Modulated Extrusion for Textured 3D Printing

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Abstract

This research utilises a Fused Deposition Modelling 3D Printer to investigate the aesthetics of 3D printing and it's broader applications. The presented research re-evaluates the 3D printer as a tool to manipulate materials, as opposed to a machine that discretely reproduces digital models at a fine resolution. The research questions the utility of automation, and attempts to find a level that permits materially expressive modes of fabrication. The exploration of aesthetics has uncovered a variety of unexpected textures and interesting material properties that may have wider use. For instance, rigid plastic has been extruded and manipulated finer than the extrusion nozzle diameter, which confers flexibility and fabric like qualities to the printed object. The discovered techniques for 3D printed aesthetics are reproducibly reliable and can be incorporated back into orthodox digital-model driven fabrication.

Introduction

This research investigates the aesthetics of 3D printing and it's broader applications. Figure 1 demonstrates a texture generated through the presented research.

Figure 1. *An example of a 'plucked' textured*

3D Printing, also known as Additive Manufacturing or Rapid Prototyping, is the fabrication of objects by the sequential deposition, fusing, laminating, binding or curing of materials along a machine actuated toolpath. 3D printing has existed as an industrial technology for some 25 years; recently there has been a large growth in low-cost 3D printers aimed at the general consumer market[32]. This change in market has opened up the technology from purely industrial or high-end usage to a wider audience with growing expectations[5].

Despite being developed primarily for industrial use, 3D printing has been used in the visual arts since the early 1990s. Early adopters in the field of sculpture include Masaki Fujihata, Peter Terezakis, and Dan Collins[10]. A distinct advantage of 3D printing is the ability to print complex or fine geometries not possible or not practical with subtractive manufacturing or traditional methods. More recently complex geometry has been exploited for exquisite form by artists and designers such as Joshua Harker[11], Kevin Mack[16], Nervous System[18] and Xuberance[34].

Complex geometry is largely afforded by the fine mechanical movement and computer numerical control that underpin a 3D printer. Using a 3D printer typically begins with the creation of a digital 3D model drawn in a computer aided design (CAD) package, or the manipulation of a 3D digital scan of an object through CAD. The complexity of machine automated fabrication is subsequently determined algorithmically through a process commonly referred to as slicing. Slicing decomposes a digital 3D model into layers, machine toolpaths and material operations. These aspects are taken as usefully automated, alleviating the otherwise intense human labour and dexterity required if fabricated manually.

Importantly, slicing algorithms encapsulate sensibilities[23] such as the efficient use of materials [22], optimisations minimising the time of fabrication [14], and the reduction of the appearance of layers [2]. When authoring in CAD, these sensibilities are to a large degree abstracted away. In terms of a creative process, a skilled CAD user could be considered a digital craftsperson, who by familiarity anticipates the constraints and affordances of the consequent 3D printing process[17]. A clear example of the influence of the current 3D printing process within art and design is perhaps 3D printed fashion, which often resemble intricate and striking chainmail rather than conventional fabric garments[29][6][34].

Authoring from a primarily CAD perspective, it is useful that slicing algorithms and 3D printing hardware work together to provide a consistent, predictable medium. 3D printers have therefore come to be appraised by how closely they reproduces any given digital model, usually by surface detail[33][23]. By this metric slicing algorithms have been developed to adapt layer thickness[9][22][30] and to deposit non-planar (curved) layers[2][7][12]. Similarly, hardware development examples include deposition quantity variation during printing[1], six axis movement in deposition dexterity[27], and continuous 'layerless' build progression[3].

From a top-down CAD perspective, any form can be described computationally and the restriction appears in determining and executing fabrication. Chiu et al[4] note, whilst printing fractal forms of infinite recursion, that it is the machine that ultimately provides the discerning resolution of 3D printable features. This is not a broadly limiting factor however; 3D printing exists at the nanometer scale[13], micrometer[28][35], and upward to the scale of habitable buildings. Rather, it is important to consider the contextual application of any given 3D printing technology.

