https://doi.org/10.24867/GRID-2024-p14 Original scientific paper

DIFFERENT METHODS FOR PRODUCING COLOR REPRODUCTIONS ON 3D PRINTED OBJECTS

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Abstract: *This article presents two methods of colour printing on programmable 3D structures and their use for practical applications in everyday life. The colour printing was done by direct printing with a flatbed UV inkjet printer and indirect printing by thermally transferring the electrophotographic toner to the 3D printed object produced with the most widely used and affordable material extrusion 3D printing technology. The print quality of the colour reproductions was determined by basic densitometric and spectrophotometric measurements, ink adhesion analysis and image analysis of the printed graphic elements. The research was also extended to the field of 4D printing, where 3D printed objects with flat geometry can be subsequently transformed when exposed to a suitable activation medium. In this case, the direct printing process was used for colour printing, as it allows printing on both sides of the programmable 3D structures compared to the indirect printing process. The advantage of colour printing on a programmed 3D structure is that the flat geometry can be easily printed with colour graphics on the entire surface and later transformed into a new 3D object shape, whereas conventional 3D objects cannot be printed in very inaccessible places due to their geometry. These methods, which use direct or indirect printing techniques to create coloured reproductions on 3D-printed objects, enable the personalisation and aesthetic enhancement of products and can also provide additional interactivity if, for example, QR codes or RFID tags are included. The research focuses on the production of colour-printed smart objects for consumer products.*

Key words: 4D printing, 3D printing, UV inkjet, electrophotography, colour reproduction

1. INTRODUCTION

3D printing technologies have undergone tremendous development over the past decade, making it possible to create complex three-dimensional structures with high precision. 3D printing is now used in many industries, from medicine to the automotive industry, where it enables flexible and affordable solutions for the production of prototypes and finished products (Jandyal et al., 2022; Ngo et al., 2018). Despite these advances, challenges remain, especially in colour reproduction on three-dimensional objects, where the accuracy and uniformity of printing depends on several factors, such as the printing technology, the materials used and the surface properties (Jiangping et al., 2021; Ngo et al., 2018; Tan et al., 2020).
The development of 3D colour printers, which enable both full-colour and multi-colour printing, is being driven forward intensively worldwide. Full-colour printing enables the accurate reproduction of a wide range of colours, but 3D printers that enable this are much more expensive than monochrome or multicolour printers. The most affordable 3D printing technologies are based on the extrusion of thermoplastic materials (FDM), with these technologies already enabling both full-colour and multicolour printing (Formlabs, 2024; Silapasuphakornwong et al., 2021). UV inkjet printing has proven to be one of the most effective methods for printing on complex 3D surfaces, as it enables instant drying of inks, high quality and flexibility when printing on three-dimensional objects (Clark et al., 2017).
Research in the field of colour printing on 3D printed objects has so far mainly focused on inkjet techniques, with UV printing enabling the reproduction of accurate and high-quality colour prints. This technology is often used for the production of personalised products, didactic tools and in the packaging industry (Yang et al., 2012). In recent years, research in the field of 4D printing, which includes active materials, offers new possibilities for interactive and adaptive structures that can change their shape according to various external factors (Pivar, Gregor-Svetec & Muck, 2022; Pivar et al., 2024; Piyush, Kumar & Singh, 2022; Kumar et al., 2024).
In addition to the challenges of color reproduction on 3D objects, research also shows the significant influence of surface properties such as roughness and gloss on print quality. A rough surface enhances color adhesion, providing a better grip for inks to adhere. However, it can also lead to issues such as uneven ink distribution and reduced optical quality of the color, resulting in a less smooth and visually appealing finish.Various surface treatment techniques such as laser, chemical and mechanical treatment can improve

the surface quality before printing, leading to a better printing result (Taufik & Jain, 2017; Adel et al., 2018; Singh et al., 2017; Garg, Bhattacharya & Batish, 2017; Chohan & Singh, 2017).
In this study, we focused on the comparative analysis of the use of UV inkjet printing and thermal transfer of electrophotographic toner for colour reproduction on three-dimensional objects. We investigated the advantages and disadvantages of both printing processes in terms of print quality and also presented an example of colour printing on a programmed 3D-printed structure that was transformed into a new 3D shape after exposure in the activation medium.

