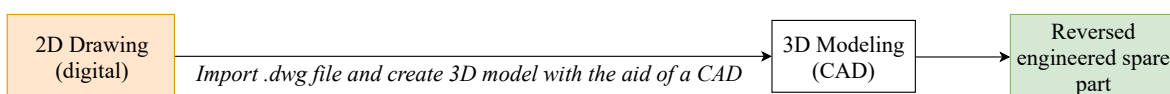


Figure 3.2 Reverse engineering from 2D digital drawing process scheme

The most diffused file format for 2D digital drawings is DWG (originally from Autodesk AutoCAD) or DXF (opensource version of the DWG format). These files can be directly imported into a 3D modeling software (SolidWorks, PTC Creo, Inventor...) and used as sketches to determine the basic geometries. Then, a standard 3D modeling or a tool-aided modeling needs to be performed. All the passages are resumed in Figure 3.2.

The DWG drawing carries all the details about tolerances and geometrical requirements. This solution allows a high quality of the final model, keeping as in 3.2.1 all the nominal values. The production tolerances, to have play or interference, can be considered directly while importing the views as sketches, modifying them directly, or after having finished the 3D modeling. It is considered as a 2D digital drawing also a vector PDF file, that can be easily converted into a DWG/DXF file with the aid of Scan2CAD software or similar. This conversion is way easier than from raster to vector, because the vector PDF already carries simple vector relations.

The method proposed is the following:

1. *PDF to DWG/DXF conversion.* The vector PDF with the aid of a specialized software (for example Adobe Illustrator, Vector Magic or Scan2CAD) can be converted to a DWG file. The converted result is saved as a DWG or DXF file.

If the DWG/DXF is already available, the previous passage can be skipped.

2. *Importing and modeling.* Every 3D CAD is able to import a DWG or a whatsoever 2D digital drawing in his environment to use it as a starting point for the modeling. Then, in some software the modeling has to be performed manually, while in others a semi-automatic function is offered.

Below examples of CAD software tools and functions to import and convert a 2D digital drawing into 3D solid model are listed:

SolidWorks 2018. The series of tools offered by SolidWorks 2018 and called “2D to 3D conversion” offer the possibility to use the views of the digital drawing as sketches. The DWG/DXF drawing can be imported in the working environment being converted into a SLDDRW file, from that it is possible to copy and paste the useful geometries and use them as sketches in the wanted plane. It is also possible to just copy/paste the views from the SLDDRW file directly into the desired sketch. Then, extrusion/cutting operations are performed to obtain the final 3D solid model.

PTC Creo 3.0. In this PTC Creo 3.0 two different options are offered: the former is a semi-automated tool called AutobuildZ, with which it is possible to clear the drawing from non-geometric entities, define the views as orthogonal, section or auxiliary and to create a 3D solid model in a new PRT file connected to the 2D imported drawing; the latter is to import the drawing views directly into the sketches, similarly to what is done with SolidWorks software, with the ‘File System’ function that is directly in the sketch toolbar.

Siemens NX 11. In Siemens NX 11 software is not offered any specific tool to operate the conversion of a 2D digital drawing to a 3D solid model. The same operation suggested for the two previous CAD software products can be performed, copying and pasting the views from the drawing into the sketches and then extruding/cutting.

Only SolidWorks and PTC Creo tools will be tested in the experimental phase. For PTC Creo both the pathways described will be followed.

3.4 Reverse engineering from physical spare part

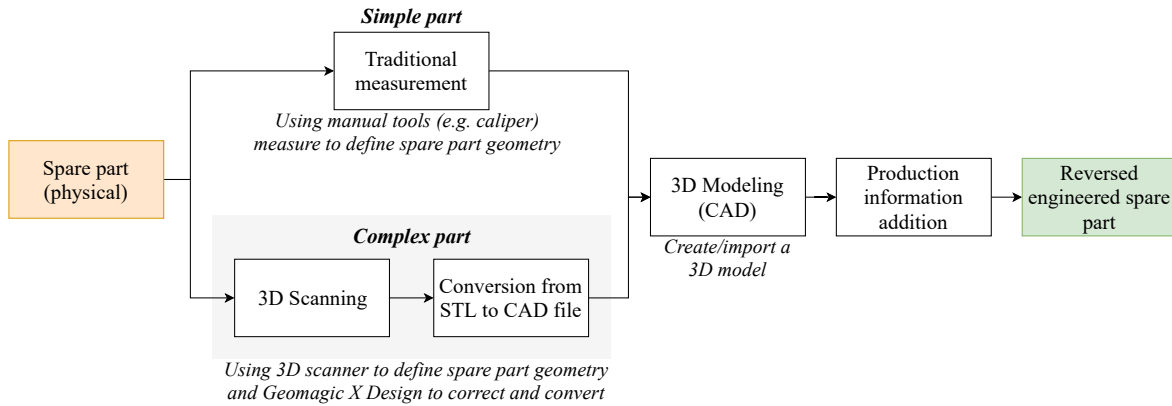


Figure 3.3 Reverse engineering from physical spare part process scheme

When the only available input is the physical spare part or the mold/tool used to fabricate it, reverse engineering becomes more complicated. Despite the fact that the first two input cases needed an average long time to complete the reverse engineering, the dimensions, the tolerances and the geometrical specifications obtained were the exact ones from the original project; in case of reverse engineering from a physical part, these data are not directly available. At a certain point the operator will need to make assumptions for the geometrical tolerances or for the exact dimensional values.

For simplicity, the method will be presented considering a physical spare part, but a similar process can be used having a mold or a tool used to fabricate the part.

Two ways to perform reverse engineering on a physical spare part are presented in Figure 3.3. These are mainly related to the method used to get the measurement data from the part: the traditional or manual measurement is suggested for parts that have a simple shape; while the 3D scanning is recommended for parts with complex shapes, being a faster way to make measurements.

3.4.1 Traditional measurement and 3D modeling

The first method considered is usually suitable for simple spare parts. The measurement of the shape can be accomplished using a caliper, a laser-meter or any calibrated measuring instrument. The measurements are done manually, so the accuracy and the precision could vary in function of the resolution of the instrument used, operator repeatability and measure reproducibility. These measurements can show a large error if the operator is not an experienced one. After having gathered all the information needed, the spare part can be modeled with the aid of a 3D CAD software. This is the method that needs the longest time, as the step of gathering all the measurements needs to be achieved before starting to draw in the CAD software. Then, after having modeled the part, all the production information needs to be obtained. Performing every single measurement manually can become really time consuming, especially for a part with numerous features.

This method has not been tested because is straight-forward.

3.4.2 3D scanning and 3D model refinement

A way to accomplish fast measurements is 3D scanning. As displayed in Chapter 2, the available techniques to perform a three-dimensional scanning are multiple. Based on each case, a suitable technique has to be found to obtain the optimal measurements: accuracy, resolution and range have to be considered. All the mentioned scanning technologies have in common the direct digitalization of the spare part into an STL discrete model.

The STL file can then be imported into a 3D software that has the ability to work on 3D scanned data, like GOM Inspect, Geomagic Design X or CATIA. Afterwards, all the errors due to the scanning inaccuracies are corrected in the software, the inner shapes are implemented, and the geometrical specifications are introduced.

If the part is converted from STL surface model to a solid CAD model, the operator has to choose which the nominal values of the part will be. This is mainly done by experience or by knowing the parts with which the spare part will be assembled.

The method proposed is the following:

1. (optional) *Coating*. If the spare part is made of reflective material and the 3D scanner selected is susceptible to shiny surfaces, the part has to be coated with a thin layer of spray-powder (TiO₂ is commonly used).
2. *3D scanning*. The spare part is scanned using a 3D scanner, usually the scanning software is provided with the scanner: for example, Aalto University owns a GOM ATOS Core (5MP) structured light scanner that uses the aid of the software GOM Scan V8. It is important to consider the positioning of the part under the scanner camera using a stereoscopic configuration or a triangulation method. The position has to be optimized in function of the triangulation lines to avoid obstruction. Then, the raw scans are converted into mesh and exported in STL format.
3. *Post-processing*. With the aid of dedicated software, e.g. GOM Inspect, it is possible to open the STL file and clean the raw scanned data from all the background and undesired scanned shapes; moreover, it is possible, using algorithms, to close holes and to do advanced manipulation of the mesh data. It has to be underlined that if the scanning is done for inspection purpose the algorithms usage can lead to lower dimensional accuracy.
4. *Conversion*. The conversion from STL file to CAD data can be done using Geomagic Design X software: using the STL data as reference it is possible to create a solid CAD model of the scanned spare part, building the model directly on the scanned data.

Two experiments have been run to verify the capability, advantages, disadvantages of the process proposed:

- Experiment 4.1. Spare part scanned without coating
In this first experiment the part has been scanned without applying a coating on it. The scanned part is a recoil starter produced by additive manufacturing in ABS+ material. The scanner used is a GOM Core (5M) based on structured light method with an accuracy of 0.080 μm . The software used has been for the scanning GOM Scan V8, for the post-processing GOM Inspect V8. No STL to CAD conversion has been performed.

- Experiment 4.2. Spare part scanned with coating
In this first experiment the part has been scanned after spraying a thin titanium dioxide powder coating on it, to avoid surface reflection of the projected light. The scanned part is a recoil starter produced by additive manufacturing in ABS+ material. The scanner used is a GOM Core (5M) based on structured light method with an accuracy of $0.080 \mu\text{m}$. The software used has been for the scanning GOM Scan V8, for the post-processing GOM Inspect V8 and for the scan-to-CAD conversion Geomagic Design X 2018.

3.5 Reverse engineering from 3D model

3.5.1 3D model

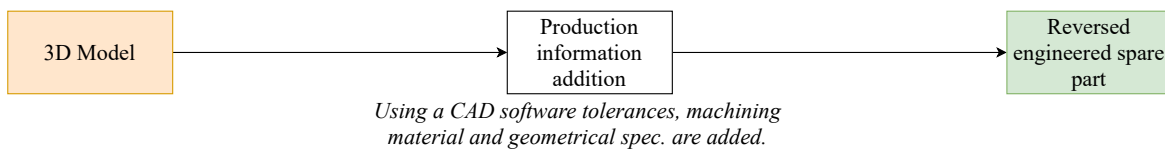


Figure 3.4 Reverse engineering from 3D model process scheme

When the 3D model of a spare part is the only input available, it does not mean that the part can be directly produced and used. The production phase needs additional data over the three-dimensional shape with nominal values, like dimensional tolerances, geometrical tolerances and where machining material is needed to allow further operations (e.g. surface milling). The information regarding dimensional tolerances can be obtained referring to standards. For example, the international standard EN 22768:1996 (50)(51) is defining the general system of tolerances, and EN ISO 286:2010 (52)(53) is defining the general tolerances regarding fits between holes and shafts. The grade of quality of the spare part being produced using the four classes of tolerance (e.g. f, m, c and v) has to be chosen. The eventual machining material, necessary for post-processing phase, can be usually determined after having understood the functionality of the spare part and may not even be necessary. A further analysis can be performed by checking whether the part will work properly with the general tolerances designated.

Then, according to the system of tolerances used, the 3D model has to be modified and some of the nominal dimensions of the part have to be changed. For example, if a small shaft that has to be additive manufactured is taken into consideration, with a fitting tolerance h/H , as prescribed by EN ISO 286:2010, it will mean that, bearing in mind the accuracy of the manufacturing method, the nominal value of the shaft diameter will be reduced to obtain a capable production.

After this phase, called “Production information addition”, it will be possible to produce a fully functional spare part. This case will not be examined in the experimental phase because it shall be of common knowledge.

3.5.2 3D model with production-and-manufacturing information (PMI)

In 2014 by the International Standards Organisation with the publishing of ISO 10303-242 (54) a new application protocol for managed model-based 3D engineering was introduced. With this, the STandard for Exchange of Product model data, or STEP, has been updated to

STEP AP242. With this, it has been given the ability to contain embedded production-and-manufacturing information (PMI). The PMI makes the exchange of data for manufacturing more efficient, embedding the non-geometrical information in the 3D model. Moreover, OEM typically send a detailed 2D drawing that needs to be converted into 3D model with the risk of errors. Having already all the information in one single file can reduce the risk factor and speed up the process (55).

It is not difficult to create this kind of file: for example, Siemens NX offers a tool called “Convert to PMI” to produce a 3D model with PMI.

So, if the available 3D model embeds PMI, the spare part information is all available and the ready-for-production CAD model, taking into consideration all the non-geometrical information, can be made directly without any reverse engineering needed.

3.6 Combined inputs

3.6.1 3D model and 2D drawing

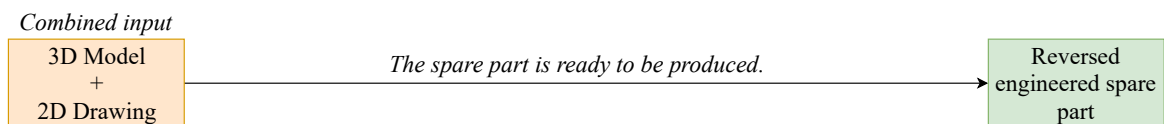


Figure 3.5 3D model and 2D drawing combined input process scheme

The spare part has already all the information needed; the nominal 3D model needs just to be adjusted according to the specifications found in the 2D drawing. Then, the model is ready to be sent to the manufacturing site. No actual reverse engineering process is needed when these two inputs are both available.

3.6.2 Physical spare part and 2D drawing (digital or paper)

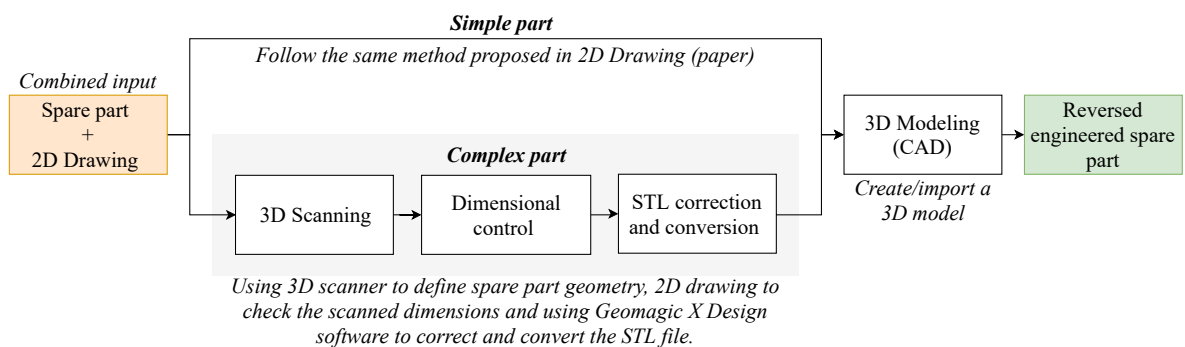


Figure 3.6 Physical spare part and 2D drawing combined input process scheme

A common combined input is composed by physical spare part and 2D drawing (in either digital or paper format). Having two inputs allows to choose between two possible paths: the former is the same described in Chapter 3.2 and 3.3, starting from the drawings; the latter is described in Chapter 3.4, considering the physical spare part.

However, as presented in Figure 3.6, there is a better way to take advantage of a combined path: the information from both inputs can be used to achieve a more accurate 3D model.

The limitations that occur with 3D scanning technologies are mainly due to the inaccuracies of the process: for example, it is not easy to understand if a plane was meant to be inclined at 88° in respect to another plane, like it was measured by the scanner, or if it was meant to be perfectly perpendicular; or again if a hole diameter was supposed to be of 13.09 mm, like measured, or a round 13 mm; due to the scanning inaccuracy in this situations a guess has to be made. With the aid of the data from the 2D drawings, the 3D modeling can be performed knowing the exact nominal values, tolerances and geometrical specifications, allowing a correction of the scanned data. This information is usually present in the drawing or can be retrieved from the general tolerance standards, e.g. EN 22768-2:1996 (50)(51).

The scanned data are usually exported as point cloud data or a discrete STL file. Those files are not easily manipulated by the standard CAD software, so an intermediate passage through a specialized software to convert the discrete model into an analytic model, like the standardized STP, IGES or most of the native CAD software files, is recommended. The software suggested to perform the conversion is Geomagic X Design: it allows to import the PCD/STL file and to convert it into a 3D CAD model. With the availability of the 2D drawing and all the nominal values the manipulability of an analytic model is a great advantage to overcome the scanning noise.

A recent research from Du et al. (56) is presenting some results related to the future of the conversion from a discrete model to an analytical one: their study proposes an algorithm that is able to synthesize a mesh into a constructive solid geometry (CSG) model.

3.7 Process validation

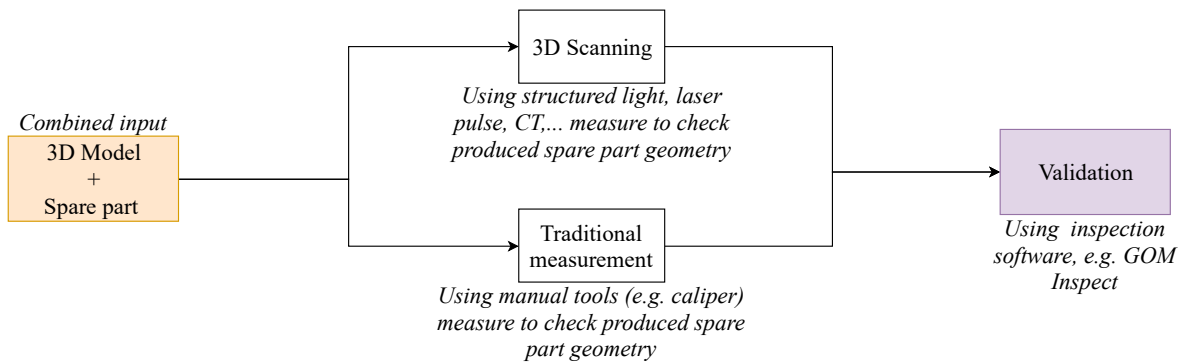


Figure 3.7 Physical spare part and 3D model combined input process scheme

When both physical spare part and 3D model are available, these are not used combined in the reverse engineering process and the same method proposed in Chapter 3.5, starting from the 3D model only, has to be followed.

