Topographical scanning and reproduction of near-planar surfaces of paintings

Willemijn S. Elkhuizen[*a], Tim Zaman[b], Wim Verhofstad[c], Pieter P. Jonker[d], Joris Dik[e], Jo M.P. Geraedts[f,g]

[a]Dept. Design Engineering, Delft University of Technology, Landbergstraat 15, 2628 CE Delft, NL, +31 15 2786367; [b]Dept. Chemical Engineering, Delft University of Technology, Julianalaan 136, 2628 BL Delft, NL; [c]Canon PPP System Development, Océ Technologies B.V., St. Urbanusweg 43, 5914 CA Venlo, NL, +31 77 3592719; [d]Dept. Biomechanical Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, NL, +31 15 2782561; [e]Dept. Materials Science and Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, NL, +31 15 2789571; [f]Dept. Design Engineering, Delft University of Technology, Landbergstraat 15, 2628 CE Delft, NL, +31 15 2784476; [g]Canon PPP Design, Océ Technologies B.V., St. Urbanusweg 43, 5914 CA Venlo, NL, +31 77 3594047

ABSTRACT

Paintings are near-planar objects with material characteristics that vary widely. The fact that paint has a material presence is often overlooked, mostly because we often encounter these artworks in the form of two-dimensional reproductions. Capturing paintings in the third dimension is not only important for study, restoration and conservation, but it also inspires 3D printing methods[1], particularly through the high demands it makes on reproducing color, gloss and texture.

"A hybrid solution between fringe projection and stereo imaging is proposed as 3D imaging method, with a setup involving two cameras and a projector. Fringe projection is aided by sparse stereo matching to serve as image encoder. These encoded images processed by the stereo cameras solve the correspondence problem in stereo matching, leading to a dense and accurate topographical map, while simultaneously capturing the composition of the painting in full color"[1].

The topographical map and color data are used to make hardcopy 3D reproductions, using a specially developed printing system. Several paintings by Dutch masters Rembrandt and Van Gogh have been scanned and reproduced using this technique. These 3D printed reproductions have been evaluated by experts, both individually and in a side-by-side comparison with the original.

Keywords: 3D scanning, topography, 3D printing, painting, stereo imaging, fringe projection, full color

1. INTRODUCTION

1.1 Digitization of cultural heritage

As stated by Zaman et al.[2]: "Making Cultural Heritage artifacts accessible to the public is an important mission of museums, libraries and archives". They state that to facilitate this, they often digitize the artifacts to remediate them and make them available on the Internet. Doing this has several advantages. Besides making the artifacts accessible for everyone, digitizing will build a database that can be easily accessed. These digital files of the artifacts can be used for purposes of preservation, relevant for items that are slowly degrading. Moreover, digitization facilitates conservation, art history studies, and restoration. Finally they can be used for exploitation for publicity or profit[2].

* w.s.elkhuizen@tudelft.nl; www.io.tudelft.nl

Measuring, Modeling, and Reproducing Material Appearance, edited by Maria V. Ortiz Segovia, Philipp Urban, Jan P. Allebach, Proc. of SPIE-IS&T Electronic Imaging, SPIE Vol. 9018, 901809

· CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2042492

1.2 A painting is a 3D landscape of paint

Paintings are generally 2D projections of a 3D world, carefully considered and realized by the artist. Zaman et al.[2] state: "Painters like Rembrandt and later van Gogh - apart from using cues such as depth from luminance and shape from shading - more and more used paint in 3D as a medium to give form to the local 3D shape of objects in their paintings", proof of which can be found in the analysis of Rembrandt's work[3]. Also Vincent van Gogh states in one of his letters: "Sometimes the subject calls for less paint, sometimes the material, the nature of the subjects themselves, demands impasto"[4]. Although his writings of a few years later also seem to contradict this: "Don't let it trouble you when in my studies I just leave the brush strokes as I put them on, with smaller or larger clots of paint. That doesn't matter at all; if one leaves them for a year (or half a year is enough), and then scrapes them off quickly with a razor, one gets a much more solid color than would be the case after painting thinly"[4].

Until recently these 3D effects created by painters (also called 'impasto'), as well as 3D texture due to aging (crackle) were overlooked in most digitization efforts of paintings. Retrieving this extra dimension had limited use, only for applications such as topographic analysis; the detection of local surface defects for restoration purposes. However, thanks to current developments in Augmented Reality, consumer 3D screens and 3D printers, the relevance of 3D scanning and publishing is increasing[2].

This paper elaborates on the design of a 3D scanner, suitable for simultaneous capture of color and topography of a painting. Three paintings have been scanned using this 3D scanner: *Self-portrait* by Rembrandt (owned by the Mauritshuis), *Flowers in a Blue Vase* by Vincent van Gogh (owned by Kröller Müller Museum), and *The Jewish Bride* also by Rembrandt (owned by the Rijksmuseum). The data is printed using Océ High Resolution 3D printing technology, creating full color 3D prints.

Finally museum experts, who were knowledgeable on the selected paintings, evaluated the reproductions on quality and relevance. This paper presents the results of this evaluation, and will suggest further areas for research.