The recent growth of low-cost 3D printers has transposed an industrial tool into the more widely accessible domain of consumers, artists and designers. A burgeoning question has become:

whilst something could be 3D printed, is it useful or desirable to do so? To transcend 3D printing for novelty's sake, a pertinent question facing new 3D printing applications is whether the methods of fabrication and uses of material are sympathetic to the form and/or function of a 3D printed object.

There is a precedent for a material and function focused CAD approach to 3D printing. The properties of fused deposition are exploited at the toolpath level through anisotropic deposition to confer strength in a similar way to wood grain[26][2]. Fused deposition filament is also exploited for optical transmission, reflective and refractive properties[8]. Volumetric CAD methodologies have been developed that model and simulate objects composed of heterogeneous materials of variable properties, which are subsequently 3D printed for largely structural gains[19][20][21].

An important distinction versus the presented research, is that the above cited research utilise a 3D printer to fabricate in measured and discrete units of material, placing the machine as the end-point mode of reproduction for a top-down CAD methodology. The presented research explores the premise that the materials themselves may have expressive and physical qualities that are otherwise hidden behind algorithmic automation.

An alternative to a top-down CAD driven approach is a bottom-up process which first of all explores the process capabilities of the materials and machine in synergy. An approach that subverts the orthodox worflow is often taken by artists and designers in the pursuit of a unique, elegant or meaningful expression that transcends expectations of the medium[31]. Such explorations are currently emerging outside of large industry and academia through access to low-cost 3D printing technology. For instance, Project Silkworm[24] experiment with extruded plastics and toolpath configurations similar to weaving and spirographic mark making. Their approach utilises the ability to stretch and bind hot extruded plastics.

The presented research also pursues the bottom-up, material-centric approach. The research has excluded the use of a CAD environment, digital models, and conventional slicing algorithms, for the sake of direct access to the fundamental operations of a 3D printer. The research re-evaluates the 3D printer as a tool to manipulate materials, as opposed to a machine that discretely reproduces digital models at a fine resolution. The following sections document an investigation made with a Fused Deposition Modelling type 3D printer. With direct control of the printer operation, a variety of texture fabrication techniques have been demonstrated that rely on the dynamic material properties at the point and time of extrusion and deposition.

Methodology

The following techniques have been developed using a low-cost Rostock Max 3D printer kit, fabricating three dimensional objects by depositing molten plastics via extrusion through the X, Y and Z axis onto a stationary bed. Consumer grade PLA plastic filament has been used, measuring 1.75mm diameter, and extruded through a 0.45mm nozzle at 175 degrees celcius onto a heated bed at 75 degrees celcius. These parameters are set and remain fixed when the 3D printer is activated.

Normally slicing software determines fabrication toward efficiency and a high degree of consistency between print jobs. The following methodologies intentionally vary the properties of deposition throughout a print process to alter the aesthetic appearance of the produced object. To achieve this, slicing software has been abandoned, and instead operational commands are sent to the 3D printer directly, exposing key variables to research. The techniques are described through this section.

The following methods have been developed at the level of the GCode standardised protocol, which is sent to the 3D Printer in real time. Object geometries were defined algorithmically, describing simple generalised shapes on which to study textures and aesthetics. The 3D printer receives spatial coordinates, movement speed and extrusion rate information in a command string such as *'G0 X10.5 Y-20.7 Z0.30 E2.33 F2000'*. These methods utilised the line number error checking available in firmware to ensure commands were received by the 3D printer.

