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# SPATIAL ACCURACY OF EMBEDDED SURFACE COLORING IN COLOR 3D PRINTING


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## INTRODUCTION

Recent years, the industrial market for full-color AM is growing rapidly. In the AM industry, most of the major technology providers are developing new systems with improved color capabilities and with improved materials. In the last 12 months alone, 5 new technology platforms have been revealed capable of full-color printing in polymers[1]. Industrial service providers increasingly expand their product-range of full-color print services, and as of today, the industry for full-color parts has grown rapidly, into a million-dollar industry [2]. With a new market emerging at such pace, it is believed a necessity to consider a new surface-metrological issue. To what accuracy are colors embedded to the surface of geometries, with relation to where specified from input data? This paper investigate the accuracy of surface coloring, by adopting a well-known metrological approach from calibrating Coordinate Measurement Machines (CMM's) and Machine Tools, that already has been transferred to be applicable for AM machine tools, [3] in order to determine the spatial accuracy of embedded color features to artifacts printed on a zCorp 650 color 3D Printer. The spatial color verification artifact is a flat plate with a series of checkered fields on the surface.

## METHOD

Following an approach developed by Hansen et al.[3] for geometrical verification of 3D printers in the horizontal plane, a series of four checkered plates was generated. Each artifact contains a series of checkered fields in one of the z650 printer's base colors, as illustrated in *figure 1*.
Upon printing the checkered artifacts, one for each base-color, these can subsequently be mapped by means of an optical CMM. A calibrated DeMeet 220 from Schut Geometrical Metrology was used to find the centre of each checkered field in order to determine the spatial position of these. The measured positions are compared to the ideal of the CAD body, and the differences are mapped. The mapping of the geometrical coloring accuracy in the horizontal plane is finally plotted, in order to describe the spatial color performance of each color channel of the zCorp printer.

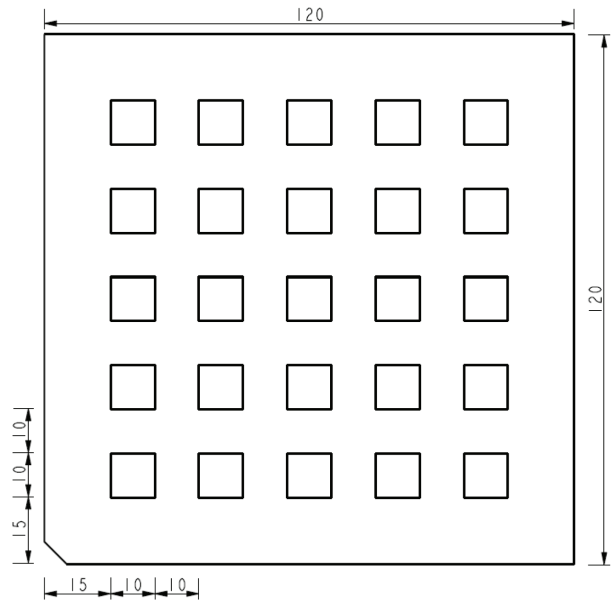


*FIGURE 1. Color calibration artifacts. Each checkered field represent a field colored in one of the base colors of the 3D printer.*

## ARTIFACT GENERATION

A common method for embedding colors to 3D geometries is by texturing. If textures are applied to geometry, the spatial accuracy of the color representation is governed on-screen by the texture file format. Image textures on CAD bodies are often handled in image file formats employing lossy image compression that will introduce a pixilation effect known as compression artifacts.[4] As a result of this, the subsequent printing of the geometry will be carried out by multiple inkjet print heads, using more than one base-color. Furthermore the capabilities of the engine in the software renderer used to display the geometry affect the accuracy of the rendered geometry, predominant when texture wrapping occur. Following this analogy, there is a risk that the accuracy of the color representation on the printed verification artifacts will be affected by the proprietary job generation software of the printer if a textural coloring of the calibration artifacts was used. To prevent this, it was decided to generate the checker board geometries by means of a tailored python script. This makes it possible to output the 3D geometries in the .OBJ with a per-face color definition, as seen in *figure 2*, to serve as the calibration artifacts. With this approach, it can be ensured that no issues related to texture interpretation and misalignment in the proprietary printer software can occur as each checkered field was generated as facet pairs, with a per-face base color defined. This eliminates the risk of error sources from the 3D body that may be transferred to the print job.

