Title:
Property Estimate for Inkjet based Direct Digital Manufacturing

Authors:
K. M. Yu, mfkmyu@polyu.edu.hk, The Hong Kong Polytechnic University
Y. M. Tang, mfymtang@polyu.edu.hk, The Hong Kong Polytechnic University
L. C. Chan, lc.chan@polyu.edu.hk, The Hong Kong Polytechnic University

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Introduction:

Nowadays, additive manufacturing (AM) is one of the easiest, fastest and most flexible technology for turning 3D design into a real object without machining, molding or assembly. There exist many kinds of AM technologies including selective laser sintering (SLS), stereolithography (SLA), Fused Deposition Modeling (FDM), InkJet Printing, etc. Common materials include aluminum, steel alloys, precious metals, plastics, etc. Table 1 summarized the number of colors and materials supported by various AM technologies.

Technology	**SLS**	**SLA**	**FDM**	**InkJet**
Color	Single	Single	Up to Four	Colorful
Materials	Single	Single	Single or two	Multiple

Tab. 1: Comparison of different AM technologies.

Common AM technologies include FDM, SLA and InkJet Printing. Despite the most updated FDM technology can produce models with up to four colors, most of the FDM machines can only produce plastic objects with 1-2 colors and materials. Although SLA can produce polymer objects with high precision, the fabricated objects are usually in single color and material. In order to fabricate an object with different colors and materials, Inkjet based direct digital manufacturing (DDM) is one common solution. DDM is the process of using a 3D digital CAD model for directly fabrication without the need for process planning [2], [5]. There are several major Inkjet based DDM such as 3D printing (3DP) and MultiJet Printing (MJM) are developed by MIT, while PolyJet and PolyJet Matrix are developed by Stratasys. However, most of the Inkjet based 3D printers can only support a few colors and materials. PolyJet Matrix type technology not only able to fabricate multiple color objects, it can also fabricate object with range of material options, and can even combine several materials into a single 3D printed model. Due to these reasons, development of PolyJet Matrix type 3d printers is growing very fast nowadays. Table 2 summarized the capability of different Inkjet based DDM technologies.

Inkjet based DDM	**capability**
MIT 3DP™	Multi-colour & FGM [3]
MJM™	Single material, single colour

PolyJet™	Single material, single colour
PolyJet Matrix™	multiple material, multiple colour

Tab. 2: The capability of various Inkjet based DDM technologies.

PolyJet Matrix Technology works by simultaneously jetting and blending two or more FullCure photopolymer model materials combined to produce multi-material parts [11] and to create up to thousands of new composite materials called Digital Materials [12] that have the desired mechanical and physical structures. The technology can achieve a range of hues, translucencies, and other properties. The FullCure model materials are jetted from designated print head nozzles according to location and model type, providing full control of the structure of the jetted material and its mechanical properties. The materials are jetted in ultra-thin, 16-micron layers onto a build tray, layer by layer, until the part is completed. Each photopolymer layer is cured by UV light immediately after it is jetted, producing fully cured models that can be handled and used immediately, without post-curing. The gel-like support material is easily removed by hand or water Jet. PolyJet Matrix printing block is built from 8 printing heads. Heads 1 and 2 are used to jet model material A, while heads 3 and 4 are used to jet model B. Heads 5 to 8 jet the support material [8]. Fig. 1 illustrates the PolyJet Matrix printing blocking and its working principle. Digital Materials are multi-phase composite materials based on a combination of different FullCure modeling materials [14].

The variability on mechanical properties of parts manufactured using PolyJet has been studied by Kesy and Kotlinski [6]. They found that the differences of the material properties is related to variations in the amount of UV energy that reaches the different zones. The UV exposure time is the main parameter affecting the final material strength. Besides, slight variations in temperature may have significant influence upon mechanical performance of the materials. In spite of numerous researches have been done on modelling mechanical properties in AM parts, a complete characterization of 3D part behavior still has great complexity due to both layer-upon-layer nature, temperature effect and various UV radiation pattern strategies [4]. In this research, we propose to estimate the property of the inkjet material fabricated by the DDM in a reasonable range. The research not only helps the designer to fabricate a prototype with desired materials, it can also facilitate the researches in improving the 3d printers' development.