Spiral Toolpath

The following techniques have all utilised a spiralling toolpath which continuously increments the Z axis (vertical) whilst traversing the object circumference. Using this approach, the extruder deposition accumulates cleanly and without a marked layer transition. It also relieves the need to stop or retract the extrusion. The principle equation for a spiral toolpath is:

$$Z_{inc} = L_{Height} / \frac{C_{object}}{M_{step}} \tag{1}$$

where Z_{inc} is the necessary increment in Z height per movement step, M_{step}; C_{object} is the known circumference of the printing object geometry; and L_{height} is the known height of a single layer of deposited material. These experiments used $L_{height} = 0.15mm$, and $M_{step} = 0.2mm$.

To print a cylinder, resolving X and Y coordinates from angular position, the following pseudo-code would be effective:

Algorithm 1 Spiral toolpath for a cylinder

```
procedure SPIRAL_MOVE
    $z = 0$
    radius = 10
    while z < object_height do
        angular_step = $(2 * \pi) / C_{object} / M_{step}$
        $Z_{inc} = L_{height} / C_{object} / M_{step}$
        $angle = 0$
        while angle $\leq (2 * \pi)$ do
            $x = radius * cos(angle)$
            $y = radius * sin(angle)$
            Execute_Move( x, y, z )
            $z = z + Z_{inc}$
            $angle = angle + angular\_step$
```

Calibration Routine

To produce the range of presented textures two key variables have been explored; the rate of extruded material, and the velocity of the extrusion nozzle. These two properties are each used within a maximal and minimal range of utility.

These two properties are interesting because the plastic extrusion is at melting point, and is therefore able to be manipulated whilst it solidifies. The values have been determined through trial-and-error and should be expected vary between machines. It is therefore necessary to calibrate the values, at which point reliable performance can be gained. At the very limits of practical extrusion and nozzle speed, the printing process is sensitive to changes in the environment, such as the flow of air through the build envelope of the machine.

To calibrate the range of practical extrusion it is useful to first run Algorithm 1 and to systematically alter the rate of extrusion with respected to the progression of printing height. Starting at zero height, a maximum extrusion rate (E_{max}) should be evaluated and set to produce a number of consistent layers as would be expected by conventional 3D printer output.

A minimum extrusion rate (E_{min}) can then be found by reducing the extrusion rate as the printing height increases. E_{min} may appear to fail by conventional 3D printing standards, however, the experimenter should continue to observe for a consistent and reliable appearance, such as shown in figure 3. Once cohesion between deposition entirely fails, E_{min} has been found. When using GCode, E_{max} and E_{min} are in units of length (mm) of filament fed into the extruder mechanism, interpolated across each M_{step}. This research has successfully used values $E_{min} = 0.001$ and $E_{max} = 0.01$ with M_{step} fixed at 0.2mm.

Once E_{min} and E_{max} have been set, the nozzle movement velocity can be usefully explored. Following Algorithm 1 again, set the extrusion rate fixed as E_{max} and increase the overall velocity of movement of the printer with respect to printing height progression. In GCode, this can be achieve with the ‘feedrate’ property of the command string, measured in mm per minute. The maximum nozzle velocity V_{max} should be recorded when the deposition appears sparsely, as it would with an extrusion rate set at E_{min} (figure 3). The procedure is then mirrored to discover the minimum nozzle velocity V_{min}, except the experimenter should observe a solid deposition at low velocity despite having set the extrusion rate to E_{min}. This research successfully used values $V_{min} = 300$ and $V_{max} = 3500$.

These calibration procedures demonstrate the relationship between the extrusion rate of plastic filament and the velocity of movement of the 3D printer; that sparse deposition can be achieved with either nozzle velocity or extrusion rate. An understanding of this relationship permits further exploration towards reliably fabricating new aesthetics and material properties.

Under-extrusion: Gauze Effect

A gauze effect can be reliable fabricated by under-extruding plastic filament relative to the nozzle velocity. The principle mechanism is illustrated in figure 2, and can be summarised as extruding and stretching singular blobs of molten filament along the direction of travel.

