Control and testing of the additive systems color gamut in engineering

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Abstract. The article discusses the issue of the additive color reproduction systems control in engineering. Additive technologies provide a wide range of possibilities for the formation of a three-dimensional product with the coloring of the product in mass. However, there is no technology for color management and control of distortion of the color formation of the cured material. In the course of the study, a method of color management in the process of manufacturing a three-dimensional model using CJP (Color Jet Printing) or Binder Jetting technology is proposed to ensure consistent color communication in the CAD system "program – 3D printer – material". The notion of the additive system in engineering is implemented. According to the developed technique the performance of the color gamut of the additive system on the basis of plant ZPrinter 450 are specified.

1. Introduction

The issues of three-dimensional printing are one of the most relevant for the development of digital technologies with element-by-element recording. They are used both in imaging on the plane and in imaging during the dimensional products molding. In both cases we consider the direct application of the image to the material, without the use of intermediate analog media information about the formed object. Both when working with two-dimensional printing, and in three-dimensional printing with direct element-by-element recording, the key technology of distribution of the binder (ink) is the technology of ink-jet printing. This technology was developed in the late 20th century and was originally designed for the formation of three-dimensional objects. However, it became more widespread in monochromatic, and further, the multicolor image on the plane. According to analytical data from Gartner, three-dimensional printing technologies for prototyping are currently on the plateau of productivity. A number of technologies related to the use of three-dimensional printing, such as three-dimensional scanning, three-dimensional printing factories, three-dimensional printed dental prostheses and many others overcome the shortcomings and are going to reach the plateau of productivity by 2020.

All this allows us to consider three-dimensional printing technology as key in prototyping and in final production in a wide range of highly profitable industries.
2. Problem statement
The aim of the work is to develop a method of color management and ensure consistent color communication in the CAD program – 3D printer – material. This technique will be relevant for three-dimensional printing methods CJP (Color Jet Printing) or Binder Jetting. For this purpose it is necessary to solve a number of problems aimed at assessing the color gamut of additive systems in engineering, matching the color palette of the product with the color gamut of the additive system.

There are some studies [1, 2] describing in detail the principle of three-dimensional printing method CJP (Color Jet Printing) or Binder Jetting. It should be noted that the work does not describe the possibility of forming colored products by using this technology, the main emphasis is on the formation of a discrete drop and ensuring the accuracy of the linear dimensions of the product reproduced by the additive system. There are some publications [3, 4] aimed at ensuring the colorimetric accuracy of digital ink-jet printing systems. Ink-jet digital printing systems are based on the data of Color Management Systems (CMS), providing consistent color communication in the system of input devices, processing and output of visual information. In the work of additive systems similar tools do not exist, therefore it is not possible to control the colorimetric accuracy of the product. Thus, the development of color management techniques in additive systems have relevance and practical significance for the development of additive technologies.

3. Theory
In this study, we consider an additive system as a set of elements with the use of which the process of layer-by-layer build-up and binding (in place of building) of a three-dimensional object is realized. The additive system is characterized by the influence of each individual element on the result of the construction of the object. The degree of influence is determined quantitatively and objectively based on the assessment of the factor impact on the optimization parameter. The optimization parameter in this case can be a parameter that takes into account the linear accuracy of the product, but given the ability of some additive systems to form the color of the product in a wide range of colors, colorimetric accuracy can also act as one of the optimization parameters to assess the colorimetric accuracy of the formation of a three-dimensional product. The colorimetric accuracy of the additive system (Binder Jetting) is influenced by a number of factors, including the dispersion of the base, the
type of coloring composition (colloidal system or solution), colorimetric characteristics of the coloring composition, the nature of the finely dispersed base and its wettability and optical characteristics. However, it is important to understand that in order to solve the problem of colorimetric accuracy control of the formation of a three-dimensional object by the additive system (Binder Jetting), it is important to have methods of quantitative and objective evaluation of all parameters of the additive system. Currently, CAD design systems and CAM systems of additive formation management do not provide for the accounting for spectral characteristics of the additive stations. To describe this process, a scheme of transformation of the information about the three-dimensional object when its manufacturing by additive method (Figure 2 a) and the proposed process model, which takes into account the individual characteristics of the additive system as a whole and the additive station and its components in particular with the help of the color management system unit are presented.