Instead, this case is more interesting for inspection and validation purpose. When a manufactured spare part wants to be dimensionally checked, it is sufficient to 3D scan the part and superpose the PCD or STL file obtained from the scan on the 3D model with nominal values in a dedicated software, like for example GOM Inspect, as presented in Figure 3.7. Or a manual measurement can be accomplished if just some of the part features has to be checked.

In this research, the cited case is used to validate the reverse engineering process, assessing the accuracy of the produced spare part by comparing the scanned data to the part 3D CAD model or to any of the available starting inputs. This process will form a feedback loop on the whole reverse engineering process: starting from the final result, that is the reversed engineered spare part, and going back to the input phase, where the original pieces of information can be found and compared.

A single experiment will be conducted to assess the effectiveness of inspection as validation method:

- Experiment 5. Process validation by inspection
The inspection has been performed with GOM Inspection V8 software, comparing the post-processed scan result of Experiment 4.2. Spare part scanned with coating with the original STL file used to additive manufacture the scanned spare part. The aim is to assess the process accuracy and to check whether or not mistakes have been made while creating or modifying the 3D model and to check if the production process is capable.

4 Results

In this chapter the results obtained while running the experiments previously described in Chapter 3 will be presented. The experimental results will appear in the same order as in the previous chapter. The outcomes presented comprise difficulties observed while testing the method, time needed to go through its steps, and the final model obtained.

To offer a better understanding of the times recorded and of the difficulties encountered while testing the methods proposed, an overview of the experimental observer will be given. The observer has a Bachelor of Science in mechanical engineering and he is currently at the last year of his Master of Science, he has a good CAD design background formed during high school and university years with AutoCAD and SolidWorks software respectively. The observer is neither a professional CAD designer nor he has previously worked in this field.

4.1 Experiment 1. Direct 3D modeling

4.1.1 Experiment 1.1. Simple spare part

In this first experiment a recoil starter defined by a simple geometry has been directly 3D modeled in SolidWorks 2018 CAD software considering the 2D paper drawing, visible in Figure 4.1, as a reference. The difficulties found during the process were mainly due to the comprehension of the drawing projections and sections. The modeling is simple and fast if the tools of the software are well-known. It consisted in standard 2D sketching and then extrusion/cut operations.

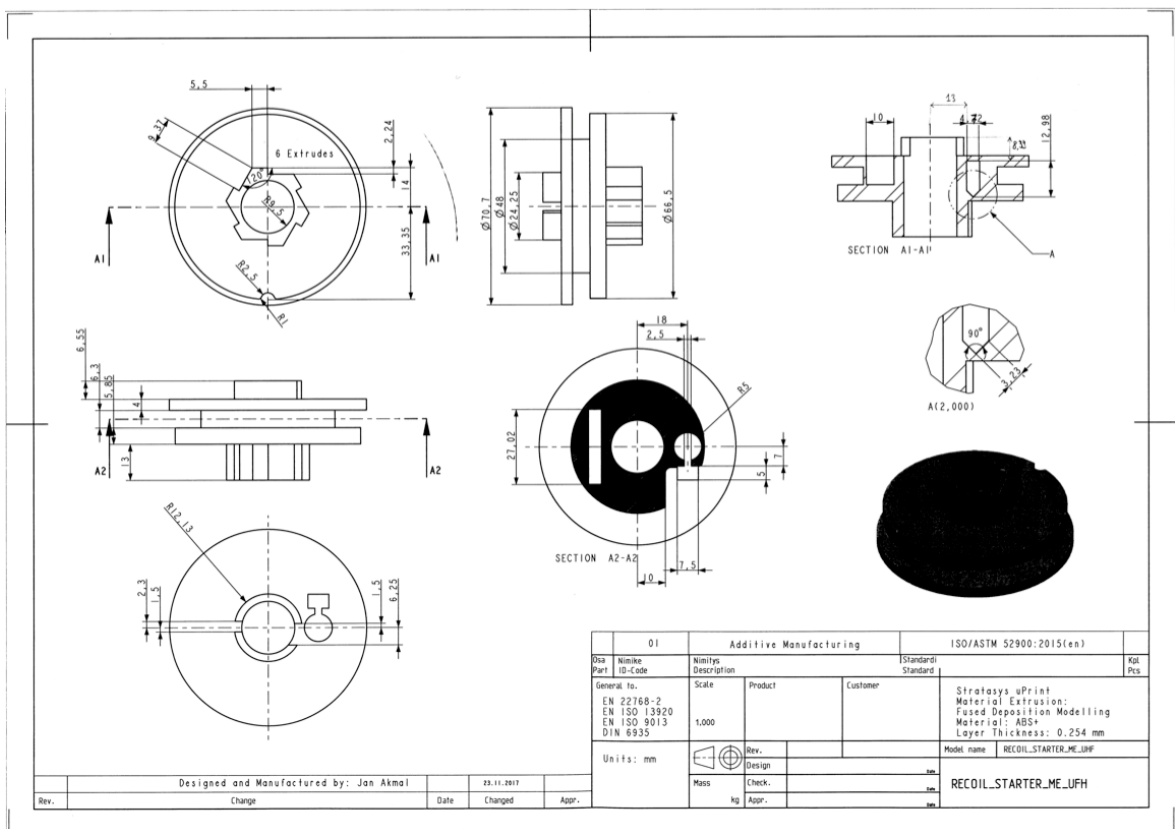


Figure 4.1 2D paper drawing input of simple recoil starter, scanned with high contrast

In the spare part drawing the quotes necessary to correctly position the enclosed sensor hole were missing, due to the parametric nature of the sensor cavity linked to the 3D model. In this case, thanks to the 1:1 scale of the drawing, it has been sufficient to measure two values to position it with a negligible error, which was confirmed with the original drawing linked to the 3D model.

The time needed, split in time understanding the drawing and time modeling, is shown in Table 4.1. It has been a fast modeling, due to the simple shapes composing the part. Because the 2D paper drawing is representing a simple spare part, it has been very efficient to model it directly.

Table 4.1 Simple recoil starter direct modeling time.

Time understanding the drawing	00:07:26
Time modeling	01:30:19
<i>Total</i>	<i>01:37:45</i>

The final result is presented in Figure 4.2, where the 3D model isometric view and a section view are visible. In the section is shown the enclosed sensor casing previously mentioned.

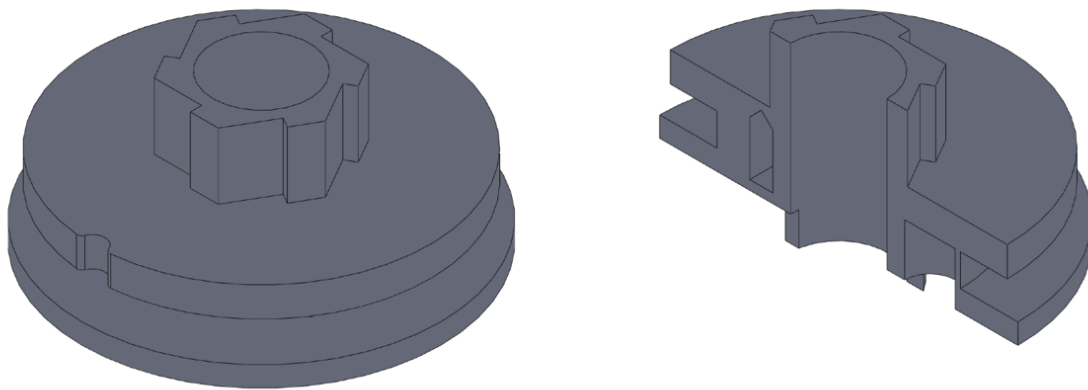


Figure 4.2 Simple recoil starter final 3D model isometric view and section view

4.1.2 Experiment 1.2. Complex spare part

While for the previous experiment the part was really simple and easily understandable, the spare part to be modeled in this second experiment was a more complex version of the recoil starter presented before. The 2D paper drawing input is visible in Figure 4.3.

The difficulties encountered in this experiment were based on understanding the drawing, that showed a great variety of shapes and details in every view and modeling the complex shapes using specific SolidWorks 2018 functions. The time needed to understand the specific functions have been recorded separately and not added in the final result, showed in Table 4.2, to give a better estimation of the effective amount of time spent modeling. The time needed to create this 3D model is significant, with more than 4 hours spent.

Table 4.2 Complex recoil starter direct modeling time

Time understanding drawing	00:12:43
Time modeling	03:56:51
Total	04:09:34

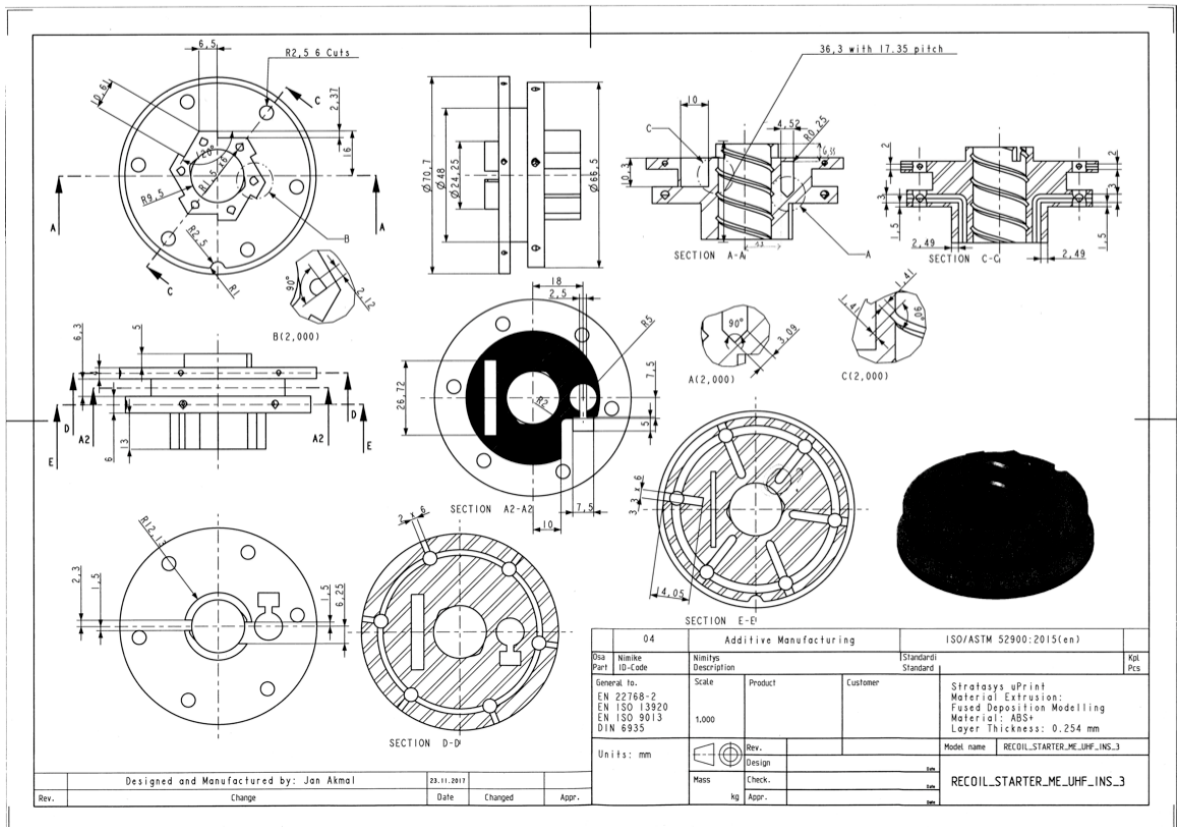


Figure 4.3 2D paper drawing input of complex recoil starter, scanned with high contrast

The final result of the modeling is presented in Figure 4.4 Complex recoil starter final 3D model where the isometric view and a section view of the 3D model are shown. In the section especially the complex channels going through the recoil starter are visible.

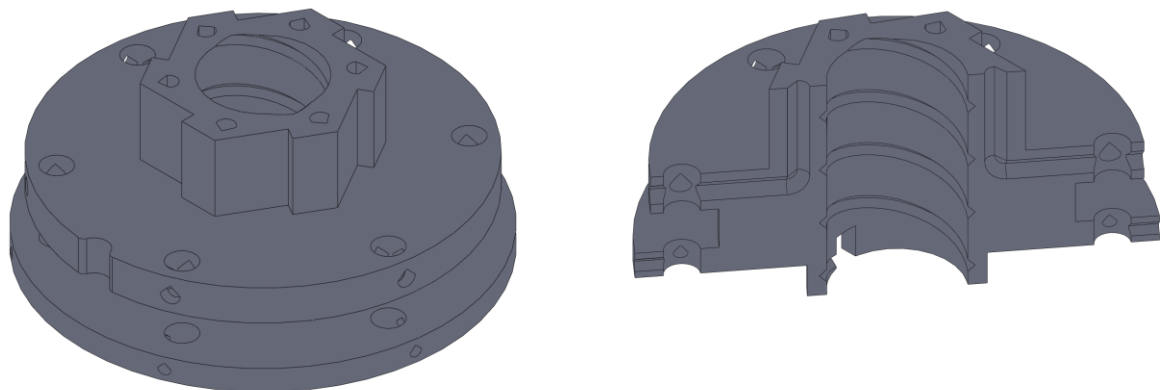


Figure 4.4 Complex recoil starter final 3D model

4.2 Experiment 2. 2D paper drawing conversion to DWG

In the two following experiments, with the aid of an EPSON Expression 11000XL scanner and Scan2CAD v10 software, the 2D paper drawing will be converted into a 2D digital drawing. The conversion from raster image to vector image, that is the principle used to obtain a DXF file, is very complex. Firstly, the procedure will be tested on the simple recoil starter drawing shown in Figure 4.1. Then, a basic geometric shape will be converted into DXF in a second experiment.

4.2.1 Experiment 2.1. Simple spare part

In this experiment an attempt has been made to convert a simple recoil starter drawing, visible in Figure 4.1, into a 2D digital drawing. Even after having followed the exact passages from Scan2CAD v10 software tutorial, that consisted mainly in the manipulation of the raster image, enhancing the contrast and removing the noise and speckles, the conversion of the PDF raster file into vector file has not given an optimal result. The result is presented as a comparison between the converted DWG file and the post processed drawing in Figure 4.5.

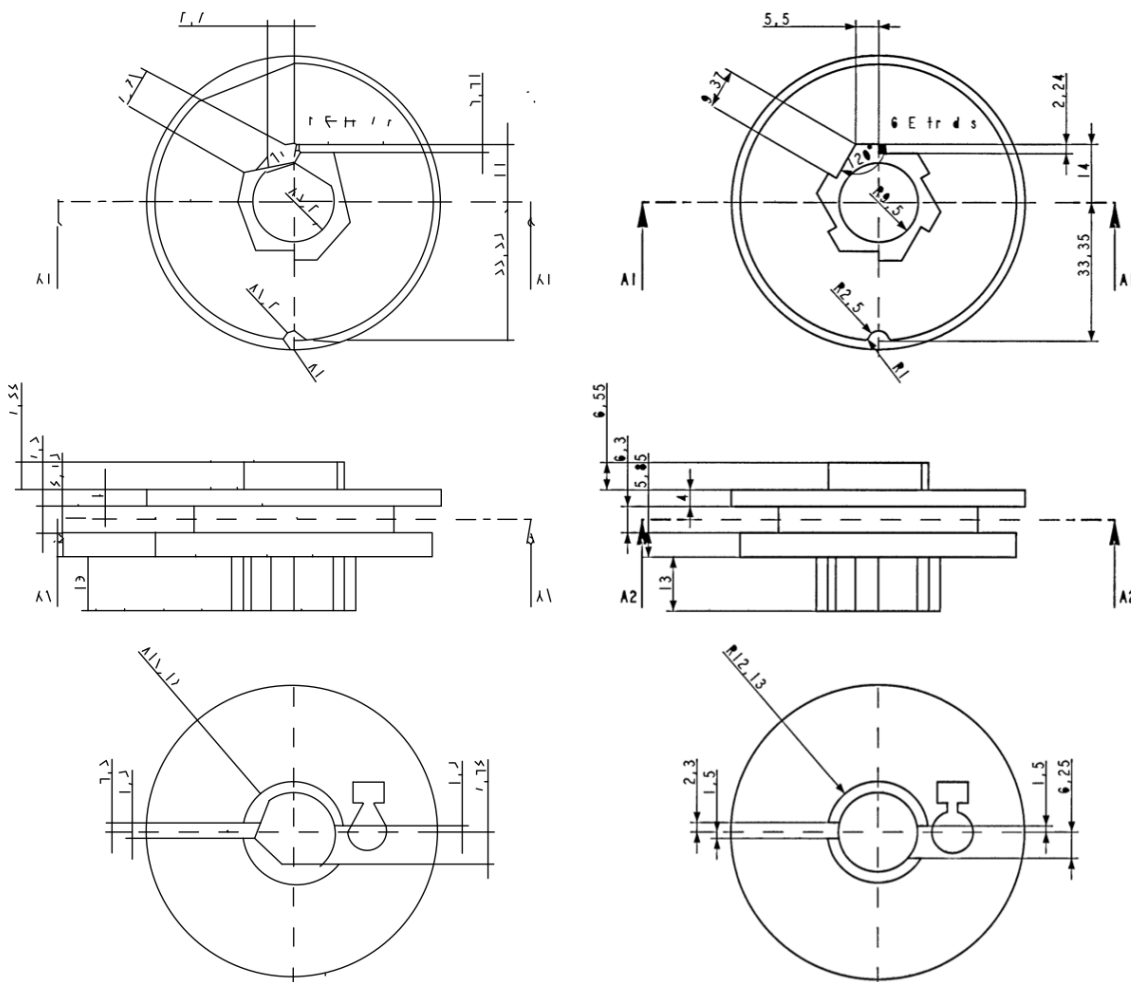


Figure 4.5 Comparison between DWG converted file (left) and post-processed 2D drawing (right)

The recognition of the geometries even for a simple mechanical part is too difficult. As it can be seen from the front view of the recoil starter represented in Figure 4.5, only a very

simple geometry consisting of lines inclined of 90° without quotes or any text in between of the views has been converted showing a satisfactory result. Instead, the circular and zig-zag geometries of the top and the bottom views have not been recognized correctly. Moreover, after having obtained the vector image, it still needed to be scaled and corrected. The estimated time needed to correct the mistaken geometries on the converted DWG file has been considered too long to continue with the conversion.

