Additive Manufacturing 21 (2018) 53–62

Contents lists available at ScienceDirect

Additive Manufacturing

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

Full Length Article

Photogrammetric measurements of 3D printed microfluidic devices

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ARTICLE INFO

Keywords:
Microfluidics
3D printing
Photogrammetry
Measurement

ABSTRACT

Additive manufacturing (AM) processes are being more frequently applied in several fields ranging from the industrial to the biomedical, in large part owing to their advantages which make them suitable for several applications such as scaffolds for tissue engineering, dental procedures, and 3D models to improve surgical planning. Moreover, these processes are particularly suited for the fabrication of microfluidic devices and labs-on-a-chip (LOC) designed to work with biological samples and chemical reaction mixtures.

An aspect not sufficiently investigated is related to the dimensional verification of these devices. The main criticality is the texture-less surface that characterizes the AM products and strongly affects the effectiveness of most currently available 3D optical measuring instruments.

In this study, a passive photogrammetric scanning system has been used as a non-destructive and low-cost technique for the reconstruction and measurement of 3D printed microfluidic devices. Four devices, manufactured with stereolithography (SLA), fused deposition modelling (FDM) a Stratasys trademark, also known as fused filament fabrication (FFF), and Polyjet have been reconstructed and measured, and the results have been compared to those obtained with optical profilometry that is considered as the gold standard.

1. Introduction

Additive manufacturing (AM) can be used to extrude metallic materials, hydrogels, or cell-loaded suspensions in order to incorporate functional components in microfluidic devices [1]. Traditional microfluidic manufacturing methods (i.e., soft lithography) require specialized fabrication skills and facilities, while AM is accessible and customizable to serve the needs of biology, chemistry, or pharma research and development [2]. Moreover, open source enables researchers to improve the design process and reduce production for specific applications [3].

Several interesting review papers have been dedicated to the topic of AM microfluidic devices such as [1,3–8]. These papers are focused on photo-polymerization-based additive processes but there is emerging evidence that extrusion-based processes could gain more importance in microfluidic applications owing to their inherent simplicity and versatility to accommodate well-defined materials along with their continuously evolving performance.

Together with the expansion of AM techniques, some questions have been raised. One of them is related to the measuring instruments capable of acquiring AM surfaces in order to perform dimensional verifications. Generally, little importance is given to the dimensional characterization of these devices. The most recent trend is to adopt non-contact methods, such as optical or x-ray techniques, instead of contact methods for dimensional verification, owing to their capability to acquire a large number of points in a short time [9]. In this context, numerous techniques have been developed that can be broadly classified into two categories: the passive (e.g., passive photogrammetry) and active methods (active photogrammetry, time of flight, and triangulation-based techniques). Active methods based on triangulation are more extensively studied and used for close-range measurement. Depending upon the nature of the structured patterns, these methods can achieve different spatial resolutions or accuracy, while fringe projection techniques use phase information to establish a correspondence that is typically robust regarding surface texture variations [10]. Most passive systems use one or multiple cameras, and image processing, to recreate the 3D form from a series of correlated images [11]. Active systems use their own light sources and recreate a 3D model of the object's form by detecting the modulation of projected illumination caused by the object's shape. The advantages of passive over active systems are that they are usually cheaper in terms of hardware requirements, lower in mass, more compact, and hence easier to use. However, they tend to be less accurate and slower compared to most active systems, and the post-processing algorithms play a fundamental role in the reconstruction process. Unlike active systems, which create an artificial texture on the object's shape, passive systems require textured surfaces in order to determine common features and hence relate multiple images taken at different positions on the object.

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https://doi.org/10.1016/j.addma.2018.02.013
Received 2 February 2018; Received in revised form 23 February 2018; Accepted 25 February 2018
Available online 26 February 2018

Recently, passive photogrammetry has been applied for the reconstruction of small objects with sub-millimetre features, proving that it is a promising alternative to other currently available optical methods. The main hurdle for the dimensional verification of AM parts is their texture-less surfaces, [11] especially those obtained with resins or plastic materials [12,13]. It is difficult for this technique to achieve high accuracy if an object surface does not have strong natural texture variations.

A way to overcome this drawback, which affects the passive photogrammetric system, has been presented in [14] with the use of a laser speckle projection to obtain an active photogrammetry.

1.1. Additive manufacturing (AM) for micro fluidic devices

AM has recently raised interest as a way to fabricate microfluidic systems, owing to its automated, assembly-free 3D fabrication, rapidly decreasing costs, and fast-improving resolution and throughput. Indeed, injection moulding and soft lithography, routinely used to fabricate valves and pumps for fluidic automation, have high set-up and running costs, while additive manufacturing techniques are efficient because they (a) promote modular CAD design, (b) do not require tooling or assembly, (c) generate very little waste, and (d) reduce costs [15]. Among the AM processes, SLA has been widely applied to fabricate microfluidic devices because of its high accuracy and availability of relatively low-cost machines.