1.3 Existing 3D imaging methods

Zaman[1] states: "Few case studies have been published that focus on the topographical scanning and digitization of paintings, but there have been many case studies on the digitization of statues[5],[6]". In these case studies the topographical and color data are captured separately, which have to be matched afterwards, making this method prone to misalignments of topography and color. A method to capture topographical and color data simultaneously is by the use of a white light laser scanner[7,8]. Although this is a very accurate method, with a laser beam diameter of (less than) 100µm, the capture speed is low. In the described configuration, (50µm resolution, 10kHz capture speed) the capture time, excluding processing and overhead time, of *The Jewish Bride* (1.22x1.67m) would take 22 hours: too long for paintings that require overnight scanning (between opening hours of the museum)[9].

Also several case studies have been published that make use of a fringe projection[7, 10, 11]. The scanning setup comprises of a projector and only one camera for the triangulation of the depth data. The drawback of this method is that the resolution is limited to that of the projector, which is often no more than 1 or 2 Megapixel (The newest consumer cameras have a resolution of 40Mp). One study was found using a setup of one projector and two cameras[12]. This implementation is inefficient for capturing larger paintings, as the scanner is not automated in x or y-direction. Besides that the researchers note that the scanner has difficulty capturing highly reflecting surfaces, which will pose a problem for scanning varnished paintings. We can therefore conclude that paintings require a novel 3D scanning method, which is further described below.

2. METHOD

2.1 Development of 3D Scanner

In order to scan the topography and color of paintings with sufficient accuracy and efficiency, Zaman[1] set to develop a high-resolution 3D scanner with the following requirements:

- Non invasive, portable and low cost
- Size (XY): 2 x 2 m, Depth (Z): 2 cm; we assumed most paintings fall within these boundaries
- Resolution: 50 µm/pixel; the resolving power of the human eye at a distance of 75 cm[13]
- Color Accuracy: ΔE conform the Technical Guidelines for Digitizing Cultural Heritage Materials, FADGI[14]

After careful analysis we devised a principle solution based on a combination of stereovision and fringe projection. Stereovision is a passive method with excellent color reproduction and a good absolute triangulation; however it requires images with much saliency i.e. it fails on surfaces without texture. To overcome this, we used a projector to project fringe patterns on the painting. Triangulation using fringe-projected patterns is a relative triangulation method that requires no saliency in the image as texture is actively projected. Our method has phase unwrapping problems, but these can be solved. In combining the methods of stereovision and fringe projection we obtain all advantages and no disadvantages by using the following procedure. The stereo matching is first performed on salient points in the image only. Then these points are used to anchor the relative matches of the fringes triangulation, making all matched pixels in the image absolute 3D points. Finally all points are fused with points obtained from dense stereo matching, providing for each pixel in the image both depth and color[2] (see Figure **1**).

A set of 2x3 fringes is used to triangulate the depth information, with two sets of phase-shifted fringes (0°, 120°, 270°), one vertically oriented and one horizontally oriented. The color data is obtained by taking the average of the RGB values from different shifted fringe captures. This results in an image that yields the intensity of the scene as would have been measured by a normal RGB camera without fringes and normal illumination. The output of our procedure is a 3-D point cloud where each point is labeled with a color RGB. For easy data validation, we estimate the plane orientation and mesh all the values into two 2-D (X, Y) maps; a depth map (Z) and RGB map[1].

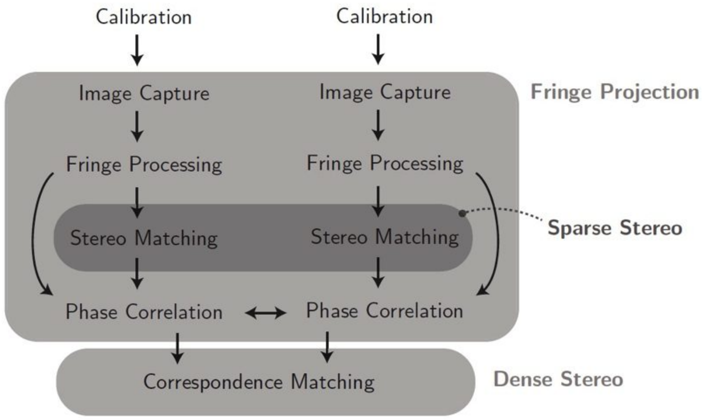


Figure 1. Procedure for using fringe projection to aid dense stereo matching

Figure **2** shows the set-up of the 3D scanner with the (Optoma PK301) pico-projector and (Scheimpflug) lenses on the 40-megapixel DSLR (Nikon D800E) cameras. A linear translation axis was used to scan with a 17x10 cm 40 Megapixel windows over the painting. For the properties of each window see Table 1. The vertical translation was done manually (see Video **1**). One capture took two minutes and processing took ten minutes per capture. All captures were 3D stitched to form the final dataset of the image[1].

The lenses on the DSLR cameras had a convenient fitting to accommodate polarization filters. These were oriented in such a way that surface reflections from the plane in front of them were optimally suppressed. We achieved cross-polarization by putting another polarization filter in front of the illuminant (projector), oriented so that it is polarized perpendicular to those of the camera. This reduced in surface reflections even further, indeed, this set-up was so effective that (at least to the eye) it eliminated reflections completely[1].