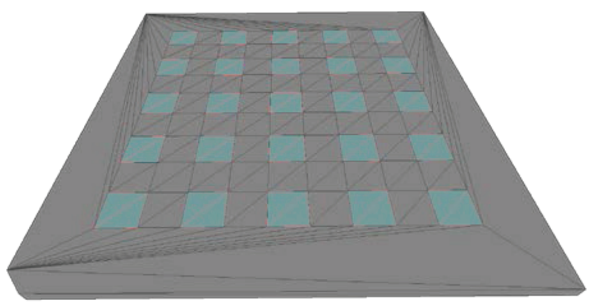

*FIGURE 2. Per-face coloring of checkers. Each checker is comprised of a facet-pair in one of the CMYK base colors.*

## ARTIFACT MANUFACTURING

A series of four artifacts was 3D printed. Each artifact was manufactured on the z650 ink-jet based powderbed printer. z151 powder was used and the print was carried out at 0.89mm layer height with a specified 540x600 - XY DPI resolution, which corresponds to a theoretical horizontal resolution of 4.7$\mu$m. All four plates were manufactured in one print-job, and stacked in the vertical plane, so that the same kinematic characteristics in the horizontal plane was present during the manufacture of all four artifacts. *Figure 3* shows the four printed artifacts upon removal from the build-chamber of the 3D printer. No infiltration or other post-processing was carried out, in order to prevent the colors to bleed and deteriorate with respect to spatial accuracy. All artifacts have been manufactured in an orientation so that within the context of this paper, the X direction is in the direction of the print head carriage, whereas the Y direction is in the travel direction of the gantry of the printer.

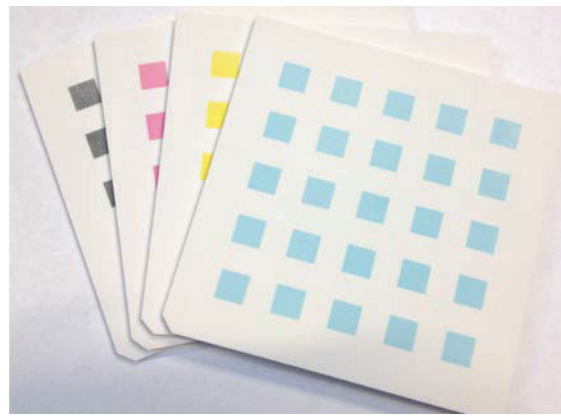

*FIGURE 3. 3D printed CMYK color calibration artifacts*

## SPATIAL PLACEMENT

Each artifact in the CMYK color space, was measured, and for every checker, the spatial center position was determined. Measurements were carried out on a DeMeet 220 from Schut Geometrical Metrology, with x5 optics, maintained with a budgeted uncertainty of approx. ~16$\mu$m. The choice to define the spatial position of each checker by its center is in order to limit measurement uncertainties from the effect of ink bleeding out from the deposited area and into the surroundings. As seen in *figure 4* (right), it can be difficult to determine the exact outline of the checkers, whereas for yellow color (left), it can be hard to distinguish the color pigment from the background. Yet, the center of each checker is unaffected with respect to where along the boundary gradient, that the measurement is taken, if kept constant.

