In the Pursuit of Perfect 3D Digitization of Surfaces of Paintings : Geometry and Color Optimization

Maciej Karaszewski[1], Krzysztof Lech[1], Eryk Bunsch[2], and Robert Sitnik[1]

[1] Warsaw University of Technology, Faculty of Mechatronics, Sw. Andrzeja Boboli 8, 02-525 Warsaw, Poland
{m.karaszewski,k.lech,r.sitnik}@mchtr.pw.edu.pl
[2]Museum of King Jan III's Palace at Wilanów, St. Kostki-Potockiego 10/16, Warsaw, Poland
ebunsch@muzeum-wilanow.pl

Abstract. In this paper the automated system for 3D shape and color digitization of paintings is presented. It uses a 10000 points per mm^2 structured-light measurement head fixed to the positioning system. The main focus of the paper is the process of optimizing results of digitization in order to obtain the best possible 3D model of surface of a painting in terms of shape and color accuracy.

Keywords: Automated, high resolution measurements; 3D digitization of paintings; shape and color digitization accuracy.

1 Introduction

The process of shape and color digitization of cultural heritage objects has recently received much attention due to still improving quality and resolution of obtained objects [1]. Dense, complete digital representation of CH entities containing information about geometry and color of their surface provides invaluable data for analysis by art historians, curators and conservators [2]. The advantage of 3D models over classical 2D photography is evident, especially when the objects being digitized are spatially varied (for example sculptures, monuments etc.). At a first glance, 3D digitization of planar objects like paintings, seems exorbitant because clearly the image on the painting is its' most interesting feature. Nevertheless, the shape of the surface contains much fascinating information, such as structure of paint layer, formations of cracks due to aging or details of paintbrush strokes [3]. Moreover, the 3D data can be also converted to ultra-high resolution 2D image, more detailed than systems used by art conservators (like digital-backed large-frame cameras [4] or GigaPan systems [5]). Having 3D model of painting surface can be used for example as a method for authenticity checking or confirmation of authorship on the basis of paintbrush strokes analysis.

In the recent years, few research teams have given their attention to this kind of painting documentation, achieving various results, from global, low resolution model [6], through high-resolution digital representations of parts of painting digitized with conoscopic microprofilometer [7], to high quality, high resolution 3D model obtained with two laser-triangulation systems [3]. This last system utilizes laser source com-

M. Ioannides et al. (Eds.): EuroMed 2014, LNCS 8740, pp. 25–34, 2014.

posed of three wavelengths which shines at the measured surface (the dot is said to be of 100um in diameter). The dot is observed by detector with color-splitting prism, thus beside shape (calculated basing on triangulation principle), surface color is digitized. The scanner is moved by precision linear stage to provide scanning within 40mm x 200mm working volume. To digitize larger objects, the tripod holding this device has to be moved to another "strip" of object. To achieve measurement integration, the scanning head position is measured by another, also triangulation-based scanner. From this information, the initial alignment of directional measurements can be calculated. While declared measurement resolution and accuracy of such system is high, little information was disclosed on global accuracy (i.e. if alignment of directional measurements allow for obtaining good accuracy of the model within the whole volume of digitized painting). Little is known about the quality of obtained color information.

The interesting shape features can be studied when the collected data is of high resolution [8], up to 10000 points per square millimeter. To obtain such high resolution using standard detector (DSLR camera), working volume has to be as small as 50mm x 50mm x 20mm (because of limited sensor resolution and shallow depth of field of its lens). Therefore, to digitize an average-sized painting, hundreds of measurements have to be taken. It is clear that this process has to be automated.

The system for automated digitization of paintings' shape and color has been developed and constructed at Warsaw University of Technology for Museum of King Jan III's Palace at Wilanów (Figure 1). It is composed from 3D measurement head based on structured-light 3dmadmac scanner [9] with resolution of 10000 pts/mm^2. Along with geometry information, color of painting's surface is sampled (with the same resolution and detector). The measurement head is moved with high precision linear positioners (in X and Y directions). This system is capable of digitizing paintings as large as 2000mm x 2000mm. For such painting, the number of collected points is 40 * 10^9. Equivalent 2D photo would have 40 gigapixels.

