A Lean Quality Control Approach for Additive Manufacturing

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Abstract. Additive Manufacturing is becoming more and more popular not just in the manufacturing industry, but also in the consumer market, because it offers a new world of opportunities, starting from the absence of constraints in geometry and the reduction in wastes due to material removal typical of subtractive manufacturing. Moreover, it is able to enhance lean manufacturing objectives of reducing activities that do not add any value for customers. However, a wide application is threatened by the lack of consistent quality. Therefore, it is necessary to further study defects that affect 3D printed products and to propose new manners to control them. This paper proposes to use a low cost, light weight, portable, device as a scanner to rapidly acquire data from 3D printed products and compare it with the original model.

Keywords: Additive manufacturing, 3D printing, quality control, lean philosophy.

1 Introduction

Additive Manufacturing (AM) is the *"process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies"* [1]. AM was born in 1986, and in recent years it is becoming popular both in the industrial and in the consumer market: nowadays, the term "additive manufacturing" is mostly used in industry markets, while "3D printing" mostly refers to the consumer market. The layer by layer production methodology has two main advantages: (i) geometry flexibility, since any geometry can be produced in a single operation without any additional cost or time constraint, and (ii) reduction in consumption of resources, since it enables to use only the precise amount of material necessary to the creation of the final product, avoiding the wastes typical of traditional subtractive manufacturing [2]. There are seven main processes for AM: VAT photopolymerisation, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition, sheet lamination. According to the Wohlers Report, *"Overall the 3D printing industry grew by 21% in the 2017/18 reporting period. This figure is an increase on the 17.4% in worldwide revenues from 2016, and is edging closer to the 25.9% growth reported in 2015"* [2]. From the industrial point of view, Rapid prototyping

(RP) has been the main driver of AM development and, as a consequence, one of its first applications. The evolution of advanced AM techniques has largely proceeded in recent years, leading to broader industry applications [3]. It is vital to consider that AM was born only forty years ago: despite being a quite new technology with respect to traditional manufacturing, AM processes are already a standard for rapid prototyping and have relevant applications in the manufacturing of final products as well. AM is considered as a promising technology that may disrupt the market.

Compared with subtractive manufacturing, AM is particularly suitable for producing low volumes of products, especially for parts with complex geometries. AM processes also offer great potential for customization, such as the fabrication of personalized spared parts, clothes, jewelleries, implants for hip and knee replacements. A further usage that is becoming quite common is the *home fabrication:* users buy the appropriate equipment and directly print objects in their own place [4]. In the past, only very passionate hobbyist owned 3D printing kits, but given the increasing adoption rate, there are some experts announcing that *''desktop manufacturing revolution [...] will change the world as much as the personal computer did"* [5].

Material extrusion, in particular Fused Deposition Modelling (FDM), is the most popular additive manufacturing technique in this field due to the purchase cost of both the printing machine and the materials used [6]. The method consists on the heating of thermoplastic polymer material above its melting point and its extrusion through a nozzle which moves in X and Y directions on a printing platform that moves in the vertical Z-axis each time a layer has been deposited.

Lean manufacturing principles were born in the Toyota company after the Second World War, even if the expression *"lean manufacturing"* was coined only in 1988 by John Krafcik in the article *"Triumph of the lean production system"* [7]. It encompasses a broad array of industrial philosophies, concepts, and strategies thus it is arduous to give a precise definition; though, it can be affirmed with no doubt that its essential aim is to create added value for customers reducing as much as possible the wastes, "doing more with less" [8]. The father of lean manufacturing and Toyota's industrial engineer Taiichi Ohno, defined *muda* (Japanese word for waste) as those activities that do not add any value to the final product and for which the final customer is not willing to pay and identified seven main categories of waste: overproduction, waiting, transporting, over processing, unnecessary inventory, unnecessary motion, defects.

Lean principles aim and succeed to crucially reduce such categories of waste, but some of them cannot be avoided in subtractive manufacturing processes [9]. One of them is the waste of material caused by the production by removal. On the contrary, AM production process consists in the overlapping of different layers and only the exact amount of necessary material is used. The entire production, from the blank to the final product, totally occurs in the 3D printer: this means that there is no components' storage and that the only source of inventory is the raw material. Another example is the waste due to movements of materials and components, which cannot be avoided in a production line. In AM, being the supply chain much shorter, transportation wastes are abated. Waiting times are radically reduced as well: set up times to adapt machineries to production of different parts do not exist in AM, which is also able to reduce time to market thanks to all the advantages it provides in the product development phase. Another important advantage of AM is the possibility to produce by batches of single product.