The controller of the system was based on an Atmel chip flashed with the Arduino bootloader allowing programming in C++. The micro stepping of the linear translation axis was performed with an Allergo A4988 chip, while manual adjustment of the axis was possible with a joystick. End-stops were realized with Hall sensors. A Six-Axis (Gyro + Accelerometer) MEMS MotionTracking™ device (MPU-6050) was used to track all movements of the scanner, which could be caused by the external influences; high motion amplitudes postponed the capture of images. The triggers to the camera and whether the cameras were actually triggered could be sensed through the connection of a synchronization (or flash-) cable between the devices[1].

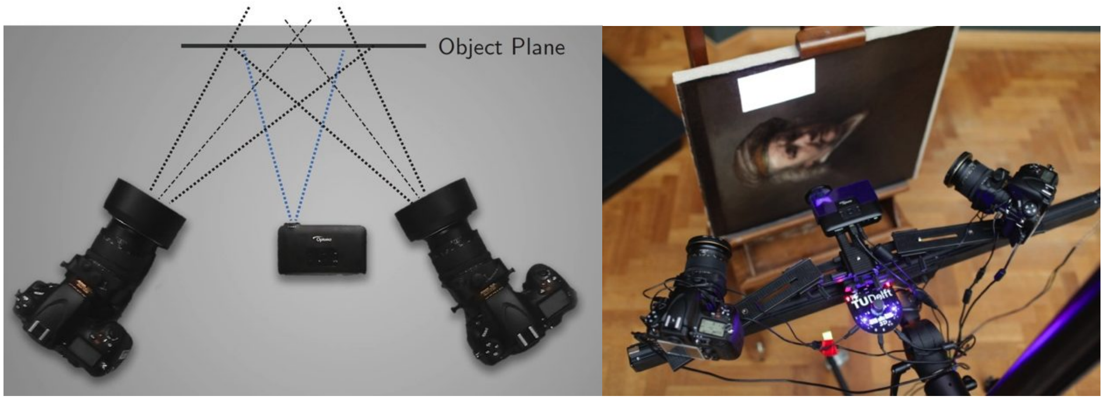
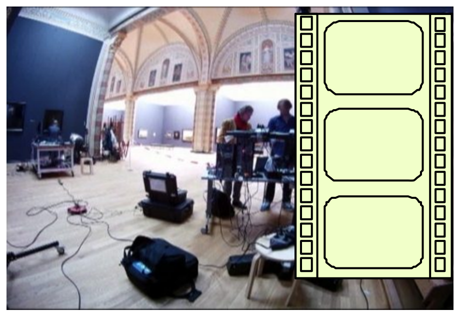


Figure 2. a) Top view of scanner setup including projector and two camera's; b) Top view of the camera including linear translation axis and PCB



Video 1. Scanning *The Jewish Bride* at the Rijksmuseum http://dx.doi.org/doi.number.goes.here

With the above described setup the image was sampled at a resolution of 22µm. Due to discrete sampling and the fact that the cameras were rotated towards our plane of interest around the vertical axis, the effective resolution is lower (in the latter case only the horizontal resolution (x) is lower). Using ISO guidelines for resolution measurement the in-plane sampling efficiency was determined[15]. The in-plane effective resolution was found to be 65µm (X) and 46µm (Y). Expressed in dots per inch (dpi) this is respectively 390dpi and 550dpi, the first being slightly lower that the printing resolution (see next paragraph). No guideline exists yet for resolution measurement of depth (Z), however the effective resolution was found to be 9.2µm[1].

Table 1. Properties of one scanned image

	x	**y**	**z**
Size	17 cm	10 cm	1 cm
Sampled Resolution	22 µm	22 µm	N/A
Effective Resolution	65 µm	46 µm	9.2 µm
Accuracy	68 µm	26 µm	38 µm

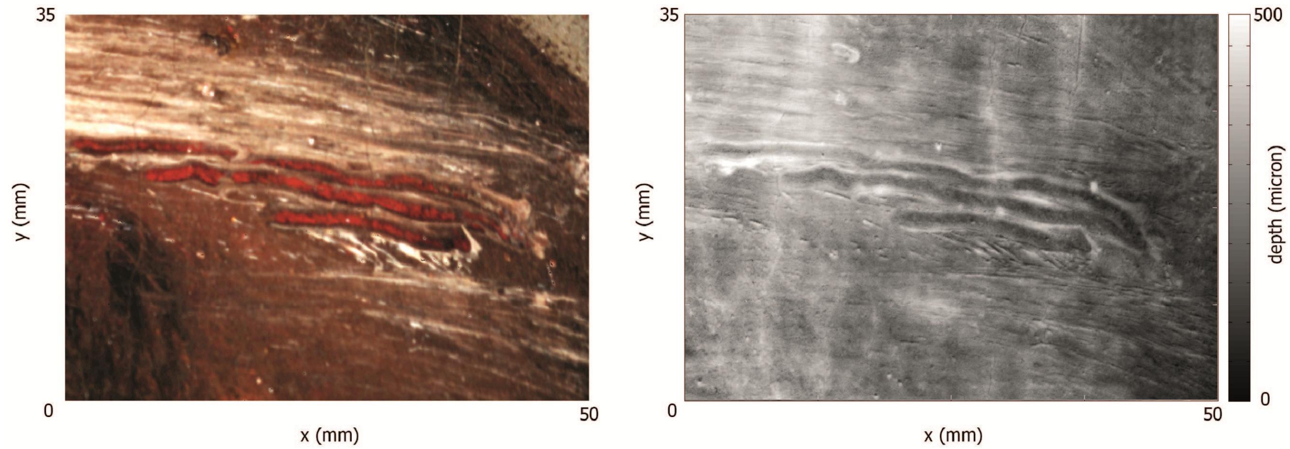


Figure 3. a) Detail of *Self-portrait* RGB color map; b) Detail of *Self-portrait* depth map in gray scale

Figure 3 shows a detail hat of Rembrandt in the *Self-portrait*; the color map in RGB and depth map in gray scale.