At high nozzle velocity the apparent diagonal striation forms an angle closer to horizontal. At low nozzle velocities the striation can be brought to near a vertical angle. The interplay of nozzle velocity to a low extrusion rate, and the resultant effects on striation pattern, is a material dynamic related to the time of solidification of the plastic once it departs the hot nozzle and cools.

This state of deposition has interesting physical properties. The inter-striation filaments are sub-millimetre in measurement. The gauze has a limited amount of stretch and compression, but a reasonable amount of torsional and lateral flexibility (figure 4).

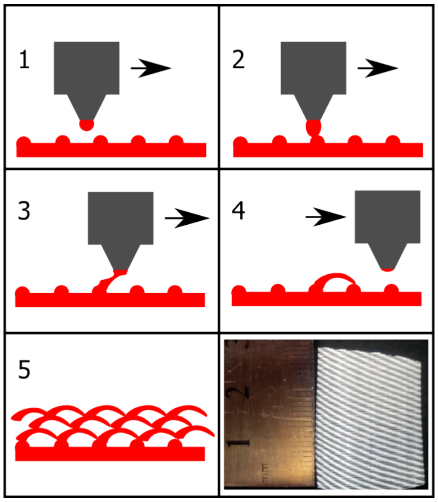

Figure 2. *An illustration of drawing filament out of the nozzle quicker than it is extruded. The filament is at melting point and stretches in the direction of travel, bonding to any available surface. The direction, strength and angle of diagonal striation is relative to the direction and velocity of the nozzle.*

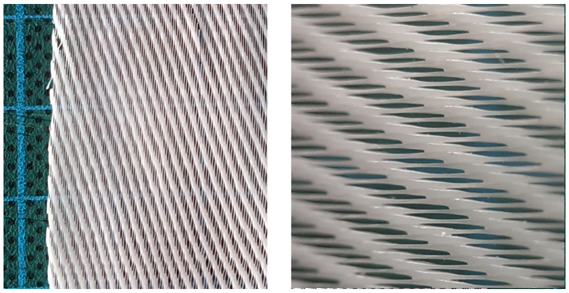

Figure 3. *Left: the gauze effect, grid squares are 10mm spaced. Right: Macro photograph capturing the fine strands of manipulated material.*

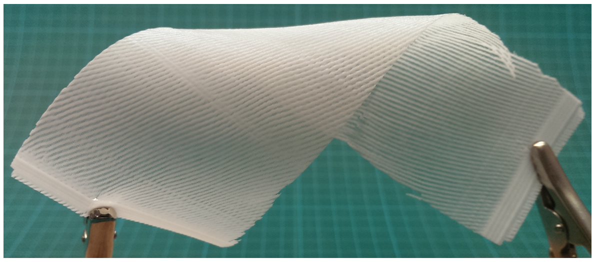

Figure 4. *A gauze printed with standard rigid PLA, consequently has reasonable flex and more fabric-like qualities.*

Modulated Extrusion: Lace Effect

A lace effect (figure 5) can be achieved by varying between gauze effect and a solid deposition. This effect is most reliably achieved when the nozzle speed is varied, rather than extrusion rate. The extrusion mechanism appears to have an unreliable back pressure, or ooze, that makes it unsuitable for quick modulation. This may be due to the long filament feed (a Bowden Tube) particular to the Rostock type of printer, that causes compression along the length of fed filament. Modulating the nozzle velocity whilst keeping extrusion constant mitigates this issue. Figure 5 was achieved by geometrically mapping a greyscale bitmap image of a floral pattern to the surface of a cylinder. For each angular and z position about the cylinder, the respective x and y pixel value was read and linearly interpolated to determine the nozzle velocity in range $V_{min} : V_{max}$. The object was printed as a cylinder and then cut along it's length to open up as a flat panel.

Figure 5. *An example of 'lace' like aesthetic created by modulated nozzle velocity.*

Radius Modulation: Wall Thickening

The spiral toolpath, as a mechanism for uninterupted deposition and extrusion, is most suitable to use when printing single wall objects with no internal material. This characteristic prompted the development of a technique for thicking the perimeter of a printed object in a single pass. This technique is illustrated in figure 6.