2. METHODS

2.1 3D printing process

3D printing of the 70 × 130 mm and 0.3 mm thick samples was performed using a ZMorph VX 3D printer (ZMorph S.A., Poland) with a heated build plate. The samples were made from white PLA filament purchased from the manufacturer Plastika Trček d.o.o. (Slovenia, Ljubljana). White PLA was chosen to achieve a wider colour gamut in printed colour reproduction. The PLA was printed directly onto temperature resistant Avery Zweckform 3560 polyester film which was purchased from CCL Industries Inc (Canada, Toronto). In one case the polyester film was unprinted, in the other case it was pre-printed with a colour test images. The 3D printing parameters are listed in Table 1. They were adjusted to achieve good adhesion between the PLA material and the polyester film and to achieve a smooth surface of the samples, which is important for good printability. Finally, they play a very important role in the toner transfer from the polyester film to the PLA material.

Table 1: 3D printing parameters

Printing parameter	Value
Nozzle Diameter [mm]	0.4
Printing Temperature [°C]	215
Build Plate Temperature [°C]	30
1st Layer Height [mm]	0.1
2nd Layer Height [mm]	0.2
Infill Pattern [/]	Rectilinear
Infill Angle [°]	0°

2.2 Colour printing process

The colour test images were printed onto the 3D-printed samples in two ways. The first indirect printing process involves the heat transfer of electrophotographic toner from the polyester film during the 3D printing process, while the second printing process involves the direct printing of UV inks onto the flat geometry of the 3D printed samples. In both cases, digital printing techniques and identical test images were used. A Xerox Vesant 280 electrophotographic digital printer (Xerox, U.S.) was used to print the test images for the indirect printing process and an Apex UV6090 UV LED inkjet flatbed printer (Apex, China) with Nazdar 260 UV LED inks was used for the direct printing process. The test images were designed so that all relevant print quality attributes could be assessed using validated methods. They consisted of colour patches for spectrophotometric measurements, colour patches for measuring optical density and tonal values, elements for evaluating geometric print quality and elements for determining ink adhesion. Five samples were printed for each printing process.

2.3 Printing evaluation

The densitometric and spectrophotometric values were measured with an X-rite Exact spectrodensitometer under D50 illumination, 2° standard observer, 45:0 measurement geometry and white backing. The optical density, tonal value and the CIELAB colour values were determined for both printing processes.
The adhesion of the UV ink and the electrophotographic toner to the PLA material was determined by the cross-cut method using a Byko-Cut device (BYK-Gardner GmbH, Germany). The cuts were made at an angle of 45° to the direction of the deposited filaments and visually inspected using a Dino-Lite AM4113ZT digital

microscope (AnMo Electronics Corporation, Taiwan). The quality of the cross-cuts was evaluated based on the ISO 2409 classification.
The geometric irregularities of the printed graphic elements were analysed with the software ImageJ 1.54 (open source). The images of the graphic elements were taken with a Dino-Lite AM4113ZT digital microscope (AnMo Electronics Corporation, Taiwan) at 50x magnification. The edge sharpness and physical gain were determined on 0.3 mm wide printed lines. They were determined by analysing the line area and perimeter and compared with the reference values (ideal) from the digital document. The influence of the printing processes on the deformation of the graphic elements was determined by measuring the roundness of dots with a diameter of 0.4 mm. The values were compared with the reference value of a geometrically perfect dot, defined by the value 1. The roundness of the dots was determined according to Equation (1).

$$\mathrm{Roundness} = 4 \times \mathrm{area}/(\pi \times \mathrm{major\_axis}^2) \tag{1}$$

2.4 Practical example of a smart structure

This chapter presents an example of the use of programmable 3D structures for practical applications in everyday life. An example is a smart mobile phone stand that transforms from a flat geometry into a new 3D shape. The example was printed with colour graphics on both sides using a UV inkjet printer. With UV inkjet printing, both sides of the programmable 3D structures can be printed, whereas with thermal transfer printing, only the underside can be printed. After colour printing, the programmable 3D structure was thermally activated in water at 80°C to change its shape.
The programmable 3D structure was made from a combination of active PLA and passive PRO-PLA thermoplastics. An aligned rectilinear pattern with a fill density of 99% was used for the active part and a rectilinear pattern with a fill density of 30% was used for the passive parts. The printing temperature and the temperature of the build plate were 195°C and 30°C respectively. The technical data of the practical example are shown in Table 2 and the schematic representation can be seen in Figure 1.

