https://doi.org/10.2352/ISSN.2169-4451.2017.32.354

Geometric Element Test Targets (GETT™) for Determination of 3D Printers' Resolutions

H. Li[1], N. Ostrout[1] and S. Chang[1,2,3], [1]College of Imaging Arts and Sciences, [2]Kate Gleason College of Engineering, [3]College of Science, Rochester Institute of Technology (USA)*

Abstract

This study presents a concept to address the dimensional and geometric viability of three-dimensional (3D) printers with test artifacts. These test artifacts we named as Geometric Element Test Targets (GETT™). GETT™ offers a simple method for quantitative appraisals of the dimensional performance of additive manufacturing processes. The design of GETT™ relies on logistically positioned and decreased feature dimensions. One characteristic of GETT™ is that the dimensional failures introduced may be inspected visually and quantitatively assessed through graphical analyses. We will illustrate the use of GETT™ to determine a printer's resolution through samples produced from fused deposition modeling (FDM) printers. Although the demonstration is from FDM systems, the concept is expected to hold for all 3D printing processes and can be process-specific. The potential applications of GETT™ include standardization, reference targets, in-line system control, and more.

Keywords: quality control, dimensional accuracy, print resolution, graphical targets, test artifacts.

Introduction

As additive manufacturing (AM) technologies advance, it has becoming increasingly important to be able to quantify the quality of fabrication processes for consistent and defect-free parts. There is a high demand for measurement science aimed at achieving predictable and repeatable operations and quality products [1]. Thus how well have the intended dimensions been produced in comparison to the design has become an important and central requirement in the AM technology advancement.

S. Moylan et. al have summarized test artifacts that have been developed and used to identify the accuracy of printed parts [2, 3]. L. Yang and M.A. Anam have utilized test artifacts to benchmark the performance of various AM processes [4]. These test artifacts focus on the dimensional and geometric accuracy of intentionally designed and coordination-wise positioned features [2]-[4]. The test artifacts include basic geometric shapes (cylinders, cubes, etc.) as well as super-positioned geometric shapes (composite of shapes). The artifacts are strategically dimensioned with the intent to expose deviations with respect to the original designs [2]-[4]. The shapes are either solitary units or repetitions of same shape in different sizes.

The measurement apparatus used to characterize the dimensional deviations are gauges, calipers, micrometers, coordinate measuring machines (CMM), profilometers (contact or non-contact), and optical microscopes. The methodology employed is the measurement of coordination points and least square fitted to reference CAD models [2]-[4]. The measurements focus on both dimensional and geometric accuracies, which L.Yang and M.A. Anam [4] have summarized into six attributes: straightness, parallelism, perpendicularity, roundness, concentricity, and true positions (for pin and for z-plane).

These test artifacts have been practiced for part accuracies as well as for benchmarking of same parts fabricated by different AM technologies. However, there lacks a methodology that reveals the process quality. The intention of this research is to address the demand through the development of Geometric Element Test Targets (GETT™). GETT™ are test artifacts transpired from two-dimensional (2D) graphic printing. They focused on the responses from the AM process and therefore are complementary to artifacts currently centered on end parts. The goal is to establish a simple method for the quantitative appraisals of the dimensional performance of AM processes. The design of GETT™ relies on positioning the features and strategically decreasing the feature's dimension. One of the objective is for the failures to be inspected visually and can be quantitatively assessed as well through graphical analyses.

We will illustrate the use of GETT™ to determine a printer's dimensional resolution through samples produced from a fused deposition modeling (FDM) printer.

Test Artifacts Practiced in Graphic Printing

Test targets are practiced in 2D graphic printing in all aspects, from marketing, to system architecture, to process control, and to the understanding of the physics and chemistry taking place at the subsystem/component level. One type of targets aims at testing limits of a printing system's functional attributes and eliciting responses from different subsystems to assess their performance [5]. Similar to AM test artifacts, the 2D graphic printing test targets such as those produced by Rochester Institute of Technology (RIT) consist of fundamental (lines, dots, grey level, etc.) and composite (pictorial) elements [6]. The fundamental targets are typically used for quantitative assessment of production/reproduction dimensional and geometrical capability while the composite images are for user's psycho-physiological responses through ranking [7].