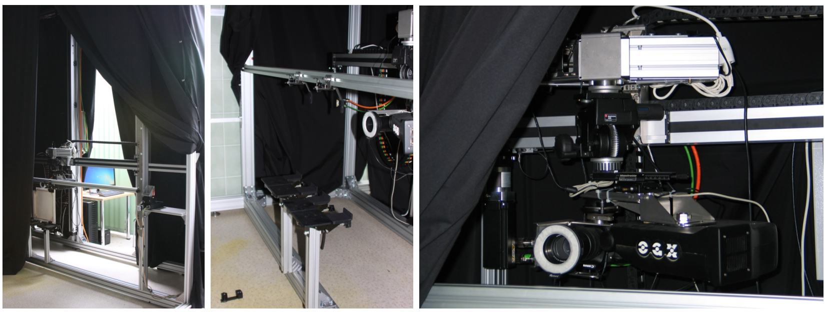

Fig. 1. Automated system for digitization of paintings

Even with high-precision positioning system some problems arise because of deformations of crossbeam during measurement head positioning. Moreover, the scanner can be rotated in any direction (with some limits) to overcome the effect of light reflection on the painting's surface. This movement, introduced at the digitization preparation phase, along with crossbeam deformations cause misalignment between subsequent directional measurements which have to be corrected.

The second problem which needs to be addressed is non-uniformity of lighting. In classical photo documentation systems, brightness uniformity is easier to achieve, mainly because they usually are placed far from the painting (for example 2m.), thus there is a lot of place for professional, shadow-less lighting system. In the presented system, working volume is about 0.4m from the scanner and positioning system, thus no lighting system can provide even lighting of the whole painting. Because of this, for texture acquisition, light right around the detector lens is used, however due to the non-zero angle between its emitting surface and the painting, non-even light field is visible. Moreover, DSLR lens introduces vignette effect. As a result, after integration into one model, color is not uniform (Figure 2). Commercially available applications for high-resolution photo documentation utilize various algorithms for optimization the brightness between adjacent photos [10,11,12] nevertheless the result is not always perfect and due to their closed-nature it is not known if the final color is not tuned, optimizing the "looks" not quality of documentation.

Fig. 2. Fragment of a painting composed from 36 directional measurements without any lighting non-uniformity correction

In this paper, procedures aiming at eliminating the effects of stated above problem are presented. The second chapter contains information regarding geometrical corrections needed to overcome problems related to crossbeam deformation and non-zero transformation between measurement and positioning coordinate systems. In the third chapter, solution for non-uniform lighting is presented, while exemplary digitization results are presented in the fourth section of the paper. Final chapter contains summary and the directions of further works.

2 Improving Accuracy of Model Integration

In the process of creating 3D model of digitized object, directional measurements are integrated into one entity. The position of each cloud within this entity is a function of position and orientation of measurement head during measurement process. This function describes transformation between coordinate systems of scanner and positioning system. In order to use (known) positioner coordinates to align directional measurements, one has to know said transformation. The process of calculating this transformation usually consists of three stages [9]:

1. Measurement of calibration unit from few positions of measurement head
2. Integrating (automated or manual) measurement results into one model
3. Calculating relation between coordinate systems basing on information about position of measurement head during scanning and transformations which had to be applied during measurements integration.

As such, the process is not very complicated, however the quality of integration of measurements is crucially important. In order to minimize the effect of potential inaccuracies of integration, the measurements should be taken with as distant scanner positions as possible, usually at different angles (Figure 3a). However, the system presented in this paper does not have enough degrees of freedom to look at object from different angles, only translation in one plane is possible (Figure 3b). Because of this, it is enough to calculate the transformation between this plane and plane XY of scanner coordinate system. In order to simplify processing of data from directional measurement, a diffusive white sphere was chosen as calibration unit. It is trivial to extract its surface from other elements present in directional measurements and it is easy to calculate the center of a sphere basing on some part of its surface. As any three points define a plane (as long as they are not collinear), it is enough to measure the same sphere from three different positions of scanning head (typically the head is moved along each axis once) to obtain definition of a plane in both coordinate systems. The calculation of transformation required to cover those two triangles is straightforward.