Table 2. Technical data of practical example

Specification of active element (AE)	Value
Number of AE	1
Number of active layers	20
Height of active layers [mm]	0.1
Length of AE [mm]	24
Width of AE [mm]	15
Bending direction	Downwards
Filament orientation [°]	0

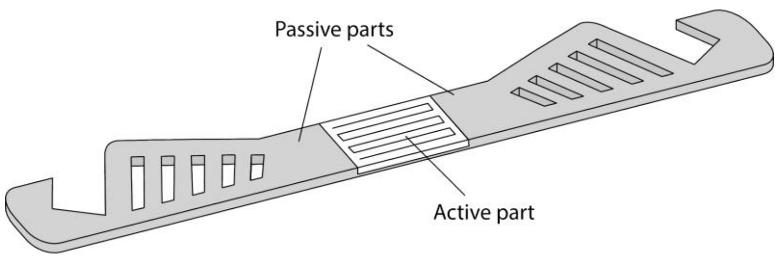

Figure 1: Schematic representation of the flat geometry of a programmable 3D structure.

3. RESULTS

3.1 Densitometric analysis

The measurements of the optical density of the solid tone (100% TV) of process colours are shown in Table 3. Higher optical density values are measured for heat transfer printing. The exception is the optical density of the colour cyan, which is higher for UV inkjet printing. The highest optical density value is achieved when the colour black is printed using the heat transfer printing process. This indicates that the dynamic range for thermal transfer printing is greater than for UV inkjet printing. The standard deviations of the optical density measurements show that the ink transfer is stable for both printing processes. It can be assumed that the surface properties of the 3D printed samples and the 3D printing parameters did not adversely affect any of the printed inks.

Table 3: Average values and standard deviations of the optical density

Colour	Optical density [/]	
	UV inkjet	Heat transfer
C	2.44 (±0.024)	2.29 (±0.028)
M	1.61 (±0.011)	2.14 (±0.050)
Y	1.71 (±0.015)	2.02 (±0.037)
K	1.71 (±0.004)	2.54 (±0.034)

Figure 2 shows the dependence between the reference value and the measured tone values for or all process colours. The investigation has shown that the dot gain is higher for all colours in the UV inkjet printing process. The smallest dot gain was found for magenta. The dot gain for the colours cyan, yellow and black is between 31.9 and 34.4% at 50% tonal value. For magenta it is 24.3%. With heat transfer printing, all colours have a lower dot gain than with UV inkjet printing, with the exception of magenta. The dot gain for all colours is between 25.2 and 28.1% at 50% tonal value. This means that printing details in light, medium and dark tones achieve a higher quality with heat transfer printing.