2.2 3D Printing

The two 2D maps (X, Y); a gray scale depth map (Z) and RGB color map formed the input for the 3D printing process[16]. The maps were used to make a physical reproduction of the data using a new developed (Océ High Resolution) 3D printing technology. The printer builds up the relief layer for layer with 5 UV-curable inks (CMYK and White). The 3D printer deposits relief layers to create the specified height (z) for every coordinate (x,y) in the image, with color layers on top (see Figure **4**). The print was printed on a rigid support medium (see Video **2**). The resolution of the print is approximately 450 dpi (X,Y).

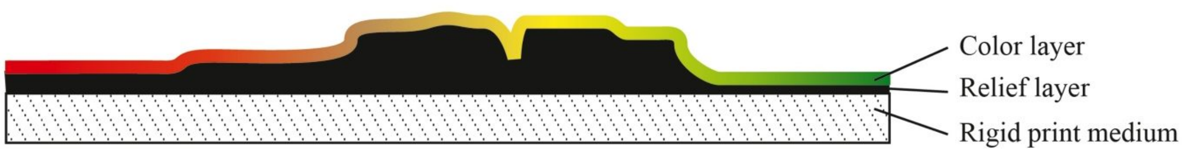


Figure 4. Graphical representation of the 3D print layers

Video 2. Printing the *The Jewish Bride* on Océ High Resolution 3D printer http://dx.doi.org/doi.number.goes.here

2.3 Paintings and reproductions

For the evaluation of the scanning and reproduction technology, three iconic Dutch paintings were selected and reproduced: *Self-portrait* by Rembrandt (owned by the Mauritshuis), *Flowers in a Blue Vase* by Vincent van Gogh (owned by Kröller Müller Museum), and *The Jewish Bride* by Rembrandt (owned by the Rijksmuseum). These paintings were selected for the fact that they all have a pronounced impasto. Figure **5** shows details of the reproductions.

A quite straightforward procedure was followed for this first evaluation: Besides camera color calibration (with 24-patch color checker)[1], no additional color matching with the original painting was undertaken.

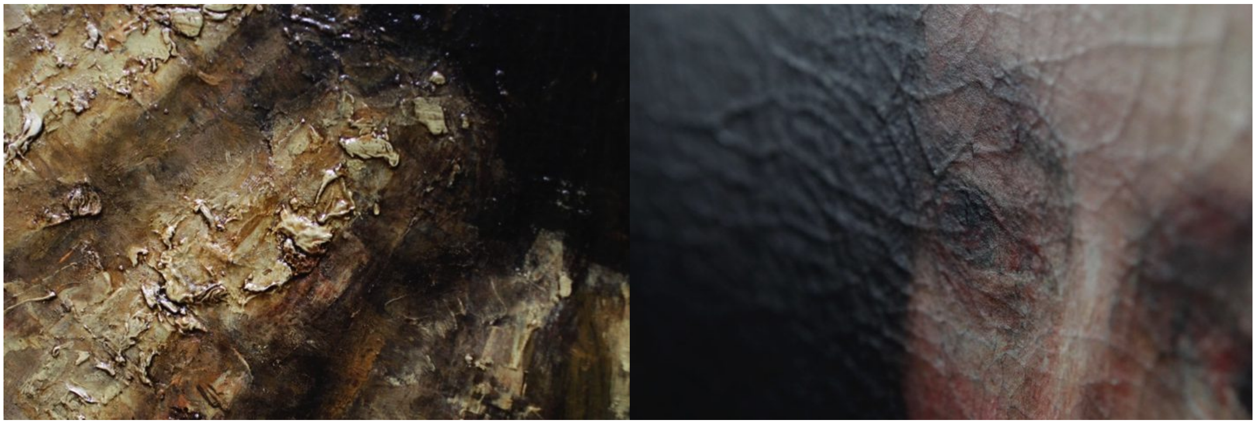


Figure 5. a) Detail of impasto of *The Jewish Bride* b) Detail of crackle on *The Jewish Bride*

2.4 Evaluation of reproductions

The reproductions were evaluated with expert interviews, as we expected them to be critical and most able to spot small differences. Each evaluation encompasses a 4-step procedure in which the reproductions were evaluated:

1. Singly by the expert from a distance, meaning a viewing distance of >75cm
2. Singly by the expert at close range, meaning a viewing distance of <75cm
3. In a side-by-side comparison with the original painting, where the reproduction and painting are standing/hanging or lying next to each other from a distance
4. In a side-by-side comparison with the original painting, where the reproduction and painting are standing/hanging or lying next to each other in close range (see Figure **6**).

Figure 6. a) Evaluation of *Flowers in a Blue Vase* step 4: close range side-by-side comparison

During each step there was an semi-structured interview with the experts to collect answers to our questions. A pilot interview was carried out evaluating the *Flowers in the Blue Vase*. The interview questions were thereafter slightly revised to include relevant feedback topics, which emerged from this first interview.