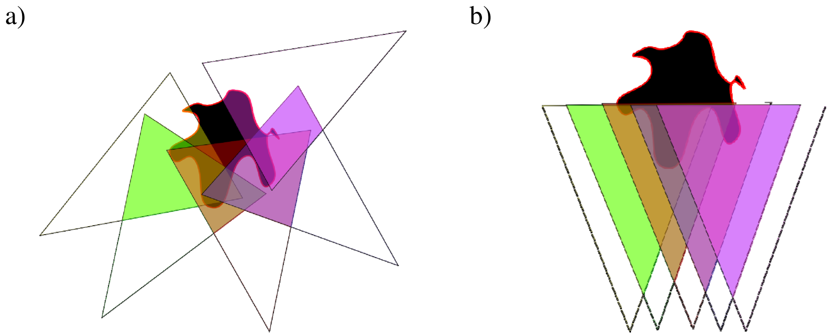

Fig. 3. Positions of the scanner during calibration measurements; a) for classic multi-degrees-of-freedom positioning system, b) for system described in this paper

Unfortunately, such calibration as presented above is correct and valid for infinitely stiff system. In reality, the crossbeam which holds the measurement head, bends and twists, and the amount of bending changes depending on the horizontal position of measurement head. The similar effect is present for vertical beams, but as they are much stiffer, it can be neglected. The bending and twisting of horizontal beam has to be corrected though, because it causes small, but visible misalignment of directional measurements (Figure 4).

The idea of calibration of beam deformation consists in performing a round of coordinate systems calibrations, for different positions of measurement head along the crossbeam. Afterwards, basing on transformations between systems obtained in few points within horizontal movement range, for each component of transformation, polynomial is best-fitted, thus making it possible to calculate optimal transformation for any position of calibration head (Figure 5).

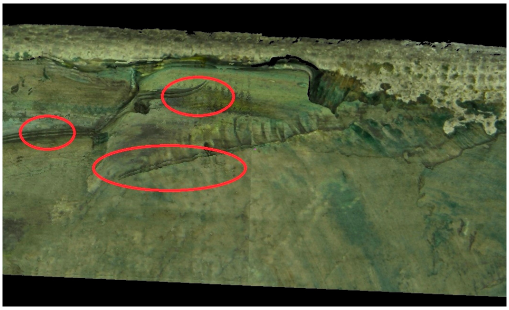

Fig. 4. Misalignment between measurements caused by bending and twisting of positioning system. The misalignment is clearly visible on edges (marked with red color).

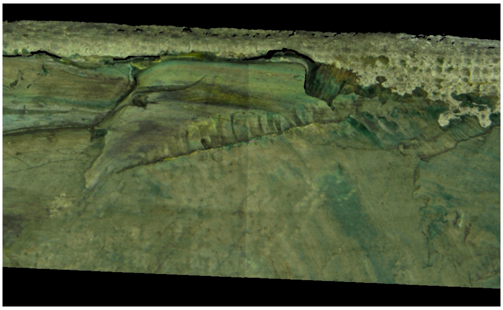

Fig. 5. Directional measurements alignment after corrections

3 Restoration of Lighting Uniformity

At the first stage of texture measurement, acquisition of the highest possible quality input data is the most relevant. As mentioned earlier, use of shadow-free studio lighting is impossible due to the shadow cast by scanning head moving close to the surface of the painting. Close-up light ring is used as the best alternative. It produces soft and nearly shadow-free light. To reduce reflections appearing on shiny parts of painting, two images are combined. Left and right side illuminated images are blended together using maxima-suppressing averaging filter. Scans at this stage are shown at Figure 6, further improvement of the texture quality is performed in post-production.

Problem of lighting uniformity restoration is related to correction of image mosaics. For system presented in this paper and quasi-flat objects like painting, non-uniformity of measured texture results mainly from:

1. DSLR lens vignetting
2. varying distance between 3D scanner head and paintings' surface
3. non-even light field produced by close-up light ring

This non-uniformity can be well described by a radial vignetting with centre offset and exposure variations, just like with panoramic images. Therefore image mosaicing correction approach, described in [13], was adapted to this slightly more complex 3D solution - estimation of vignetting and exposure from overlapping clouds of points.

Instead of 2D images our input data are 3D scans. After cloud of points final alignment, corresponding 3D point pairs between the clouds are extracted. For a given point (from the area of clouds overlapping), the closest points from other scans are found and linked. Choice of appropriate search radius has a significant impact on the time of calculations. From all found point pairs, we select only those satisfying further criteria. By choosing corresponding points in areas with quite uniform texture, significant numbers of outliers can be removed. Pairs of points with difference in saturation or lightness significantly higher than average value, can be ignored as outliers too. Finally, we sample about 10000 point pairs uniformly distributed in 3D space.

The essential part of the lighting uniformity restoration procedure is calculation of image rectification parameters with [12] software. Exposure correction, polynomial vignetting and offset of vignetting centre coefficients are calculated. In specific cases camera sensor's response and white balance correction coefficients may also be estimated.