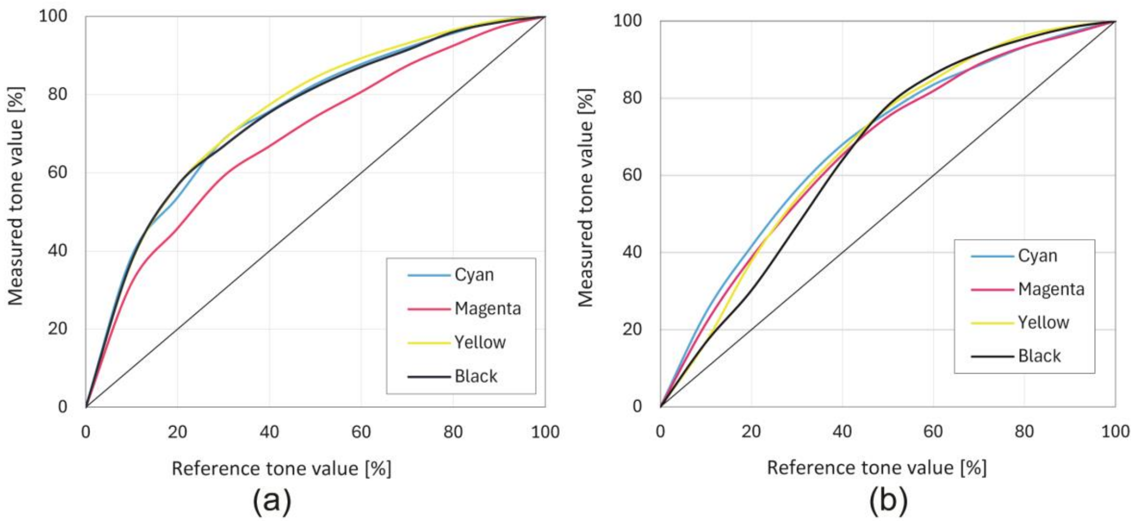

Figure 2: Dependence between the reference value and the measured tonal value for both printing processes. (a) UV inkjet printing and (b) heat transfer printing.

3.2 Spectrophotometric analysis

Based on the measured CIELAB colour values (Table 4) of the primary and secondary solid colours, a colour gamut diagram was created for both printing processes (Figure 3). The larger the colour gamut, the better the colour reproduction. A comparison of the colour gamuts of prints produced with both printing processes shows some differences. The comparative analysis of the colour gamut areas showed that the UV inkjet colour prints have a slightly larger colour gamut than the electrophotographic prints. However, a detailed analysis of the colour gamuts showed that the UV inkjet printing process reproduces richer magenta and blue tones as well as slightly richer green tones, while the indirect electrophotographic printing process mainly reproduces more saturated yellow tones.

Table 4: CIELAB colour values for both printing processes.

Colour	UV inkjet			Heat transfer		
	L*	a*	b*	L*	a*	b*
C	45.53	–35.86	–49.67	46.88	–32.81	–52.71
M	47.33	74.89	–5.95	41.50	74.17	6.01
Y	85.54	–4.91	90.82	87.18	–8.27	100.25
K	17.80	1.80	5.02	13.52	–0.42	–1.36
R	46.69	66.78	52.36	40.29	70.37	44.71
G	39.80	–78.45	18.23	39.28	–73.18	24.46
B	16.90	23.98	-49.15	14.46	17.51	–38.14

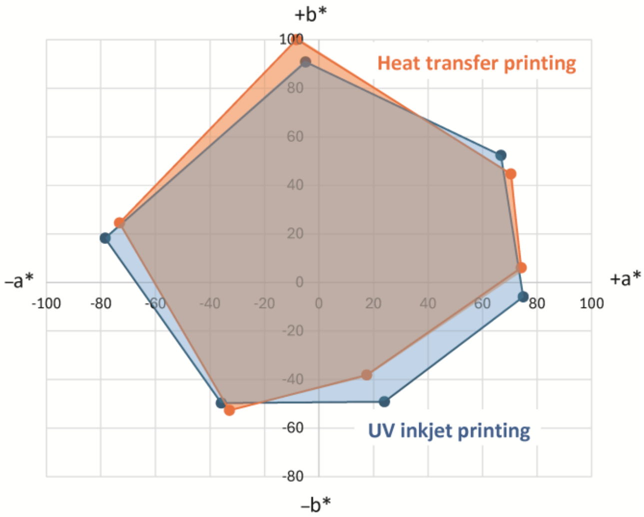

Figure 3: Colour gamut for both printing processes.

3.3 Ink adhesion

The optical images (Figure 4) of the cross-cut pattern show that the adhesion of the UV ink and the electrophotographic toner to the 3D printed samples is very good. The adhesion of the UV ink achieves ISO classification 0 with smooth cut edges and no detached ink. The adhesion of the electrophotographic toner achieved ISO classification 1, with slightly damaged chipped edges and up to 5% detached ink. The analysis of the adhesion showed that both printing processes are suitable for printing on the 3D printed PLA material.