Fundamental graphic targets rely on inducing failures in the production of intended amplitudes of repetitive patterns at high spatial frequencies, such as describe by H. Mizes [8]. The shape of the pattern and its decrease in sizes is to locate where the pattern will be distorted during the printing process. Some of the failures will have distinguished characteristics that can be identified, even visually (or through an eye loop), while others will require instrumental and statistical assessments [6]. The statistical 2D graphic targets are used to measure systematically transfer functions between the system or subsystem variables and their corresponding print quality [7]. For example, the laser beam size or charge spreading on the surface of a photoconductor in electrophotographic printers will affect the dot size and shape of the addressable dot and can determined through the use of targets. The elemental targets typically consist text, curved and high spatial frequency lines, and halftones at different gray levels as exampled in [5], [6], [7], [8], and [9]. The fundamental targets have been used for in-process quality assurance, process controls, and printer's models [10], [11].

In this paper, we will highlight two test targets practiced in graphic reproductions, a checkerboard and a ray [6], [9], [10]. The checkerboard pattern is used for assessing printers' dimensional resolutions and dot gains. It contains a sequence of checkerboard patterns. The sequence starts at the printer's addressability for 1-dot "on" and 1-dot "off" where the "on" versus "off" denotes a physical mark that is delivered versus that is not delivered respectively. The sequence of the checkboards is for them to continue to n-dot "on" and n-dot "off", with n being an integer and n-dot being much larger than the addressability. For a printer with an addressability of 600 dots-per-inch (dpi), 1-dot "on" by 1-dot "off" checker square has an area of 42.3 µm x 42.3 µm in two dimension. When used in assessment, a printer's resolution will be the m-dot "on" and m-dot "off" checker size where the checkerboard pattern is just producible. It means that m is an integer and less than n. The checkerboard pattern can also be measured using graphical referencing with the original designs, or using scanners or microscopes. The dot gains are determined as the over-fillings or under-fillings of the checker square area through instrumental measurements.

The ray test target are "on-off" wedges of equal sizes and distributed evenly in 360°. The ray target converges to a singularity point at the center [10]. There exists no process that can produce the singularity; as a result the outcome is a zone with the wedges aliasing. With ray test targets, the resolution of the process is determined by the width of the wedge where the rays are just reproduced. Because of the circular nature, ray targets are capable to detect orientation-dependent dimensional deviations [10].

The transfer for 2D graphic targets into 3D AM targets has been explored recently. B.H. Jerad et. al. have investigated changing the ray chart into a 3D artifact [12]. His adaptation is a ray star with a raised center and diminished arms outwards. The translation of the ray star is intended for quantitative measurement.

In the same publication, B.H. Jerad et. al. [12] have also created a "Manhattan" test artifact for examining dimensional accuracy throughout the 3D space. The "Manhattan" test artifact entails separated squares of the same area in the x,y-plane (horizontal plane) but different z-axis positions (vertical heights) for measurements at various positions in space, in analogue to a checkerboard of different gray levels.

The existing AM test artifacts have also incorporated series of structures at decreasing size with repeating geometric shapes [2]-[4], [13]. The repetitions are directed at covering measurement accuracy and precision for a range of dimensions [2]-[4], [13] and are not directed at introducing failures as the purpose of checkerboard and ray targets for graphic printing.

Checkerboard and Ray GETT™ in 3D

The objective of this study is to illustrate that the 2D graphic targets can be transformed into 3D AM test targets with proper care for similar uses. The focus of this study is the feasibility of the checkerboard and the ray graphics as 3D printer resolution targets. The other intent is to complement the existing AM test artifacts which provide quantitative assessments of produced geometric shapes and parts with the means of assessing printers' resolutions [2]-[4],[12]. The long term goal of GETT™ is to assess system responses and in-process sampling.

The checkerboard translation is straight forward. The "on" versus "off" checkers become raised versus recessed squares. Figure 1 depicts this translation with the left sketch displaying a 2D graphic version of the checkerboard target and the right sketch its 3D interpretation. The black squares (or "on" squares) in the left have been rendered as physical heights for the 3D translation in the right diagram. The raised checker squares in the 3D checkerboard have the same heights. The value of the height is at least as the thickness of a single build-layer; we recommend multiple layers for the ease of assessment. The raised and recessed checkers are to replace the contrast between black and white in 2D graphics. Differently from the "Manhattan" squares by B.H. Jerad et. al., the 3D checkerboard shown in the right diagram of Figure 1 primarily directs at the horizontal plane, or the x,y-plane, system resolution.

