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Process parameters tuning and online re-slicing for robotized additive manufacturing of big plastic objects

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ABSTRACT

Complex parts can be successfully manufactured by means of Additive Manufacturing (AM) techniques based on thermoplastic polymer extrusion, whose use for mass production is restricted by their slow printing speed. To address this limitation, a flexible AM platform for big plastic objects has been realized mounting an industrial screw-based extruder on an anthropomorphic robot. An experimental campaign has been performed to set a suitable range of relevant process parameters, with the aim of ensuring a regular deposited layer geometry. Moreover, a closed-loop control strategy has been developed to correct the robot height based on data measured during the material deposition, thus further improving the process parameter setting and compensating the material shrinkage or other unexpected defects. Eventually, an online re-slicing algorithm has been implemented to preserve the desired height of the manufactured object, despite the layer height changes. The proposed approach allows a deposition flow rate up to 1250 cm^3/h within a building volume limited only by the robot workspace.

1. Introduction and objectives

In recent years, Additive Manufacturing (AM) techniques based on the extrusion of thermoplastic polymers, such as Fused Deposition Modeling (FDM), have become widely used [1,2]. The AM processes allow the fabrication of customized and complex parts, but standard AM systems have a slow printing speed limiting their use for mass production. Consequently, the key targets for future manufacturing systems are a productivity improvement and an increment of achievable part size [3]. Industrial microextruders achieve a fused material deposition rate equal to 3 kg/hour, that is 10 to 20 times higher than the average deposition rate of commercial FDM systems [4,5]. Moreover, AM systems based on robotic platforms provide more flexibility, better motion software support and an industrial level of reliability, being able to replace FDM printers in some applications [6]. Eventually, using plastic pellets instead of commercial filaments allows a cost reduction and a higher freedom in material selection. Despite of these advantages, the additive manufacturing of big parts with high deposition rates has some limitations, e.g. non-optimally tuned process parameters could result in an irregular shape of deposited material and, then, in geometrical errors on the printed object. The material shrinkage during the cooling phase is another critical issue, since it could modify the deposited layer geometry. Moreover, the mismatch between the nominal geometry and the actual one is of utmost importance when the component is supposed to be assembled, as well as when the component need supports that have been designed according to the nominal geometry.

In this study, a flexible platform for the additive manufacturing of big objects has been realized modifying an industrial screw-based extruder and mounting it on an anthropomorphic robot and suitable methods have been designed to overcome the aforementioned drawbacks. This work proposes a procedure to set optimal values for the most important process parameters (i.e. rotational speed of the extruder motor, robot translation speed, nominal layer height commanded to the robot) (Section 3). This objective has been achieved thanks to a suitable experimental campaign on single-layer rectilinear tracks, which has been developed according to Design of Experiments (DoE). The described approach can be applied to different materials, as proved by the use of two polymeric materials in the reported experiments. This paper proposes also a closed-loop control strategy to correct the robot height when depositing many layers (Section 4.1). This procedure is based on a discrete control law and on the integration of sensors into the robotic system to make measurements during the material deposition. The sensor-guided corrections change the adopted layer height, hence this work implemented a fast online re-slicing algorithm to respect the desired dimension of the part, but requiring low computational times

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Nomenclature

e_k	Error between $\Delta x_{ref,k}$ and $\Delta\tilde{x}_{mean,k}$
v_t	Robot translation speed
$z_{reslice}$	z-coordinate in correspondence of which a re-slicing is ordered
w_{mean}	Measured mean layer width
β	Overlap factor
$\Delta x_{ref,k}$	Nominal layer height (k^{th} layer) with an additional height to guarantee an overlap between layers
$\Delta\tilde{x}_{mean,k}$	Measured mean layer height (k^{th} layer) with an additional height to guarantee an overlap between layers
Δz_{diff}	Difference between nominal and measured mean layer height
Δz_{mean}	Measured mean layer height
$\Delta z_{ref,k}$	Nominal layer height (k^{th} layer)
λ	Proportional gain in the control law
ω_m	Extruder motor rotational speed

(Section 4.2). A representative case study of additive manufacturing of big parts, i.e. a piece of furniture, demonstrates the effectiveness of the proposed procedures (Section 5).