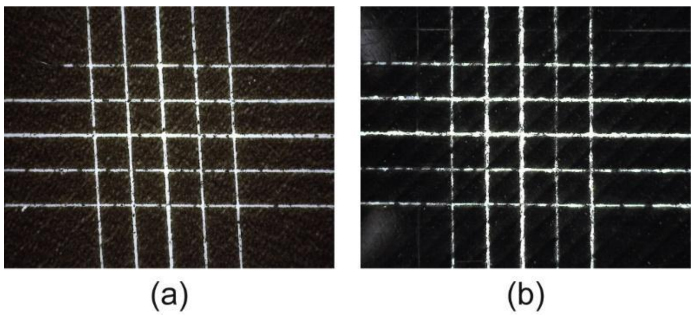

Figure 4: Analysis of ink adhesion on prints with both printing processes. (a) UV inkjet and (b) heat transfer printing.

3.4 Image analysis

The image analysis has shown that geometric irregularities of the printed graphic elements occur in both printing processes, as can be seen from microscopic images (Figures 5 and 6) and from measurements of the roundness of the printed dots (Table 5) and the perimeter and area of the printed lines (Table 6).

The analysis of the roundness of the dots (Table 5) showed that UV inkjet printing leads to a higher deformation of the printed dots. The roundness of the dots printed with a UV inkjet printer reaches a value of 0.821, while the roundness of the dots printed with an indirect printing process is slightly higher at around 0.975 and comes very close to an ideal circular shape with a roundness value of 1. The deformation of the graphic elements during UV printing is due to the distribution of the droplets and the spreading of the UV ink in the channels between the deposited filaments.

Table 5: Average values and standard deviation of dot roundness

Printing process	Dot Roundness
UV inkjet	0.821 (±0.027)
Heat transfer	0.975 (±0.012)

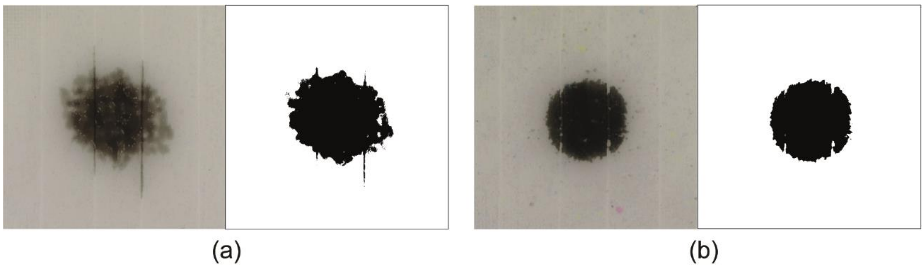

Figure 5: Visual comparison of microscopic images of printed dots with both printing processes: (a) UV inkjet and (b) heat transfer printing.

The comparison of the measurements of the printed line area with the reference value of the ideal line (Table 6) shows that there is a physical increase in the lines with both printing processes. The physical increase is greater with UV inkjet printing. The perimeter of the lines also increases significantly with both printing processes, which indicates a poor sharpness of the edges. In both cases, the deformation of the edges is caused by the channels between the deposited filaments in the 3D printed sample. In UV printing, the liquid UV ink is spread into the channels before the UV light cures it (Figure 6a), while in the indirect process, the electrophotographic toner is not transferred into the channels over the entire surface (Figure 6b), resulting in lower edge sharpness.

Table 6: Average values and standard deviations of the area and perimeter measurements of the printed line with both printing processes.

Printing process	Area [mm^2]	Perimeter [mm]
Reference value	2.1	14.6
UV inkjet	2.58 (±0.022)	23.99 (±1.400)
Heat transfer	2.33 (±0.003)	20.96 (±0.428)

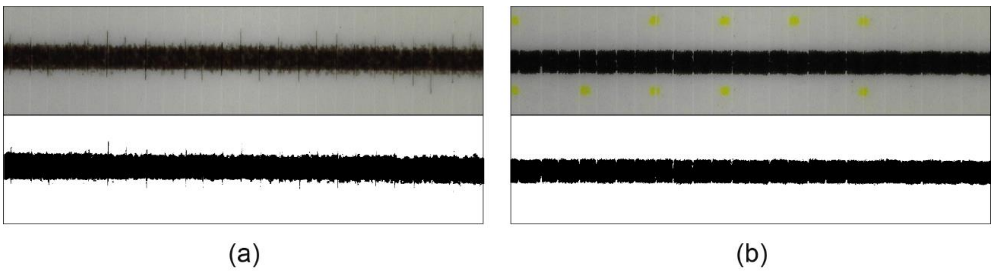

Figure 6: Visual comparison of microscopic images of printed lines with both printing processes: (a) UV inkjet and (b) heat transfer printing.