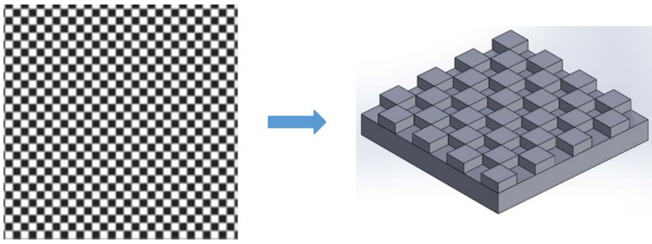

Figure.1. embodiment of a 2D graphic checkerboard target (left) into a 3D checkerboard GETT™ (right).

The translation of the ray target is more complex since the center radiated wedges can be interpreted as either an axial (same raised height from edge to center) or a point (diminished raised height from edge to zero at center) convergence. Figure 2 describes the two translations in a) and b) for a flat ray and a slanted ray respectively. Both ray GETT™ have the potential for visual inspections as well as quantitative instrumentational measurements as in the publication of B.H. Jerad et. al. [12].

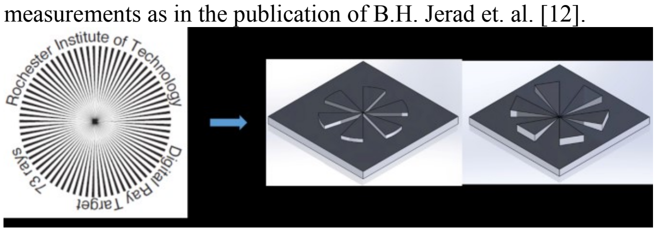

Figure.2. Conversion of a 2D graphic ray chart into a flat ray GETT™ a) and a slanted ray GETT™ b).

In general, GETT™ can be designed specifically to probe unique characteristics relevant to a particular printing method. In the RIT's GETT™ portfolio, we have designed line, angular, and circular suites in the likeness of their 2D graphic counterparts with specific consideration given to the z-direction processing. Some of the designs from these suites have been published in reference [14] and more will be disclosed with follow-up publications [15].

The guidelines for designing GETT™ are:

- The fundamental units of GETT™ are simple geometric elements, such as cubes, triangular wedges, cylinders, etc.
- The placements of elements are in reference to the process-related orientations.
- The same elements are repeated at diminishing sizes (xy-plane) and amplitudes (z-positions).
- The dimensional range is set to be less than the addressability of the printer as the lower limit to integer multiples of the addressability as increments.
- When the addressability is not known, the lowest element size should be less than the anticipated addressability.
- The dimensional changes can be continuous or discrete.
- The elements can be positioned in isolation, intercepted, or integrated with either the same or different elements.
- Elements can be raised or recessed with respect to a reference plane.

Construction of GETT

The specimens in this work are produced with a fused deposition modeling (FDM) machine. The FDM process drives a thermoplastic wire to a heater which melts the thermoplastic to deliver the molten material through a nozzle [16]. The process thus deposits a thread of thermoplastic material to builds the part line-by-line in the xy-plane and then layer upon layer in the z-direction.

A CubePro® by 3D Systems was used to fabricate the GETT™ specimens. We used the default settings for the GETT™ manufacturing and selected 0.2mm as the build-layer thickness, a choice provided by the original engine manufacturer (OEM). We selected the infill density to be 10%. The nozzle opening dimension was not provided by the OEM; therefore, GETT™ are designed in the English system of millimeter. The designs of GETT™ were done in SolidWorks. The design files were saved as STereoLithography (STL) format. Acrylonitrile Butadiene Styrene (ABS) material was used for the part building.

Photographs were taken with a Canon EOS 5D Mark Ⅲ camera. SOFV-1 light booth made by Graphic Technology was used as light sources during photographing. Microscope images were captured using a VHX-2000E series microscope made by Keyence© Inc at 20X magnification. The photographs were used to illustrate the feasibility of visual assessment. The images were captured with the microscope for better observations of specific characteristics. The microscope was set at minimal magnification to simulate the situation of inspection with eye-loops.

Determination of Printers' Resolutions

Figure 3 captures images from four GETT^{TM} checkerboard samples positioned clockwise at descending dimensions of the squares from 10mm (top-left), to 5mm (top-right), to 2.5mm (bottom-right), and ending at 1.25mm (bottom-left). All specimens are 1mm in height. The checker square dimensions are labelled in Figure 3 correspondingly with an arc arrow indicating the presentation direction for the images.