Unfortunately, the method proposed has not been able to satisfy the requirements. The time needed to perform the conversion has been excessively high, compared with the potentialities of the software. Because the digital drawing obtained was full of errors, it was not worth to continue with the DWG adjusting phase. It has been assumed that a manual conversion from paper drawing to digital drawing would have been more efficient.

Table 4.3 Simple recoil starter paper to digital drawing conversion time

Time scanning drawing	00:02:00
Time converting pdf to dwg	00:04:15
Time adjusting the dwg	-
<i>Total</i>	<i>00:06:15</i>

4.2.2 Experiment 2.2. Basic geometry

In this experiment a basic geometry 2D paper drawing, shown in Figure 4.6, has been scanned using an EPSON Expression 11000XL A3 scanner and then it has been converted into 2D digital drawing, in DWG file format. As for Experiment 2.1, the drawing has been pre-processed in Scan2CAD v10 software and then converted. The result has been a good starting point, with most of the geometry recognized and respected proportions. Still, some of the geometrical features have not been recognized correctly, including all the semi-circular shapes that are visible in Figure 4.6. The drawing has been then scaled and the mistaken geometries have been adjusted using AutoCAD 2018.

The time needed adjusting the drawing, considering that a very simple shape was considered, is very long in comparison to the conversion time, as can be seen in Table 4.4.

Table 4.4 Basic geometry paper to digital drawing conversion time

Time scanning drawing	00:01:17
Time converting pdf to dwg	00:01:48
Time adjusting the dwg	00:09:36
<i>Total</i>	<i>00:12:41</i>

In order to better analyze the software output, the basic geometry starting drawing, shown in Figure 4.6 and the converted drawing before any correction, shown in Figure 4.7, have been compared, underlining where the software has failed: first, it was unable to detect the rounding visible in the top view; second, it was unable to detect correctly the semicircular shape of the lateral view; and finally, it was unable to detect correctly the dashed lines. Moreover, the quote lines are mixed with the drawing figure lines.

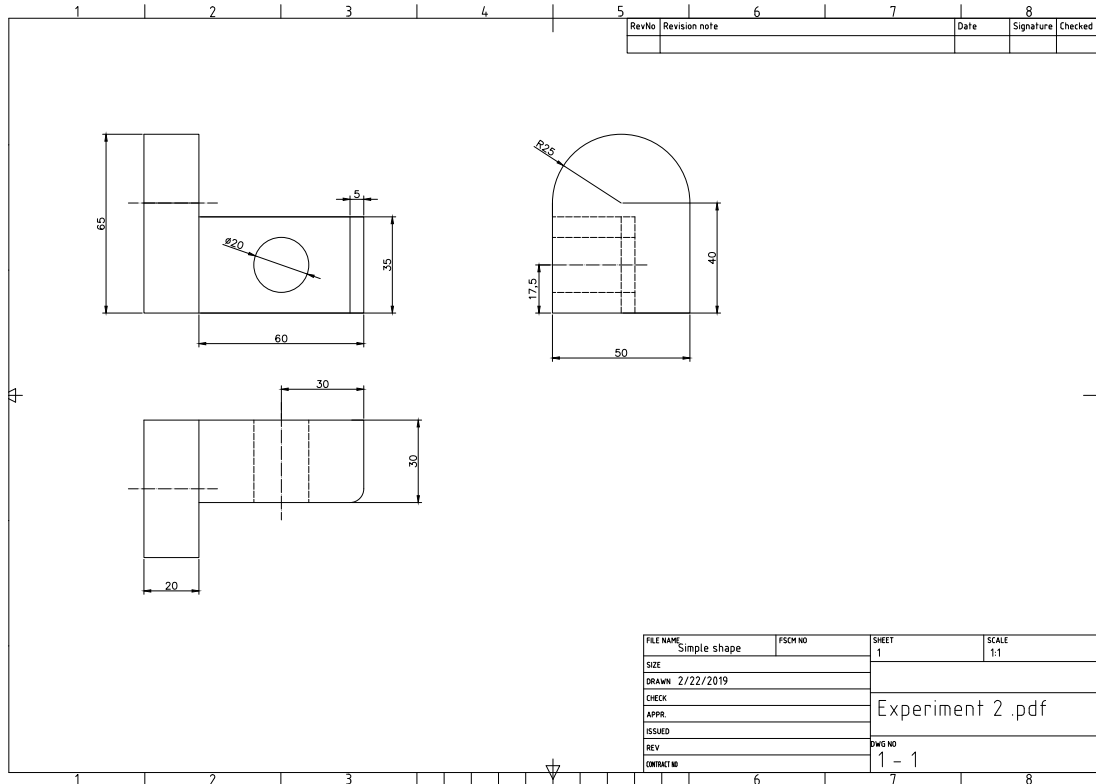


Figure 4.6 Original basic geometry drawing

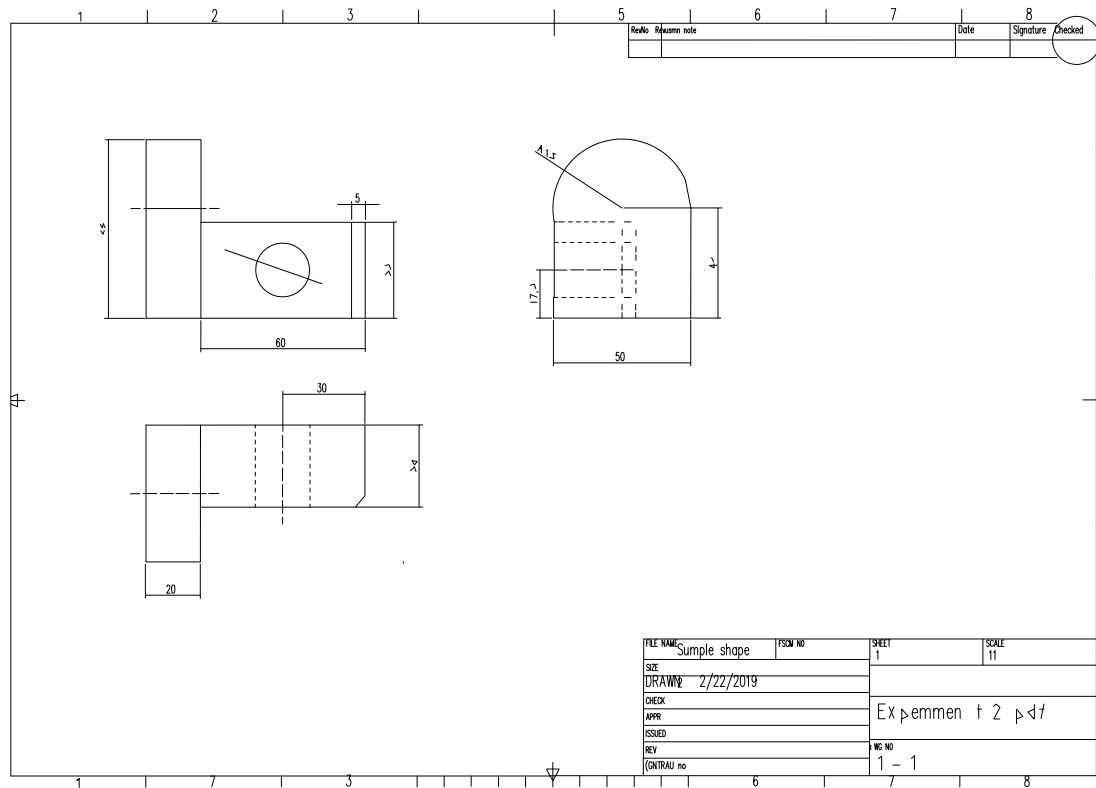


Figure 4.7 Basic geometry drawing after PDF to DWG conversion in Scan2CAD

The geometrical error analysis, shown in Table 4.5, evidenced an average error on the measures of 0,59% and an absolute maximum error of 2,69%.

Table 4.5 Geometric error analysis of the converted DWG quotes after scaling

Converted value	65	19,96	59,86	5,05	34,93	30,23	19,81	29,94	48,67	17,53
Nominal value	65	20	60	5	35	30	20	30	50	17,5
	0,00%	0,21%	0,24%	1,02%	0,19%	0,75%	0,96%	0,19%	2,69%	0,16%

4.3 Experiment 3. 2D digital drawing imported and 3D modeled

4.3.1 Experiment 3.1. SolidWorks 2018

In this experiment, a 2D digital drawing has been imported in SolidWorks 2018 software to be 3D modeled. The drawing represents a third version of the recoil starter presented in 4.1, which can be placed in between the two for level of complexity.

SolidWorks software offers a tool to import the DWG file: it can be imported directly into a sketch or converted into a SolidWorks drawing (SLDDRW file format). Using the second option, it is possible to select the layers to be imported; and finally, the paper size and the scale has to be chosen. The final result is shown in Figure 4.8.

The SolidWorks drawing created has kept the quotes and almost all the elements have been converted correctly and precisely: only an error regarding a polyline in the section A2-A2 has been evidenced, where two points were not perfectly linked leaving an open geometry.

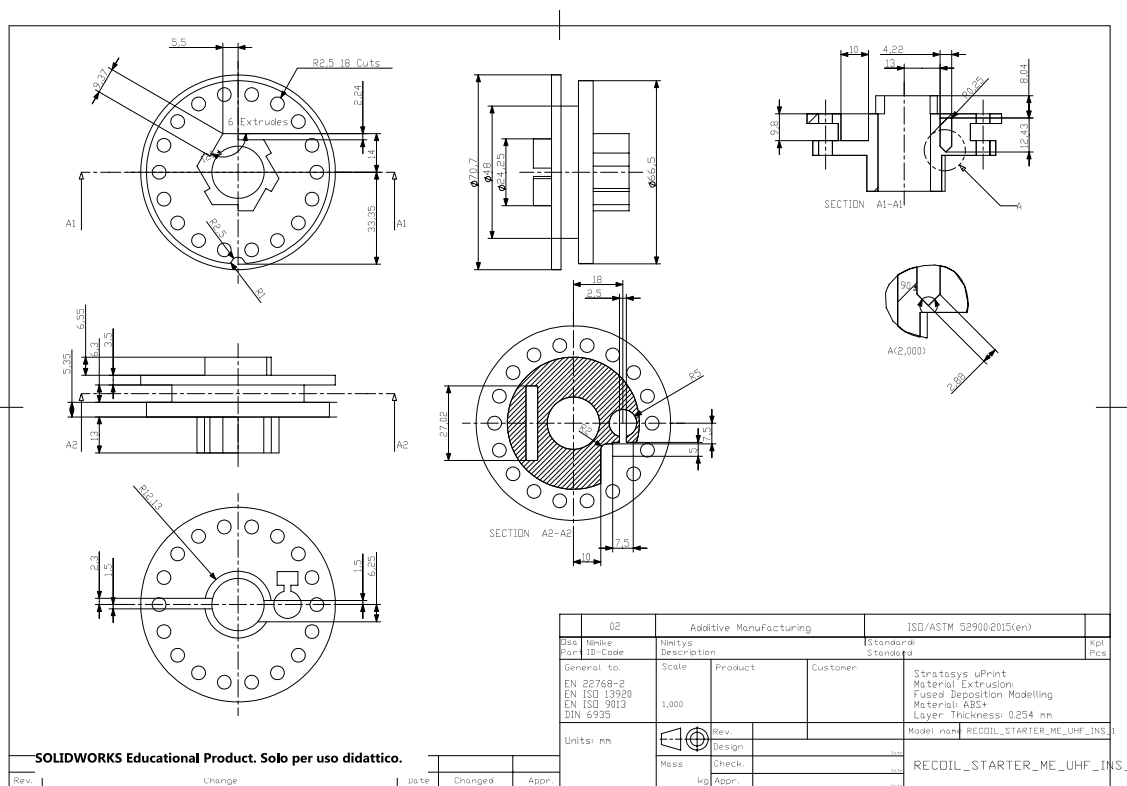


Figure 4.8 Drawing after conversion in SLDDRW format

Afterward, a new part file has been opened. Each view has been copied into the respective plane as a sketch and centered in the origin. For example, the superior view has been copied from the SLDDRW drawing selecting it and using the command ctrl+C; then, opening back the part file, after selecting the superior plane and having started a new sketch in it, it has been possible to paste the view (ctrl+V) and to center it using “Move entity” command. The partial result with superior, frontal and bottom view pasted as sketches is visible in Figure 4.9.

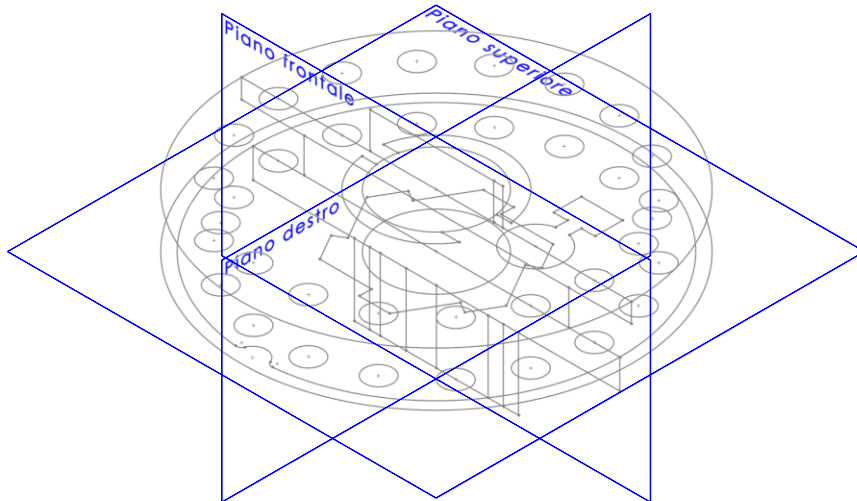


Figure 4.9 Top, front and bottom drawing views inserted as sketches in the appropriate plane in SolidWorks part file

After having imported the three mentioned views, the modeling has been started using mainly the extrusion function and selecting from “Vertex” and for the end condition “Up to vertex”: in this way it is possible to select the starting and ending vertex of the extrusion, defined by the orthogonal view. Alternatively, it is possible to use the function “Convert to Extrusion” in 2D to 3D conversion toolbar: with this function it is sufficient to select the segment of the orthogonal view to define the depth of the extrusion. A similar discussion can be done for “Extruded cut” and “Cut” (2D to 3D toolbar) functions.

The final result is the 3D model presented in Figure 4.10: a virtual circumference is tracked in the middle of the central hole due to the two different extrusions performed to obtain it.

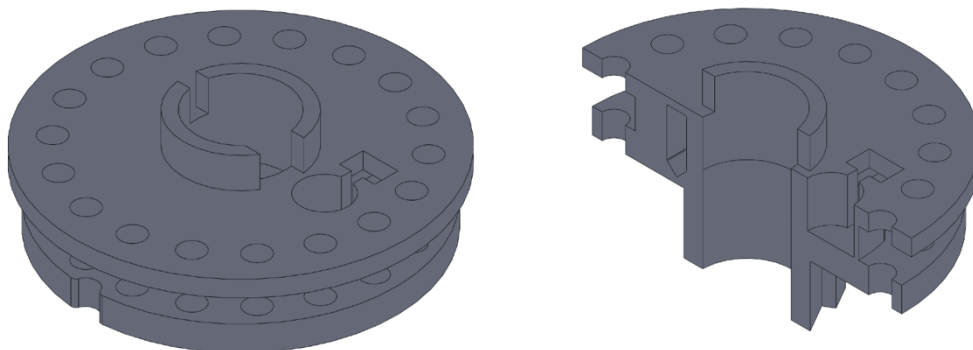


Figure 4.10 Recoil starter (third version) obtained after 3D modeling

The time needed to perform this modeling has been extremely low and is presented in Table 4.6. The time reduction in respect to the direct 3D modeling from a 2D paper drawing (performed in Chapter 4.1.1) has been of 83%.