3.5 Practical example of a smart structure

The practical example, which was printed on both sides with colour graphics using a UV inkjet printer, shows the simplest form of a programmable 3D structure (Figure 7). This example structure demonstrates a unilateral, unidirectional transformation. It contains only one active element, printed with an aligned rectilinear infill pattern, and two symmetrical passive elements that have a specific shape to hold the phone. The printing sequence of the first active layers and the second passive layer causes the phone stand to transform in a convex (downward) direction. The passive elements remain stable during thermal activation and have good mechanical properties to hold the phone. The results of the basic example printed with colour graphics show that the programmable 3D structures are sufficiently stable to produce the intended practical objects and that UV inkjet printing is the appropriate printing process as there are no visible irregularities in the printed UV ink.

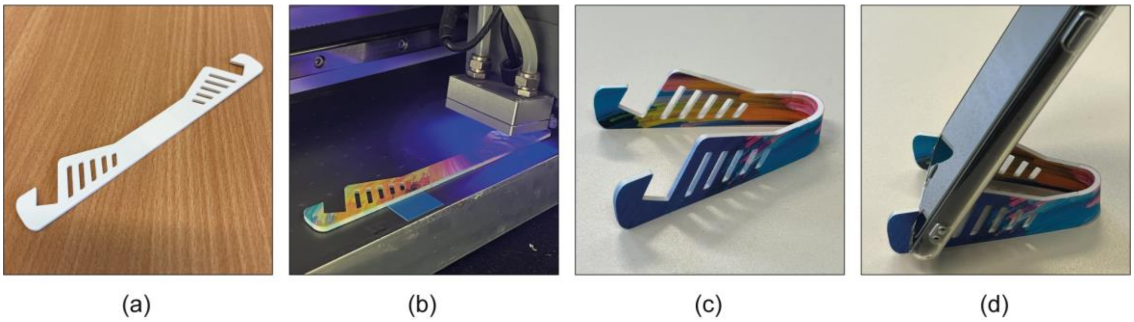

Figure 7: (a) Programmed mobile phone stand in flat geometry. (b) Printing of colour graphics with a digital UV inkjet flatbed printer on a programmed mobile phone stand. (c) Thermally activated mobile phone stand. (c) The final shape of the mobile phone stand in practical use.

The process of thermal activation of the programmed 3D structure is demonstrated in the attached video 1 (supplementary material) or on request (matej.pivar@ntf.uni-lj.si).

4. CONCLUSIONS

The research provides important insights into colour printing techniques on 3D-printed objects and opens up new possibilities in the field of 4D printing. A comparison of direct UV inkjet printing and indirect electrophotographic printing shows differences in the quality of the colour reproductions. The heat transfer of the electrophotographic toner ensures less dot gain and no major deformation of the graphic elements. However, UV inkjet printing allows for a wider colour gamut, especially in blue and green tones, which is an advantage for certain applications. Both printing processes enable good adhesion and are suitable for printing on 3D-printed objects. However, the print quality of both printing processes is affected by the surface of the 3D printed sample, which reduces the sharpness of the edges of the printed elements. It is important to emphasise that for colour printing in 4D printing, UV inkjet printing is more suitable than indirect electrophotography, as it allows colour printing on both sides of the programmable 3D structures. Heat transfer printing only allows printing on the underside of the programmable 3D structures.

The integration of 2D printing into 4D printing represents the next development step, which enables personalisation and aesthetic refinement of the products and can offer additional interactivity. The process presented for the production of practical objects enables 3D printing without support structures and thus avoids plastic waste. The flat geometry of the 3D objects enables volume-efficient storage, shipping and transport of the printed objects.
Research has shown that both printing techniques, direct and indirect printing, can produce an adequateprint quality. However, the requirements of the product must be carefully analysed in order to select the appropriate technique. The expansion of research into 4D printing opens the door to many innovations, particularly in the use of active elements that utilise dynamic morphing. Further research could improve the accuracy and efficiency of these processes while providing new solutions for industrial applications in 3D and 4D printing.

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