In the top-left photograph, the square shapes are well defined in the top-left 10mm image (although with rounded corners). The raised features, however, appear larger than the recessed squares. This overfilling effect becomes more pronounced in the top-right image of 5mm squares, as well as the rounding of the square corners. The bottom-right image of 2.5mm underlines the almost elliptical shape of the checkers. For the 1.25 mm checkerboard GETT™, the checker shapes cannot be reproduced and lost their designed periodicity.

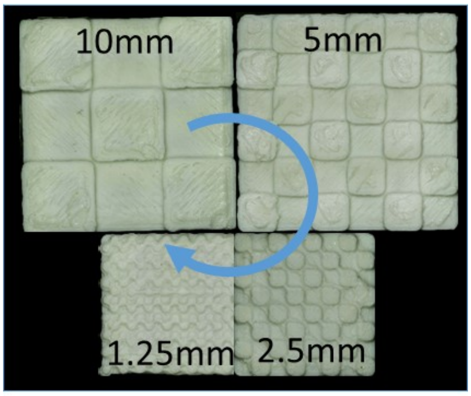

Figure.3. A sequence of decreasing sizes of checkerboard GETT™ shows resolution limitation to be around 2.5mm. When further reduced in size, the checker squares cannot be reproduced.

From the visual inspection of this sequence of GETT™, one may conclude that the resolving capability of a square shape of this CubePro® printer is at about 2.5mm.

The amount of overfilling can be determined through the use of graphical analysis. This analysis as well as defects detected through the use of checkerboard GETT™ will be discussed elsewhere [16].

Figure 4 shows a set of photographs of the same flat ray GETT™ to illustrate the process in evaluating the minimal producible wedge width. The flat ray GETT™ in Figure 4 has nine wedges with a length of 10 mm from the center to the end (or a diameter of 20mm) and same height of 1 mm. The wedges are designed to have equal widths and 20° angles for both protruding features and separations.

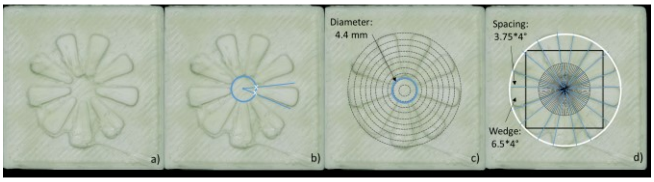

Figure.4. A series of photographs of the same flat ray GETT™. The resulted center void marks the area that the printer has failed to print. The width of the ray wedges at this failure point is defined as resolution for converging lines.

The ray GETT™ is for wedges to converge to a singularity point at the center. Since the convergence is impossible, a forbidden zone emerges at the center of the ray as a result. This forbidden zone is revealed as a void in Figure 4a). The size of the forbidden zone reflects the producible line width by a FDM system.

Figure 4b) overlays a circle to mark the forbidden zone. There are also two lines radiating from the center of the circle. The two lines are tangent to the curvatures at the termination end of the selected wedge (between 3 to 4 o'clocks) and intersected with the overlay circle which marks the forbidden zone. The two intersections are distinguished by the two crosses in Figure 4b). The distance between these two intersections defines the minimal producible line width.

In order to estimate the minimal producible line width of the wedge, one must know the diameter of the circle defining the forbidden zone. Figure 4c) shows the ray GETT™ overlaid with circular grids at 1mm apart in radii. In reference to the grids, the diameter of the circle amounts to about 4.4mm (respectively labelled).

The other value needed is the angle occupied by the wedge. Therefore Figure 4d) shows an overlay of an angular grid with lines radiated from the center at four degrees (4°) apart. The example wedge (between 8 to 9 o'clock) occupies about 6.5 grid separation and thus about 6.5*4°, or 26° of angular spread. Similarly, the separation between wedges measures to about 3.75*4°, or 15° of angular spread.

Thus the width of the ray wedge at the point of failing to reproduce can be calculated as:

$$\begin{aligned} &Width\ of\ Ray\ at\ Failure \\ &\qquad = Sin\left(\frac{Wedge\ Angle}{2}\right) \times Diameter \end{aligned}$$

In the example shown in Figure 4, the wedge width at failure is computed to be 0.84mm.

