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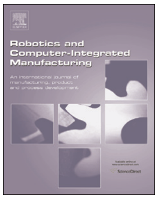

Design for manufacturing of surfaces to improve accuracy in Fused Deposition Modeling

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ABSTRACT

Fused Deposition Modeling is an Additive Manufacturing technology able to fabricate prototypes, tooling and functional parts without geometrical complexity limitations. Despite of the potential advantages of this technology, a limiting aspect of its industrial diffusion is the obtainable accuracy. The literature highlighted that significant deviations from the nominal values are observed: these deviations are not constant over all the part surfaces but strictly depend upon the process parameters, i.e. the layer thickness and the deposition angle. This involves poor surface quality: the parts could not satisfy the design specifications nor assure the functionality and the assembly fit with other components. The aim of this work is the development of a design for manufacturing methodology able to improve the dimensional accuracy obtainable by this technology. It operates in the design model step performing a virtual model preprocessing: an anisotropic offset is applied to the surfaces, defined by a mathematical formulation, in order to compensate for the abovementioned dimensional deviations. This way, without to eliminate the physical sources of the errors, it is possible to obtain a part with dimensional values very close to nominal ones. This method does not require any additional resources for its application such as preliminary artifact construction and measurements.

1. Introduction

Design for Manufacturing (DFM) is a set of methods and methodologies that the designers employ to tailor their designs to reduce manufacturing difficulties with the aim to minimize fabricating, assembly and logistic costs [1]. DFM scopes are about the designer understanding the constraints imposed by the manufacturing process in order to provide the better solution to comply with the desired product shape.

The capabilities of Additive Manufacturing (AM) technologies enable to lessen or to avoid some difficulties such as the undercutting features, the tool accessibility, the toolpath generation but some other problems need particular attention especially when the aim is the improvement of the technology [2].

Fused Deposition Modeling (FDM) is one of the most diffused technologies able to fabricate prototypes, tooling accessories and functional parts directly from a virtual model.

The fabrication process consists in the deposition of a thermoplastic material layer by layer. A temperature-controlled extrusion head is fed with filament form material which is heated to a semiliquid state. The head extrudes, directs and crushes the filament in thin layers onto a fixtureless base. Since the surrounding air is maintained below the material melting point a rapid cooling takes place. The head builds the desired layer following the toolpath generated by the Computer Aided Manufacturing (CAM) software. Two materials are extruded: the model, i.e. the material of the final component, and the support necessary to sustain the overhanging parts. When a layer is completed the base lowers and the next layer can be deposited [3].

The manufacturing process needs the following steps. The first is the generation of the virtual model and the creation of an interchange file, which encloses tessellated surfaces, necessary to communicate with the prototyping system. In the second step the file is transferred in the CAM environment where the process parameters are chosen. The 3D model is checked and sliced into layers. In the fourth step the support structures are created, the toolpath of the extrusion head is generated and the file is transferred to the prototyping system. The fabrication of the physical part takes place in an automatic way by a Computer Numerical Control (CNC) system. The last stage is the post-processing where the support structures are removed by mechanical or chemical actions. The strengths of this technology are: the manufacturing time reduction for complex shapes, the fabrication without tooling, the production of functional parts, input materials are kept to a minimum, and the easy support removal. Although these advantages, FDM presents the shortcoming of a limited accuracy. In

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the past the dimensional accuracy of FDM prototypes has been investigated by benchmarking studies. Their purpose is the comparison of different AM systems by a systematic method consisting in the fabrication of benchmarking test geometry [4]. Iuliano et al. [5] designed a test part to evaluate the accuracy and the tolerance grades: the observations undertaken on the FDM part fabricated by a layer thickness of 0.254 mm, showed a dimensional deviation until 0.7 mm. Mahesh et al. [6] proposed a geometry characterized by free form surfaces finding deviations from the nominal dimensions ranging from 5% to 15%. In one case the shape deformation led to a deviation of 2.5 mm. In [7] two anatomic parts have been employed to investigate the errors generated by the entire fabrication stage starting from the computer tomography measurements to the physical prototype. The results showed an average absolute difference of 0.12 mm with a small standard deviation of 0.02 mm. The benchmarking study presented in [3] is related to a small part called “button tree display”: flat features showed a disagreement of few tenths of millimeters with a large scattering; curved surfaces had a deviation of about a millimeter. Also in [8] the investigation undertaken on a small size product showed a large scattering of dimensional measures which spread over four IT grades according to [9]. Stratasys, the producer of FDM systems, assures a dimensional accuracy following the rule ± 0.127 mm or ± 0.0015 mm per mm whichever is greater [3]. The abovementioned literature results highlight a large difference of the observed accuracy. An explanation of the variability observed on these prototypes has been given by Boschetto and Bottini [10] which correlated the dimensional accuracy to the surface local slope of the part. They developed a geometrical model of the filament section providing the prediction of the dimensional deviation from the nominal value as function of the deposition angle, i.e. the angle between the stratification direction and the normal to the part surface, and the layer thickness. The experimentation, undertaken on simple geometry parts produced with different materials, prototyping systems, and process parameters, validated the model. The observations at layer thickness of 0.254 mm pointed out a dimensional deviations ranging from zero, at 90° deposition angle, to 0.4 mm for near horizontal wall with a standard deviation less than 0.05 mm. These results have been proved on a particular geometry focusing on the deposition stage but several problems can arise from the other manufacturing steps. In the first one the 3D model generation can lead to a virtual object with problems having effect at the fabrication stage; its translation in the interchange file can add further errors related to the approximation introduced by the tessellation. The slicing operation originates the so called staircase effect which unavoidably affects the surface quality [11,12]. The CNC system causes problems related to the position and the speed control of the nozzle trajectory which must take into account the deformation of the filament after the deposition [13]. A general formulation has been proposed by Yardimci and Guceri [14] in order to predict the degree of the bonding distribution for a given part. The fast cooling can cause inaccuracies such as warp distortions, delaminations and surface defects attributed to the solidification induced residual strains [15]; the prototype warp deformation has been quantitatively analyzed by Wang et al. [16] providing a tool for controlling and adjusting the effects. Also the post-processing operations can provoke surface quality modifications both in the case of manual or chemical actions [2].

