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Short Paper

Tactile prints in colour: Studying the Visual Appearance of 2.5D Prints for Heritage Recreations

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Abstract

Printing applications for heritage recreation are a means to allow audiences to appreciate details and engage with cultural materials through closer interaction. A 2.5D print is a media suitable to incorporate visual and tactile qualities such as colour, low relief, textures and roughness. Designing a colour-accurate tactile print requires, nevertheless, anticipating how specific shapes and meso-geometries will affect the reflective properties of the surface, thus changing its appearance. Hence, this paper contributes to improve the understanding of the interaction between geometry and colour when deploying 2.5D prints so that tactile portable replicas can be easily produced. For this, we have produced a series of 2.5D printed patches with varying meso-textures, based on procedural noise functions, and measured their colour coordinates and glossiness. We aim to find a correlation between colour shift (expressed as lightness, chroma and ΔE) and the scale and distribution of surface details.

CCS Concepts

• ***Applied computing*** → ***Arts and humanities; Physical sciences and engineering;***

1. Introduction

A large amount of the documentation of archaeological sites around the world, which were produced by European explorers in the 19th and early 20th century, remains in UK museums and contains unique insights into the sites. However, long before the digital age, common methods to record shapes and colours were based on illustration, painting, casting and later on photography. This project explores how these analogue and hand-made records, as well as current documentation, can be translated into 2.5D objects that support a richer interpretation of the monuments and artefacts in the archaeological sites [SR19].

In particular, this research aims to recreate the frieze of the Palace of Stuccoes, dated ca. 500-600AD and located in Yucatan Mexico. The monument and the artwork are currently severely damaged mainly by the harsh environmental conditions of the area. Nowadays the only records of the imagery and colours, are the watercolours painted by Adela Breton and a series of analogue photographs taken by Teobert Maler and coloured by Breton (see Figure 1), most of them held by the Bristol Museum and Art Gallery.

Furthermore, the need of protecting material heritage creates a distance between the visitor and the object, thus restricting the cultural experience of exhibits to only visual interaction. Such constraints compromise one of the main aims of heritage institutions, which is to enable visitors to access heritage artefacts, especially those who are too young or have physical difficulties engaging with the objects by visual means [NRRK14]. Multisensory experiences, which incorporate touch amongst other senses, have the potential to increase engagement and make knowledge more accessible to wider audiences. Museums visitors who are allowed to handle replicas will have, potentially, a more meaningful and enjoyable experience [WSW*17] which highlights the possible educational benefits of using printed reproductions.

Figure 1: *Watercolour panel from the Acanceh frieze Ca. Ea8186a ©Bristol Culture.*

Recently, 3D printing has become an alternative for the creation of relief maps and tactile representations for blind and visually impaired people [SRSE17], offering designers more control over tactile configurations, than other methods such as thermoforming and microcapsule [TC17] [GP11].

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A 2.5D print is a 2D print with added relief. The 2.5D printing method, also called elevated printing, is based on inkjet deposition and is suitable to produce volumetric forms in colour, with applications in the reproduction of artworks, such as oil paintings [EEL*17], or in the recreation of wall reliefs made by casting surfaces from a 2.5D print [Fou]. As such, elevated printing makes it possible to add a tactile dimension to designs in full colour and high resolution by stacking layers of UV curable inks. In this research, we deploy a prototype printer at Canon Production Printing, which is capable to produce prints up to 5mm high, in contrast with the commercial versions that print up to 1 mm in height. The elevation layers are built up in a blackish mixture of all inks, which are covered by a layer of white ink, and finished with a multi-coloured layer to create a full-colour print according to a raster image.

Recreating the Acanceh frieze in 2.5D format has involved producing 3D information from the scarce 2D records, and to design an appearance that communicates to the user the properties of the monument, including the material context. In this work, we focus on studying the appearance properties of 2.5D prints through the combined visual effect of surface geometry and colour, which is essential to render accurate colour appearance and meaningful tactile effects on a relief surface. Unlike other works [BSUO16] that have studied the effect of regular patterns on the surface, our approach is based on the use of procedural noise, which intends to generate more realistic-looking prints with a tactile robust surface. Moreover, to develop pipelines for material reproduction using 2.5D printing, we investigate its application in reproducing the appearance of an ancient stucco relief in an on-scaled elevated print.