The following topics were covered in the interviews: general evaluation of the reproduction; feedback on color, texture, gloss and transparency/layers; and potential applications for the technology. It should be noted that although we asked experts for feedback on gloss and transparency/layers, these aspects were not measured in paintings and for this research not actively addressed in the reproduction. In addition to this we are aware that the comparison of reproduction and painting took place in situ, which is not ideally suited for color evaluation, as set in ISO standard 'graphic technology and photography – viewing conditions'[17]. We had to deviate from the ISO standard for practical reasons, as museums are not keen to move their precious paintings. In total six interviews were conducted with fine art experts, working at the respective museums (see Table **2**). The experts are employees of the before mentioned museums, in charge of these paintings (see table 4). All experts had a background in art history and/or conservation-restoration and have multiple years of experience in this field; they are trained in observation and evaluation of paintings. Most participants were excited to evaluate the technical advancements of 3D scanning and printing, although some were skeptical, especially of the scientific relevance for the field of art history and conservation-restoration.

Table 2. Expert interviews

Reproduction of:	Number of experts	Professional background of experts
Flowers in a Blue Vase by Vincent van Gogh	1	Conservator-restorer
The Jewish Bride by Rembrandt	4	2 Heads of fine art department 2 Conservator-restorers
Self-portrait by Rembrandt	1	Head of conservation & restoration department

2.5 Analysis of interviews

At the pilot interview, notes were taken and summarized in a report. The other five interviews were recorded and transcribed. This data was analyzed by applying the qualitative data analytic process of data coding[18]. Several complementary first cycle coding methods were used: descriptive coding, in vivo coding, evaluation coding, values coding and domain & taxonomic coding. In the second cycle coding, similar codes were clustered and reorganized following an axial coding method. A summary was sent to the experts to provide opportunity for correction.

3. RESULTS

3.1 Feedback on reproduction evaluation and comparison

Table 3 gives and overview of codes that were assigned to the data that was related to the evaluation of the reproduction and the comparison of the reproduction to the respective painting. The codes are grouped into four main categories: (1) feedback on the visual appearance, (2) causes/effects of how painting techniques and methods lead to the current visual appearance of the painting, (3) comments on viewing conditions and viewing strategies, and (4) feedback regarding the tactile sensation. We will discuss each code in this chapter.

Table 3. Codes: Evaluation of reproduction and comparison to painting

Visual appearance	***Color***	Saturation*
		Hue*
		Brightness*
		Contrast
		Overall score/evaluation
	Texture	Added effect
		Difference
		Sharpness
		Overall score/evaluation
	Gloss	Visual effect of gloss
		Score/evaluation
	Transparency / layers	Visual effect of transparency/gloss
		Overall score/evaluation
	Sharpness & smoothness	Edge sharpness*
		Smoothness*
	Total effect	Pictoral depth perception
		'Magic' of a painting
		Overall score/evaluation
Cause/effect	***Painting techniques/ materials***	Painting materials
		Painting techniques
		Material aging/damage/degradation
Viewing condition/ strategy	***Viewing light***	
	Evaluation strategy	
Other senses	***Touch***	

* These perceptual attributes are also used in image quality evaluation of 2D color images[19]

Color

When viewing the reproduction of the *Flowers in the Blue Vase* and the *Self-portrait* singly the colors were evaluated good and ok, respectively. In side-by-side comparison experts could however spot several differences. They evaluated the colors in the *The Jewish Bride* reproduction as too saturated. *The Jewish Bride* was “too red”, and the “red nearly looks like rosacea in the faces”. In all paintings experts evaluated that the hue was 'off' in various colors (green, blue, red and yellow) when comparing the reproduction to the painting. The flesh tones in *Self-portrait* were evaluated as being good. Also the brightness of the colors was not evaluated as ‘spot on’; the *The Jewish Bride* and *Flowers in the Blue Vase* were too dark and in the *Self-portrait* the black tones were not intense enough. Overall the reproduction of color was evaluated ‘below average’ in the evaluation and ‘low’ when compared to the original painting (the distance to the painting and reproduction had little influence on the evaluation.

Texture

The experts thought the texture was impressive. They stated the reproduction “approaches the original”. However, they also observed a difference between the reproduction and the original. At close evaluation they noted that the texture lacked “crispness” and that the edges seemed rounded, therefore remaining on a reproduction level. Overall the texture was evaluated as average to good.

Gloss

Experts perceived the gloss of the reproductions as too uniform compared to the original paintings. They stated that the gloss of paintings varies throughout the surface of a painting and also between paintings. The “uniform gloss emphasizes that is it a reproduction, not original”. The gloss makes the reproduction look “plastic” and gives it a “synthetic appearance”. Overall the gloss is quite a good match to a painting: not too glossy, not too matte.

Transparency/layers

It was evaluated that layering (of paint) and the transparency of layers are missing in the reproductions of the Rembrandt paintings. A “large contribution of the brown ground is coming through”, making the contribution of the ground layer too “harsh” in the reproduction. Overall the transparency was evaluated as low. An expert explained that it is “essential to get depth from transparency”. Translucent layers of lacquer create a pictorial depth effect oriented backward (where impasto creates a depth effect oriented towards the viewer). Layers were also said to create a “glowing effect” in the painting, which is missing in the reproduction.

