DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-051

Towards automated, high resolution 3D scanning of large surfaces for cultural heritage documentation

Robert Sitnik*, Eryk Bunsch**, Grzegorz Mączkowski*, Wojciech Załuski*, Krzysztof Lech*, Jakub Michoński*, Jakub Krzesłowski*, Piotr Foryś*; *Warsaw University of Technology, Warsaw, Poland; **Museum of King Jan III's Palace at Wilanow, Warsaw, Poland

Abstract

In this paper we present a 3D imaging system for high-quality documentation of cultural heritage surfaces. The main challenge in this kind of documentation is related to the requirements of high accuracy and resolution for large and complex surfaces. Our test subject was the King's Chinese Cabinet (Museum of King Jan III's Palace at Wilanów) consisting of geometrically complex wall decorations (European lacquer technique). The technical requirements for documentation in the form of clouds of points were: <0.1 mm point to point spatial resolution, <0.05 mm spatial accuracy and color representation in unified lighting conditions (without local reflections from light sources). The total area of walls and ceiling to be covered by the measurements was approximately equal to 96m^2. Illumination had to be limited to the visible spectrum only. We developed a structured light measurement head with a group of additional LED illuminators. To speed up the measurement process we mounted the measurement head on a robot arm and integrated their coordinate systems. This step gives us automatic rough view registration within the range of motion of the robot arm. The arm was mounted on a specially developed, moveable and stabilized platform that can be extended to measure surfaces at an altitude of 5,5 meters. In the paper we discuss main aspects connected with development, calibration and data processing related to the measurement process. We also describe main processing algorithms being used. Exemplary result of King's Chinese Cabinet measurement are presented with discussion of main data processing steps.

Introduction

Techniques and systems for digitization of both cultural heritage (CH) sites as well as single objects are under constant development. There are established strategies for CH sites documentation using terrestrial laser scanning [1] and/or photogrammetry [2]. Final resolution and accuracy of the resulting 3D model could reach single millimeters and parts of millimeters respectively for the two methods. Strong expert guidance is required in such processes even in cases when unmanned aerial vehicle (UAV) techniques [3] are used.

On the other hand, there have been some attempts to mass 3D digitization of small CH objects (up to 2 meters) [4, 5]. In those cases it is possible to develop methods and systems for automated acquisition and processing of the whole object surface with the required resolution and accuracy. Such systems could currently reach up to 10µm resolution and 5µm accuracy of final 3D model representation [6].

The system presented in this paper has been designed and implemented for high resolution 3D documentation of indoor wooden panel structures with complex geometry and rich color. Our test subject was the King's Chinese Cabinet, part of the Museum of King Jan III's Palace at Wilanów, Warsaw, Poland. The cabinet consists of geometrically complex wall decorations with partially reflective and transparent surfaces (Figure 1.). This unique example of interior decorative art was made using 18th century European lacquer technique and is attributed to the famous craftsman Martin Schnell and his workshop [7]. The technical requirements for documentation in the form of cloud of points were specified as follows: spatial resolution of at least 0.1 millimeter, with spatial accuracy of 0.05 mm, together with color representation in standard CIELab color space [8] with unified lighting conditions, eliminating local light source reflections. The surface of walls and ceiling is approximately equal to 96 m^2, which yields an impressive amount of required 3D scans and processing power for view integration. The expected total amount of spatially aligned data exceeds 10 billion point. An additional requirement is associated with the applied light spectrum – it should only be in the visible range with as low intensity as possible due to sensitive nature of the measured surface (highly sensitive organic pigments).

***Figure 1**. View of King's Chinese Cabinet (east wall fragment).*

The main challenge for such documentation is connected with the requirement of high accuracy and resolution for large and complex surfaces. To scan a whole room comprising such amount of rich decorations, constant attention and coordination of a human operator is required [9]. Taking into account all these requirements there is no commercially available hardware for such measurements (known light spectrum and acquisition of RGB image without any light source reflection in the camera's field of view) and no software that could even load and process such data (careful assessment of 10 billion measurement points).