The paper is organised as follows. Section 2 describes the generation of 2.5D designed textures, while Section 3 focuses on the characterisation of 2.5D prints, along with analytical results. Finally, Section 4 presents conclusions and further work.

2. Designing Texture for Tactile 2.5D Print

The appearance of any surface is an identifier of its material qualities and can be described in terms of the perceptual and interrelated appearance attributes of colour, glossiness, texture, and translucency. The scale, distribution and periodicity of morphological features, affect the way the light is reflected or scattered, and ultimately perceived.

The appearance of a 2.5D print is related to the optical properties of the inks, substrate [BSB*14] and surface texture [BSUO16]. The complexity of the height distribution across the surface (shape, waviness and roughness), will have a more significant influence than in a flat print, therefore the colour and glossiness of the outcomes will be more difficult to control.

The creation of a 2.5D model involves firstly, designing the surface geometry as a 3D model or as an elevation map. We have used the second approach to encode different levels of roughness or meso-texture in grayscale images, which we use as elevation files to produce printed patches.

To describe elevation we use a 16bit grayscale image, where the intensity values correspond to height values allowing for 65,536 levels in the z-direction. The native resolution of the printer is about 450x450dpi, although in this case, we used 400dpi resolution for printing.

To generate an elevation model that simulates the texture of a stucco surface we used a Perlin noise-based algorithm. This procedural noise is able to resemble textures with desired stochastic characteristics at different visual scales [Per85]. This algorithm is implemented in Matlab and takes as input parameters the texture size required, and others described below.

Previous tactile studies [TZG18] on the perception of roughness on 3D prints, found that the noise distribution is not as important as the height and the type of *cap* used for the noise. For instance, more sharply pointed elements feel rougher, whereas flatter elements feel smoother. Taking into account these results, we experimented with varying two elements on the texture through two additional parameters: 1) the maximum elevation height for the noise, and 2) the density level for the distribution of noise. We created texture samples for six different density levels. The density level parameter is used to define the grid for the Perlin noise algorithm and ranges from coarse distribution using a 4x4 grid to a much denser distribution using a 128x128 grid. For each height, we also combine different levels of noise by overlapping noise from coarser distributions including finer details.

Figure 2 illustrates the 6.5 cm x 6.5 cm texture samples created at different heights for the six different levels of density. These are created at 400 dpi and use a 2^{16} grayscale. The effects of the density level parameter are evident as 128x128 grids (level 6) produce a denser noise per pixel when compared to the 4x4 grid (level 1). Figure 3 illustrates the 6.5 cm x 6.5 cm texture samples created by combining noise at different density levels. These samples range from a 4x4 grid (level 1) (first texture from left to right in Figure 3) to what we refer to as accumulated level 6 which is an aggregation of the various previous levels to create finer details.

Two sets of texture samples were made using the colour measurements from the original Breton's watercolour paintings (see Figure 1) using a colourimeter X-Rite i1Profiler. Another set of samples was printed in gray for consistency with previous literature where gloss is studied [BSUO16]. Figure 4(Right) highlights some patches which upon visual inspection display a stucco-like surface.

Moreover, to understand how colours in different regions of the colour space are affected by texture, we have reproduced a colour chart of 16 patches (10 mm x 10 mm) Fig.4 (Left), at 9 maximum heights, namely 0.0 mm, 0.1 mm, 0.2 mm, 0.25 mm, 0.5 mm, 0.75 mm,1.0 mm, 1.25 mm, 1.5 mm and 1.75 mm, all at level 5 (grid 64x64); plus one chart with accumulated levels up to grid 128x128 and height 0.5mm. These levels were chosen, as, based on our visual judgement, they have textural features in the scale of a real stucco sample.