Lean production is distinguished by mass production for being demand driven and for fosters smaller sized batches in order to minimize final product inventory, however the latter can be eliminated only by producing a part only when demanded by customers. This makes it possible to customize every product without any consequence on the production line thanks to AM design freedom.

Thus, AM is able to enhance lean manufacturing objectives of reducing activities that do not add any value for customers, since it can radically reduce supply chain management costs as it is able to shorten the supply chain and be more proximal to customers. The *muda* that AM is not able to solve yet is the one about defects. In fact, AM technology is not mature enough to grant a consistent quality [10]. Indeed, the most mature AM technologies, such as material extrusion, have a TRL between 6 and 7 [11]. This is the main reason why it has not yet spread. To address this issue, this paper presents a methodology to analyse the defects affecting 3D printed products and to control their quality.

The rest of the paper is organized as follows: section 2 provides a description of defects and quality control proposals for AM, section 3 presents a methodology to perform a quasi-real time quality control through a low-cost, energy efficient, light weight and portable device. The methodology is tested through a use case, described in section 4. Finally, results of the tests and future works are exposed.

2 Quality Control in AM

Quality is defined as *"conformance to requirements or specifications"* [12]. The quality of 3D printed parts can be affected by defects in the following categories: (1) geometry and dimension, (2) surface quality, (3) mechanical properties.

Geometry accuracy is the deviation of the printed object with respect to the form of the CAD model; dimension accuracy is the degree of compatibility between the dimensions of the obtained product and the nominal dimensions foreseen by the CAD model [13]. The most widespread defects affecting geometry and dimensions are shrinkage and warping. The former is a geometric reduction in the size of the product [14] whilst the latter is a change in the nominal shape caused by a non-uniform shrinkage [15].

The surface may present the following criticalities: (i) Staircase effect, a common defect that occurs in the process of slicing when the layer marks become distinctly visible on the surface of the parts [16]; (ii) surface roughness, which deals with the topographical structure of a surface part, which can range from smooth to coarse, depending on build material and printer settings [17]; (iii) Stringing or Oozing, *s*mall strands of plastic on places where the printer shouldn't print and the print.

Finally, 3D printed products may present the following mechanical defects: (i) porosity: parts produced with additive manufacturing can present void spaces that, despite being very small, can affect mechanical properties [18]; (ii) low strength and stress behaviour: there may not be high cohesion between layers deposited through FDM may, causing a low resistance to the stress traction.

Another point to take into account is the repeatability, which is the degree of dimensional compatibility of two products of the same nominal geometry, manufactured in the same conditions, with identical values of the process parameters [19].

Quality control in mass manufacturing utilizes the Statistical Process Control, a series of statistical tools to monitor in real time the production process in order to detect any variations that may result into the production of an article that does not meet specifications [20]. Since this method relies on a sufficient sample data, it cannot properly be adapted to AM, which is mostly used to produce a low number of pieces of the same type.

Being AM a relatively recent technology, there is not a consolidated unique methodology for the quality control. In literature, there are several proposals that follow two main approaches: process control and product control.

The former monitors the process parameters and uses statistical and analytical methods to predict the effect they may have on the product quality. Boschetto and Bottini 19] developed a model to predict dimensional deviations of fabricated parts as a function of the process parameters; Rao et al. [21] used statistical analysis and nonparametric sensor-based Bayesian modelling approaches to optimize process conditions for obtaining the best surface roughness and to detect process drifts in real-time; Shirke et al. [22] used Taguchi method to study the effect of process parameters on tensile strength; Mokhtarian et al. [23] proposed a systematic methodology to extract cause-effect relationships among variables to predict the effect of specific design and manufacturing parameters on part defects and to estimate the needed input parameters backwards.

The later directly monitors the piece. Lin [24] simulated an online quality control to detect and identify defects by comparing the surface point cloud obtained by laser scanning with the ideal surface extracted from the CAD model.

The methodologies proposed in literature involve the usage of very expensive equipment (scanner, sensor) with respect to the result and that cannot be generally used by standard consumers. They use 3D printing more like a trial and error process [25] and produce parts with a very low quality, which results in high wastes in material and energy and can be optimized through a MES [26].