Table 4.6 2D digital drawing to 3D model conversion time with SolidWorks

Time importing the dwg	00:00:32
Time modeling	00:15:09
<i>Total</i>	<i>00:15:41</i>

4.3.2 Experiment 3.2. PTC Creo 3.0

PTC Creo 3.0 software has a quite old tool called AutobuildZ that offers a semi-automated conversion between a 2D digital drawing in DWG/DWF format into a 3D model. It allows to import the drawing and to clean it from the non-geometric entities like notes, quotes and symbols very rapidly within a single operation. Then, it is possible to define the views to let the computer understand which it is the front view, the top view, the bottom view and so on. The first problem appears when a section view has to be chosen: the support is not enough to understand how the definition of the section view should be performed. After having cleaned the imported drawing, a part file has been created and the extrusions have been performed directly from the 2D drawing that was directly connected with the part file. The extrusion defined just from the orthogonal views have been performed easily; meanwhile, the extrusion defined from the section view has not been successful at it was decentered with respect to the others.

A proper solution has not been found and, after four hours of tentative, the test has been stopped. The partial solution obtained is visible in Figure 4.11, where it is possible to see that for simple shapes the software has worked, but it failed in centering the section extrusion. The total time needed to get to this point, between support reading and software practice, has been very high.

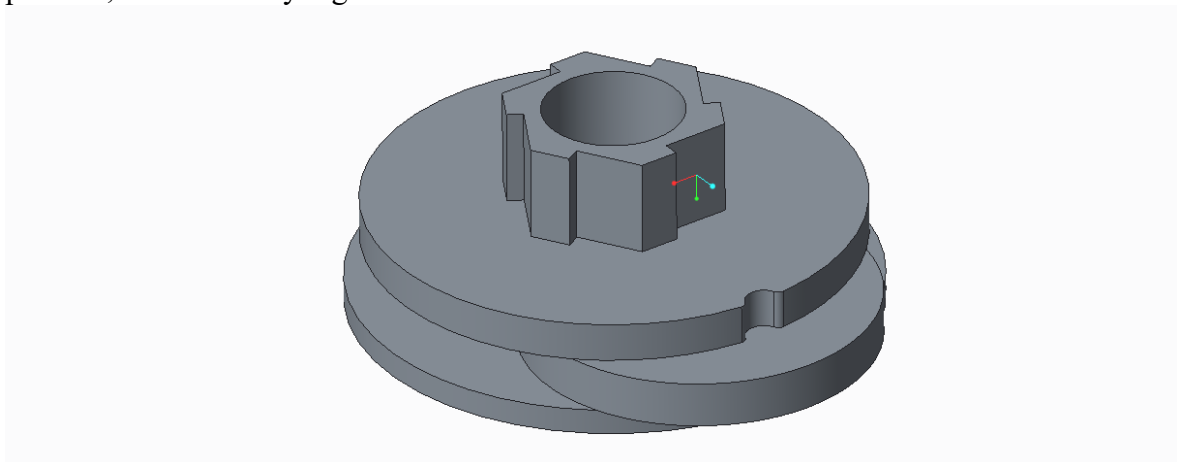


Figure 4.11 2D to 3D conversion with PTC Creo AutobuildZ tool result

To compare the validity of the method proposed in SolidWorks 2018 experiment, the same procedure has been applied in PTC Creo Parametric 3.0 and the same result has been obtained in 28 minutes and 34 seconds, as shown in Table 4.7. The higher time is due to the

amount of work needed to clean the sketches before being able to use the extrusion function and it is partially due to the low experience of the observer with PTC Creo software. The procedure is exactly the same as with SolidWorks, and moreover Creo offers a function inside the sketch toolbar called “File System” that allows to import data from a DWG/DXF file directly into the sketch, instead of just copying and pasting the entities.

Table 4.7 2D digital drawing to 3D model conversion time with PTC Creo

Time importing the dwg	00:00:27
Time cleaning the dwg	00:00:26
Time modeling	00:27:41
<i>Total</i>	<i>00:28:34</i>

4.3.3 Experiment 3.3. Siemens NX 11

Siemens NX 11 does not offer an automatic or semi-automatic building tool and the procedure is again similar to the one tested for SolidWorks 2018 and PTC Creo 3.0. Another test has not been performed, considering that the time range suggested by the previous two experiments, is accurate enough to describe similar procedures with every CAD software.

4.4 Experiment 4. Physical spare part 3D scanned to CAD

Two experiments have been conducted to reverse engineer a physical spare part with the aid of a GOM ATOS Core (5M) structured light scanner. The spare part to be scanned is a fourth version of previously presented recoil starter. It has been produced by additive manufacturing in ABS+ and is shown in Figure 4.12.

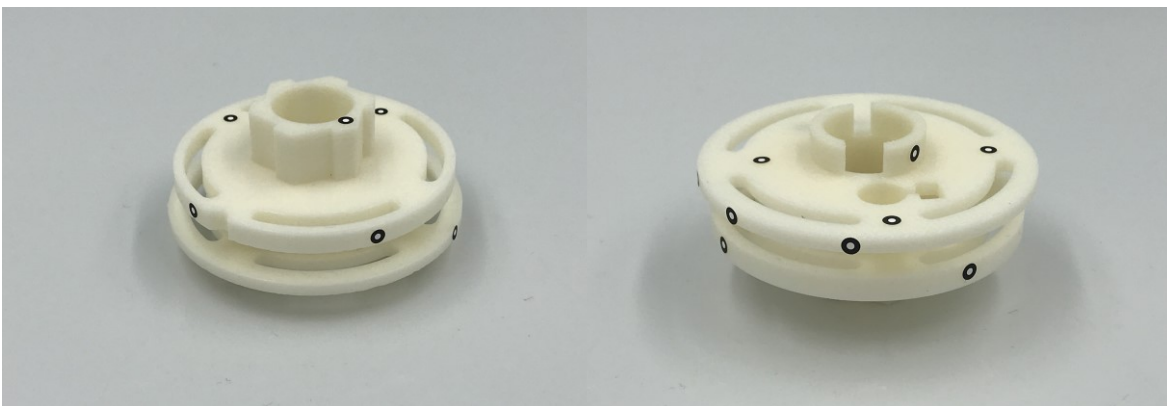


Figure 4.12 Spare part to be 3D scanned after reference marks application

The surface is reflective. In the first experiment the part will be scanned in its original conditions and in the second experiment the part will be scanned after being coated with a titanium dioxide (TiO₂) thin powder layer, in order to reduce its surface reflectivity.

The scanning is performed using GOM Scan V8 software, that is the scanner native software. After the scanner is turned on it needs 15 minutes to warm-up the sensor. It is possible to start scanning even without waiting for the sensor to warm-up, but the measurement accuracy will be decreased. Then, if it is suggested by the scanner software, a calibration of the sensor has to be performed and it will take, as reported in Table 4.8, additional 10

minutes. The calibration is usually necessary when there is a change in the environmental condition.

Because the experiments are run using a combined structured light-stereovision scanner, some reference marks have to be applied on the part to allow the alignment of the multiple scans. While scanning, at least three reference marks have to be seen contemporarily from the two cameras of the scanner.

4.4.1 Experiment 4.1. Spare part scanned without coating

As can be seen in Figure 4.12, some reference marks have been applied all over the part. A total of 18 reference marks have been used. These have been applied during the scanning phase where needed.

The scanning process took a long time and a total of 80 single scans have been performed in order to obtain a satisfactory result. The positioning has been aided, especially for positions with high inclination angle or lateral positioning, by two bolts screwed directly into the scanning plate. After every big change of position, that was not consisting in a rotation of the part only, the level of brightness of the projector and the level of exposition of the cameras have been adjusted. The threshold between no overexposed points and the appearance of some overexposed points has been used as control parameter. To scan the surfaces inside holes it is useful to increase the brightness of the projector lamp to achieve a better illumination of the inner surface. Without the coating the brightness and exposure have to be kept low to avoid reflection. Thus, decreasing the amount of surface scanned per single scan.

While scanning the spare part, a simple post-processing has been performed in GOM Scan V8 software. It consisted in the elimination of most of the background data that were obstructing the vision of the part in the digital preview. After the scanned data has been established sufficient, polygonization and recalculation have been performed successfully, and the resulting mesh data has been exported as STL file. Note that only after the polygonization phase all the details of the scanned part were finally shown, while before only a rough preview was presented.

As reported in Table 4.8, the scanning process took a long time of more than two and a half hours: this is mainly due to the difficulty of the scanner to scan the reflective surface that lead to a high number of repositioning and single scans performed.

Table 4.8 Physical spare part without coating experiment time

Sensor warm-up	00:15:00
Calibration	00:09:47
3D scanning	02:35:00
Post-processing	01:06:00
<i>Total</i>	<i>04:05:47</i>

The scanned data needed a post-processing. It has been performed using GOM Inspect V8 software. The first thing done has been the complete removal of background surfaces and undesired shapes. This step made it possible to analyze the scanned result without obstructions: due to the reflective surface of the part, the scanner encountered a difficulty in

scanning it, leaving discontinuous surfaces full of holes. The partial result is visible in Figure 4.13 and in detail in Figure 4.14.

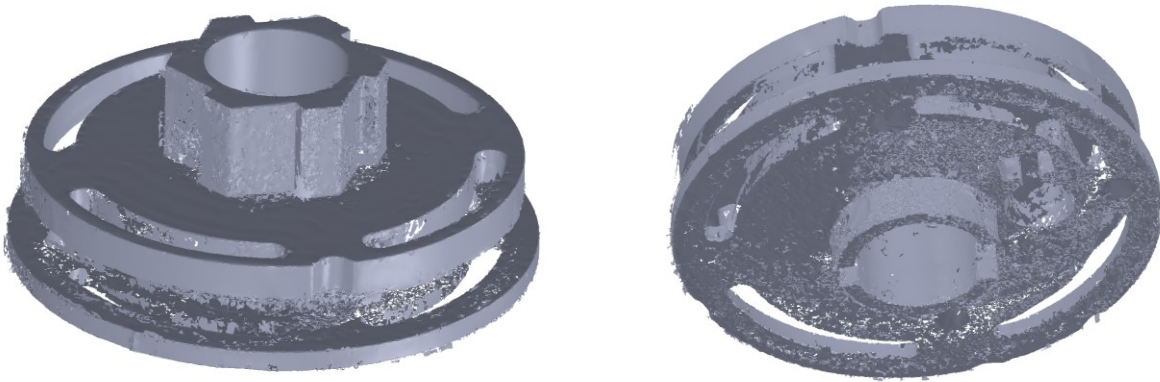


Figure 4.13 Overview of scanned spare part before application of corrective algorithms

Moreover, in Figure 4.14 (a) the misalignment of a single scan, that generated a new surface offset respect to the previous one, is shown; probably this error is extended not only to the face evidenced but to the whole single scan. Also, clearly visible in Figure 4.14 (b), highlighted with a circle, is the inaccuracy caused by the extrapolation of the surface behind a reference mark: the surface is flat and without texture. These errors are very significant if the scan is done for inspection. If the scan is done to convert the part into CAD model the reference mark error is negligible, but the misalignment error could lead to a mistaken geometry.

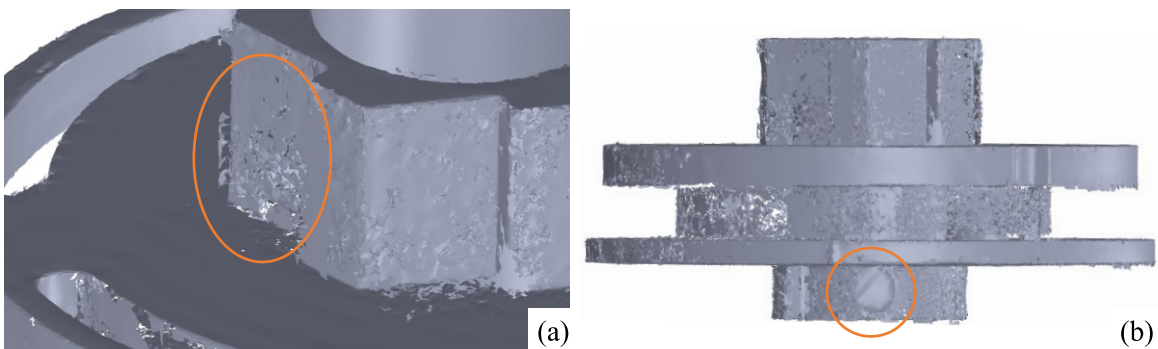


Figure 4.14 Detail (a) and lateral overview (b) of scanned spare part before application of corrective algorithms

Afterwards, a manual cleaning operation has been performed and errors like the one evidenced in Figure 4.14 (a) have been removed.

GOM Inspect V8 software offers different algorithm-based tools that are able to modify the mesh data. The tool “Close holes” has been used to obtain a better result on the bottom and top surface. The post-processed data can be seen in Figure 4.15. The surfaces are looking better than before, because the majority of the holes have been closed, but by using this kind of algorithms the real measurement is lost in favor of an interpolated result.

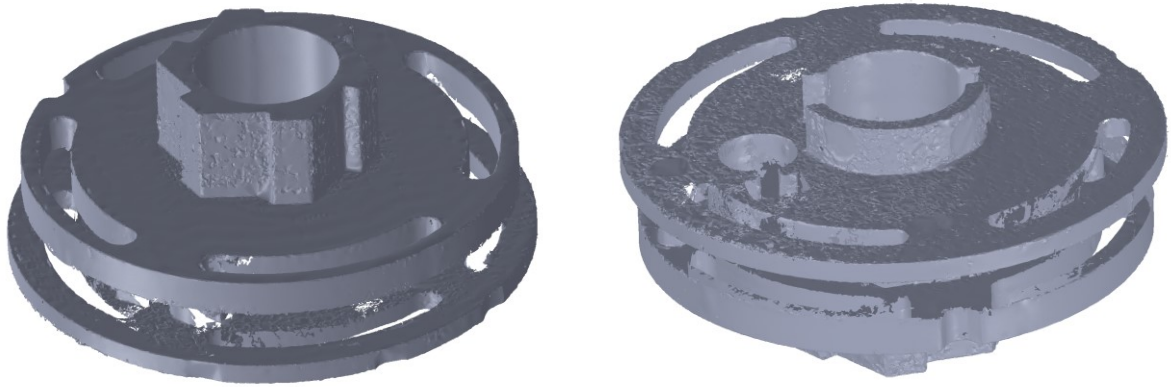


Figure 4.15 Overview of scanned spare part after application of corrective algorithms

The data were very rough even after the post processing. In particular, the cylindrical shape in between the two larger disks, visible in the lateral view of Figure 4.14 (b), has been scanned with such a poor quality that it was not recognized as part of the same solid by the software.

For the part scanned without coating the STL to CAD conversion has not been performed, because the results obtained were not accurate enough to be post-processed effectively.

4.4.2 Experiment 4.2. Spare part scanned with coating

The part scanned is the same of Experiment 4.1 and the reference marks have been kept in position during the application of the titanium dioxide powder layer. Then, the reference marks have been cleaned one per time with a cotton bud. The time needed for coating and cleaning the reference marks from the powder is about 13 minutes, as reported in Table 4.9, which is a low amount of time to invest compared to remarkable enhancement in surface detection and accuracy achievable. The warm-up time and the calibration time are considered constant and are assumed equal to the ones recorded in Experiment 4.1.

The 3D scanning has been performed similarly to Experiment 4.1 and it took just the necessary time to achieve a complete result. A total of 60 single scans have been performed. The positioning has been aided, especially for positions with high inclination angle or lateral positioning, by two screws screwed directly into the scanning plate. After a significant position change, that did not consist only in a rotation of the part, the level of brightness of the projector and the level of exposition of the cameras have been adjusted. The threshold between no overexposed points and the appearance of some overexposed points has been used as control parameter. The level of brightness of the projector lamp, due to the powder layer, has been kept at higher value than in Experiment 4.1. This helped the scanner to be more efficient and it allowed also to scan almost completely the partially obstructed features of the spare part.

While scanning the spare part, a simple post-processing has been performed in GOM Scan V8 software, that consisted in the elimination of most of the background data that were obstructing the vision of the part in the digital file. After the scanned data has been established sufficient, polygonization and recalculation have been performed successfully, and the resulting mesh data has been exported as STL file. Note that only after the polygonization phase all the details of the scanned part are evident, while before only a rough preview is presented.

The scanning process, as reported in Table 4.9, took around one and a half hours, that is still a long time considering the potentialities of 3D scanning technology, but it was anyway much more efficient than the scanning phase of Experiment 4.1. It has to be mentioned that reference marks were applied during the first experiment and those have been kept performing this second one. Consequently, the time needed to place the marks is counted into the overall scanning time. This time can be estimated to 10 minutes and it is not taken into account in Table 4.9.

Table 4.9 Physical spare part with coating experiment time

Sensor warm-up	00:15:00
Calibration	00:09:47
Coating	00:09:36
Reference marks cleaning	00:03:15
3D scanning	01:35:00
Post-processing	00:03:00
STL to CAD conversion	00:49:22
<i>Total</i>	<i>03:05:00</i>

The scanned data, exported in STL format, needed a post-processing in GOM Inspect software, that has been used to remove the background data in a quicker way. The final result is visible in Figure 4.16. An improvement in respect to the result obtained in Experiment 4.1 (Figure 4.13) is clearly visible. Also, the surfaces textures, typical of 3D printed parts, have been caught by the scanner. Additionally, the overall level of detail is very high and almost no holes have been left.