3. Analysis of Gloss and Colour for varying textures

Gloss is an indicator of the roughness of a surface and can be measured based on the directional reflected light [14]. We measured the glossiness of a set of patches using an RA532H Canon surface reflectance analyser. This device measures specular gloss in gloss

Figure 2: *From left to right at the height specified: Perlin noise texture tests with a* 1 mm *height with level 1 (4x4 grid), level 2 (8x8 grid), level 3 (16x16 grid), level 4 (32x32 grid), level 5 (64x64 grid), and level 6 (128x128 grid)*

Figure 3: *From left to right at the height specified: Perlin noise texture tests with a* 1 mm *height with accumulated levels*

units (GU). The measures were taken according to the method defined by the standard ISO 2813, for both at 60° (semi-gloss) and 85° (low-gloss).

Colour values were measured with a colourimeter X-Rite i1Profiler as CIEL*a*b* coordinates. The measurements were taken in the M1 mode for an observer at 2 degrees, with the spectral distribution specified by CIE illuminant D65. The CIEL*a*b* colour system represents quantitative relationships of colours on three axes: The $L*$ value indicates lightness, whereas $a*$ and $b*$ specify chromaticity coordinates. Chroma (C*) or colour saturation can be calculated from the a* and b*coordinates as 1:

$$C = \sqrt{a*^2 + b*^2} \tag{1}$$

To explore the relationship between lightness and chroma and the differences in colour, we calculated the Euclidean distance between two points in the L*a*b*space, known as ΔE 2,:

$$\Delta E*_{ab} = \sqrt{(L*_2 - L*_1)^2 + (a*_2 - a*_1)^2 + (b*_2 - b*_1)^2} \tag{2}$$

According to perceptual studies when ΔE >2 observers can notice a colour difference, whereas if ΔE>5 the colours appear different [MT11].

Through the analysis of the data we observed that the glossiness decreases as the maximum height of the relief increases. It also decreases for higher individual levels (finer grid), whereas for accumulated density levels there is no significant variation of gloss when increasing level. In general, higher individual density levels of noise led to a more matt appearance than the accumulated levels.

The measured colour differences ΔE for the 16 colours charts are shown in Figure 5. Here, we observe that darker colours have a bigger colour shift expressed as ΔE, when increasing the texture height, for instance, green, and purple, whose L*a*b* coordinates are (43.9,-73.1,16) and (17.6,32.5,-45.3) respectively. Whereas the patches with the less significant colour shift are white and lilac with coordinates (93.6,-2.7,3.56) and (81.69,1.68,-4.96) respectively. Figures 6 and 7 show the differences of chroma (C) and lightness (L) when increasing the elevation of samples with the same density level (level 5 or 64x64 grid). In Figure 7 we observe that in darker patches (L closer to zero) this value increases, especially until reaching a height of 0.5 mm. On the other end, the lightness value L of the clearest patches (L closer to 100, such

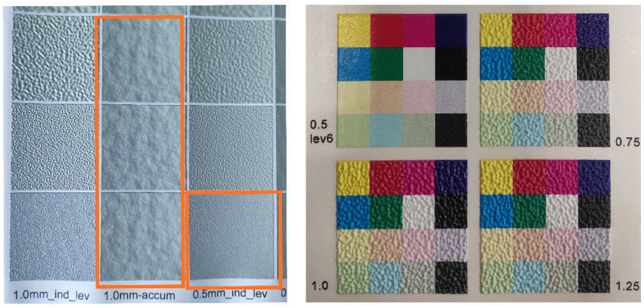

Figure 4: *(Right) 2.5D Printed samples displaying a stone-like surface. (Left) Colour charts with different texture pattern. Each colour patch has an area of 10 mm x 10 mm. Numbers indicate maximum height.*