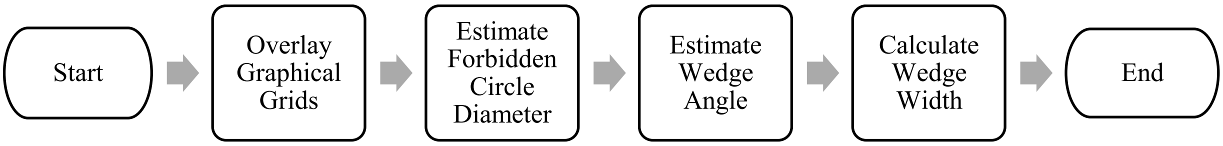

Figure.5. The workflow determines the minimal ray wedge width which can be produced by a 3D printer.

Figure 5 summarizes the graphical analysis process illustrated in Figure 4. The process can be conducted through pre-made grids as gauges to superposition over printed rays with estimation through visual comparison. Or the process can be conducted using image or photo captures and comparing with overlaying grids electronically.

Table 1 contains measurements for all 9 wedges from the ray GETT™ exhibited in Figure 4, following the graphical methodology outlined above. Table 1 presents the deduced angular values of the raised and recessed wedges in columns 2 and 3 respectively. The measurement of the wedges starts at about 8 o'clock with the raised wedge shown in Figure 4c) and proceeds clockwise for all 9 wedges listed in column 1. Column 4 estimates the values of line width for all 9 raised wedges at termination.

9-Wedge Ray GETT™

Number	Raised Ray	Recessed Ray	Width
	(Degrees)	Degrees)	(mm)
1	26	15	0.84
2	25	16	0.82
3	26	16	0.84
4	26	15	0.84
5	24	15	0.80
6	24	16	0.80
7	25	14	0.82
8	24	16	0.80
9	24	16	0.80
Mean	25	15	0.82
Standard Deviation	0.9	0.7	0.02

Table.1. The angular values of both raised and recess wedges are in columns 2 and 3, and the estimated widths at termination for the raised wedges are in column 4. The values in column 4 conclude a mean resolution for this ray GETT™ to be 0.82mm ± 0.02mm.

Please note that in both Figure 4 and Table 1 the angles for either the raised wedges (or the separations) are roughly the same. This indicates an orientation-independent FDM print process in the xy-plane, as one expects.

In comparison to the flat ray GETT™, the slanted ray GETT™, in addition to the resolution evaluation, is also reveals the Z-direction's addressability. Figure 6 shows a 6-wedge slanted ray GETT™. The GETT™ in Figure 6 has a length of 10 mm (or a diameter of 20mm) and a height changed from 0mm to 2mm from center to the end of the wedge. Both raised and recessed wedges are of 30° angular spread. Inspecting the image exposes the void forbidden zone in the center, as in the case of the flat ray GETT™.

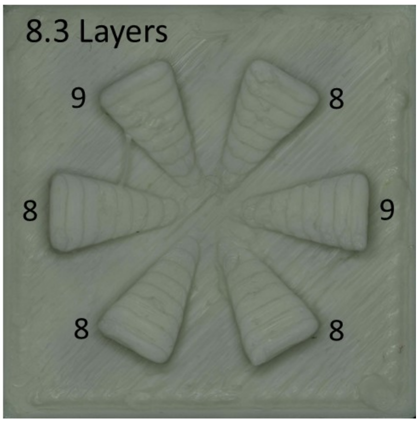

Figure.6. Convergent slanted ray GETT™ divulges FDM printers' z-direction effective addressability through the number of steps on the slanted plane.

Differently from the flat ray GETT™, the angled wedge surfaces are comprised of steps. These steps are results of the layered-building nature of 3D printing. The numbers next to each of the wedges in Figure 6 are the number of steps on each of the six rays. This averages to 8.3 layers of building for this artifacts. Since the highest height of the wedge is at the outer-most circle, a division of the height at the edge by the number of steps gives the true layer thickness. The outer-most height is designed to be 2mm and measured the same with a caliper. Thus, the effective z-direction addressability of this CubePro® is 0.24mm, higher than the 0.2mm layer thickness per printer manufacturer's specification.

Potential Usage

In the 2D graphic and document production industry, targets are generally produced using high resolution printers and then used as references for both visual inspections and measurement standards. They are also widely used to calibrate printers for their manufacturing consistencies within the same processes and among different processes. It is a common practice to have specific targets integrate into the printer's process controls and feedbacks. Targets are also widely employed in the interactions with customers to get their requirements and providing quality proofs. With research and exploration, GETT™ has the potential to attain all these traits for practice in the AM industry.