For this reason, the aim of our research is to find an alternative methodology that allows consumers to carry out the quality control simply through a new low cost, light weight, portable, device that can be used as a scanner for rapid data acquisitions rather than using sophisticated and expensive equipment. In this manner, it is expected that users are educated to quality control and that there will be a reduction in wastes due to the production of faulty products.

3 Methodological Proposal

The proposed methodology is represented in Figure 1. AM process starts with a CAD file, which must be converted into a standard 3D format, such as .STL. Successively, slicing process is applied to the 3D file so that it can be manufactured layer by layer. The methodology proposes to pause the process every time that k layers (e.g., $k = 15$ - 20) are deposed and verify whether the intermediate product is compatible with the STL model. If it results that the product is not compatible with the model, the production is stopped. In this manner, it is soon understood whether the product will present important defects and wastes in material and energy are prevented.

In order to perform a quasi-real time monitoring, it is necessary that the acquisition process occurs rapidly, otherwise it would be impossible to stop the production so often.

However, professional scanners, even though they ensure high accuracy and precision levels, require such long times and complex procedures.

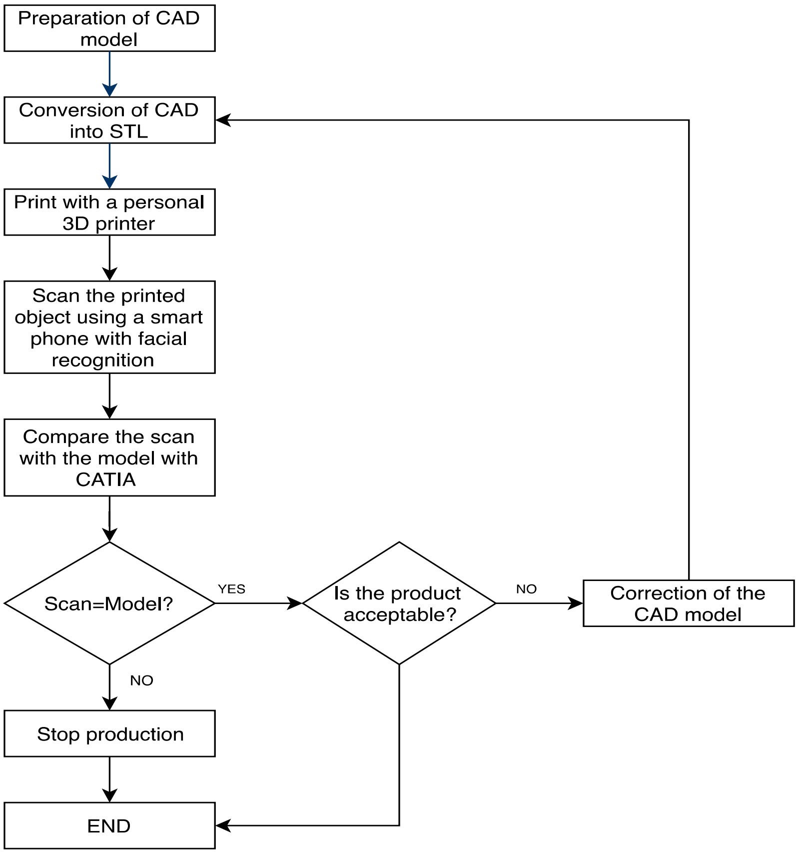

Figure 1: Methodology for AM quality control

For this reason, it is presented a new low cost, light weight, portable, device that can be used as a scanner for rapid data acquisitions: it is proposed to utilize a last generation iPhone (X models) as a scanner for 3D printed products. Indeed, they are equipped with the TrueDepth Camera, which is the system used as internal frontal camera. Figure 2 shows the so-called notch of iPhone X with the components of the TrueDepth Camera: a part of a traditional 7MP camera, there are other crucial components. Flood illuminator beams infrared light in order to verify the presence of a face; afterwards the 30,000 points are flashed onto the object surface in front of the device by the dot projector; the light points are received and read by the infrared camera, which is able to create a model of the surface. An infrared radiator ensures accuracy in the detection even when there are poor lighting conditions and a proximity sensor makes the system know when a user is close enough to activate.