Sharpness/smoothness

Experts mentioned that the contours seem sharper in the reproduction than the original. The “sfumato” transitions (one of the four canonical painting modes of the Renaissance) give the edges in the painting a softer appearance. In the reproduction the “linearity is sharper”. At close range the experts perceive a graininess of the reproduction and mention seeing the pixels of the reproduction: “I immediately see those pixels”. With a head magnifier this is even clearer. An expert commented: “You get thrown back”.

Total effect of visual appearance

When looking at the overall composition of the painting, the experts concluded that the reproduction looses some of the depth that can be found in the painting: “Faces are quite flat actually”, and “despite the 3D quality the reproduction appears flat”. One commented that in *The Jewish Bride* the “hand falls apart”.

It is interesting to note that several experts described the overall look of the painting as the “magic of the painting” or as being “enchanted by the original” and that “normally your eyes drown in these wet-in-wet details”.

The overall evaluation of the experts was that the reproductions “approach the paintings closely”, but remains “a copy that is not there yet”. In contrast another expert exclaimed: “I thought this was a real painting for a minute”, when someone touched the surface of the reproduction.

Cause/effect

The experts reasoned what they see in the painting in comparison to the reproduction by their knowledge of the painting. For instance: “Rembrandt used a transparent lacquer on a opaque underlayer”. They also explained the colors they perceived by the knowledge of the pigments that were used: “I know the painting is bone black”, and that the layering of the painting by the knowledge that the "ground is a brown color". An expert explained that the gloss between paintings can vary because "You can have a very glossy varnish on a painting and also a matter varnish". Also for the gloss variation within a painting they had an explanation at hand ("some areas are more porous that others") and they also knew that the painting was "painted with different kind of pigments that absorb varnishes to different degrees".

Furthermore, they also explained the sharpness of the texture by the technique that Rembrandt used "with a sharp tool, the back end, *pffft*, scratched into it [the painting]".

Experts also partially explained the visual presence of the paintings was by the aging of the materials. They generally evaluate a painting by looking for original paint, later additions but also sign of material aging: changes in gloss and color. Degradation can "vary from centimeter to centimeter", for instance chemical degradation: "surface whitening can occur due to crystal formation", but also physical degradation in the form of cracks and abrasion.

Viewing condition, viewing strategy

All experts were aware of the influence of the ambient lighting on the visual perception of a painting. Restorers use either daylight or a daylight-simulating lighting when evaluating and restoring a painting. They need to have "real light" not "pretty light". An expert explained her strategy for the evaluation of a painting as follows: first looking from a distance, with the naked eye, and then coming closer, inspecting the material and details, and continuing with a magnifying glass and microscope: "when you come closer and closer you begin to understand". In their viewing strategy they also look at a painting from several angles. Besides that, they practice "informed looking", and state to "have a certain expectation". Their knowledge of a certain artist or period helps them to evaluate a painting.

Other senses

All experts remarked that they were fascinated by the fact that they could now "touch a painting". The reproductions were considered to be "inviting" to touch.

3.2 Applications of 3D reproduction technology

Experts were asked what potential they saw for 3D fine art reproduction technology. Aside from the in their eyes obvious application - commercial - various other opportunities were mentioned. The technology might be used for educational programs with museums: showing (children) how paintings are build up, and being able to touch the whole surface. This might be extension of the current practice where guides carry small, repainted fragments of paintings with them. It also might play a role in making painting more accessible for the visually impaired.

Experts remarked that the technology of creating a texture map might be useful to make so called condition reports. The condition of a painting is currently visually assessed at the departure and arrival after transport. The texture map could help to objectify this and "sideline personal vision".

Experts explained how a reconstruction of the original state of a painting could play a role in art historic research. They wonder "what was the color in the past" and "which changes take place in the painting". One expert stated: "historic color is important for the experience of fine art". But maybe even more importantly the remark was made: "How will it [the color] change in the next 100 or 200 years?" The technology may provide the opportunity to make a physical reconstruction of a painting in its original state, when it was just painted. This could also include making a reconstruction of the original size as "many paintings have missing pieces". This could never be done on an original work of art, as this would be an "enormous intervention on the original painting" and the "current construction has a history and also value".

Two examples were given of how the technology could support current restoration practice. Making "six different versions" of a piece, which needs to be restored, could help "solve a restoration dilemma". And maybe the most radical suggestion was that pieces of 3D printed material might be used as restoration material. The piece of 3D printed painting could replace a piece where "the texture is not good" or is missing. The 3D printed piece could be stuck on the painting with "stable glue", and would in itself need to be a "stable material", having no interaction with painting.

3.3 Values, beliefs and attitudes of experts

Several values, beliefs and attitudes toward fine art and reproductions could be extracted from the interviews. Experts value the authenticity of a painting, and find it important not to make forgeries: all current restoration work should be reversible. They believe that the "magic of a painting cannot be reproduced" and that a "reproduction is mechanical". They believe humans are very well equipped to detect subtle differences. Making an indistinguishable reproduction will be very challenging indeed. Several experts expressed that they know the evaluated painting by heart, making a literal comparison superfluous. They were also not interested in evaluating the color, as they felt only the texture had added value compared to a 2D reproduction, and was therefore the only aspect that was interesting.