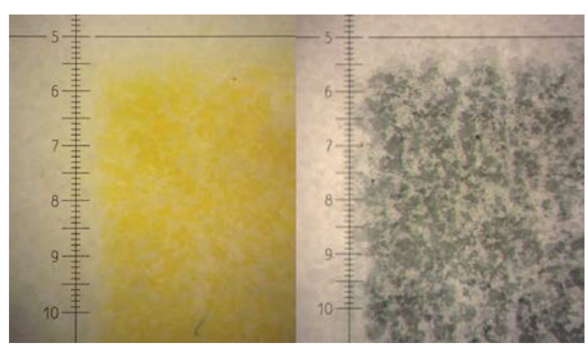

*FIGURE 4. Microscopy of gradients from checker to background, K and Y color channel.*

With the DeMeet 220, an NC programme was defined to allow for the construction of four lines following the sides of each checker. The line intersections define the corners of the checker, and is exported to a data file. From the four corners, two new lines are constructed. Since these four lines will not be perfect diagonals, their intersection is calculated from equations (1) and (2), for the intersection of two lines, and following the diagram in *figure 5.*

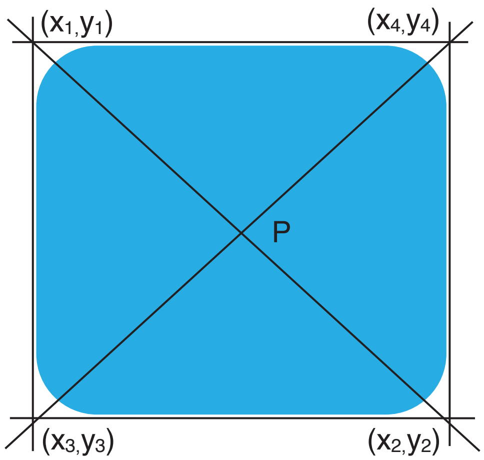


*FIGURE 5. Diagram showing the center point definition (P) of a checker.*

$$Px = \frac{(x_1y_2 - y_1x_2)(x_3 - x_4) - (x_1 - x_2)(x_3y_4 - y_3x_4)}{(x_1 - x_2)(y_3 - y_4) - (y_1 - y_2)(x_3 - x_4)} \quad (1)$$

$$Py = \frac{(x_1y_2 - y_1x_2)(y_3 - y_4) - (y_1 - y_2)(x_3y_4 - y_3x_4)}{(x_1 - x_2)(y_3 - y_4) - (y_1 - y_2)(x_3 - x_4)} \quad (2)$$

Finally the spatial position of every checker and thus the spatial color representation capabilities can be mapped in one plot, showing how well the z650 printer perform on the CMY and K color channel.

## RESULTS

Figure 6 show the complete mapping of geometrical position errors within the four color-fields in the CMYK-space, magnified by a factor of 50, with a common origin in the lower left corner of the space. For each color channel, a grid show the position errors of each square centre, relative to the ideal position, which is shown as slashed gridlines. This makes it possible, in a single graph, to study the behavior of the z650 in the color- and the spatial domain.

An evident general trend, is that for all color channels, the scaling in both the X and Y directions of the machine are too short, resulting in an under-shoot. The error is seemingly linear, and of a magnitude of approx. 100$\mu$m in the X-direction (print head travel direction) and approx. 150$\mu$m in the Y direction (gantry travel direction). Thus, it will be extremely simple to compensate for this error contribution, if manual machine calibration will be allowed by the machine manufacturer.
Second, it can be seen that the grid lines for all color channels are skewed to the left. This is an indication of the machine axes not being orthogonal. The contribution from this error is largest in the point farthest from the common origin, with a spatial error component of app. 100$\mu$m The maximum combined position error cross the 80x80mm artifact error was found to be approx. 350$\mu$m.