The color control system unit should consist of a set of elements for color measurements based on spectrophotometric measurement methods, test elements for testing the colorimetric characteristics of the additive system, processing of measurement data, and a tool for analyzing the color reproducibility of a three-dimensional model. In this study, Adobe software was used as a tool for analyzing color reproducibility. To analyze the reproducibility of the test image TS 2.83 RGB was used (Figure 3).

Color management in technical systems is described in detail in [5, 6, 7] for computer graphics systems. Such issues as the work of the CMS, providing the agreement of the color parameters of the product digital copy at different stages of the product reproduction through individual color profiles of devices are shown in Figure 2.

Color description between individual devices occurs in different color models:
- RGB – at the stage of image input and processing;
- Lab – at the stage of coordination of devices technical characteristics;
- CMYK – at the stage of subtractive color formation of the product.
Figure 2. a) Interaction of the elements of the three-dimensional object formation system to provide a consistent description of the color in the digitization devices of the three-dimensional object, CAD programs, CAM and output devices (additive stations Binder Jetting); b) the proposed model of matching the colorimetric characteristics of the three-dimensional object in the devices of digitization, processing and additive construction.

It is important to note that the recalculation of the color coordinates between the hardware-dependent RGB and CMYK color spaces cannot be achieved without taking into account the individual characteristics of the color reproduction of a particular device. To solve the problem, the method of color management is based on the comparison of actually reproducible values of color coordinates with reference values using the color difference index ($\Delta E_{00}$).
4. Methods and means of research
To carry out the study, the following methods were used:

1. To perform color measurements – spectrophotometry technique in accordance with DIN 6174 with the parameters of the Gretag Machbeth Spectro Eye:
   - Light source - D65 (6500 K),
   - Viewing angle – 2°,
   - White standard - absolute value,
   - The geometry of measurement is 45°/0.
2. To perform color calculations of the color difference formula (\(\Delta E_{00}\)) was used [8].
3. To build a color profile – scale TC 3.5 CMYK.
4. To build a body of color gamut – Quick Hull algorithm in Matlab
5. To build a test object – a printer for three-dimensional printing ZPrinter 450, technology – Binder Jetting. The printhead is HP-11 (C4810A) thermal jet for binder application and HP 57 (C6657AE) for color ink application. Color delimitation is three-color C-cyan; M-Magenta; Y-yellow. Ink – HP water-based.
6. Materials for scale construction: sculptural plaster G-16 (sample 1); plaster Zp-150 (sample 2).

5. Results and discussion
Thus, in the course of studying the technology of manufacturing a three-dimensional object using the additive system the algorithm of processing three-dimensional digital model considering colorimetric
characteristics of additive system, the color scheme of a three-dimensional object, for ensuring the coordinated color communication between CAD design systems and control systems of additive station CAM and reproducibility of colors by additive station ZPrinter 450 is offered (Figure 4).

During the experimental evaluation of the color gamut of the additive system, the color profile of the additive station ZPrinter 450 was constructed. A graphical interpretation of the color gamut of the ZPrinter 450 using different materials is shown in figure 5.

![Figure 4. Scheme of the harmonization of color communication in the additive system.](image-url)
Figure 5. Comparison of the color gamut of the additive system under study (1) with the standard color gamut sRGB (2) in three projections in the color space Lab - Lb (a), La (b), ab (b). Comparison of color gamut of additive systems based on G16.
The optical characteristics of the material for the construction of a three-dimensional product have an impact on the color reproduction of the additive installation, however, it is worth noting that the material G-16 has a color gamut comparable to the color reproduction of a multi-color image on newspaper materials by jet method.