As for research and development, GETT™ offers a method to examine and optimize system and subsystem performance with process critical parameters and material specifications as variables. Determinations of functional responses will enable tradeoffs between objectives and attributes in the engine architecture designs. Furthermore, with the establishment of a printer's fundamental dimensional and geometric capability, there is a potential to predict and simulate final build parts.

Conclusion

This study presents a concept to address the dimensional and geometric viability of 3D printers with test artifacts. The concept is in analogue with how test artifacts are practiced in the 2D graphic industry. The examples given here have focused on inducing dimensional reproduction failures by using the shape and the spatial frequency of test artifacts. The distinguishing characteristic is that the failures can be designed to show visually and to assess quantitatively with the aid from graphical analyses. We have illustrated the process of visual inspection and the graphical analysis through the use of a checkerboard and two ray GETT™. The potential applications of GETT™ include standardization, reference targets, in-line system control, and more.

Acknowledgements

This research is supported by the Melbert B. Cary Jr. endowment from the College of Imaging Arts and Science at Rochester Institute of Technology.

References

[1] National Institute of Standards and Technology website, “NIST’s Measurement Science for Additive Manufacturing Program”, http://www.nist.gov/el/isd/sbm/msam.cfm.

[2] S. Moylan, J.Slotwinski, A.Cooke, K Jurrens, M. A Donmez, “An Additive Manufacturing Test Artifact,” Journal of Research of the National Institute of Standards and Technology, 119:429, (2014).

[3] S. Moylan, J. Slotwinski, A. Cooke, K. Jurrens, and M. A. Donmez, “Proposal for a Standardized Test Artifact for Additive Manufacturing Machines and Processes”, In Proceedings of the Solid Freeform Fabrication Symposium, Austin, TX, August 2012.

[4] L. Yang, M. A. Anam, “An investigation of standard test part design for additive manufacturing,” in Solid Freeform Fabrication Symposium, pp. 901-922, 2014.

[5] R. Chung, F. Hsu, M. Riordan, F. Sigg, “Test Targets 8.0: A Collaborative effort exploring the use of scientific methods for color imaging and process control,” (2008).

[6] R. Chung, F. Sigg, D. Ploumidis, “Test Targets 6.0: A Collaborative effort exploring the use of scientific methods for color imaging and process control,” RIT School of Print Media Publication (RIT, Rochester, NY, 2006).

[7] Eric K. Zeise, D. René Rasmussen, Yee S. Ng, E. Dalal, A. McCarthy, D. Williams, “INCITS W1.1 development update: Appearance-based image quality standards for printers,” Proceedings of SPIE-the International Society for Optical Engineering, Vol. 6808, Jan 2008.

[8] H. Mizes, “Empirically Based Printer Model of Halftone Structure”, NIP & Digital Fabrication Conferences, 2004:1, 35, (2004).

[9] F. Sigg and D. Romano, "How to Calibrate and Linearize an Imagesetter Using the Digital UGRA/FOGRA Wedge", Society for Imaging Science and Technology, Proceedings of the Fourth Technical Symposium on Prepress Proofing and Printing, (IS&T, Springfield, VA, 1995) pp. 88-92.

[10] F. Sigg, “Ray_Doc_6”, Rochester Institute of Technology, May 2005.

[11] F. Sigg, “Testing for Resolution and Contrast,” RIT School of Print Media Publication, Id TF_12, version v2.2.

[12] B. H. Jared, H. D. Tran, D. Saiz, C. L. Boucher, Joseph E. Dinardo, “Metrology for Additive Manufacturing Parts and Processes,” Spring Topical Meeting, 57, (2014).

[13] D. Dimitrov, “Advances in three dimensional printing – state of the art and future perspectives,” Rapid Prototyping Journal, 12, 3:136, (2006).

[14] S. Chang, H. Li, N. Ostrout, M. Jhuria, S.A. Mottal, F,Sigg, “Geometric Element Test Target for Visual Inference of a Printer’s Dimension Limitations,” 26th Annual International Solid Freeform Symposium, (SFFF, Austin,TX, 2015) pp.1491-1503.

[15] S. Chang, H. Li, and N. Ostrout, to be published.

[16] C.K. Chua, K.F. Leong, “Rapid Prototyping: Principles and Application,” 3rd Edition, (World Scientific Publishing Co. Pte. Ltd, Singapore, 2010).