We have decided to develop measurement hardware that supports partial automation of 3D acquisition with a robotized arm. Additionally, we have developed the FRAMES (Framework and Robust Algorithms for Models of Extreme Size) software environment that supports huge 3D data manipulation, parallel

DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-051

computing and graph based organization of data structures. We believe that the development of semi-automatic technology for performing such measurements and further processing of captured data (filtering, view integration and visualization) breaks down existing barriers, allowing generation of high quality 3D documentations of very complex structures relatively fast.

Measurement system

Due to the requirements concerning resolution, accuracy and illumination conditions, we developed a custom measurement set-up. We decided to use the structured light technique (SL) [10] for geometry measurement and additional illumination for high quality color registration. Additionally, we decided to use computer-controlled manipulators to speed up the acquisition and processing phases.

We have decided to design a custom illumination set-up based on the fact that in a majority of 3D scanner solutions, the images for surface color reproduction are captured only using the built-in DLP projector illumination, which causes several complications. Stitching the final 3D model from separate scans, each captured with a different scanner position, results in a non-uniform color of the final model. Additionally, some specific parts of the King's Chinese Cabinet are extremely shiny, resulting in unpleasant highlights visible on the final model (Figure 2.).

***Figure 2**. Highlights and brightness non-uniformity visible on separate 3D scans.*

Hardware design

The proposed measurement head (Figure 3.) consists of a custom LED projector and two detectors. The digital projector has a 1280x800 pixels native resolution. Spectral characteristics of the custom LED light sources have been approved by the Museum's Conservation Department. Two detectors (Point Grey 9 megapixel color cameras) mounted on the left and right side of the projector were attached to increase the coverage of the registered surface.

The measurement head was equipped with two laser pointers. Laser rays intersect in the middle of the working volume to help the human operator in positioning and monitoring of the whole process. All elements are rigidly connected by a carbon fiber fixing structure. The total weight of the measurement head does not exceed 4 kg.