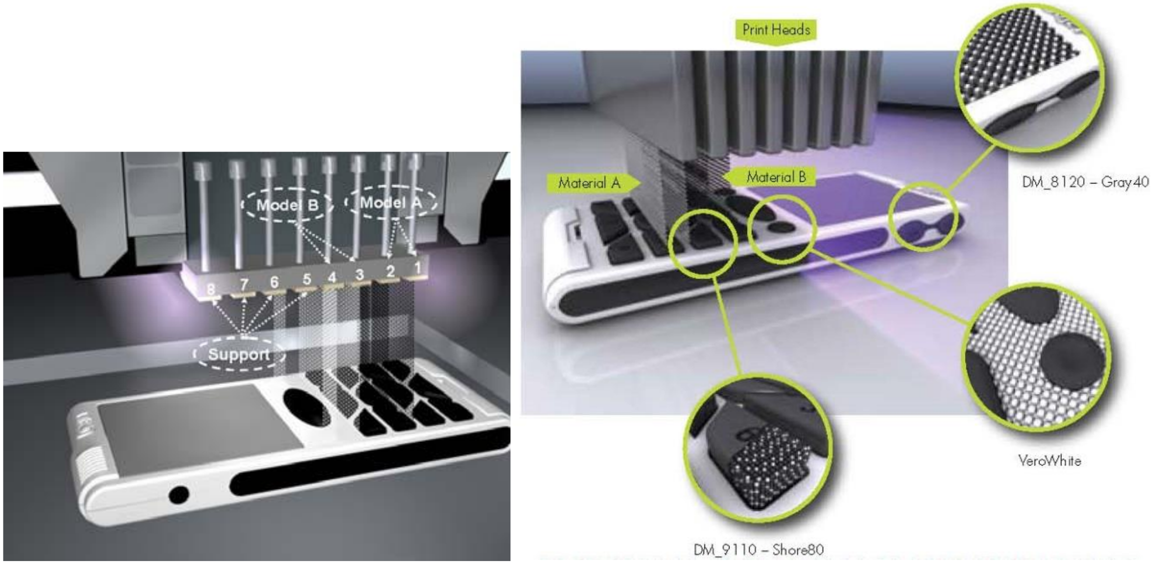
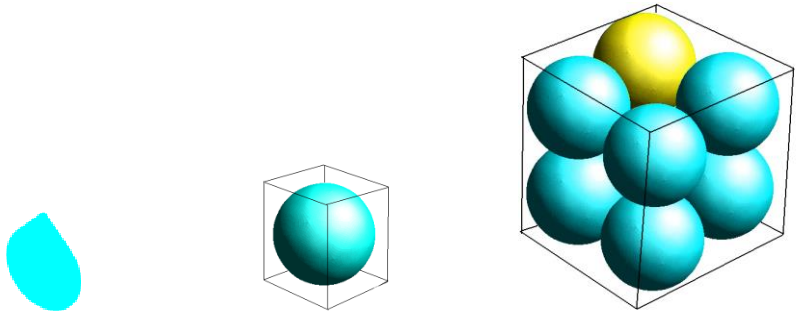


Fig. 1: The PolyJet Matrix printing block and its working principle [10].

Methodology:

In materials science, various properties of a composite material can be predicted by using a weighted mean called a rule of mixtures [13]. For instance, it provides a theoretical upper- and lower-bound on mass density, modulus of elasticity, shear modulus, Poisson's ratio, ultimate tensile strength, thermal conductivity, electrical conductivity, and coefficient of thermal expansion. In general there are two models, the Voigt one for axial loading or constant strain, and the Reuss one for transverse loading or constant stress. Mathematically, the former is formulated with arithmetic sum while the latter with harmonic sum. Graphically, they are represented as straight line (upper-bound) and rectangular hyperbola (lower-bound) respectively.

In order to create a 3D model, PolyJet Matrix Technology simultaneously jetting two or more FullCure model materials. Each jetted material is an inkdrop which can be considered as a voxel in 3D space (Fig. 2.). A 3D texels is an array of voxel composite together to form a tiny element of an object. For instance in Fig. 2(b)., a texel with 8 voxels is formed by 7 voxels of material 1 and 1 voxel of material 2. Different materials can be obtained by varying the combinations of two or more model materials [7].



(a) inkdrop (b) voxel (c) 3D texel

Fig. 2: Inkdrop approximation for the formation of a composite material.

Referring to [13], multiple materials can be represented by the arithmetic sum and harmonic sum in discrete form is given by Eqn. (6.1) and Eqn. (6.2):

$$\left(\sum_{\forall i} n_i\right) \mathit{Parithmetic\ sum} = \sum_{\forall i} n_i p_i \qquad (6.1)$$

and

$$\frac{\sum_{\forall i} n_i}{\mathit{Parithmetic\ sum}} = \sum_{\forall i} \frac{n_i}{p_i} \qquad (6.2)$$

where i is material/ color. For a texel with 8 voxels,

$$\sum_{\forall i} n_i = 8 \qquad (6.3)$$

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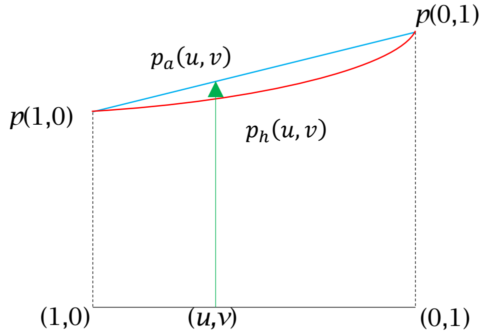

Fig. 3: Continuous interpolation between two materials.

