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COMPENSATION OF GEOMETRICAL ERRORS OF PARTS OBTAINED BY FUSED FILAMENT ADDITIVE FABRICATION

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Notation

Abbreviation	Definition
AM	Additive Manufacturing
AMF	Additive Manufacturing File
AC	Aligned Contour
BJT	Binder Jetting
CCD	Charge-Coupled Device
CSV	Comma-separated values
CAC	Compensated Aligned Contour
CC	Compensated Contour
CNC	Computer Numerical control
CAD	Computer-Aided Design
CH	Conoscopic Holography
CIS	Contact Image Sensor
CMM	Coordinate Measuring Machine
DOF	Depth of Field
DED	Directed Energy Deposition
DC	Distorted Contour
dpi	Dots per inch
FEM	Finite Element Method
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
GUI	Graphical User Interface
IR	Infrared
ICP	Iterative Closest Point
ML	Machine Learing
MC	Machining Centre
MEX	Material Extrusion
MJT	Material Jetting
NIST	National Institute of Standards and Technology
NIR	Near-infrared
NC	Nominal Contour
PBF	Powder Bed Fusion
PCA	Principal Component Analysis
PCB	Printed Circuit Board
SLS	Selective Laser Sintering
SHL	Sheet Lamination
SVD	Singular Value Decomposition

SPC	Statistical Process Control
STL	Stereolitography, Standard Triangulation Language
TTL	Transistor-Transistor Logic
VPP	Vat Photopolymerisation
WAAM	Wire Arc Additive Manufacturing

Abstract

The concept of Additive Manufacturing (AM) refers to those processes and technologies by which parts are built directly from 3D digital models generated by a CAD system. To this aim, the part is constructed by successively adding thin layers of material, obtained by a slicing process of the CAD model. AM offers interesting advantages, such as the ability to produce parts with complex geometries, the elimination of tooling and fixturing costs and the wide variety of materials that can be processed (e.g., polymers, metals, ceramics and composites). This fact has led to apply AM in multiple industrial sectors such as metalworking, energy, automotive, aerospace, medicine, etc.

Despite the many advantages of AM, there are factors intrinsic to the process and the used technology that limit the geometric accuracy of the produced parts and therefore its applicability when high quality end-product specifications are required. For this reason, a number of studies have aimed to address these limitations. However, the complex nature of AM processes makes it very difficult to achieve physical models that faithfully represent them and does not allow to fully consider the events taking place in real time. For this reason, other solutions have addressed the problem by in-situ monitoring and controlling the process, in order to improve the quality of AM produced parts and to reduce the final verification stages, resulting in fewer defective parts and, consequently, lower costs.

In this context, the aim of this doctoral thesis is **to develop a system that allows for the compensation of geometric and dimensional errors in parts manufactured by Fused Filament Fabrication (FFF), based on in-situ layer geometry measurement when building a part**. For this purpose, a prototype FFF machine has been developed with an additional head that enables the use of a sensor for non-contact digitising of part layers as they are deposited. Particularly, sensors based on 2D digital image capture and others on 3D point acquisition have been tested. Based on the information captured by these sensors, procedures have been implemented to recognise the layer contours and the results have been contrasted with the measurements performed on a Coordinate Measuring Machine (CMM), which have made it possible to validate the methodology. To improve part geometry, a procedure that first analyses geometric deviations of the layer contours detected in-situ with respect to the equivalent nominal ones from the CAD model of the part has also been developed. This requires carrying out an alignment process between the two types of contours and a local comparison by regions. Compensation for deviations is then applied by inverting the contour points in the opposite direction to the point observed deviation. To validate the method, different parts have been manufactured without and with the application of the compensation algorithm, with satisfactory results.

The application to several case studies of the in-situ digitising methodology, analysis, and compensation procedures, resulted in a dimensional and geometric improvement of the analysed parts which demonstrates the effectiveness of the developed methodology and its interest at an industrial level, especially in the manufacture of serial parts.

Resumen

El término Fabricación Aditiva (FA) hace referencia a aquellos procesos y tecnologías mediante las cuales se construyen piezas directamente a partir de modelos digitales en 3D generados mediante un sistema de CAD. Para ello, la pieza es construida mediante la adición progresiva de capas de material de pequeño espesor, obtenidas mediante un procedimiento de rebanado del modelo CAD. La FA ofrece ventajas interesantes, tales como la capacidad de producir piezas de geometría compleja, la eliminación de costes derivados de herramientas y utillajes o la gran variedad de materiales con los que es posible trabajar (polímeros, metales, cerámicas o materiales compuestos). Esto ha llevado a su adopción en múltiples sectores industriales como metalmecánico, energía, automóvil, aeroespacial, medicina, etc.