4. DISCUSSION

Some of the perceived color differences can be explained from the limitations of the 3D scanning, 3D printing and viewing conditions. The limitations of the 3D scanning system lay in the non-neutral illuminant (RGB-LEDs) and non-consistent illumination during the scanning procedure - when working in a museum environment with a not fully controlled lighting situation. This uncontrolled lighting situation also occurs when comparing the reproduction with the painting. In all cases the spectral properties of the illuminants *in situ* were not known and the painting and reproduction were not illuminated in an identical way. Although, when resolving these issues, perceivable color differences might still occur as the painting and reproduction as they are not spectrally matched. Spectral imaging and reproduction of fine art would potentially solve this, which was already explored for art reproduction by Berns et al (2008)[20].

The cause of the observed differences in texture between the reproduction and the original painting has currently not been determined. This could either be a limitation of the 3D scanner or a limitation of the current print strategy; some characterization of texture printing has been undertaken[21]. Gloss, transparency and layering – not measured or reproduced in the reproduction – were also found to play a role in the visual perception of the reproduction (gloss manipulation in prints has recently been researched[22]). The way these visual attributes play a role in the perception of paintings has not been investigated presently.
Feedback on the reproductions showed that resolution requirement of the print (300dpi) - matching the resolving power of the human eye at a viewing distance of >75cm – would probably suffice for viewing at that distance. However, when experts inspected the reproduction at much closer range, a common practice when evaluating a painting, they noticed the pixels of the reproduction. It becomes apparent that the used resolution does not suffice for observation at close range. Additionally experts observed increased edge sharpness in the reproduction. This can currently not be quantified or explained, as RAW color data was used which was not digitally sharpened.
In many instances the experts used their considerable prior knowledge of the paintings, materials and techniques - used by painters in the past - to explain differences between the painting and reproduction. This aspect should be taken into account in further research into visual perception, as currently the effect on the evaluation is unknown. What part of the feedback is really visually perceived and which parts might be inferred, based on experts' extensive knowledge of the artworks? Follow-up studies using laymen may shed light on this issue. Also, the experts' attitude towards comparison hints to this: an explicit comparison of the painting and reproduction was deemed not necessary, as they know the painting by heart. However many studies have shown that human memory can be anything but a reliable source.

5. CONCLUSIONS

The evaluation of the three reproductions and comparison with their respective originals by experts showed that adding texture to a printed reproduction has great added value to realistically reproducing artwork. The 3D texture has the effect that experts approach the reproductions as if they are real paintings, rather that viewing them as 'just a reproduction', like a poster or canvas print. The reproductions also open up a new dimension for appreciation, touching a painting.

However, currently experts can still observe various noticeable differences between the reproduction and the painting. The colors were not exactly the same – in some cases very clearly different - and were found to be a very dominant factor in the evaluation. Some of these perceived differences could be explained from the limitations of the 3D scanning, 3D printing and viewing conditions. This can be improved by changing illumination at capture and viewing, or potentially eliminated when resorting to multispectral imaging and the use of more print colors.

The texture was impressive although noticeably different, even when compared at a distance. At close examination the experts determined that the edge sharpness of the texture appeared to create the difference. The cause of this effect remains to be determined.

Other aspects – not measured or reproduced in the reproduction – were also found to play a role in the visual perception of the reproduction. In contrast to varying gloss in a painting, the uniform gloss of the reproduction is a clear hint to the experts that they are dealing with a reproduction. It gives the reproduction a synthetic and 'plastic' look. Also the overall gloss should be matched, which varies between paintings. In addition the material buildup of the reproduction seemed to be perceivable, as compared to the paintings. (Semi) transparent layering of materials creates visually perceivable depth in an artwork and 'glowing' colors, which is currently not measured and therefore not reproduced.

The sharpness and smoothness of the reproduction also showed noticeable differences for the experts. Edges of the image (not the texture) were perceived sharper, which we can currently not explain. And at close range the pixels of the 3D print become visible to the experts. Further research must determine which viewing distance would suffice for a specific application and which resolution is attainable by the 3D scanner and 3D printer.

5.1 Improvements and Future Work

The design of the 3D scanner should be adapted to improve the color reproduction performance. This can be achieved by using a neutral illuminant, as currently a three-color illuminant (i.e. the projector) is used. Additionally, external illumination should be controlled when scanning the painting, as well as the lighting situation when evaluating the reproduction (in comparison to the painting). To further increase the performance, color calibration should be done with a reference chart containing more color patches. The reproduction of the texture should also be improved. The lack of edge sharpness needs to be quantified, the cause of this effect determined and corrected for.

Further research will be conducted into the capture and reproduction of other visual properties, which were not addressed in this research: gloss measurement and gloss reproduction. Ultimately also the transparency and layers should be measured and reproduced, in order to come close to the perfect reproduction of the visual properties of paintings, and potentially also other materials.

And finally, the role of visual perception should be investigated: how are various visual characteristics perceived, and to what level of detail do visual characteristics need to be reproduced to make an indistinguishable reproduction? A comparison might be made between experts and layman, to determine the effect of prior knowledge but potentially also effects of trained looking and evaluation.