Two points were particularly difficult to scan with the scanner available: the surfaces of the cut on the middle disk, showed in Figure 4.17 (a); and the surfaces of the extruded cut on the bottom disk, showed in Figure 4.17 (b).

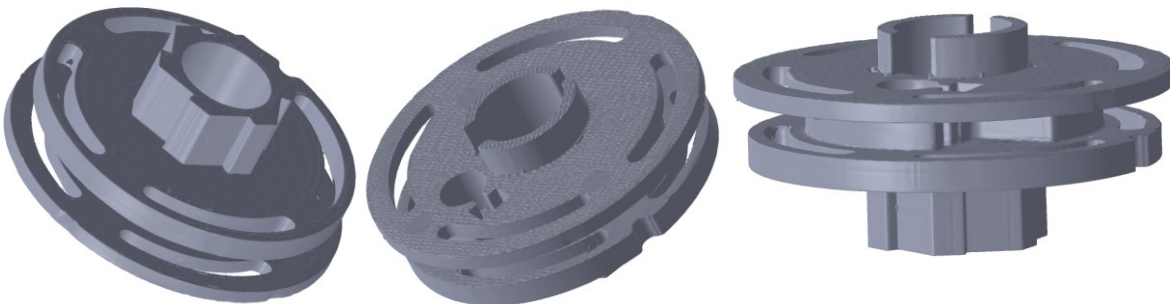


Figure 4.16 Overview of scanned spare part with coating

In Figure 4.17 (a) a typical error occurring while 3D scanning is shown: the scanned surface is partially obstructed by the two larger disks, which leads to some missing triangles in the mesh data. This error can be eliminated using holes removal algorithm.

In Figure 4.17 (b) detail n°1 is visible how a reference mark has been removed from the surface, leaving a plain leveled circular shape. This error is much more significant now in respect to the same error in Experiment 4.1: with the greater accuracy achieved thanks to the coating, it is clearly visible that, where the reference mark has been removed by the software,

the superficial texture is missing. Meanwhile, in Figure 4.17 (b) detail n°2 the noise generated while scanning a deep feature is evidenced. This is caused by the difficult penetration of the light in a small hole.

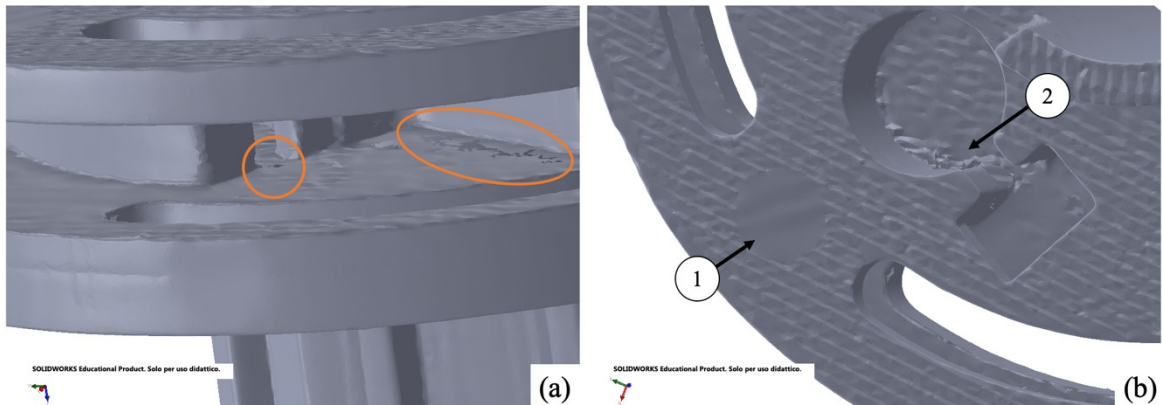


Figure 4.17 Details of scanned result of the coated part. (a) series of holes left in semi-obstructed surface; (b) detail n°1 reference mark elimination, detail n°2 scanning noise

The errors evidenced in Figure 4.17 are due to the kind of scanning method used: the structured light scanner used had a stereoscopic camera configuration combined with a fringe projector placed in the middle of the two cameras and positioned orthogonally in respect to the base plane. This configuration carries a limit in the detection of shapes inside holes, because both the cameras need to see the shape to be able to triangulate and obtain the measurement. Moreover, it has been impossible to detect any inner geometry of the spare part, and there was by design an enclosed sensor casing.

The next step has been to import the STL cleaned file coming from GOM Inspect V8 software to a software that allowed to convert it into a solid CAD model, e.g. STEP file. The software used in this experiment is Geomagic Design X 2018. This software allows to parallelly build on the imported STL file the CAD model, by using the mesh data as reference.

Firstly, the mesh of the STL file has been optimized accomplishing three operations: a “Rewrap”, that filled all the holes of the spare part mesh by interpolating it in order to achieve a continuous result; a mesh refinement using a triangle subdivision tool, that increased the resolution of the mesh; and mesh optimization, that modified the triangle edges to obtain a better definition of the borders of different geometries. This passage is mandatory to be able to use the modeling tools efficiently. These operations have taken around 11 minutes and 30 seconds.

Then, the software offered an automatic segmentation of the mesh into different regions. These regions lately have been used to define the different features to be extruded, cut or revolved during the CAD modeling phase.

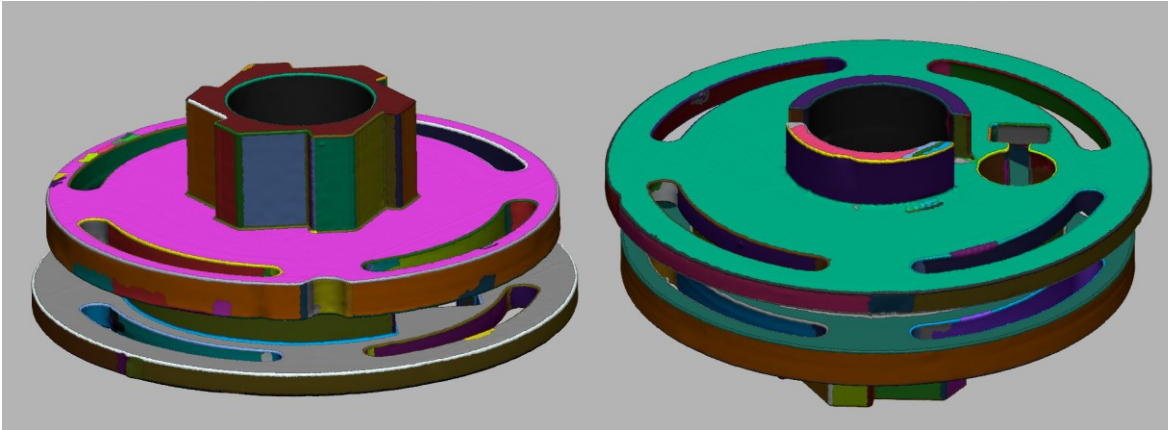


Figure 4.18 Automatic mesh subdivision into different regions

In Figure 4.18 the result after the automatic region definition is shown, with the regions evidenced in different colors. If the result shows too many different regions for a single surface, that is supposed to be only one, it is possible to manually group them or to reduce the sensitivity of the automatic tool.

This subdivision has allowed to use the “Extrusion wizard”, that, after having defined the sides, the top and the bottom plane by selecting one or more regions, has been able to generate a sketch and to extrude it all automatically. If the sketch has a shape that is not satisfactory, e.g. due to an error in the mesh, it is possible to modify it like in every standard CAD software. For example, the spare part scanned had all the vertical corners rounded due to the diameter of the extrusion nozzle, so the extrusion wizard has generated a sketch with rounded corners, following the scanned shape: after having assumed that this was an error, it has been possible to modify and correct it by just editing the sketch. Furthermore, on the lateral surface of the bottom larger disc there were scanning errors where the reference marks have been applied and the software was not sketching a perfect circle: even here it has been possible to modify the sketch and correct the errors.

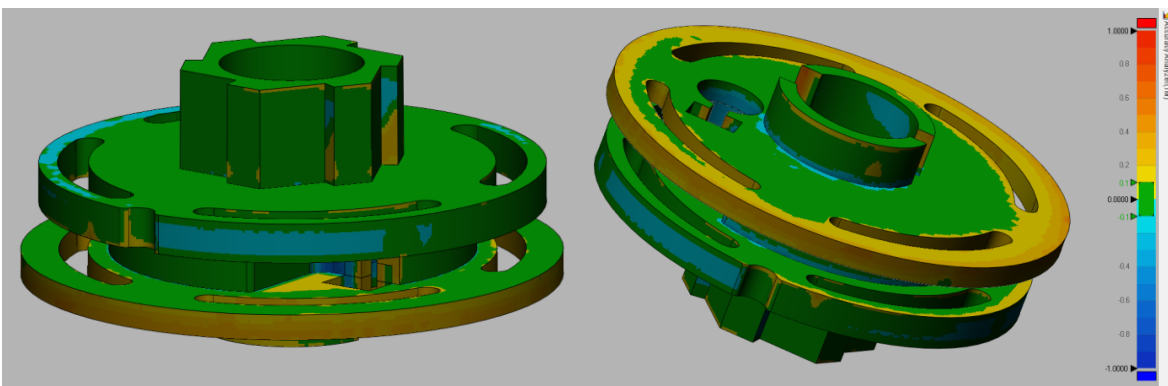


Figure 4.19 CAD model obtained with deviation analysis in respect to STL data

The final result after the CAD has been modeled is presented in Figure 4.19: the different colors present the deviation analysis in respect to the STL scanned mesh data. The result is satisfying and shows a good accuracy. There are some zones where the error is larger, evidenced in blue and in red: these zones are the ones where the mesh was giving a bad approximation and a manual intervention has been needed. Moreover, it seems that the bottom larger disk of the spare part scanned was presenting a non-planar surface.

The time needed to perform all the conversion, as reported in Table 4.9, has been of only 50 minutes, which has to be considered as a low amount of time.

The limitations of the software are related to the accuracy of the scanned data. If the mesh is very rough, like the result obtained in Experiment 4.1, the software is not as helpful as it can be with an accurate mesh, because the automatic features will not be able to run without making a lot of errors.

4.5 Experiment 5. Process validation by inspection

This experiment has been conducted to assess the process accuracy and to check any eventual mistake. These could have been made while creating and modifying the 3D model or due to errors in the manufactured part. The inspection has been performed with GOM Inspection V8 software, by comparing the post-processed scan result of Experiment 4.2. Spare part scanned with coating (Figure 4.19) with the original STL file used to additive manufacture the scanned spare part. The software mentioned allows to accomplish measurements and to conduct geometrical deviation analyses.

The first step is to import the CAD model of reference that conserves the nominal values, into GOM Inspect environment. In this case the STL file used to 3D print the part has been used as reference CAD model. It has been noticed that the mesh was quite rough and consisting of large triangles: to achieve a better result in the surface comparison the mesh has been subdivided using midpoint algorithm in Meshlab v2016.12 software; this has been repeated for three times. The refined STL with nominal values has been imported as CAD reference model. Then, the STL file containing the scanned data has been imported in the same project.

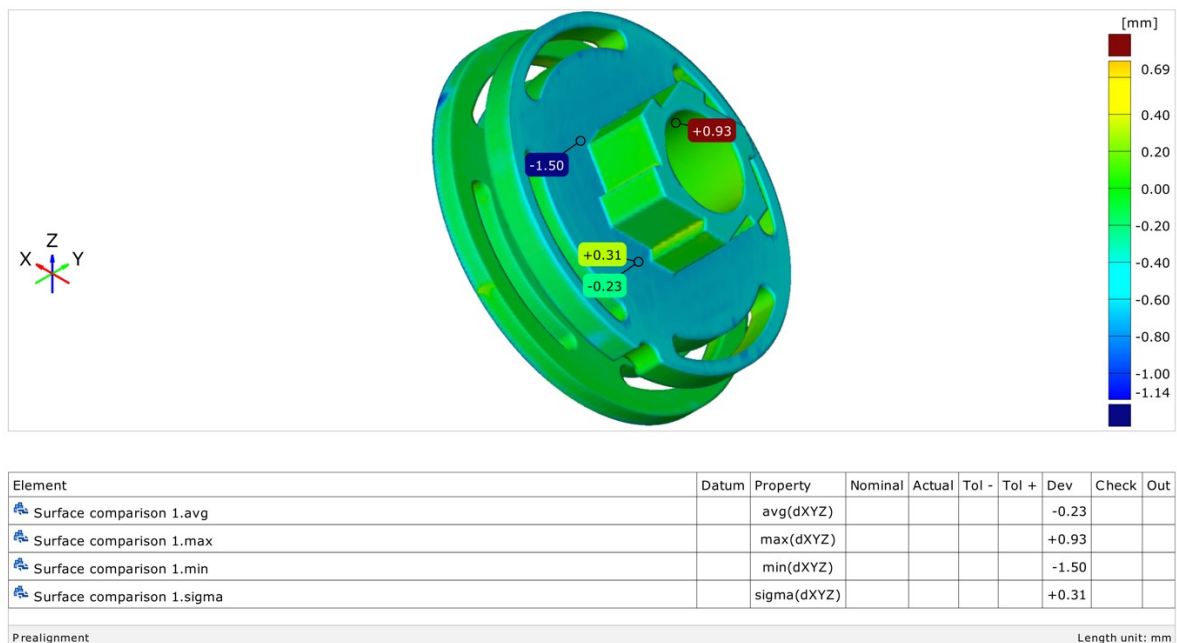


Figure 4.20 Surface comparison after pre-alignment with average, maximum, minimum and sigma deviation computed for the whole spare part

From now on for this experiment the reference STL will be called “CAD” and the scan STL will be referred as “Mesh” to avoid any confusion; this is the same denomination used by GOM Inspect V8 software.

Thus, before starting with the inspection, CAD and Mesh needed to be aligned. To perform this the software offers automated alignment tools and firstly a pre-alignment has been executed. Based on this pre-alignment the first round of inspections has been carried out.

In Figure 4.20 the surface comparison between CAD and Mesh data is represented. It is evident that the part has been produced with a globally good dimensional accuracy, showing a standard deviation (sigma) of only 0.31 mm. Meanwhile, the arithmetical average of the deviations shows that the part seems generally slightly smaller than what it should have been: as can be seen Figure 4.20 there are a lot of areas that tend to a light blue color, and it means that in those areas there is a lack of material.

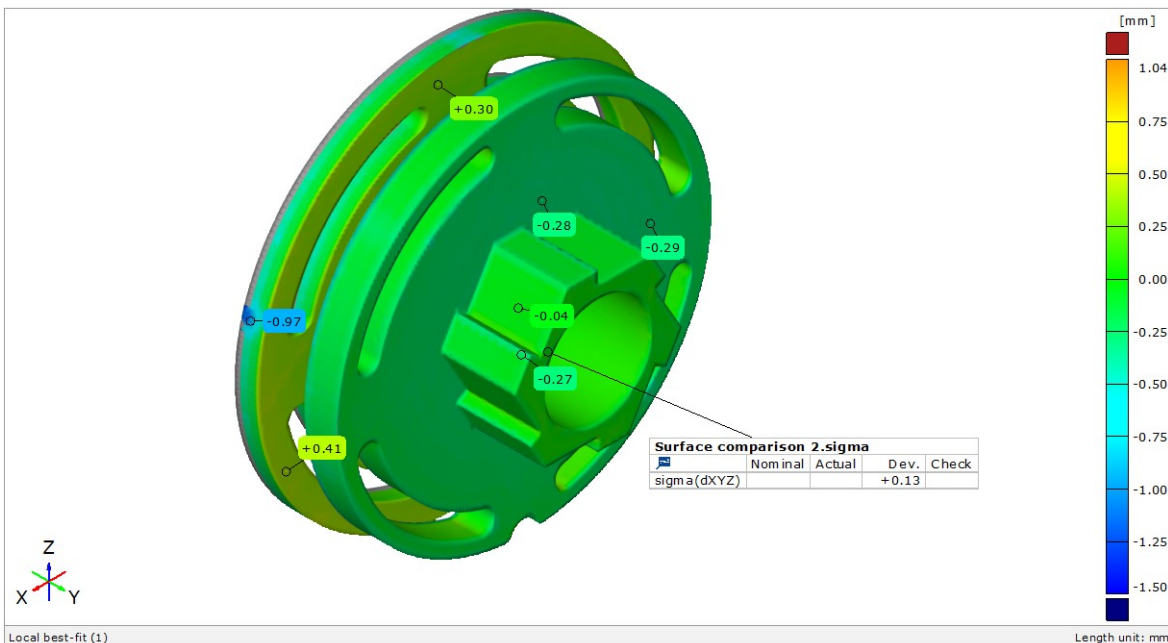


Figure 4.21 Local-best fit n°1. Top cylinder with teeth surface comparison

Afterwards, a local best-fit has been performed to better check the geometric accuracy of a singular feature. The first local alignment has been done on the top cylinder with teeth, and the result is shown in Figure 4.21. The surface comparison shows a good dimensional accuracy, with a standard deviation on the observed feature of 0.13 mm.

Figure 4.21 also visualizes the errors due to the reference marks used in the scanning phase: the most evident one shows a deviation of -0.97 mm and it is evidenced in blue color. As it can be noticed, the error related to the reference marks, especially if not glued on a plain surface is quite remarkable.