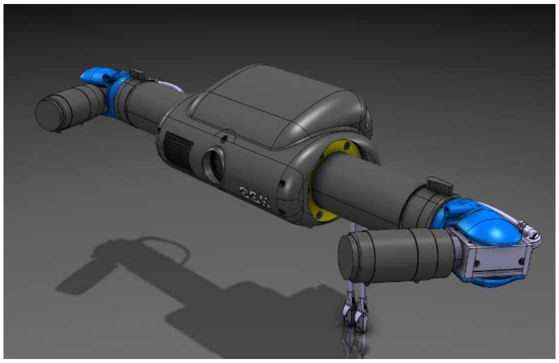

***Figure 3.** CAD visualization of the double camera measurement head.*

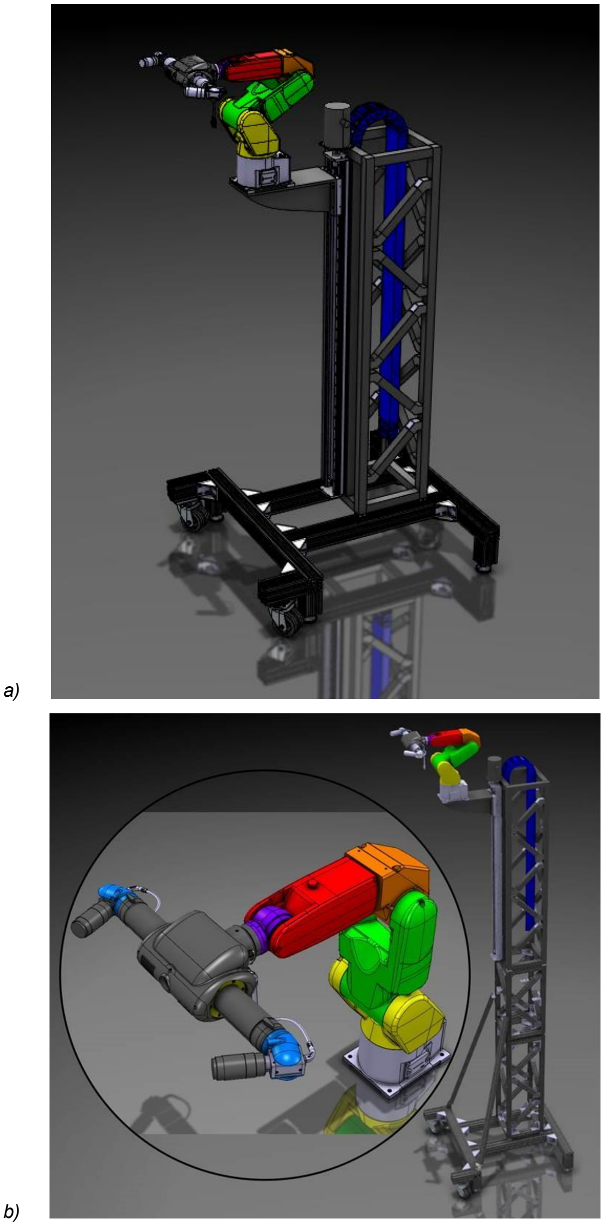

***Figure 4**. CAD visualization of the whole hardware structure: a) set-up with 3 m maximum elevation and b) 5.5 m maximum elevation.*

©2016 Society for Imaging Science and Technology
DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-051

To speed up the measurement process the measurement head was mounted on a robot arm (Fanuc LR Mate 200iC) and their coordinate systems integrated [11]. This step provides us with automatic rough view registration within the robot arm range, which is approximately 1 square meter. In each single measurement the transformation related to robot arm position and orientation was stored as 3D transformation metadata. To further increase surface coverage, we mounted the robot arm on a custom-developed, moveable stabilized platform that could be extended to measure surfaces at an altitude of 5.5 meters (Figure 4). The platform was equipped with a linear stage that could transport the robot arm vertically. Due to safety reasons we decided to automatically control the measurement head and robot arm but the vertical platform had to be moved between positions manually. This manual step could be performed by one person.

Ideally, the illumination used for color acquisition should be diffuse, geometrically fixed and have high Color Rendering Index. Because the task involved documentation of the whole room, including the ceiling, it was not possible to provide fixed illumination without occlusions caused by the measurement setup itself. Six additional moveable light sources were used to capture multiple images for the color correction algorithm (Figure 5.). Two small LED panels were attached directly to the scanner head, next to the cameras. Four bigger panels were attached directly to the lift of the vertical column and they were arranged in a square layout of 1.2 meter size. Bigger lights were further than 2 meters from the currently measured surface and moved only when the level of the vertical column was changed. All lights produce diffuse daylight with color temperature of 5650K. Additionally, smaller panels are certified for ability of faithful color reproduction of illuminated objects with CRI Ra>95.

Figure 5. *Photo of developed measurement system with additional light illuminators.*

Two computer units have been used to control the whole system and to process the measurement data. First unit was used for controlling the measurement head's synchronized acquisition and the second for controlling all manipulators and integration of the measured data. The whole scanning system development process was consulted with Museum's Laboratory for 3D Documentation and specialists from the Conservation Department.

Final parameters of a single measurement were:

- measurement time: 15 seconds,
- measurement volume size: 200mm x 300mm x 200mm,
- maximum measurement point count: 18 million,
- measurement data: XYZRGB.

Color and geometry measurement method

We have chosen the SL method as a basis for geometry measurement. The phase shifting method combined with Gray codes for improved phase unwrapping has been chosen as the most accurate [10] SL implementation. We select six phase shifts after careful assessment of the developed measurement head intensity transfer nonlinearities. We used an SL calibration method based on modelling of phase distribution in relation to detector coordinates [12].