ACKNOWLEDGEMENTS

We would like to thank the Mauritshuis, Kröller Müller Museum and Rijksmuseum for their collaboration in this project. They were kind enough to grant access to one of their iconic paintings and assist us with the scanning of the paintings and evaluation of the reproductions.

REFERENCES

[1] Zaman, T., "Development of a Topographic Imaging Device for the Near-Planer Surfaces of Paintings," Repository, Delft University of Technology (2013).

[2] Zaman, T., Dik, J., and Jonker, P., "Modern Digitization for Cultural Heritage: Simultaneous Capture of 3D Topography and Colour in Paintings of Van Gogh and Rembrandt," in AR[t] - Mag. about Augment. Reality, art Technol., The Hague, pp. 56–59 (2013).

[3] Van de Wetering, E., [Rembrandt: The Painter at Work] , Amsterdam University Press, Amsterdam, 175;251–252 (1997).

[4] Van Gogh, V., [The Letters of Vincent van Gogh] , R. de Leeuw, Ed., Penguin, London (1996).

[5] Levoy, M., "The Digital Michelangelo Project," Computer Graphics Forum 18(3), (1999).

[6] Bernardini, F., Rushmeier, H., Ioana, M.M., Mittleman, J., and Taubin, G., "Building a Digital Model of Michelangelo's Florentine Pietà," IEEE Computer Graphics and Applications 22(1), 59–67 (2002).

[7] Lahanier, C., Aitken, G., Pillay, R., Beraldin, J.-A., Blais, F., Borgeat, L., Cournoyer, L., Picard, M., Rioux, M., et al., "Two-dimensional multi-spectral digitization and three-dimensional modelling of easel paintings," in 14th Trienn. Meet. Hague, Rome Int. Counc. Museums, 1–20 (2005).

[8] Blais, F., Taylor, J., Cournoyer, L., Picard, M., Borgeat, L., Godin, G., Beraldin, J.-A., Rioux, M., and Lahanier, C., "Ultra High-Resolution 3D Laser Color Imaging of Paintings: The Mona Lisa by Leonardo Da Vinci," in 7th Int. Conf. Lasers Conserv. Artworks. Madrid, Spain, 1–8 (2007).

[9] Blais, F., Taylor, J., Cournoyer, L., Picard, M., Borgeat, L., Dicaire, L.-G., Rioux, M., Beraldin, J.-A., Godin, G., et al., "Ultra-High Resolution Imaging at 50µm using a Portable XYZ-RGB Color Laser Scanner," in Int. Work. Rec. Model. Vis. Cult. Heritage. Cent. Stefano Franscini, Monte Verit. Ascona, Switz., 1–16 (2005).

[10] Bunsch, E., Sitnik, R., and Michonski, J., "Art documentation quality in function of 3D scanning resolution and precision" 7869, (2011).

[11] Karaszewski, M., Adamczyk, M., Sitnik, R., Michoński, J., Załuski, W., Bunsch, E., and Bolewicki, P., "Automated full-3D digitization system for documentation of paintings," in Opt. Arts, Archit. Archaeol. IV 8790, L. Pezzati and P. Targowski, Eds., 1–11 (2013).

[12] Payeur, P., and Desjardins, D., "Structured light stereoscopic imaging with dynamic pseudo-random patterns," Image Analysis and Recognition687–696 (2009).

[13] Curcio, C.A., Sloan, K.R., Kalina, R.E., and Hendrickson, A.E., "Human photoreceptor topography.," The Journal of comparative neurology 292(4), 497–523 (1990).

[14] Puglia, S., Reed, J., and Rhodes, E., "Technical Guidelines for Digitizing Cultural Heritage Materials: Creation of Raster Image Master Files," 1–101 (2010).

[15] "ISO 12233:2000 Photography - Electronic still-picture cameras - Resolution measurements," International Organization for Standardization (2000).

[16] Geraedts, J., Doubrovski, E., Verlinden, J., and Stellingwerff, M., "Three views on additive manufacturing: business, research and education," in Ninth Int. Symp. Tools Methods Compet. Eng., I. Horváth, A. Albers, M. Behrendt, and Z. Rusák, Eds., 1–15 (2012).

[17] "ISO 3664:2009 Graphic technology and photography - viewing conditions," International Organization for Standardization (2009).

[18] Saldana, J., [The Coding Manual for Qualitative Researchers] , in coding Man. Qual. Res., SAGE Publications, 1–223 (2009).

[19] Dijk, J., [In search of an objective measure for the perceptual quality of printed images] , Delft University of Technology, Delft (2004).

[20] Berns, R.S., Taplln, L.A., Urban, P., and Zhao, Y., "Spectral color reproduction of paintings," in Soc. Imaging Sci. Technol. - 4th Eur. Conf. Colour Graph. Imaging, Vis. 10th Int. Symp. Multispectral Colour Sci. CGIV 2008/MCS'08, 484–488 (2008).

[21] Liu, X., Chen, L., Ortiz Segovia, M. V., Ferwerda, J.A., and Allebach, J.P., "Characterization of relief printing," in Electron. Imaging Meas. Model. Reprod. Mater. Appear. (2014).

[22] Baar, T., Samadzadegan, S., Ortiz Segovia, M. V., Urban, P., and Brettel, H., "Printing gloss effects in a 2.5D system," in Electron. Imaging Meas. Model. Reprod. Mater. Appear. (2014).