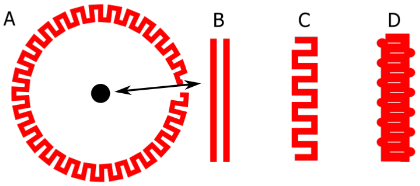

Figure 6. *Creating thick walls on a spiral path using an oscillating modulation of radius (A). Conventional methods use adjacent perimeters with an in-fill if necessary (B). The modulation can be altered to provide indentations (C) or textured relief(D).*

Figure 7. *An image of the bobbled texture and a macro photo of wall thickness inset.*

The period and magnitude of the radius modulation be calibrated to achieve a smooth surface and generate a thicker perimeter wall. Alternatively, the radius modulation period can be set for an intentionally high density, which results in stochastically displaced deposition. This technique can be used asthetically to produce a bobbling technique, similar to that found on woolen garments, shown in figure 7.

Modulated Thickness: Emboss & Relief

The modulated radius technique can utilised to fabricate an embossed or relief texture in a similar way to the lace technique. Figure 8 was created by using a greyscale bitmap image of a leaf to control the variation in radius modulation magnitude. The x and y pixel values of the image were read relative the angular and z position of the printing progression, essentially wrapping the image around the object geometry.

Figure 8. *An example of 'embossed', or 'relief' texture.*

Radical Departures: Unsensible Toolpaths

Beyond relatively small variations to the velocity of movement and rate of extrusion, it is possible to explore toolpath variations that far exceed conventional ideas of practicality and sensibility. Such criteria are determined when viewing the 3D printer as an end-point tool for reproducing CAD derived digital models. If the 3D printer is positioned as a tool for manipulating materials, then it is a matter of interest to explore the limitations of worked materials.

Figure 9. *A 'hairy' texture, which can be printed consistently yet retains a unique character bestowed by the material medium itself.*

In figure 9, the 3D printer has been instructed to periodically print directly away from the centre of the object geometry, by 20mm, on the horizontal plane into empty space. The extrusion rate is zeroed at the departure point, and it is the movement of the extrusion nozzle that draws out a hair-like filament of plastic. This plastic stiffens in the air, suspended without support. The printer is then instructed to return to the object geometry and continue printing the perimeter. This process creates a texture that is stochastic - it is both consistently 'hairy', yet each filament is entirely unique in character.

Figure 10. *A 'plucked' texture, with macro photo inset detailing state of manipulated material.*

Similarly, figure 10 was created by adding a periodic yet fast oscillation to the nozzle movement, similar to a zig-zag stitch of a sewing machine. This has the effect of plucking the deposition away from the object geometry.

Conclusions

This paper has described the context and motivation for a very material and machine based exploration of a Fused Deposition Modelling type 3D printer. The exploration has excluded the use of a CAD environment, digital models, and conventional slicing algorithms, for the sake of direct access to the fundamental operations of a 3D printer.

The presented research re-evaluates the 3D printer as a tool to manipulate materials, as opposed to a machine that discretely reproduces digital models at a fine resolution. With direct control of the printer operation, a variety of texture fabrication techniques have been demonstrated that rely on the dynamic material properties at the point and time of extrusion.

The exploration of material manipulation has generated textures and a 3D print aesthetic that are largely stochastic - that is, the textures can be consistently and reliably reproduced, yet they retain an unpredictable and unique character bestowed by the material itself. The techniques therefore take advantage of both the automation of a 3D printer as well as the broader potential of the material. This synergetic approach can be considered a step closer to a sympathetic use of process/material and form/function.