Suppose two materials are blended continuously, the property function such as tensile strength, $p(u, v)$ can be estimated by the interpolation between these two materials. Given the number of inkdrop n_1 and n_2 for materials 1 and 2, the material proportions in the straight line interval (u, v) is calculated by $u = \frac{n_1}{n_1 + n_2}, v = \frac{n_2}{n_1 + n_2}$, such that $0 \le u, v \le 1$, and $u+v=1$ (see Fig. 3.) Given material proportion (u, v) and using forward mapping, the material property limits $p_h(u,v)$ and $p_a(u,v)$ can be determined by:

$$\begin{cases} p_a(u,v) = u * p(1,0) + v * p(0,1) \\ \dfrac{1}{p_h(u,v)} = \dfrac{u}{p(1,0)} + \dfrac{v}{p(0,)} \\ u + v = 1 \end{cases} \tag{6.4}$$

where subscripts a and h represent arithmetic (straight line) and harmonic sum (rectangular hyperbola) respectively.

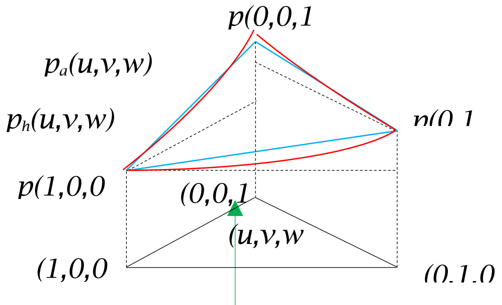

Fig. 4: Continuous interpolation between three materials.

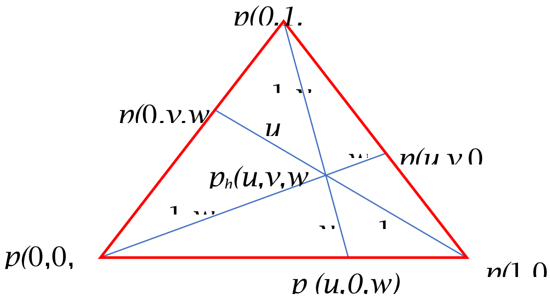

Fig. 5: Top view of the triangular element.

Similarly, we can extend the continuous blending models into three different model materials. The material proportions in triangular region (u, v, w) is calculated by: $u=\frac{n_1}{n_1+n_2+n_3}, v=\frac{n_2}{n_1+n_2++n_3}, w=\frac{n_3}{n_1+n_2++n_3}$, such that $0 \le u, v, w \le 1$, and $u+v+w = 1$ (Fig. 4. and Fig. 5.)

Given the material proportion (u, v, w) and using forward mapping, the material property limits $p_h(u,v,w)$ and $p_a(u,v,w)$ can be calculated by:

$$\begin{cases} p_a(u,v,w)=u*p(1,0,0)+v*p(0,1,0)+w*p(0,0,1) \\ p_h(u,v,w)=\wp p(u,v,w) \end{cases} \tag{6.5}$$

where subscripts a and h represent arithmetic (triangle) sum and harmonic sum (tri-rectangular hyperbola Coons patch) respectively, and $\wp$ is the Boolean sum (triangular Coons patch) [1]. In the Eqn. (6.5), the harmonic material property limit is calculated by:

$$\wp p(u,v,w)=(1-u)*p\left(0,\frac{v}{v+w},\frac{w}{v+w}\right)+(1-v)*p\left(\frac{u}{u+w},0,\frac{w}{v+w}\right)+(1-w)*p\left(\frac{u}{u+v},\frac{v}{u+v},0\right)$$
$$-u*p(1,0,0)-v*p(0,1,0)-w*p(0,0,1)=z-coordinate$$

$$\wp p(u,v,w)=(1-u)*p(0,v,w)+(1-v)*p(u,0,w)+(1-w)*p(u,v,0)-u*p(1,0,0)-v*p(0,1,0)-w*p(0,0,1)$$