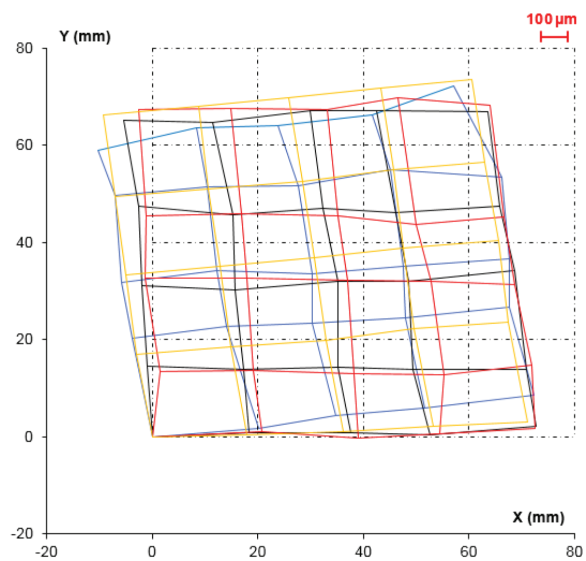


*FIGURE 6. Center position of checkers compared to the ideal per color channel. Spatial position errors magnified 50 times.*

The error mapping plot does also reveal errors inherent to the individual base colors, and thus the alignment of the print-heads within the tool-head of the printer. Since each color channel has been plotted with a normalized common origin, each color plot should theoretically be identical. When this is not the case, it can be ruled down to one of two causes. First, it can be measurement errors from the measurements of the artifacts, which in this case has been carried out on accredited equipment. Second, and more plausible given the magnitude of the variance within the color-space is that it can be related to the printer having trouble with compensating for print head misalignment in software. The z650 printer has an automated print head alignment routine The routine is constituted by first, the print of a multi-colored grid spanning over the entire build plane of the machine. Subsequently a photo-sensor detects the grid, and computes a compensation matrix, that is superimposed over the machine movement, to ensure correct color deposition for all color channels. When each color channel of the verification plot in figure 6 share common origin, then it is then evident that variance between the different color channels could be directly linked to performance of the color calibration of the printer itself. Any variance within the CMY & K color can originate from this built-in routine for compensation of print head misalignment. Indications are therefore that the print heads in the z650 is aligned to ±100 $\mu$m over the area of the verification artifact.

## CONCLUSIONS

Aimed to bring attention to the spatial color accuracy of Additive Machine Tools with full-color capabilities, a study was carried out to determine the spatial coloring accuracy of a zCorp 650 color capable 3D printer in the horizontal plane. The global spatial accuracy of the machine was found to be no more than 350 $\mu$m within the extent of the calibration artifact. The main error components was identified to be general axis scaling errors and skewness of the axes, affecting all color channels. A lower, yet significant error component relates to the individual color channels of the printer, and can be seen as the variance of the CMY & K grids in figure 6. Since all color channels share a common gantry and carriage, the variance between the grids from the different colored artifacts was expected to only reflect the measurement uncertainty of the CMM used for the mapping of the verification artifacts. The variance was however found to be approx. ±100 $\mu$m, well beyond the measurement uncertainty, and a suspected source of this variance has been proposed, relating to the built-in print head alignment routine of the printer. It is too early to conclude if this indeed is the direct contributor, yet a sub-standard print head alignment strategy will be a valid explanation to the cause behind the variance seen.

## FUTURE WORK

It is believed that in order to achieve better spatial coloring accuracy of ink-jet based full-color AM technologies, further attention to the importance of machine calibration and verification this must be raised, and routines for correcting and optimizing color deposition must be improved. A variance between color channels of the manufactured verification artifacts indicated that better spatial coloring accuracy can be achieved by implementing a better print head alignment strategy than the one used in the machine subjected to this study. It is suggested to expand on the analysis to span over the entire horizontal build-envelope, and to expand the study to multiple artifacts for each color channel in order perform statistical hypothesis testing. Finally, this study aimed to propose a general method for spatial color verification within full color Additive Manufacturing. Vertical spatial color verification has not been carried out yet, but will yield more evidence of the capabilities of the method proposed.

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