At first, SLA was used as a model for polydimethylsiloxane (PDMS) casting, such as in [16], where a micro-stereolithography 3D printer (Miicraft) was adopted to fabricate templates with a proprietary resin. Subsequently, the 3D-printed template was covered by PDMS, after protecting the surface of the template with a PDMS-compatible material. Subsequently, there has been a considerable amount of work focused on printing open microfluidic channels. This option is often chosen instead of printing enclosed channels because it is easier to remove the uncross-linked resin. In [2], a Miicraft printer was used to print a complex open microfluidic channel, which was then sealed with adhesive tape. The device was printed in the XY-plane, reducing both the surface roughness of the channels and printing time. This printing direction also exploited the resolution limit of the printer. Direct fabrication of transparent microfluidic devices with enclosed channels is also reported in [17], with square sections of side equal to 250 μm.

Moreover, FDM and FFF have gained market penetration in microfluidics recently, because of the finishing treatments, tuning of process parameters, increasing positioning accuracy, and reduction of available nozzle diameters. The existing approaches for the fabrication of microfluidic devices described in [14] using 3D printing are also applicable for FDM and FFF: (i) AM of templates for replicas of conventional materials (such as Polydimethylsiloxane-PDMS or Poly(methyl methacrylate)-PMMA); and (ii) direct AM of microchips, including open channels to be sealed and closed channels. One example of (i) is reported in [18], which used sacrificial FDM printing to create a complex 3D scaffold of cylindrical segments using organic ink, and subsequently embedded the scaffold with a UV-curable epoxy resin. By heating to 60 °C, the organic ink was thermally removed leaving the epoxy hollow geometry.

More recent examples of (ii) are reported in [19], such as the descriptions of reaction-ware devices by Cronin's group, using a 3D printer to initiate the chemical reactions and printing the reagents directly into a 3D reaction-ware matrix. Comparisons of photo-polymerization processes are reported in [20], where open channel devices were fabricated using a Form1 and compared to an i3DP drop-on-demand 3D printing machine (Shapeways Frosted Ultra Detail). The main interest of this paper was the dimensional comparison, which was made qualitatively, using scanning electron microscope (SEMs) images to observe the smallest features manufacturable with both methods. To investigate the surface roughness of each printing method, SEMs images were taken from the two printed test pieces using both the fabrication methods.

1.2. Dimensional verification of micro fluidic devices

The measurement of micro-channels is a challenging task, as sectioning the device with a destructive procedure and analysing it with a microscope is the most popular method for their dimensional and geometric characterization. One of the most important non-destructive, quantitative inspection methods involves confocal sensors. Some examples of confocal sensors are the following: In [21] a confocal point sensor (CF 4) and a tactile roughness device (DEKTAK 3030) were used for measuring laser ablated channels in terms of ablation depth, wall-angle, and surface roughness. In [22], micro-channels were measured with a profilometer based on a confocal chromatic sensor and with a confocal microscope with higher lateral resolution. In [23], a comparison between the micro-milled channels on electron beam melted (EBM) and direct metal laser sintered (DMLS) workpieces was reported, and scanning electron and confocal microscopes were the measuring instruments employed. Unfortunately, this kind of instrumentation suffers severe limitations when a highly sloped surface must be measured. In micro-channels, the micro-geometry retrieval of areas near vertical walls is important to better understand and predict the fluid flow. In this context, photogrammetry is capable of entirely reconstructing an object with any 3D shape, and could be applied to exploit its positive features. Close-range photogrammetry includes methodologies still under experimentation, which have developed considerably owing to their low cost, fast, and non-invasive scanning processes.

In the last years, photogrammetry has been used in several experiments to demonstrate its suitability for most dimensional ranges, down to sub-millimetric features [12,24–28]. Some of the aspects that limit its applicability, particularly in the case of sub-millimetric features, are related to the magnification level required, calibration pattern realization, and effectiveness of the camera calibration models. When high magnifications are required, the angle of view (AOV) becomes smaller and the depth of focus (DOF) gets narrower, leading to blurred images. The higher the magnification is, the smaller and more accurate the pattern used for camera calibration must be. Moreover, the pinhole camera model is theoretically effective under several assumptions that cannot be verified for millimetre and micro-scale applications. Another critical aspect, rarely treated in the research literature, regards the scale adjustment of the photogrammetric point clouds, as photogrammetry normally captures a model that must be scaled after processing.

Basically, using commercial software, the scale is retrieved through the following procedures [26]. In the first procedure, a known distance is measured between two codified markers within the images [29–34], which is largely used for large-sized objects. However, small measurement volumes lead to a lower field of view with the following issues: (i) the markers must be smaller, resulting in increasing costs and technical problems for fabricating them; and (ii) blurring involves more extended image areas. In these conditions, marker detection becomes difficult. The second procedure consists in placing the camera(s) in known positions [23,28,35] or at a known distance between each other, as in traditional aerial photogrammetry, where each photo is geo-mapped through GPS. In [26], the scaling method finds the factor λ, under the hypothesis that the magnification ratio M of the camera is known with the considered extension tube and L, the lateral size of the pixel. The disadvantage of this method is the dependency on the operator. The operator's work consists of detecting non-blurred areas and computing the coordinates of two points on the images in these areas.

In the present study, a 3D passive photogrammetric measuring system has been adopted as a non-destructive and low-cost methodology for the reconstruction and dimensional verification of four AM micro-fluidic devices realized through SLA, FDM, FFF and Polyjet.

This paper is organized as follows. Section 2 describes the equipment involved during both the manufacturing and measuring processes.