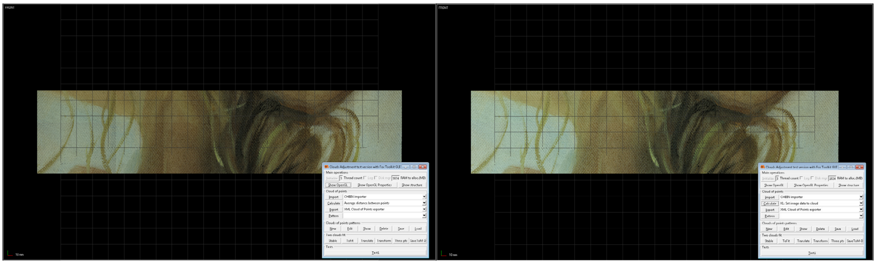

Fig. 6. Aligned scans before (left) and after (right) lighting uniformity restoration

At the final restoration step, clouds of points are treated just like 2D images. Every single cloud is corrected, while points are treated as pixels of the image. Final result of lighting uniformity restoration is shown at Figure 6.

Texture quality improvement is clearly visible and proven by decrease in CIE ΔE colour difference between points in overlapping areas. What is more important, with known exposure, the scene radiance may be recovered [10].

4 Exemplary Digitization Results

Exemplary results of digitization process performed with the system presented in this paper are shown at Figures 8 and 10. The first painting, self-portrait of Adam Bunsch was digitized with 412 directional measurements. The second painting was digitized with 188 measurements. Average number of points in one directional measurement is about $11 * 10^6$.

Two different styles of paintings were chosen for the project to show the accuracy of the measurements and the system's ability to present details which are difficult to notice by human eye. The first art work consists of many thick layers of paint and the brush strokes are clearly visible. On the other hand, the second painting was created by artist specializing in the visions in surreal style. His linear, delicate, smooth work has almost academic "*fini*". The system and precise measurements provide information on a very high level of accuracy. Mentioned details can be properly shown and emphasized in our software, capable of real-time visualization of such large 3D models, by the manipulation of digital light model. The final user of the software can appreciate the expressiveness and uniqueness of the artists' gestures.

Fig. 7. Adam Bunsch, Self-portrait, 1969, oil on canvas, 60 cm x 45 cm, view of the whole painting

As a matter of fact, the closer look at the second painting proofs that it is not entirely flat and that it also has its unique texture. This kind of knowledge is essential not only for art historians or conservators but also when trying to identify and eliminate the problem of art forgery.

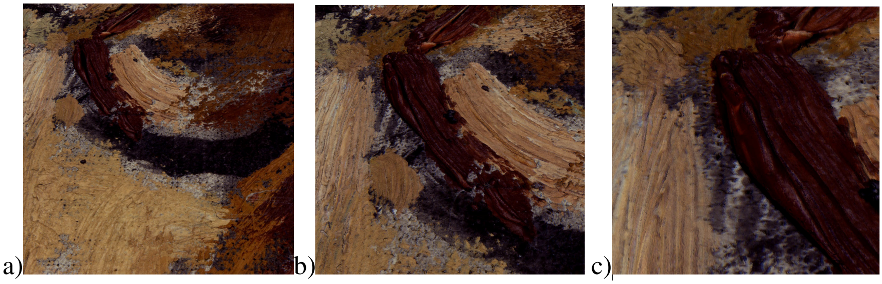

Fig. 8. Adam Bunsch, Self-portrait, 1969, details (a,b,c) – close-up on the dense cloud of points (region of the right eye). Brush marks details are emphasized with a directional digital lighting.

Fig. 9. Maksymilian Nowak-Zempliński, Submarine, 2011, oil on wood, 36cm x 14 cm, 3D view of the whole painting

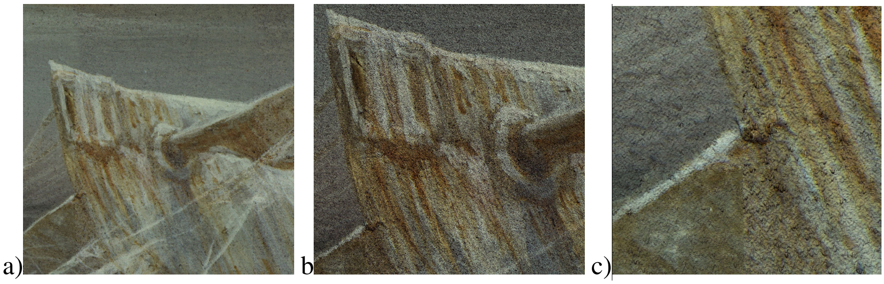

Fig. 10. Maksymilian Nowak-Zempliński, Submarine, details – dense cloud of points with details accentuated by a directional digital lighting

5 Conclusions

In this paper, algorithms and methods for optimization of 3D digital model of painting is presented. As a result of their application, the model is of much better quality, allowing to treat it as a real, professional documentation. Those methods are not very complicated, nevertheless, to the best of our knowledge, there is no equivalent for them in existing systems for digitization of similar objects.