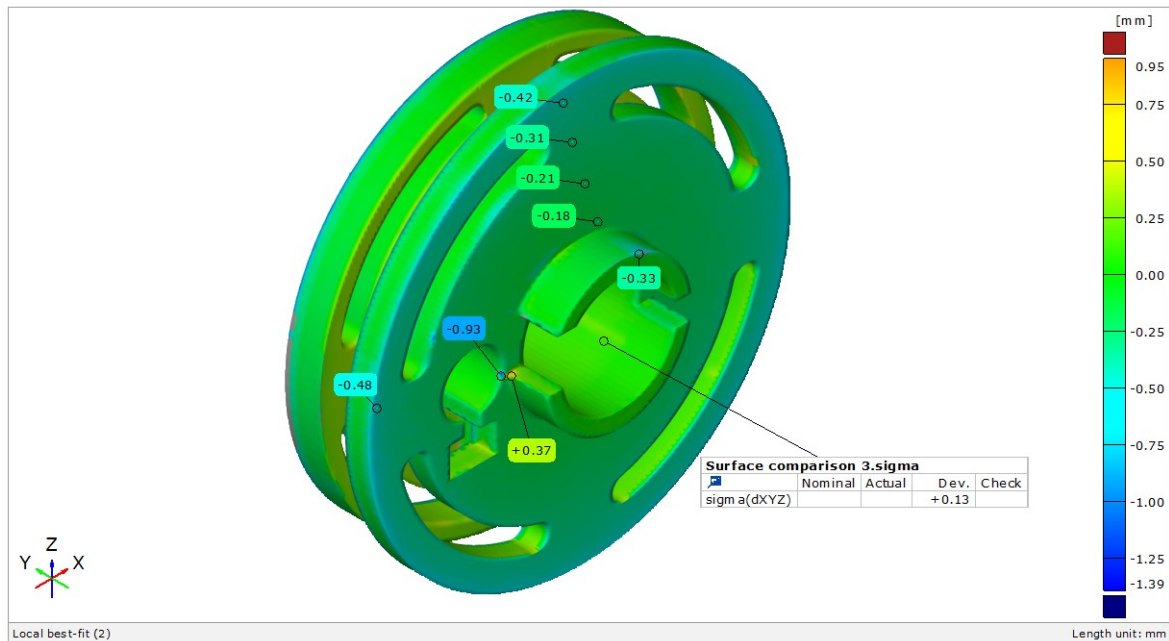


Figure 4.22 Local-best fit n°2. Bottom cut cylinder surface comparison

Then, another local best-fit has been performed: this time considering the bottom cut cylinder. The result shown in Figure 4.22 evidences a lower accuracy of the bottom disk: its surface is not planar but inclined in the radial direction, that can be understood by looking at the four aligned points going from -0.18 mm until -0.42 mm. In addition, it is evidenced by the color gradient that is going from green to light blue. This can be a fault of the manufacturing process. In general, it has to be noticed that the surfaces with a normal perpendicular to Y axis have been built with a very good accuracy. The largest error is on the positioning of the surfaces with normal parallel to the Y axis, that seem to be slightly too close to each other.

The inspection evidenced errors due to the manufacturing process and errors due to the 3D scanning of the spare part. At any point it must be possible to clearly distinguish those two errors categories, as the prior goal is to correct the manufacturing errors. The time needed to perform this inspection has been of 1 hour and 40 minutes.

The complete inspection report directly produced in GOM Inspect V8 software is attached in Appendix II.

4.6 Results summary

In the following table all the results from the performed experiments have been summarized. A brief description of the experiments is given. Advantages and disadvantages of each method proposed have been listed considering their potential application in industrial fields.

Experiment 1: Direct modeling from 2D paper drawing		<i>Description of experiments</i>	<i>Pros</i>	<i>Cons</i>
Experiment 1.1: 3D modeling simple part from 2D paper drawing		A simple spare part has been reverse engineered by direct 3D modeling from a 2D paper drawing using Solidworks CAD software.	Fast modeling for simple parts High accuracy Complete information available Exact values Easy to measure a paper drawing in scale	Long time needed to model complex parts Manual process Opportunity cost of missed automation
Time understanding drawing	00:07:26			
Time modeling	01:30:19			
<i>Total</i>	<i>01:37:45</i>			
Experiment 1.2: 3D modeling complex part from 2D paper drawing		A complex spare part has been reverse engineered by direct 3D modeling from a 2D paper drawing using Solidworks CAD software.		
Time understanding drawing	00:12:43			
Time modeling	03:56:51			
<i>Total</i>	<i>04:09:34</i>			

Experiment 2: Vectorial-image-aided modeling from 2D paper drawing

Experiment 2: Vectorial-image-aided modeling from 2D paper drawing		<i>Description of experiments</i>	<i>Pros</i>	<i>Cons</i>
Experiment 2.1: 2D scanning and dwg conversion of simple part		A simple spare part (same of Exp. 1.1) has been converted from 2D paper drawing into 2D digital drawing using a 2D scanner and Scan2CAD software.	Fast conversion Potential to reduce the total modeling time Automated tool	Not capable of accurate shape detection Not capable of entity recognition Hard to separate quotes from drawing lines Long adjusting time High computing power needed Technology not ready
Time scanning drawing	00:02:00			
Time converting pdf to dwg	00:04:15			
Time adjusting the dwg	-			
<i>Partial total *</i>	<i>00:06:15</i>			
Experiment 2.2: 2D scanning and dwg conversion of basic geometry		A basic geometry has been converted from 2D paper drawing into 2D digital drawing using a 2D scanner and Scan2CAD software.		
Time scanning drawing	00:01:17			
Time converting pdf to dwg	00:01:48			
Time adjusting the dwg	00:09:36			
<i>Partial total *</i>	<i>00:12:41</i>			

* the modeling has not been performed, this phase is carried out in Experiment 3.

Experiment 3: Reverse engineering from 2D digital drawings

Experiment 3: Reverse engineering from 2D digital drawings		<i>Description of experiments</i>	<i>Pros</i>	<i>Cons</i>
Experiment 3.1: 2D digital drawing of simple part imported in SolidWorks		A spare part 2D digital drawing (dwg) has been imported in SolidWorks and then 3D modeled.	Very fast conversion Intuitive process Exact values High accuracy Complete information available	Experiences strongly affect the total time Manual process Opportunity cost of missed automation Tools offered by CAD are not useful
Time importing the dwg	00:00:32			
Time modeling	00:15:09			
<i>Total</i>	<i>00:15:41</i>			
Experiment 3.2: 2D digital drawing of simple part imported in PTC Creo		A spare part 2D digital drawing (dwg) has been imported in PTC Creo and then 3D modeled.		
Time importing the dwg	00:00:27			
Time cleaning the dwg	00:00:26			
Time modeling	00:27:41			
<i>Total</i>	<i>00:28:34</i>			

Experiment 4: Reverse engineering from physical spare part		<i>Description of experiments</i>	<i>Pros</i>	<i>Cons</i>
Experiment 4.1: 3D scanning of physical part without coating		A spare part has been 3D scanned using a structured light scanner.	Accurate measurements Fast measurement Fast STL to CAD conversion Discrete model obtained directly Complex and free-form shapes detection	Long time needed Pre- and post-processing needed Powder coating needed for reflective surfaces Reference marks application Reference marks removal model distortion Difficulties measuring inside holes No inner geometries detection High equipment cost
Sensor warm-up	00:15:00			
Calibration	00:09:47	A spare part has been coated with titanium dioxide matte powder, 3D scanned using a structured light scanner and then the obtained STL file has been converted from discrete to analytic 3D model.		
3D scanning	02:35:00			
Post-processing	01:06:00			
<i>Partial total *</i>	<i>04:05:47</i>			
Experiment 4.2: 3D scanning of physical part with coating and CAD conversion				
Sensor warm-up	00:15:00			
Calibration	00:09:47			
Coating	00:09:36			
Reference marks cleaning	00:03:15			
3D scanning	01:35:00			
Post-processing	00:03:00			
STL to CAD conversion	00:49:22			
<i>Total</i>	<i>03:05:00</i>			

* the CAD conversion has not been performed, this phase is carried out only in Experiment 4.2.

Experiment 5: Process validation by inspection		<i>Description of experiment</i>	<i>Pros</i>	<i>Cons</i>
Only the total time of the inspection has been recorded for this experiment.		The scanned STL file from Experiment 4.2 has been compared to the original STL file used to additive manufacture the spare part using GOM Inspect software.	Semi-automated inspection Fast measurement Intuitive process Report produced semi-automatically	Experience strongly affect the total time Opportunity cost of missed automation Complicated comparison of single geometries
<i>Total</i>	<i>01:42:00</i>			

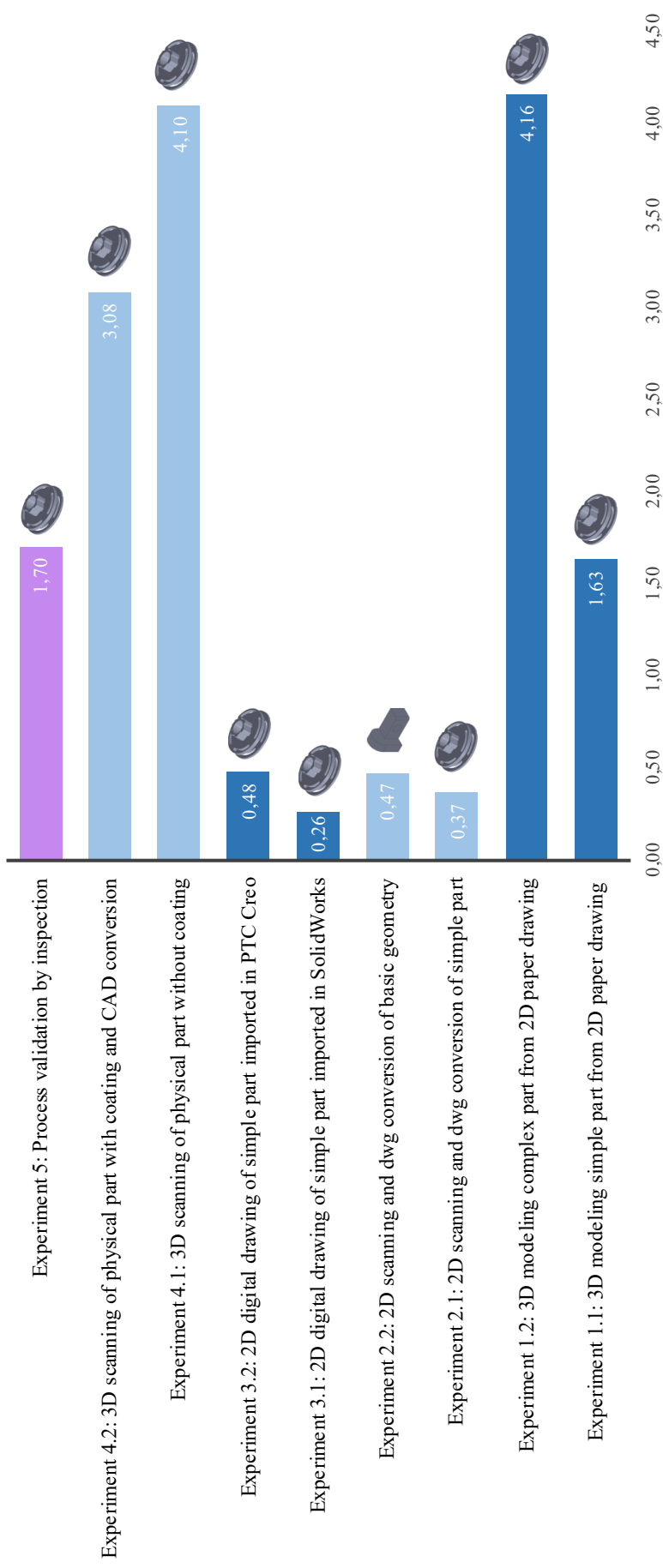


Figure 4.23 Times comparison of the performed experiments (results shown in hours)

In Figure 4.23 the different times of the experiments, in hours, have been compared. The experiments are coupled in blue and light blue colors according to the input considered in the reverse engineering task. In violet is evidenced the time of the process validation experiment. On the right of each time is shown the part reversed engineered: for Experiment 2.2. *Basic geometry* the part considered has not been a recoil starter, differently from all other experiments.

For Experiment 2.1. *Simple spare part* and Experiment 2.2. *Basic geometry* the time needed to perform the conversion from 2D digital drawing to 3D model of Experiment 3.1. *SolidWorks 2018* has been added to allow a fair comparison with the others. This is done to give an idea of the potentialities of this method despite direct 3D modeling, considering a full process including both paper to DWG and DWG to CAD conversion. Moreover
Meanwhile, for Experiment 4.1. *Spare part scanned without coating* the time of the STL to CAD conversion has not been added for two reasons: the time was already high enough to not recommend this procedure and it was actually not possible to perform a proper conversion due to the roughness of the data obtained.

5 Discussion

5.1 Reverse engineering from 2D paper drawings

Experiment 1. Direct 3D modeling

In Experiment 1.1. *Simple spare part* a simple recoil starter has been directly 3D modeled. One significant advantage of this method is to obtain the exact values coming from the drawing manually imported in the model, allowing to create the ready-to-be-produced model in one single step. The modeling for a simple spare part can be performed in an acceptable time: one hour and a half has been used to obtain the final model, that is an adequate amount of time for a standard CAD modeling. Even if a quote was missing, by having an in-scale drawing, it has been possible to measure it directly, rapidly solving the problem.

In comparison, more than four hours were needed to obtain the final model for the complex part reverse engineered in Experiment 1.2. *Complex spare part*, that is a very long time. Spending a high amount of work to generate the 3D model can make the cost of the spare part manufacturing raise sharply.

A disadvantage of this method is that it will always take a significant amount of time to model a spare part from zero, because it is a completely manual operation. This amount of time is a cost that can be reduced and almost eliminated with an automated process.

Experiment 2. 2D paper drawing conversion to DWG

The method tested in both Experiment 2.1. *Simple spare part* and Experiment 2.2. *Basic geometry* could have been the automated solution that has been suggested in the previous paragraph. This process could have avoided the long time needed to perform a manual direct modeling but, unluckily, this technology is still not developed enough to be used effectively. The software at the actual state is not very useful to reverse engineer spare parts. The conversion accuracy can be improved if the quotes are removed from the drawing, but if a 2D paper drawing has to be reverse engineered, there will be quotes on it, and those cannot be removed easily. Thus, the process has potential, considering that the time needed to perform the conversion, without taking into account the post-processing, consists of only approximately 3 minutes: if the conversion will become accurate enough to perform just a quick post-processing of minor errors, this method is likely to be the best way to reverse engineer a 2D paper drawing, especially in combination with the process described in Chapter 4.3, where the DWG/DXF file has been imported to SolidWorks and converted to 3D model in just 15 minutes.

Although those shape recognition tasks are computationally very demanding, it is likely for them to become more effective. Especially with a more powerful AI integration. Thus, this method can become a valid alternative to direct 3D modeling.

5.2 Reverse engineering from 2D digital drawings

Having a 2D digital drawing instead of a 2D paper drawing is a big advantage in terms of time reduction for the 3D modeling: comparing the time needed to directly 3D model the spare part from the paper drawing in Experiment 1.1. *Simple spare part* with the one needed to build it from the imported digital drawing in Experiment 3.1. *SolidWorks* the time reduction has been of 83%. This is also the reason why the conversion from 2D paper

drawing to 2D digital drawing can lead to a large reduction of the reverse engineering time for 2D paper drawings.

The method proposed and tested for SolidWorks 2018 software is simple, fast and effective, especially for axial-symmetric spare parts: those can be modeled in less than a fifth of the time needed to directly model the same part.

AutobuildZ tool offered by PTC Creo to aid the 2D to 3D conversion is old and probably has not been updated since a long time. Moreover, it is very difficult to understand how it works having a few support materials available online. However, AutobuildZ has a really good feature that automatically cleans the drawing from non-geometrical entities (like notes, quotes, etc.), that has been used also in the second part of

Experiment 3.2. *PTC Creo*, before importing the views into the part sketches.

PTC Creo tool that allows to import elements directly from a 2D digital drawings into sketches, with a consequent 3D modeling, is a more easy and direct way to obtain the CAD model, even if it is a completely manual process. The time needed to 3D model the spare part in Creo has been longer, almost doubled, than in SolidWorks because the observer was not used to the software: it is plausible that an expert designer with more experience with PTC Creo CAD software can sharply reduce the time reported.

Thus, to import entities from the DWG into sketches and then to 3D model the part is the most simple, intuitive and fast way to perform reverse engineering of a 2D digital drawing.

It is possible that an automatic conversion feature of 2D digital drawing has not been implemented taking advantage of the last technologies, because the field of application of this feature is limited, and it could not have been worth for CAD software developer to invest money in this field, at least until now.

5.3 Reverse engineering from physical spare part

When only a physical input, in this case a spare part, is available and a 3D model needs to be obtained, the most practical solution is to use a 3D scanner, based on the technologies cited in Chapter 2.2, to digitalize its shape.

In both the experiments carried the sensor warm-up was needed to be able to achieve the scanner maximum accuracy. It is a significant waste of resources considering that it takes 15 minutes. That is approximately 6% of the total amount of time needed in Experiment 4.2. *Spare part scanned with coating*. So, a reduction in the warm-up time can be of great benefit for the process efficiency.

In Experiment 4.1. *Spare part scanned without coating* the scan of the spare part has not reached satisfactory results. The resulting STL file has been left full of holes. Moreover, the middle disk surface was scanned with a so low accuracy that it was not recognized by the software as part of the same solid body. Shiny surfaces are a weak point of structured light scanners. Employing HDR technology may at least partially solve the problem, as previously stated in Paragraph 2.2.1.2.