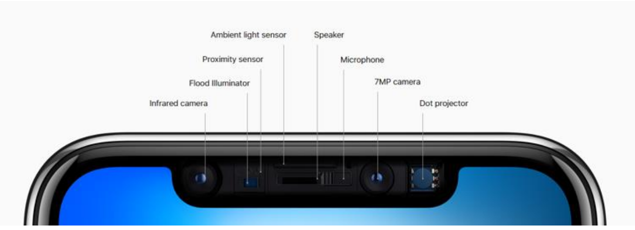

Figure 2: TrueDepth Camera System. Source:

Thanks to this innovative technology, users can unlock the phone, authorize payments and purchases through the facial recognition, but it also opens new doors for several industries. In the interest of this research, it is crucial to explore TrueDepth Camera performance characteristics as a scanner and explore whether it can be used as a portable, light, cheap scanner with rapid acquisition time and low energy consumption. The efficacy of such instrument is tested through a use case, which will be described in the following section.

4 Use Case

The methodology and the idea to use employ the TrueDepth Camera as a scanner are tested through a use case, i.e., the production of a gnome. Gnomes are considered the perfect 3D printing tests as they have some standard characteristics that are suitable to assess printer and scanner features: triangular slouched cap, rounded face and nose, detailed beard, heavy clothes and boots. Among several gnomes that can be found online, Makerbot gnome is undoubtedly the most common and the easiest to find on Thingiverse. Even though it is a simple object, Makerbot gnome presents curves, several surface details, and different types of geometries; at the same time, it does not have any deep depressions or overlapping features that would be difficult to capture even with a professional scanner.
The makerbot gnome has been printed through a FDM technique and it has been scanned with the TrueDepth Camera. The scanning process is extremely fast and easy: it is enough that a person turns the telephone around the object and it takes only a few minutes (6 minutes). The acquisition process may be further simplified and automatized. It is possible to imagine a tool that make the phone turn around the object so that it is not necessary that a person performs this task.
The point cloud obtained by the scan is transformed into a .stl file and uploaded on CATIA, a software developed by Dassault Systèmes, which supports computer-aided design (CAD) and computer-aided manufacturing (CAM),. The scan allows to perfectly recognize the shape of the gnome, although not all details are accurately detected. However, it is necessary to clean and refine the point cloud because it presents some isolated points and because the TrueDepth Camera detects not just the object of interest but also the surface on which it lays.
Once the scan is clean, it is possible to compare it with the original .STL model. The two point clouds are overlapped and a dimensional deviation analysis is performed. Figure 3 shows the result of such comparison: from the dimensional deviation analysis, it results that there are some areas highlighted with a red colour, which indicates a 2

mm deviations and some area are highlighted for a -1.6 mm difference. Thus, the difference between the scanned object and the original model ranges between -1.6 and 2 mm.

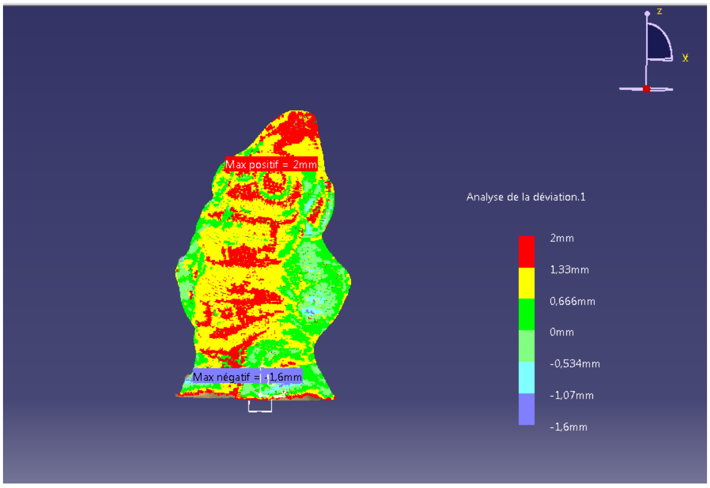

Figure 3: Comparison between the model and the scan done with the smartphone

At this point, it is vital to understand whether such difference is due to a defective production of the gnome or it is caused by a systematic instrumental error. In order to investigate on this question, the same printed object has been scanned with the Solutionix D500, a professional scanner which is specialized for small and detailed objects such as jewelleries, the most complex products to scan. It grants the capture even of small details thanks to its accuracy of 0.01 mm and a resolution (point spacing) of 0.056 mm. The result of the comparison between the original model and the point cloud generated by the Solutionix D500 are shown in Figure 4: it can be appreciated that in this case the deviation ranges from -0.709 to 0.794 mm, against the range -1.6 / 2 mm. If on the one hand the Solutionix D500 ensures high accuracy, on the other hand the time required to obtain such a good result is way longer that the time required to scan the object through the TrueDepth Camera. Indeed, the scan and the transformation of the point cloud into an .STL file took 1 hour and 20 minutes. Such a long time makes it impossible to consider the idea to use the scanner for a quasi-real time quality control and control the product each 15/20 layers are deposited.
Considering the difference between the results obtained using the TrueDepth Camera and the professional scanner, it can be said that TrueDepth Camera has an accuracy that is suitable for the quality control in 3D printing in case no submillimetre precision is required. Considered that the accuracy of the TrueDepth Camera is way lower than the one of professional scanners, it is necessary to make further analysis on its accuracy, precision and stability as an instrument.