In the future, we plan to exchange measurement head to the one capable of acquiring multispectral data (directly mapped to points). We have designed such a device [14], but the integration into automated positioning system is somehow cumbersome due to its size and weight. As for the method for improving uneven lighting conditions, we plan to extend it to objects which have much complicated shapes (for example sculptures).

We hope that growing popularity and quality of 3D documentation of paintings will open a new opportunities for analyzing this kind of works of art, not possible with simple 2D photography.

Acknowledgments. This work has been partially supported by the Ministry of Culture and National Heritage (Poland) by KULTURA+ framework (2011-2015).

References

1. Rizzi, A., Voltolini, F., Girardi, S., Gonzo, L., Remondino, F.: Digital Preservation, Documentation and Analysis of Paintings, Monuments and Large Cultural Heritage with Infrared Technology, Digital Cameras and Range Sensors. In: XXI International CIPA Symposium, Athens, Greece, October 1-6 (2007)
2. Bunsch, E., Sitnik, R., Michoński, J.: Art documentation quality in function of 3D scanning resolution and precision. In: Proc. SPIE 7869, Computer Vision and Image Analysis of Art II, 78690D (March 08, 2011), doi:10.1117/12.876647.
3. Blais, F., Taylor, J., Cournoyer, L., Picard, M., Borgeat, L., Dicaire, L.G., Rioux, M., Beraldin, J.-A., Godin, G., Lahnanier, C., Aitken, G.: Ultra-High Resolution Imaging at 50μm using a Portable XYZ-RGB Color Laser Scanner. In: Proceedings of International Workshop on Recording, Modeling and Visualization of Cultural Heritage. Centro Stefano Franscini, Monte Verita, Ascona, Switzerland, May 22-27. NRC 48099 (2005)
4. `http://www.hasselblad.com/products/digital-backs.aspx`, (accessed May 20, 2014)
5. `http://www.gigapan.com/` (accessed May 20, 2014)
6. Guidi, G., Atzeni, C., Lazzari, S.: 3D optical scanning diagnostics for Leonardo Da Vinci's 'Adorazi- one dei Magi' conservation. In: Proceedings of the 4th International Conference on 3-D Digital Imaging and Modeling (3DIM 2003), Banff, Alberta, Canada, October 6-10 (2003)
7. Fontana, R., Gambino, M.C., Greco, M., Marras, L., Pampaloni, E., Pelagotti, A., Pezzati, L., Poggi, P.: 2D imaging and 3D sensing data acquisition and mutual registration for painting conservation. In: Proc. SPIE Videometrics VIII, January 12-20, vol. 5665, pp. 51–58 (2005)
8. Karaszewski, M., Adamczyk, M., Sitnik, R., Michoński, J., Załuski, W., Bunsch, E., Bolewicki, P.: Automated full-3D digitization system for documentation of paintings. In: Proc. SPIE 8790, Optics for Arts, Architecture, and Archaeology IV, 87900X (May 30, 2013), doi:10.1117/12.2020447
9. Karaszewski, M., Sitnik, R., Bunsch, E.: On-line, collision-free positioning of a scanner during fully automated three-dimensional measurement of cultural heritage objects. Robotics and Autonomous Systems 60(9), 1205–1219 (2012)

10. http://www.kolor.com/panorama-software-autopano-pro.html (accessed May 21, 2014)
11. http://research.microsoft.com/en-us/um/redmond/groups/ivm/ICE/ (accessed May 21, 2014)
12. http://hugin.sourceforge.net/ (accessed May 21, 2014)
13. d'Angelo, P.: Radiometric alignment and vignetting calibration. In: ICVS 2007 (2007)
14. Krzesłowski, J., Sitnik, R., Mączkowski, G.: Integrated three-dimensional shape and reflection properties measurement system. Applied Optics 50(4), 532–541 (2011), http://dx.doi.org/10.1364/AO.50.000532