The time needed to accomplish the scan has been very high; it is mainly due to the small surface portion obtainable per single scan because of the high reflectivity of the spare

exterior. For all the aforementioned reasons, it is therefore recommended to avoid scanning shiny surfaces with structured light scanners without taking proper countermeasures.

Meanwhile, Experiment 4.2. *Spare part scanned with coating* has showed a diametrically opposite result: thanks to the TiO₂ powder coating the part has been scanned with a really high accuracy, being able to evidence also the characteristic additive manufacturing texture of the part surface. The coating is mandatory to perform a successful scan on shiny spare parts with the structured light scanner used. The scan-to-CAD software used (Geomagic Design X 2018) can show many troubles with the manipulation of an inaccurate STL file: for example, it was not possible to correctly select the features, because those were not well defined.

Any kind of triangulation method is not the perfect technology to scan a spare part if it shows inner channels or a whatever kind of enclosed geometry, not accessible from the outside. In the case of the recoil starter reverse engineered in Experiment 4.1 and 4.2, two solutions could have been exploited to scan the enclosed sensor casing: the first would have been to perform a destructive scan by cutting the part in half, and then merging the result in a single STL file; the second would have been to use a computed tomography scanner, that with x-ray technology is able to penetrate the part and to show inner geometries. When a destructive test is not doable, CT is the only alternative. Unfortunately, it can be very expensive to have a part scanned with CT technology, due to the high cost of the machines. Moreover, time-of-flight technology could have been used to improve the result of the triangulation method in the partially obstructed surfaces of Figure 4.17, because it uses a laser that runs on a straight path that would not have been obstructed.

Geomagic Design X, the software used for the scan-to-CAD operation, is a very well-built software. Its automatic tools work almost perfectly if used with the right settings and after having pre-processed the mesh, a step that can be done directly in the software. It also offers the direct connection for some supported scanners, for example FARO scanners. Thus, it can be used to perform a complete scan-to-CAD process, from the physical part or mold/tool to the CAD model. A GOM Core (5M) scanner has been used in Experiment 4.1 and 4.2. It was unluckily not supported by Geomagic Design X. Thus, it was necessary to use GOM Scan V8, native software of the scanner, to perform the scan.

Generally, the software is easy to understand because it works exactly as all the other CAD software, and also the specific scan-to-CAD tools are intuitive and well explained inside the software.

While performing reverse engineering on a spare part it has to be considered that, if the part has been used before, worn geometries need to be corrected and restored to the initial state. This is an easier task to perform working with a parametric model rather than with a discrete model, because the former is based on mathematical relations that can be easily adjusted, while the latter is based on a triangular mesh that can be hard to modify.

A fully automatic scan-to-CAD process could be the next step, taking advantage of an automated scanning process, already available in manufacturing plants, and AI to perform the conversion of the discrete model into an analytical model, that is the same operation performed manually nowadays.

5.4 Reverse engineering from 3D model

No experiment has been performed to test the method proposed to reverse engineer a 3D nominal model: due to the great variance of possible cases it would have been out of scope to perform it for a single part. Furthermore, to add the production information to a 3D nominal model without having any indication is a very hard task that requires experience in the production sector of the spare part in question.

The method described in this research is proposed to remind what needs to be considered when only a nominal 3D model is available. Meanwhile, if a 3D model with PMI is available, no reverse engineering process is needed.

5.5 Process validation by inspection

The method suggested in Experiment 5. *Process validation by inspection* for the combined input 3D model and physical spare part is already widely used as inspection method in the manufacturing sector, because it can be fast, accurate and easily automated.

The software used, GOM Inspect, has a very effective video tutorial available online, that helped to understand its main functions and tools. The alignment and the surface comparison tools are user-friendly, and it has been very intuitive to analyze the results as well. The level of automation of the functions is remarkable. Moreover, a report can be generated directly inside the software and exported as PDF. The complete report of the carried inspection is attached in Appendix II.

The inspection carried out for the recoil starter has evidenced that the part was built with an overall good accuracy, with a total standard deviation from nominal dimensions of only 0.31 mm. It can be concluded that the spare part has been produced with a capable process. Nonetheless, some of the evidenced errors need to be analyzed more deeply, like for example the bottom disk surface that is tilted in radial direction and the impact of reference marks removal error. For the former it can be hypothesized that the additive manufacturing process has not been very accurate in the Z direction, thus it can be suggested a change in the production method to avoid this curling effect if it is not tolerable. Meanwhile, for the latter it has to be stated if reference marks elimination inaccuracies are affecting excessively the overall result. For sure these have affected all the statistical values displayed in Figure 4.20, where the whole spare part has been taken into consideration.

Another common error found has been mesh missing triangles and the same question as before needs to be answered: do these affect excessively the inspection result? The answer is yes if not treated opportunely. The missing triangles are areas with an infinite distance from the reference CAD model, so they can create a huge noise in the statistical data. Luckily, the software asks which is the maximum deviation that wants to be taken into account while performing surface comparison, in Experiment 5 this has been set to 1.5 mm. Another way to solve the problem is by manually or automatically correcting the mesh, generating by interpolation new triangles where needed.

The time needed to perform this report has been quite long: one hour and forty minutes is an excessive amount of time considering the time needed to reverse engineer a part, as can be seen in Figure 4.23. The automation of this process can sharply reduce the time needed, but also with experience, or by knowing exactly what needs to be measured, the process can be speeded up.

The method proposed is an effective tool to validate the process chain, combining the available starting input with the reproduced spare part. Thus, generating a feedback loop that is going backwards from the end product to the starting point.

5.6 Possible developments

The best way to improve the methods proposed is with the integration of artificial intelligence (AI), that can be able to recognize shapes as the human brain does. The integration of AI would enable a full automation of the processes. This is particularly useful for the reverse engineering from 2D paper and digital drawings: both the processes are repetitive and the only reason why a human operator is needed is because of the difficult shape recognition tasks. In case of the conversion from 2D raster image into 2D digital drawing (performed in Experiment 2. *2D paper drawing conversion to DWG*) the AI is already employed, but the algorithms used are not powerful enough. This can be applied also for reverse engineering from physical spare parts or molds/tools: the process can be integrated with AI to automatically convert the PCD directly into an analytic model.

The computational power needed to accomplish a full reverse engineering process automatically is really high, and because of that a risk of error has to be accepted. If this will be the direction taken by software developers to perform these tasks a huge reduction in the times shown in this research will be seen.

6 Conclusion

This thesis aimed to define methods to reverse engineer spare parts in function of the inputs available, in order to obtain a ready-to-be-produced 3D model to be additive manufactured. The need to give a definition of the aforementioned procedures comes from a future implementation of a digital spare parts distribution network, where the spares can be additive manufactured close to the place where those are needed on-demand.

Firstly, a research on the available technique commonly used to reverse engineer spare parts has been conducted, obtaining a solid basis on 3D scanning technologies, computer-aided design software and reverse engineering software. Especially, in 3D scanning technologies research, additionally to the literature review, a market analysis has been performed to understand which the actual condition of the available hardware and the economical aspect of each technology was.

Afterwards, for each of the possible available inputs, e.g. 2D paper or digital drawings, physical spare part or mold/tool used to manufacture it, nominal 3D model and their combinations, has been defined one or more than one method to achieve a ready-to-be-produced 3D model from the starting available input.

The methods proposed have been tested performing reverse engineering on different design of the same recoil starter spare part. At this stage one of the methods tested showed a non-sufficient effectiveness to be efficiently used for an industrial application: the conversion from 2D paper drawing to 2D digital drawing did not show enough accuracy to be used worthily. Based on this conclusion, it is certainly worth to push the image recognition power of artificial intelligence-based software to obtain a large time reduction in reverse engineer process with 2D paper drawing as input. All the other methods proposed have been effective and have given successful results in converting the available inputs into ready-to-be-produced 3D model, even if some critical points have been evidenced: for example the long time needed for directly 3D model a drawing or the long time needed to 3D scan an object; or the long time needed to directly 3D model a part. To avoid this long times, for the latter are already available very fast and accurate 3D scanners, the problem is in the cost of the equipment, that can reach easily 100.000,00 €; for the former automation should be improved making possible to convert a 2D paper drawing into a vector file and then automatically convert it into an analytical 3D model. The limit right now is the computational power needed to perform these automated tasks, but since the trend of price over computational power is decreasing in time is fair to hypothesize a future improvement in this direction. Furthermore, a validation process has been proposed and tested to assess the capability of the production and reverse engineering methods defined.

In conclusion the work done in this thesis has shown how it is possible to retrieve a 3D model ready to be additive manufactured of a spare part from each of the potential available inputs, presenting all the pros and cons and the times analysis of the proposed methods. The final result of the methods definition is the full diagram presented in Appendix I. Even if not all the available software that could have completed a task equal or similar to the ones needed have been tested, the experimental work just aimed to proof the validity of the general methods proposed.

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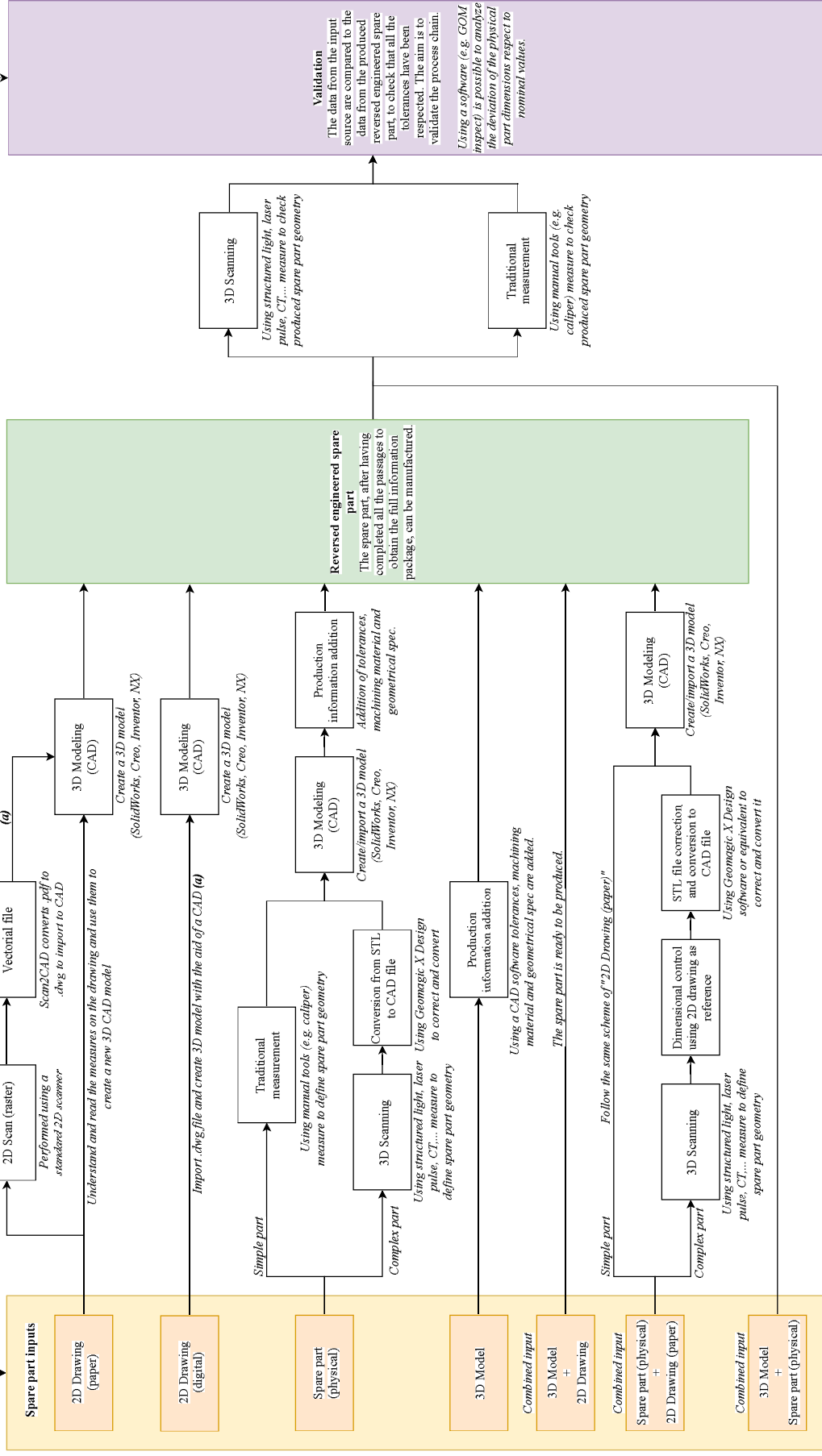
Appendix

Appendix I. Full diagram of the reverse engineering process chain.

Appendix II: Inspection report

Appendix I

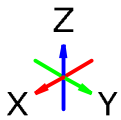
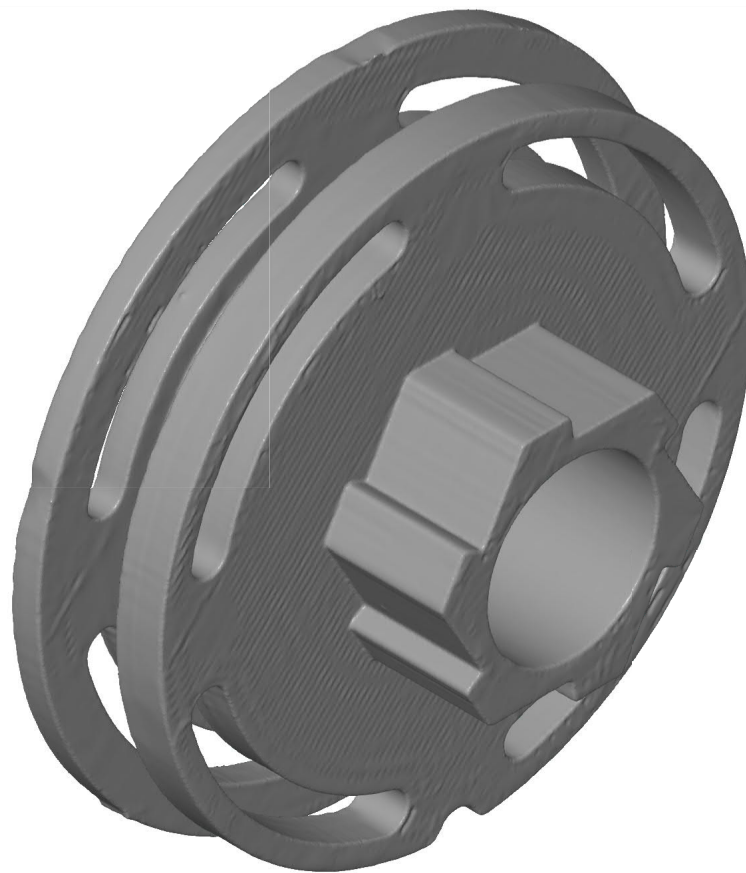
Feedback loop



NOTES

- (a) Different tools are offered by different softwares to convert a 2D digital drawing into a 3D model:
 - PTC Creo offers AutoBuildZ tool or an entities import function from the .dwg file.
 - SolidWorks offers 2D to 3D conversion tools.
- Or in alternative a manual conversion can be performed by copying and pasting the views in their correspondent plane, then extruding and cutting.