The research hypothesis is that existing advanced, automated technologies which have been commercially developed for reliability and consistency, may infact obscure other latent potential. The presented research has been holistic in approach, developing an intimate understanding of material, machine and process, and therefore may contribute to the debate on the standing of digital craft versus traditional craft. With some thought, the philosophy of the presented research approach could be transposed to other technologies in the search for novel creative applications, and provide valuable accessibility to the art, design and craft communities.

The processes required to achieve the machine performance are documented, and each new technique explained in overview. The techniques have a simplicity to them and provide a foundation for further exploration. Of particular note are the techniques that define texture using a geometrically mapped bitmap image. These techniques provide an avenue for future research, whereby textures that rely on material properties may be incorporated back in to a conventional top-down CAD approach to 3D printing. Whilst the textures may not be able to be explicitely defined in CAD due to their stochastic nature, it should be possible to define and represent regions of texture that are realised by the printer.

Lastly, this research has documented the exploration of two key variables; extrusion rate and nozzle velocity. As previously mentioned, the methods have been observed to be sensitive to changes in the environment, such as airflow within the build envelope of the 3D printer. Futurework will therefore explore more variables, such as the temperature of extruded plastics and cooling rates, as well as study the manifest physical properties of various states of material deposition. Futhermore, other 3D printing technologies will be explored with the same philosophical approach.

References

[1] H. Brooks, A. Rennie, T. Abram, J. McGovern, F. Caron, Variable Fused Deposition Modelling - Concept Design and Tool Path Generation, Rapid Design, Prototyping and Manufacturing, Pages 113-122 (2011)

[2] D. Chakraborty, B. A. Reddy, A. R. Choudhury, Extruder path generation for Curved Layer Fused Deposition Modeling, Computer-Aided Design, Volume 40(2), Pages 235-243, 2008

[3] Y. Chen, C. Zhou, J. Lao, A Layerless Additive Manufacturing Process based on CNC Accumulation, Rapid Prototyping Journal, Volume 17, Issue 3, Pages 218-227 (2011)

[4] W.K. Chiu, Y.C. Yeung, K.M. Yu, Toolpath generation for layer manufacturing of fractal objects, Rapid Prototyping Journal, Volume 12, Issue 4, Pages 214-221 (2006)

[5] B.P. Conner, G. P. Manogharan, A. N. Martof, L. M. Rodomsky, C. M. Rodomsky, D. C. Jordan, J. W. Limperos, Making sense of 3-D printing: Creating a map of additive manufacturing products and services, Additive Manufacturing, Volumes 1-4, Pages 64-76. (2014)

[6] Continuum Fashion, http://www.continuumfashion.com, date accessed July 8, 2015

[7] O. Diegel, S. Singamneni, B. Huang, I. Gibson, Getting rid of the wires: curved layer fused deposition modeling in conductive polymer additive manufacturing, International Conference on Materials, Mechatronics and Automation, Pages 662-667 (2011)

[8] E. L. Doubrovski, J. C. Verlinden, J. M. P. Geraedts, Exploring the links between CAD Model and Build Strategy for Inexpensive FDM. International Conference on Digital Printing Technologies, Pages 418-826 (2011)

[9] R.L. Hope, R.N. Roth, P.A. Jacobs, Adaptive slicing with sloping layer surfaces, Rapid Prototyping Journal, Volume 3, Issue 3, Pages 89-98, 1997

[10] S. Hoskins, 3D Printing for Arists Designers and Makers, Bloomsbury Visual Arts, Bloomsbury Publishing Plc UK, 2013

[11] Joshua Harker, http://www.joshharker.com/blog/, date accessed July 8, 2015

[12] B. Huang, S. Singamneni, Alternate slicing and deposition strategies for fused deposition modelling of light curved parts, Journal of Achievements in Materials and Manufacturing Engineering, Volume 55, Issue 2, Pages 511-517 (2002)

[13] M. Huth, F. Porrati, C. Schwalb, M. Winhold, R. Sachser, M. Dukic, J. Adams, G. Fantner, Focused electron beam induced deposition: A perspective, Beilstein Journal of Nanotechnology, Volume 3, Pages 597-619 (2012)

