Title:

A Characterization of 3D Printability

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Introduction:

Additive Manufacturing (AM) is currently being considered as the spark of a new industrial revolution, due to its versatility in creating 3D structures of unprecedented design freedom and geometric complexity in comparison with conventional manufacturing techniques[4]. AM refers to a great variety of commercially available technologies applied to manufacture 3D models directly from CAD data, based on successive layer deposition of material in a pre-arranged pattern. Due to differences in AM technologies, in regards to employed processes, machines and materials, the final fabricated part can sometimes vary from the original leading to problems in terms of dimensional accuracy, surface finish, mechanical properties, functional and geometrical requirements[8],[10]. Various research efforts have articulated the correlation between AM technologies and design process, in terms of integrating specific design characteristics or guidelines pertinent to model complexity, design potentials and constraints of each AM process [13],[12],[9],[6],[1].

In this work we study, determine and correlate the complexity and the design properties of a CAD model with its ability to be printed - a.k.a. *printability* - using a specific printing technology. This is accomplished mainly in terms of structural robustness and dimensional accuracy of the corresponding 3D model. We propose a novel approach that, by taking into consideration the model mesh complexity and certain part design characteristics, computes a *printability score* for a specific 3D printing technology which expresses the probability of a robust and accurate 3D printing result on a specific AM machine. This metric can be used either to determine which 3D technology is more suitable for manufacturing a specific model or as a guide to re-design the model to ensure printability. We verify this measure by conducting printing experiments for several benchmark models which are printed on AM machines employing three different technologies: Fused Deposition Modeling (FDM), Binder Jetting (3DP), and Material Jetting (Polyjet).

Model and Part Characteristics that Affect Printability:

The quality of a 3D printed model, in reference to its robustness and conformance to the initial model, depends on various parameters. One such parameter is the mesh representation of the CAD model which is submitted to the AM machine for slicing (and/or *g-code* production) and printing. Models are exported as polygon meshes, commonly in the form of a triangular mesh in an STL file. We define the mesh complexity C of a CAD model M that is converted to a mesh that consists of a set of triangular faces *F(M)* that approximates the initial CAD model as $C_M = |F(M)|$.

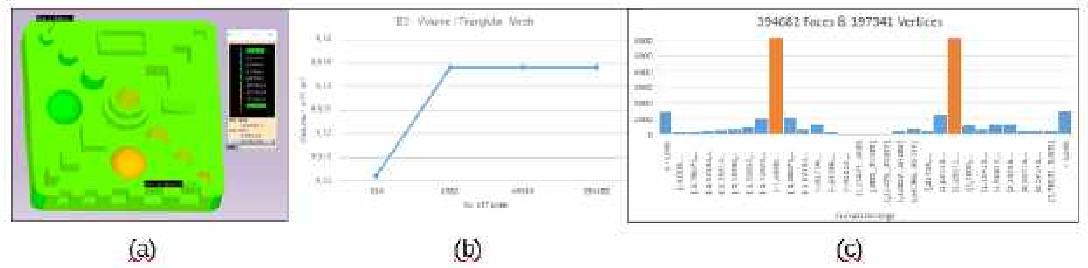

Fig. 1: Benchmark model representing (a) curvature analysis on the initial model, (b) deviation graph between different surface qualities and (c) histogram of the highest quality mesh

Models with lower resolution meshes produce printed models that exhibit significant deviations from the original model through loss of detail and surface quality reduction as presented in Fig. 1. Mesh complexity is also related to the morphology of the model since surfaces of high curvature must be represented by higher resolution meshes to better approximate the initial CAD model geometry[7].

In this work we examine design characteristics and rules that must be enforced for a CAD model to ensure its printability using a specific AM technology while a print failure may occur because of structural problems (e.g. a collapsed wall), dimensional accuracy deviations (e.g. holes with a smaller diameter), functionality and assembly issues (e.g. a fitting screw) and secondary reasons such as high level of detail on a small surface part or post-processing issues (e.g. removal of multiple support structures).

To this end, we propose a suite of part characteristics based on best design practices depicted in Fig. 2 that ensure structural robustness such as walls, holes, pins etc. There are also design guidelines defined for achieving distinct level of detail for embossed or engraved parts or pertain to support construction which should be added in the case of overhangs and bridges (for some AM machines) to achieve printability. Lastly, there are design rules that refer to tolerance and dimensional accuracy issues and practices that ensure the functionality of connected and/or moving parts. Several examples are used that characterize 3D printability by translating such rules and practices with respect to the FDM, 3DP and Polyjet 3D printing technologies, the presented framework can be used to characterize printability in other AM technologies as well by tuning model parameters.

A Characterization of 3D printability:

In this work we define a measure that characterizes the printability P of a model M on a 3D printing technology T. This printability score is expressed by a number on a scale of 0 to 100, where 0 is a model that will result in a print failure on a specific printing technology and 100 corresponds to a model that is structurally robust amd flawless when printed using a specific AM technology. The printability score is defined by two factors: the global probability function(GP function) and the part characteristic probability function (PCP function).