The 3 rectangular hyperbolic boundary curves from harmonic sum are:

$$\frac{u+v}{p\left(\frac{u}{u+v},\frac{v}{u+v},0\right)}=\frac{1}{p(u,v,0)}=\frac{u}{p(1,0,0)}+\frac{v}{p(0,1,0)}$$

$$\frac{v+w}{p\left(0,\frac{v}{v+w},\frac{w}{v+w}\right)}=\frac{1}{p(0,v,w)}=\frac{v}{p(0,1,0)}+\frac{w}{p(0,0,1)}$$

$$\frac{u+w}{p\left(\frac{u}{u+w},0,\frac{w}{u+w}\right)}=\frac{1}{p(u,0,w)}=\frac{u}{p(1,0,0)}+\frac{w}{p(0,0,1)}$$

Similarly, we can extend the continuous blending models into four or more different model materials. However, since Stratasys Connex machines make use of 3 colors: cyan, magenta and yellow, and support up to 3 model materials, the arithmetic and harmonic material property limit is not discussed in this article.

Results:

In order to verify the material property of the digital materials that falls within the range of the arithmetic and harmonic limit of the proposed models. We have compared the tensile strength of the digital materials obtained in [9] with the arithmetic and harmonic limit results calculated using Eqn. (6.4). Tab. 3 summarized the results of the tensile strength between the digital material and the corresponding material limits. Fig. 6 shows the relationship between the digital material and the material limits. The x-axis indicates the number of voxels with material A in a texel, whereas y-axis is the tensile strength.

		Tensile Strength [MPa]				
n_A	n_B	$\sigma_{arithmetic\ sum}$	$\sigma_{harmonic\ sum}$	Digital Material	Trade name	
0	8	49.8	49.8	49.8	Vero White Full Cure 830	Base
1	7	43.825	12.48902821	42	DM 8120	Digital
2	6	37.85	7.139784946			
3	5	31.875	4.998745295	30	DM 8130	Digital
4	4	25.9	3.845559846			
5	3	19.925	3.124705882			
6	2	13.95	2.631439894	9	DM 9130	Digital
7	1	7.975	2.272675414	4	DM 9120	Digital
8	0	2	2	2	Tango Black Full Cure 970	base

Tab. 3: The tensile strength between the digital material and the proposed material limits.

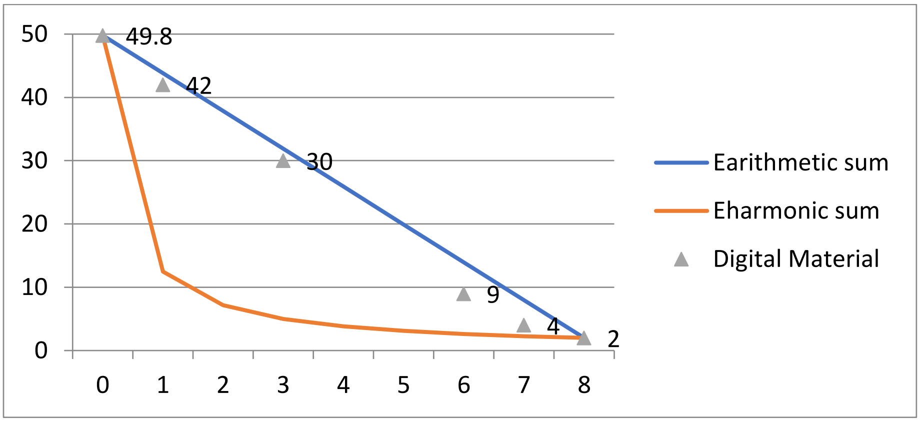

Fig. 6: The tensile strength relationship between the digital material and the proposed material limits.

Conclusion:

Nowadays, PolyJet matrix is one of the common and important technologies in DDM. In spite of numerous researches have been done on modelling mechanical properties in AM parts, a complete characterization of 3D part behaviour still has great complexity due to its multi layers nature, temperature effect and various ultra-violet (UV) radiation pattern strategies. In this research, we propose to estimate the property of the inkjet material in a reasonable range within the upper boundary using arithmetic sum and lower boundary using harmonic sum. We have suggested a mathematical model to approximate the boundaries of the arithmetic sum and harmonic sum. By comparing the material property of the digital material obtained from a literature with our proposed models, we have found that the material property of the digital material fits into the range of our calculated arithmetic sum and harmonic sum. Nevertheless, there are some limitations of this research. The digital material properties vary according to the setting such as UV and other external factors such as temperature. On the other hand, the comparison results only focused on the composition of two model materials. The mathematical models for the composition of three or more model materials have not been verified. In the future, more experiments should be done to determine the material properties of different digital materials with different AM technologies in order to have a more comprehensive comparison between different kinds of digital materials and their properties (e.g. Young's modulus or tensile strength) with the results of the calculated models.

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