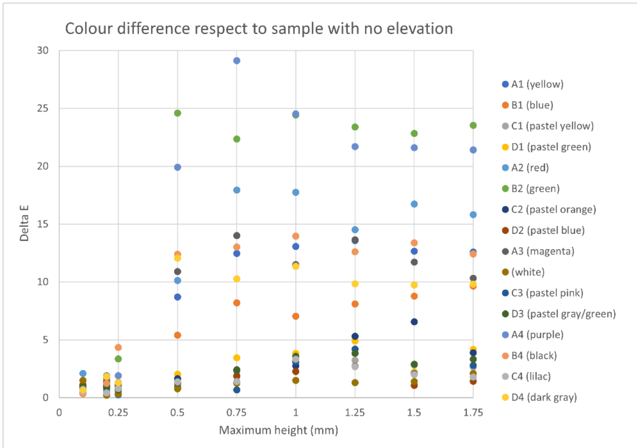

Figure 5: *Colour differences between patches with different texture heights.*

as white or pastels) decreases overall the studied height interval, whereas patches with an intermediate L value, become clearer until 0.5 mm, then this value decreases for higher textures. The changes in chroma, as shown in Figure 6, are more noticeable in yellow, magenta, red, green and blue which are the colours of the inks in the printing method, or their basic combinations. The chroma in general decreases, which means that colours become desaturated, except for patches originally low in chroma such as black, white, pastel pink and lilac. We see that increasing the texture then makes the prints more matt, apparently whiter and less saturated.

On the other hand, the printing process could help explain why the lightness of the clearer colours decreases when increasing the height. The print elevation is built up in black ink, which is covered with a white ink layer, and finally the colour layer. When the print texture is too steep or consists of sharp peaks, the dark background layer can be seen through, as the colour layer becomes thinner than in flat areas, and therefore the lightness does not increase with finer details. Finally, the surfaces made with accumulated levels are smoother, which keeps the background layer hidden, and the lightness increases as the surface becomes rougher and more matt.

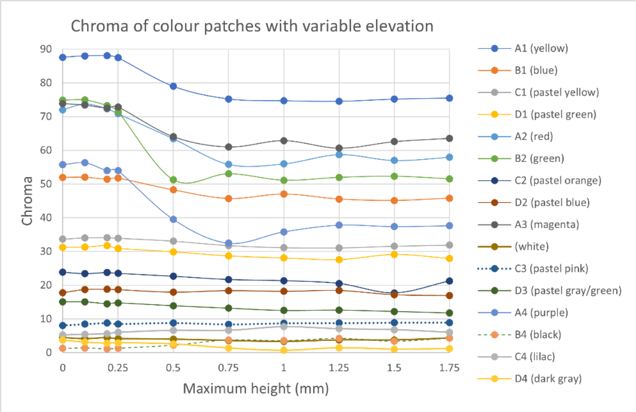

Figure 6: *Chroma of patches with different texture heights.*

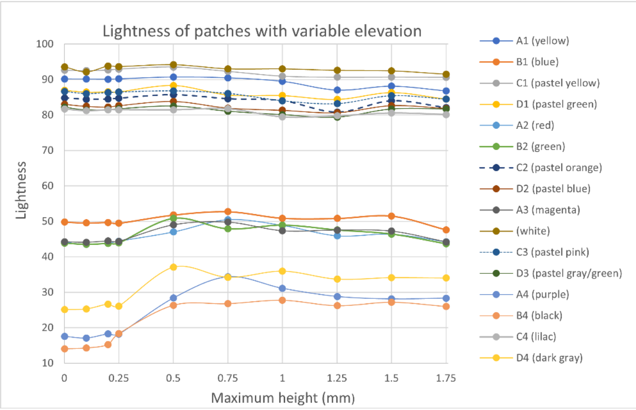

Figure 7: *Lightness of patches with different texture heights.*

4. Conclusions and Further Work

We have measured the colour and glossiness in 2.5D printed patches with variable surface texture or roughness, to better estimate the influence of tactile features and geometry of the design on the print appearance, and potentially correct the shifts in these properties by modifying the colour file. By studying the dependency of gloss, lightness and chroma are on the height and density level of the prints, we observed that the glossiness decreases and ΔE increases more significantly with the height for individual levels. Moreover, darker colours become lighter, and the chroma of primary and secondary colours decreases for higher levels of texture. Lighter colours, on the other hand, are less affected by increasing the density of the texture. This initial characterisation work will allow us to develop a model to relate the bidirectional reflection function to surface normals statistics to design an accurate 2.5D print in the next stage of the research.

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