The GP function expresses the probability of printing problems due to the printing characteristics of

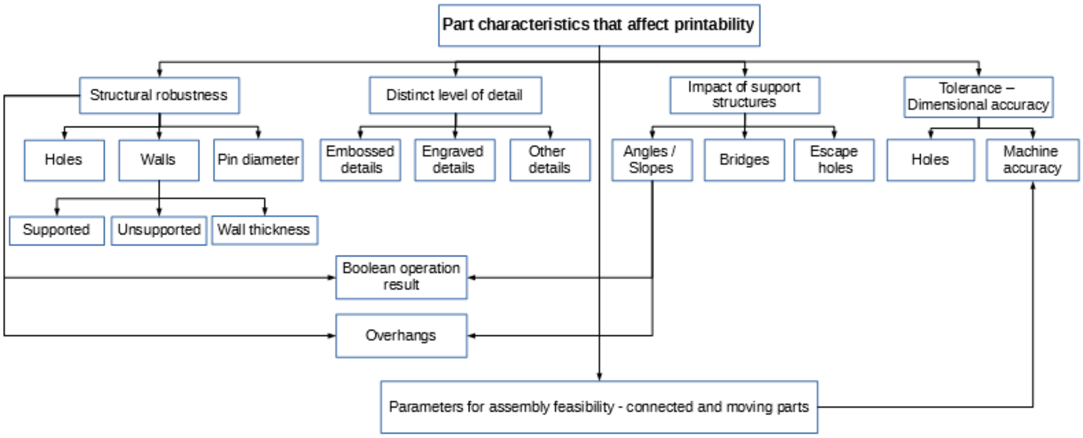

Fig. 2: Part characteristics

the AM machine to be employed and the model mesh complexity. If $P_G(C_M, T)$ is the GP function for printing problems on a technology T, based on the mesh complexity C_M of the model and the technology used, then $(1 - P_G(C_M, T))$ is the corresponding probability function for a successful print.

A meshed model M can also be described by a set of part characteristics i, that affect the printability of the model. If $P_F(i, D, T, A)$ is the probability of a part characteristic i with a set of characteristic parameters D to exhibit a flaw regarding an application A that will affect the entire printed model for a specific printing technology T, then $(1 - P_F(i, D, T, A))$ is the probability of the part characteristic to lead to a successful overall printing result. The overall probability of a model M to be successfully printed on technology T is:

$$P(M, T) = (1 - P_G(C_M, T)) * \prod_{1}^{n}(1 - P_F(i, D, T, A)) \tag{1}$$

Then the printability measure (score) of M on T is:

$$PS(M, T) = 100 * P(M, T) \tag{2}$$

Global Probability Function

The GP function is related to the machine characteristics h of the technology employed for printing such as accuracy, surface texture, abnormalities and support construction and for each one an initial quality score $QS_T(h)$ was assigned. This quality score was transformed into probability values with "***" meaning that the characteristic will hardly have a negative effect on the printing process and a small probability value, e.g. 0.1, will be assigned to this characteristic whereas a lower quality score of "*" means that this characteristic will have a negative effect on the process and so a higher print penalty, such as 0.9 is applied.

The quality score QS_T of a specific technology T corresponds to the product of the quality score of each of $m = 4$ selected characteristics (Equation 3).

$$QS_T = \prod_{h=1}^{m} QS_T(h) \tag{3}$$

The other factor that determines the global probability function of a model on a specific technology is mesh complexity. Therefore, we assign a quality score QS_{C_M} to the model based on the ratio of the mesh surface area A_M and the surface area A_O of the original CAD model. This ratio expresses the probability of a satisfactory printing result due to mesh resolution (Eq. 4).

$$QS_{C_M} = A_M/A_O \tag{4}$$

Therefore, the probability of an inadequate printing result is expressed by $1 - QS_{C_M}$, and as such the the GP function of a model M is evaluated by Equation 5:

$$P_G(C_M, T) = k * QS_T * (1 - QS_{C_M}) \tag{5}$$

where k is a constant ($k > 0$) that changes the sensitivity of the GP function, intensifies or reduces its overall contribution to the printability score.

Part Characteristic Probability Function

For each design part characteristic i we determine a part characteristic probability function P_F that depends on the printing technology T, the design characteristic i and the application A. A part characteristic i that falls under the categorization depicted in Fig. 2 is susceptible to flaws occurring for each design rule that is violated (since this increases the probability of a print failure). To determine the flaw probability function $P_F(i, d, T, A) = f(w(T, i), s(A, i))$ of a part characteristic we consider the following parameters: (i) The weight $w(T, i) \geq 0$ is a numerical parameter that depends on the technology and the design characteristic, and is the dimension value of the design characteristic i that has probability 0.5 to exhibit a significant flaw during printing on technology T. This parameter can be determined by the thresholds reported by [2]. (ii) The significance $0 < s(A, i) \leq 1$ expresses the impact of the corresponding design characteristic i on the printed model regarding application A. The corresponding formula that describes function f is presented in the extended journal version of this paper.

Validation of the printability measure through test cases:

The evaluation of our proposed scoring method was performed using three AM machines representing different technologies: FDM(Ultimaker 3 Extended), 3DP(ZCorp 450) and Polyjet(Stratasys Connex3 Objet 260).

The test models used for evaluation were geometric primitives (sphere, torus, rectangular parallelepiped and cylinder) and three benchmark models (Fig. 3). The printability score for each model on each technology was calculated before printing, and verified after printing, the results are reported in the extended version of the paper.

Fig. 3: Benchmark models manufactured on three AM machines.

Conclusions:

In this paper we have proposed a novel approach to characterizing the efficacy of manufacturing a designed CAD model on an AM machine of a certain technology, based on its model complexity and part characteristics. These elements are mapped to parameters and functions, that make up a linear formula that corresponds to a *printability* score. This measure, which is evaluated using worst case printing scenarios, can be used either to determine which 3D technology is more suitable for manufacturing a specific model or can be used as a guide to redesigning the model so that it is more suitable for an intended specific technology.

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