1.1. State-of-the-art

Only few examples of AM systems for plastic parts with deposition rates more than 20 times higher than standard high-end 3D printers (the so-called Big Area Additive Manufacturing – BAAM systems) can be found in literature. A system with a 15,000 cm^3/h flow rate has been developed by the Oak-Ridge-National-Laboratory in collaboration with Cincinnati Inc. [7]. The final quality of the workpiece is affected by warpage, shrinkage and irregularities in the shape of the deposited layers. To limit this issues, a mechanical compactor could be included in the extruder design [5]. Moreover, materials with low warpage/shrinkage ratios (i.e. carbon fiber composites) can be used [5]. In this system the extruder has been mounted on a gantry-style robotic cell, but there are some commercial setups in which robotized AM systems have been created using anthropomorphic robots [8,9]. A further example in the market is the Deltawasp 3MT [10], a 3 degrees-of-freedom parallel kinematic machine equipped with an extrusion head on the mobile platform. This machine achieves a high flow rate through a feeding system that supplies pellets to the extrusion head. However, a limited layer resolution is achievable, as well as there are difficulties in a proper control of the deposition [11].

Nevertheless, two issues are still poorly investigated. Firstly, there is still lack of discussion about the procedure to find printing parameters or control loops to apply during the deposition process. Secondly, the path-planning and slicing issues regarding such machines are still not sufficiently addressed.

Focusing on the former issue, the existing literature dealing with the estimation of optimal deposition parameters considers only standard 3D printing, and not BAAM. Sood [12] studied the influence of process parameters (namely, layer thickness, orientation, raster angle, raster width and air gap), which can affect the dimensional accuracy, the surface roughness and the mechanical properties of the printed part. The work by Sood is based on the assumptions that each deposited layer has a regular geometry, as typical of many studies [13–15]. However, when using a large deposition rate or non-standard materials, this assumption cannot be considered true; therefore, this study will focus on setting the fundamental parameter values to guarantee a regular deposition of each layer.

Many works are available in literature about the monitoring of laser-based metal AM processes to achieve a better deposition and Mazumder et al. [16] resume the state-of-art. Fewer works are focused on the process monitoring in case of plastic deposition techniques. The temperature of the deposited material have been measured in the works by Dinwiddie et al. [17,18], while Faes et al. [19] integrated a laser triangulation scanner into a standard 3D printer to acquire the shape of the deposited material. However, most FDM machines are not equipped with any feedback system. The possible causes of this lack are: (i) a feedback control is not required thanks to the FDM process stability for standard deposition rates (i.e. for standard nozzle diameter values); (ii) control loops are more difficult to implement in 3D printers and CNC machines than in robot controllers where multi-threading can be exploited; (iii) the standard AM systems have a relatively low cost.

Focusing on the latter issue, the computational time required to generate the tool path is very large according to the industrial practice. Indeed, CAM software are designed for the slicing of small parts and create paths with a large amount of points at a small distance. According to Minetto et al. [20], the algorithms for the path generation for a 3D printer starting from a 3D triangle mesh can be divided in three phases (Fig. 1): (i) the "slicing step", where the geometric model is intersected with parallel planes to obtain the contour of each material layer; (ii) the "contour construction step", where the segments produced by slicing are organized into one or more closed polygons that delimit the object; (iii) the "connection step", where the contours are connected to create the printing path. Some strategies to improve each step of the layered manufacturing path planning can be found in [21–25].

The most critical phase for the computational time is the slicing step. As an example, the first algorithms used to slice a STL file for stereolithographic applications employed more than 60% of the time to prepare the part to be produced [26]. These algorithms were highly inefficient, because they tested every cutting plane against every triangle. Over the years, the computational time required by the slicing step has been reduced thanks to the sorting of triangles in sub-groups to avoid useless intersection checks [27] and to parallel computing [26].

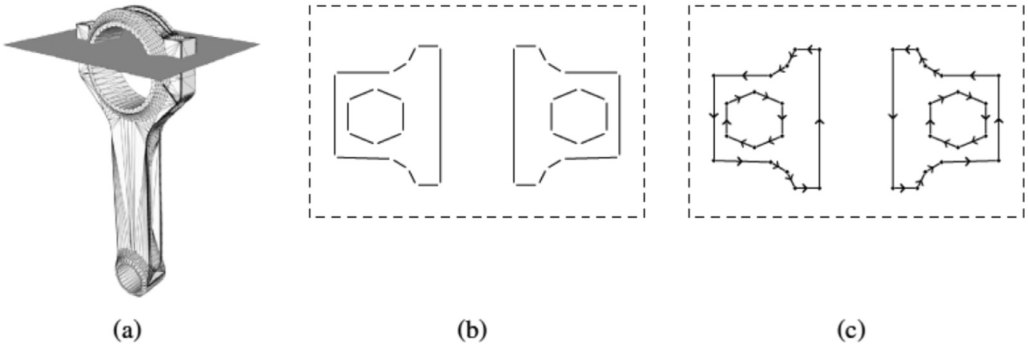

Fig. 1. Steps in the additive layered manufacturing process planning: (a) slicing step; (b) contour construction step; (c) path creation step (adapted from [20]).