A pesar de las numerosas ventajas de la FA, existen factores intrínsecos al proceso y a la tecnología utilizada que limitan la precisión geométrica de las piezas producidas y, por tanto, su aplicación cuando las especificaciones de calidad exigidas al producto son elevadas. Por este motivo, son variadas las investigaciones que se han propuesto hacer frente a estas limitaciones. Sin embargo, la compleja naturaleza de los procesos de FA supone una gran dificultad para alcanzar modelos físicos que los representen con fidelidad y no permiten controlar sucesos que ocurran en tiempo real. Por este motivo, otras soluciones han abordado el problema mediante la monitorización y control in situ del proceso, con el fin de mejorar la calidad de las piezas producidas por AM y reducir las etapas de verificación finales, disminuyendo las piezas defectuosas y, en consecuencia, los costes.

En este contexto, esta tesis doctoral plantea como objetivo desarrollar un sistema que permita la compensación de los errores geométricos y dimensionales en las piezas fabricadas por Fabricación Aditiva de Hilo Fundido (FFF), a partir de la medición in situ de la geometría de las capas depositadas en la construcción de una pieza. Para ello, se ha desarrollado un prototipo de máquina de FFF dotada de un cabezal adicional que permite utilizar un sensor para el digitalizado sin contacto de las capas de la pieza, a medida que son depositadas. En particular, se han probado sensores basados en captura de imágenes digitales en 2D y otros en la adquisición de puntos 3D. A partir de la información capturada por estos sensores se han implementado procedimientos para reconocer los contornos de capa y se han contrastado los resultados con las mediciones realizadas mediante una Máquina de Medición por Coordenadas (CMM) que han permitido validar la metodología. Para mejorar la geometría de la pieza, se ha desarrollado también un procedimiento que analiza, en primer lugar, las desviaciones geométricas de los contornos de las capas detectadas in situ con respecto a los contornos nominales equivalentes, obtenidos del modelo CAD de la pieza. Esto exige un proceso de alineación entre ambos tipos de contornos y una comparación local por

regiones. A continuación, se aplica una compensación de las desviaciones mediante la inversión de los puntos del contorno en dirección contraria a la desviación puntual observada. Para la validación del método, se han fabricado diferentes piezas sin y con la aplicación del algoritmo de compensación, obteniendo resultados satisfactorios.

La aplicación de la metodología de digitalizado in-situ, análisis y compensación de desviaciones a varios casos de estudio, proporcionó una mejora dimensional y geométrica de las piezas analizadas que demuestra la eficacia de la metodología desarrollada y su interés a nivel industrial, especialmente en la fabricación de piezas en serie.

Chapter 1

Introduction and objectives

1.1. Introduction

This chapter describes the context of the research carried out in this doctoral thesis, as well as the objectives and the way in which this thesis document has been structured.

1.2. Scope

Additive manufacturing (AM) refers to a class of technology in which physical parts are directly built from 3D computer-aided design (CAD) models. Unlike conventional manufacturing processes (machining, casting, forging, etc.), AM can produce parts of greater geometric complexity by reducing design-to-manufacture cycle and avoiding costs associated with the use of tools and fixtures. For this reason, the application of AM has been extended to many industrial sectors, such as metalworking, energy, automotive, aerospace, medicine, etc. In addition, considering the emergence of different AM technologies and the possibility of manufacturing parts using ever more different materials, it is safe to say that this category of processes will continue to grow in the coming years. This can be confirmed with the figures provided by the Wohlers Report 2022 [1], which show the immense growth in the AM industry over the course of 2021. According to the press release, research for the report showed AM industry growth of 19.5% in 2021. This is of course a significant increase from the previous year which showed only a 7.5% increase due to the impact of the pandemic, though it still has not quite yet reached pre-covid levels, the 10-year average before 2020 was 27.4% growth. However, it is still a significant milestone. It is also worth highlighting the interest shown by all the governments of the world that currently consider AM as a technology of the future and a key strategic line in their research and development plans.