Inspection on additive manufactured recoil starter



Local best-fit (2)

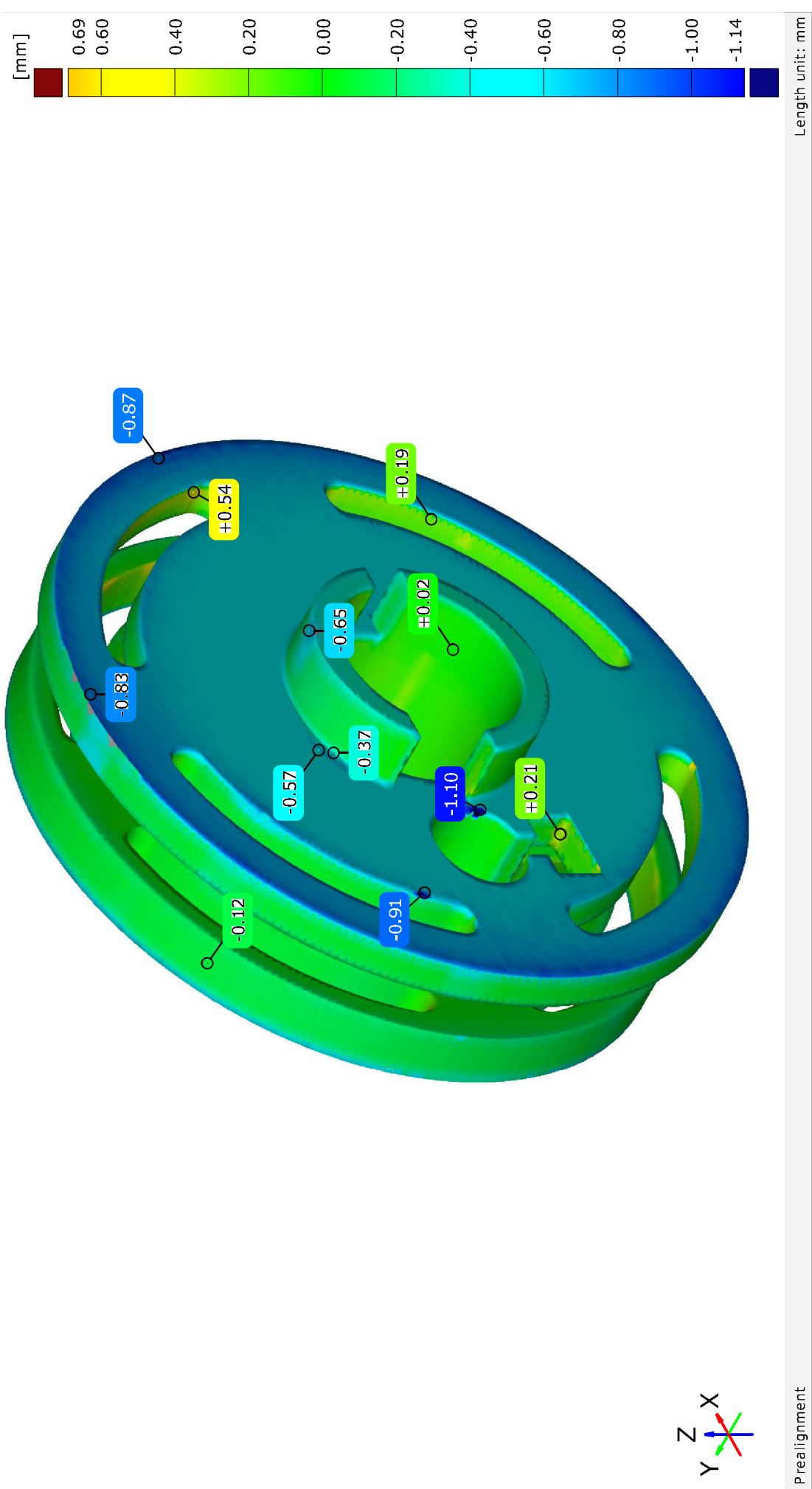
Length unit: mm

Inspector: Edoardo Colombo
Company: Aalto University
Department: Mechanical Engineering
Location: Helsinki
Date: 30/03/19
Project: Master's Thesis
Part: Recoil starter

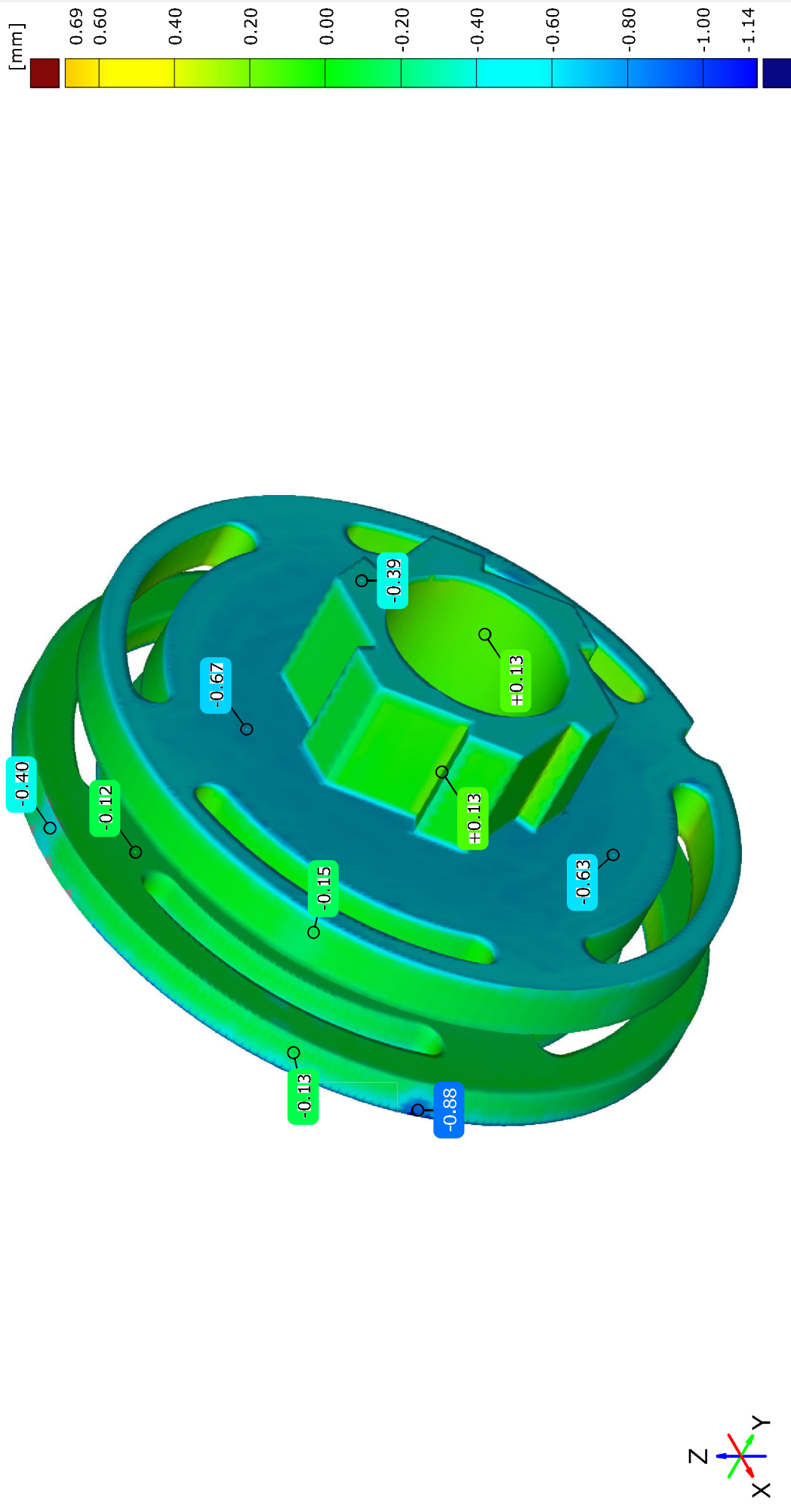
Table of contents

Inspection on additive manufactucred recoil starter.....	1
Table of contents.....	2
Prealignment: bottom view.....	3
Prealignment: top view.....	4
Prealignment: Hole inspection.....	5
Prealignment: Statistical deviation values.....	6
Local best-fit n°1: Top cylinder with teeth.....	7
Local best-fit n°2: Bottom cut cylinder.....	8
Local best-fit n°2: Detail of the extruded cut.....	9

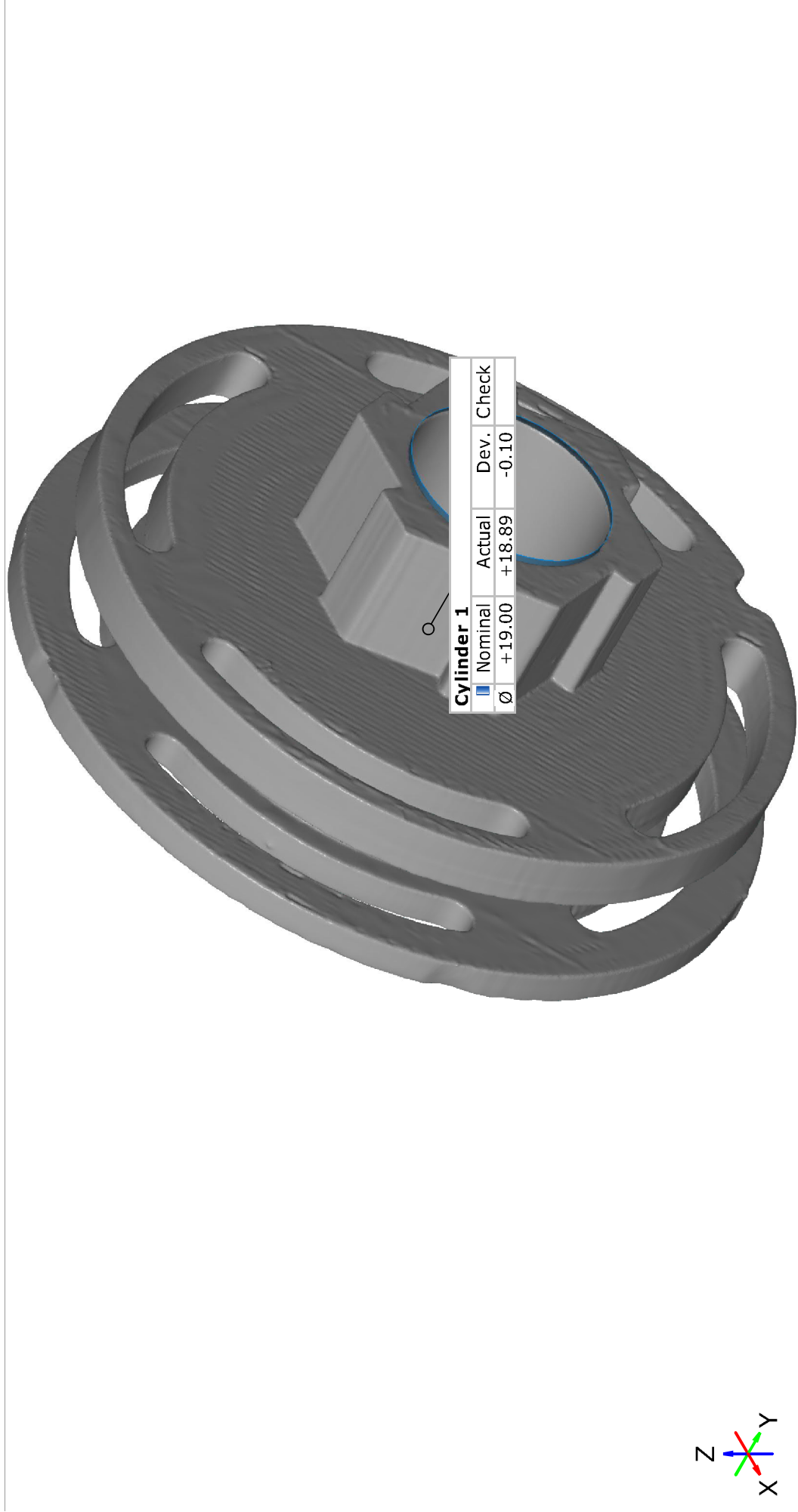
Prealignment: bottom view



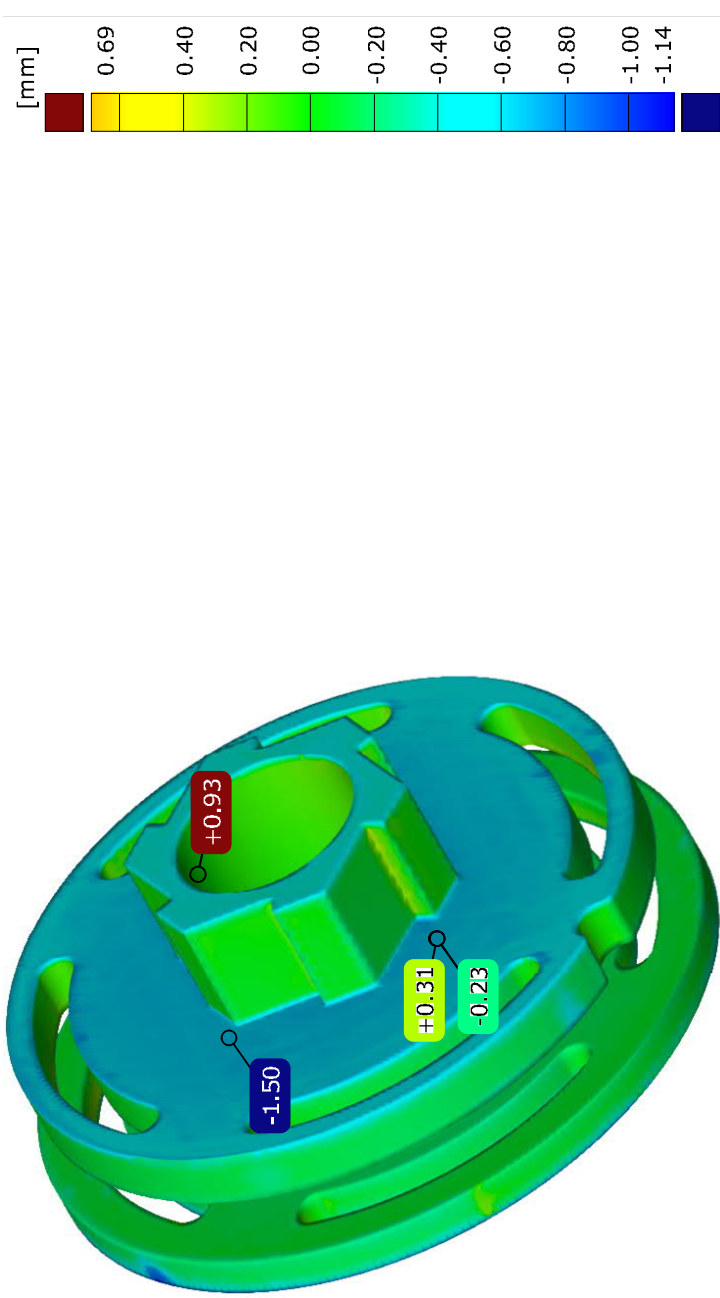
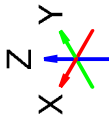
Prealignment: top view



Prealignment: Hole inspection



Prealignment: Statistical deviation values

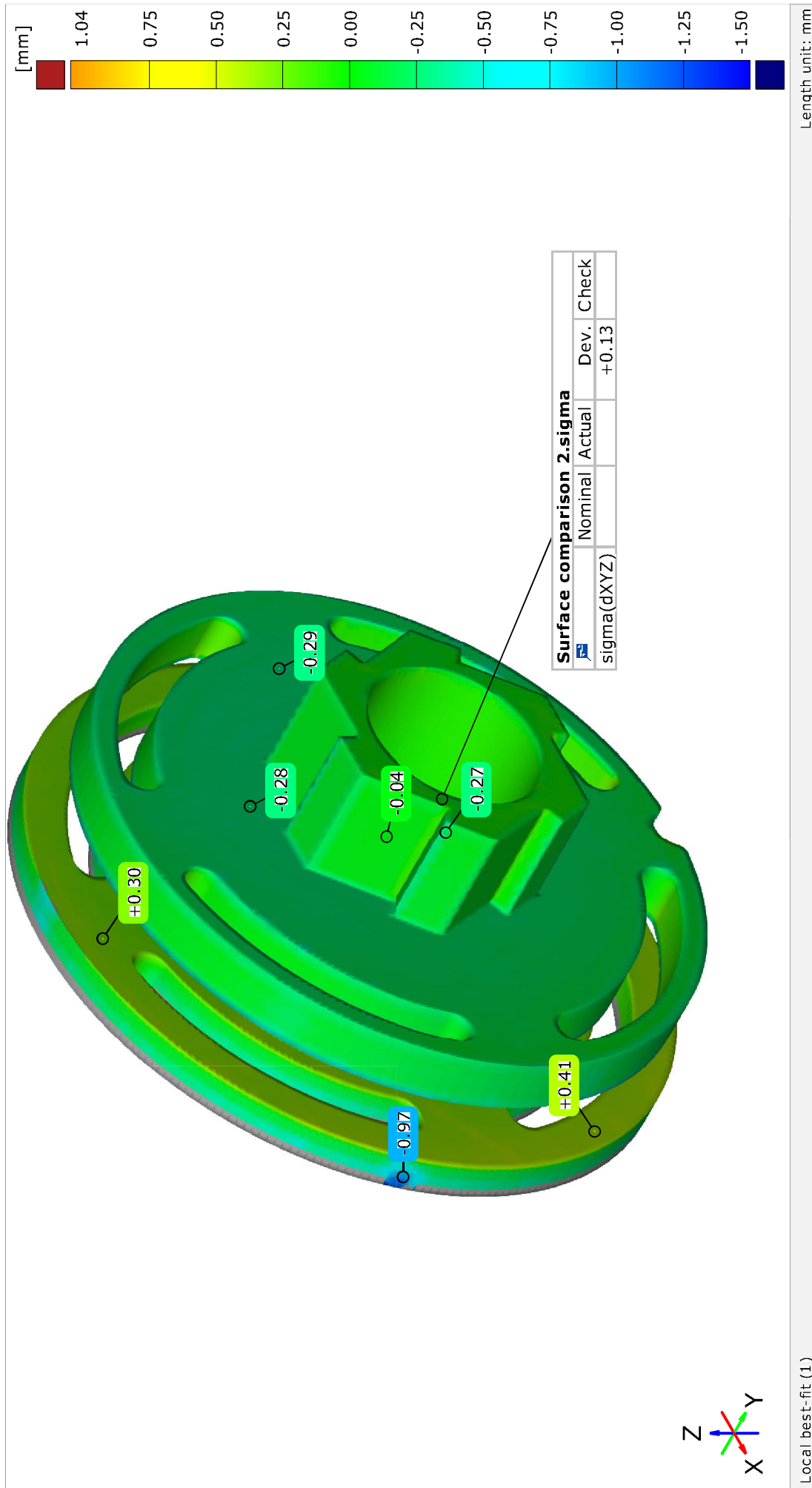


Element	Datum	Property	Nominal	Actual	Tol -	Tol +	Dev	Check	Out
Surface comparison 1.avg		avg(dXYZ)					-0.23		
Surface comparison 1.max		max(dXYZ)					+0.93		
Surface comparison 1.min		min(dXYZ)					-1.50		
Surface comparison 1.sigma		sigma(dXYZ)					+0.31		

Prealignment

Length unit: mm

Local best-fit n°1: Top cylinder with teeth



Local best-fit n°2: Bottom cut cylinder