Great effort has been spent to improve the AM part accuracy through two general approaches namely the error avoidance and the error compensation. The former seeks to eliminate the source of the errors while the latter strives to reduce the effects without removing the source. Most research falls within the first category including the data file correction, the slicing technique improvement, the support structure generation, the toolpath planning, the process parameters tailoring and the built orientation optimization. In Kulkarni and Dutta [17] a slicing procedure for layered manufacturing has been presented with the aim to suggest solutions for geometric inaccuracies. Chiu et al. [18] developed a slicing algorithm to ensure unilateral tolerance over the prototypes surface; proper solutions, which depends upon the geometric part shape and the features, has been proposed and experimentally validated. A stable algorithm for support structures generation in FDM has been presented by Huang et al. [19]: it employs the parts' self-support ability and helps the volume reduction and the removal of redundant structures. Jin et al. [20] seek to improve the geometrical accuracy and the built time of complex biomedical objects by introducing an adaptive toolpath generation approach. They proposed some optimization strategies such as the process planning, the slicing, the hybrid contour and the zigzag toolpath generation, the speed control, the geometrical accuracy analysis. In Sood et al. [21] the effects of several factors on the dimensional accuracy of FDM parts have been studied. Taguchi Grey method has been used to find significant factors and optimum factors level in order to minimize changes in length, width and thickness. Observed results showed that the FDM accuracy is influenced in a highly nonlinear manner, hence an artificial neural network modeling has been proposed.

The error compensation approach was inspired by the parametric evaluation of Coordinate Measurement Machine (CMM) errors which employs specific experimental setup to retrieve direct evidence of the individual error source [22]. In AM processes the allowable tolerance is quite larger than CMM systems but a number of other error sources affect the process [23]. Tong et al. [24] presented a comprehensive method for the AM systems error evaluation and the error compensation using “virtual” parametric errors. This approach was applied to Stereolythography Apparatus highlighting a considerable improvement. In Tong et al. [25] it was extended to the FDM machine developing a compensation method based on correcting slice files. This methodology employs the construction of an artifact by the machine considered for the error compensation; then by a CMM a point cloud is acquired to gain coefficients for the model; finally the STL file is modified according to the formulation.

Other compensation methods are focused on the model preprocessing. They are typically employed to compensate for the shrinkage by scaling the original virtual model; at present the predictive capabilities are not accurate enough to understand the shrinkage variation [2]. There are two strategies involving the preprocessing of the model. The first technique moves each facet by a constant distance along the normal direction and reconnects the 3D model by the repetitive calculation of the surfaces intersections. This methodology is common but presents many drawbacks related to the creation of a closed 3D model: it is necessary at each step to identify all the gaps and the overlapping triangles and to fill or to eliminate these defects. The second approach overcomes these problems by considering the vertices instead of the triangular facet. In Qu and Stucker [26] the offsetting is obtained displacing each vertex and taking into account the normal direction of the surrounding triangular facets. Both these methodologies need the knowledge of the offset value: a constant value is typically considered for the most of the AM techniques in order to compensate for the average shrinkage. However some features shrink more or less than the average and many studies assess that this variation is geometry dependent [2]. In particular the FDM process is characterized by a large shrinkage variation because the employed polymers show a marked nonlinear behavior. Moreover the shrinkage phenomenon is covered by the effect of the layer thickness and the deposition angle: in Boschetto and Bottini [10] a deterministic model, depending upon these two process parameters, provides the dimensional displacement between the