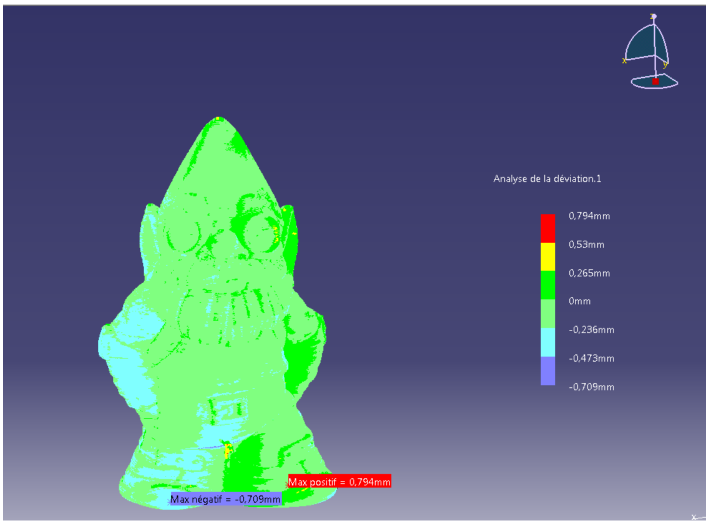

Figure 4: Comparison between the model and the scan done with the Solutionix D500 scanner

If a more detailed analysis is made on the results obtained with the two instruments, it can be noticed that the areas in which TrueDepth Camera had more difficulties in precisely detecting the details, resulting in a less accurate scanning, is the central part in which there are the recesses. Apparently, the Camera is not able to recognize the differences in depth and measures in such kinds of area. However, there is ground to believe that TrueDepth Camera is able to give more reliable results in case of surfaces without this kind of recessions and irregularities.

Further experiments should be performed in order to confirm this hypothesis. Further studies about the TrueDepth Camera were made in and it is discovered that it is the result of the acquisition by Apple of an Israeli 3D company pioneer in 3D sensor technology, PrimeSense, which developed the system used by Microsoft's Kinect to detect movements and enable users to play Xbox videogames without any controller. The company was acquired by Apple for $ 360 Million in 2013; therefore, it can be supposed that the technical features are at least as good as Microsoft's Kinect used as a scanner. The accuracy of a Kinect as a scanner for biological science ranged between 2.5 mm and 5.8 mm. Even though a higher experimental sample would be necessary, it is possible to state that TrueDepth Camera has resulted into a better scanning instrument that Microsoft's Kinect.

5 Conclusion and Future Works

Despite being way cheaper than a professional scanner, TrueDepth Camera is able to perfectly recognize the shape of the use case and has the great advantage of guaranteeing a very rapid process acquisition (in the order of minutes) compared to professional scanners (one hour and twenty minutes for the scanner Solutionix D500, whose performance was compared with TrueDepth Camera one). As it can be expected, accuracy level is lower than the one of a professional scanner: indeed, some errors were detected even though there was not any relevant difference between the model and the sample dimensions. However, it is safe to state that TrueDepth Camera can be used as an instrument to perform quality control for 3D printing when no submillimetre precision is needed. Moreover, it is believed that it can represent a tool to educate 3D printer users to take into account how relevant is performing quality control and the wastes in terms of material, energy consumption and costs it can help to minimize. The usage can also be suggested to small and medium enterprises that start their approach toward additive manufacturing technologies and do not want or cannot afford a significant investment in an instrument for quality control. Certainly, more investigations should be made regarding the accuracy of the TrueDepth Camera as an instrument for scanning 3D printed products in order to better define the cases in which it is opportune to use it without any concern: in future, it could be studied whether there exist some shapes that are detected in a better manner or whether there are some parameters that influence positively or negatively the acquisition process.

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