[14] Y. Jin, Y. He, J. Fu, W. Gan, Z. Lin, Optimization of tool-path generation for material extrustion-based additive manufacturing technology. Additive Manufacturing, Volumes 14, Pages 32-47, 2014

[15] J. Keep, http://keep-art.co.uk/, date accessed July 8, 2015

[16] K. Mack, http://www.kevinmackart.com/, date accessed July 8, 2015

[17] M. McCullough, Abstracting Craft: The Practiced Digital Hand, MIT Press, Cambridge, MA, USA. 1996

[18] Nervous System, http://n-e-r-v-o-u-s.com/, date accessed July 8, 2015

[19] N. Oxman, Structuring Materiality: Design Fabrication of Heterogeneous Materials. Architectural Design, Volume 80, Issue 4, Pages 7885 (2010)

[20] N. Oxman,Programming Matter. Architectural Design, Volume 82, Issue 2, Pages 8895 (2012)

[21] N. Oxman, Variable Property Rapid Prototyping. Virtual and Physical Prototyping, Volume 6, Issue 1, Pages 3-31 (2011)

[22] P. M. Pandey, N. V. Reddy, S. G. Dhande, Real time adaptive slicing for fused deposition modelling, International Journal of Machine Tools and Manufacture, Volume 43, Issue 1, Pages 61-71 (2003)

[23] P. M. Pandey, N. V. Reddy, S. G. Dhande, Slicing procedures in layered manufacturing: a review, Rapid Prototyping Journal, Volume 9, Issue 5, Pages 274-288 (2003)

[24] Project Silkworm, http://www.projectsilkworm.com/, date accessed July 8, 2015

[25] Rostock Max, SeeMeCnc, http://seemecnc.com/products/rostock-max-complete-kit, date accessed July 8, 2015

[26] S. Singamneni, A. Roychoudhury, O. Diegel, B. Huang, Modeling and evaluation of curved layer fused deposition, Journal of Materials Processing Technology, Volume 212, Issue 1, Pages 27-35 (2012)

[27] X. Song, Y. Pan, Y. Chen, Development of a Low-Cost Parallel Kinematic Machine for Multidirectional Additive Manufacturing. ASME. Journal of Manufacturing Science and Engineering, Volume 137, Issue 2 (2015)

[28] K. Sun, T. Wei, B. Y. Ahn, J. Y. Seo, J. S. Dillon, J. A. Lewis, 3D Printing of Interdigitated Li-Ion Microbattery Architectures, Journal of Advanced Materials, Volume 25, Issue 33, Pages 4539-4543, VCH Verlag (2013)

[29] [Trans]LAB, http://www.thetranslab.com, date accessed July 8, 2015

[30] J. Tyberg and J. H. Bhn, Local adaptive slicing, Rapid Prototyping Journal, Volume 4, Issue 3, Pages 118-127, 1998

[31] P. Walters, P. Thirkell, New technologies for 3D realization in Art and Design practice. Artifact, Volume 1, Issue 4. pages 232-245 (2007)

[32] T. Wohlers, Wohlers Report 2014, Additive Manufacturing State of the Industry Annual Worldwide Progress Report, Fort Collins, Colarod: Wohlers Associates, Inc. 2014

[33] R. Udroi, L. A. Mihail, Experimental determination of surface roughness of parts obtained by rapid prototyping, Proceedings of the 8th WSEAS International Conference on Circuits, Systems, Electronics, Control & Signal Processing, Pages 283-286 (2009)

[34] Xuberance, http://www.xuberance.org/, date accessed July 8, 2015

[35] I. Zein, D. W. Hutmacher, K. C. Tan, S. H. Teoh, Fused deposition modeling of novel scaffold architectures for tissue engineering applications, Biomaterials, Volume 23, Issue 4, Pages 1169-1185 (2002)

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