Small values of color gamut is a result of a three-component synthesis of color without using black ink that minimizes the color gamut in the deep shadows. Providing a consistent color communication in the additive system allowed to reduce the color difference between the specified and the actual reproducible values of the color coordinates of the three-dimensional object elements, which increases the predictability of the three-dimensional product result manufacturing by the additive system. Table 1 presents the results of color gamut measurements of additive systems, as well as optical characteristics of G-16, Zp-150 materials.

Table 1. Colorimetric characteristics of additive system based on additive station ZPrinter 450 with various sets of components.

| № | The additive system name | Station | Base material | Optical characteristics of the material, % | The volume of the body color gamut, units. (ΔE) |
|---|---------------------------|---------|---------------|------------------------------------------|-----------------------------------------------|
| 1 | Additive system 1         | ZPrinter 450 | G16 | 86 | 118159 |
| 2 | Additive system 2         | ZPrinter 450 | ZP 150 | 92 | 139165 |

During the method evaluation, the following values of color coordinates in the system of MKO Lab-1976, presented in table 2, were obtained.

Table 2. Results of evaluating the colorimetric fidelity of a three-dimensional object using the additive system under study while preparing the printing using the CMS technology (columns 9-15) and without the use of CMS (columns 2-8) (the coordinate values of the Lab color are rounded to an integer).

| The color sample on the scale | Printing without using CMS | Printing using CMS | The color difference, ΔE |
|------------------------------|----------------------------|--------------------|--------------------------|
|                             | original coordinates of the colors | actual color coordinates |                             | original coordinates of the colors | actual color coordinates |                             |
| L | a | b | L | a | b | L | a | b | L | a | b | L | a | b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | K7 | 64 | -48 | 70 | -2 | 21.91 | 61 | -15 | 70 | -2 | 30.05 |
|   | L7 | 54 | -7 | 63 | -11 | 16.86 | 69 | -41 | 74 | -11 | 16.13 |
|   | M7 | 95 | -91 | 74 | -46 | 17.83 | 91 | -41 | 74 | -46 | 11.69 |
|   | N7 | 22 | 1 | 47 | 52 | 20.76 | 41 | 7 | 47 | 52 | 8.44 |
|   | A10 | 52 | 74 | 61 | 23 | 15.63 | 71 | 24 | 61 | 23 | 8.50 |
|   | F10 | 85 | 9 | 75 | 26 | 20.26 | 83 | 4 | 75 | 26 | 9.83 |
|   | E6 | 25 | 55. | 47 | -27 | 19.84 | 36 | 8 | 47 | -27 | 12.24 |
|   | J10 | 51 | -60 | 24 | -21 | 25.15 | 62 | 6 | 76 | -21 | 14.68 |

The analysis of the experimental data suggests that the optical characteristics of the base material in additive systems operating on CJP (Binder jetting) technology influence the color gamut of the additive system (table 1). The analysis of the experimental data in table 2 shows that the use of color
management techniques in additive systems solves the problem of coordinated color communication between design programs and 3D printing devices. The average values of the color difference between the original color coordinates of the digital three-dimensional model and the actual color coordinates of the three-dimensional object made by the additive system based on the Zprinter 450 and the G-16 material differ by 5.84 units $\Delta E$ in favor of the use of color management techniques for the best color matching of the digital three-dimensional model and the finished product.

6. Conclusion
Color management in additive systems will allow to reach a new qualitative level of manufacturing three-dimensional products. This problem can be solved in several ways, such as the use of the above technique, however, it requires the introduction of additional operations in the preparation of a three-dimensional digital model, and therefore additional competencies from technologists and operators of additive plants. Colorimetric data show the effectiveness of the proposed technique, which allowed to reduce the average color difference from 19.78 $\Delta E$ to 13.95 $\Delta E$ between the original and actual values of the color coordinates of the test object fields on the basis of the scale TC 3.5 CMYK.

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