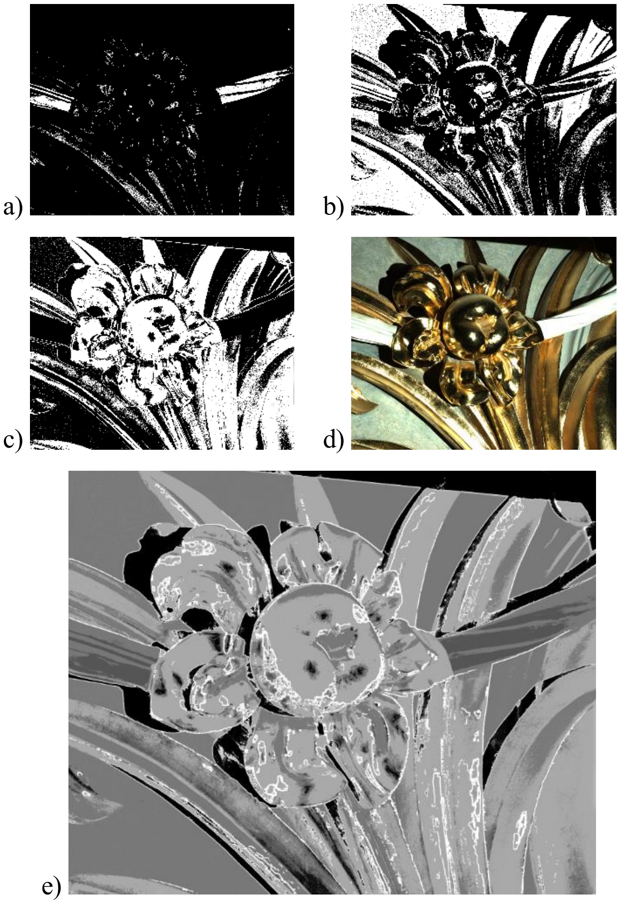

Figure 6. *Phase maps' regions chosen from different exposures (black – no phase map; shades of grey/white – exposures): a) 50ms, b) 200ms, c) 500ms, d) photo with additional illumination, e) integrated three exposures.*

DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-051

Highly glossy surfaces of wall decorations are difficult to capture with a structured light method with fringe projection because reflection highlights suppress visibility of the projected pattern. This results in low fringes contrast and errors in phase calculation. These phenomena influence phase modulo 2π calculation and Gray codes reconstruction.

To overcome these problems the proposed solution utilizes high dynamic range (HDR) image capture. Sets of phase-shifted fringe sequences are acquired with three different exposures: 50, 200 and 500 milliseconds, carefully selected for King's Chinese Cabinet decorations. At short exposure the fringes contrast is preserved in highlighted areas, whereas at longer exposures the fringes become visible in the shaded regions and less reflective parts, where the contrast is otherwise low. The proposed solution calculates phase and modulation maps for each exposure value and composes the final phase map by choosing the phase value with the highest modulation at each point. Additionally, over-saturated areas are filtered out. Figure 6. presents patches of phase maps coming from different exposures.

The proposed procedure increases the valid phase map area captured from a single direction, compared to the outcome from a single-exposure measurement. However, high levels of noise registered on glossy parts of the surface result in large number of solitary pixels and edges with invalid phase shifts, which cause phase discontinuities. They are observed in the resulting point cloud as points randomly distributed along the depth of the measurement volume. To minimize this effect a phase map filtering method is proposed. It relies on the observation that invalid phase shifts differ from phase shifts in the neighborhood pixels. The filtering algorithm first analyzes a small neighborhood of every pixel in the phase map and calculates phase shifts with respect to the neighbors. Next, the number of neighbors phase-shifted by more than a predefined value is found. If this number exceeds the given threshold value, the pixel is considered as discontinuity and masked out. Figure 7. shows the final point cloud obtained from multiple exposures with applied filtering.

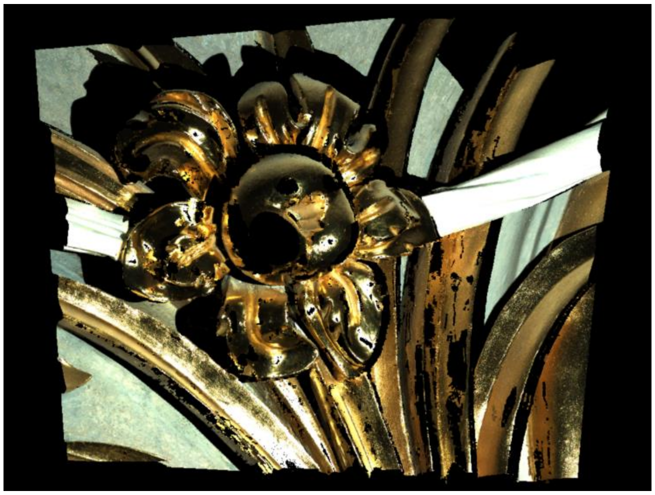

***Figure 7**. Final point cloud after phase map filtering.*

For color measurement, six images are captured using illumination of each of the light sources. The first objective is to correct the texture images colorimetrically, so that differences between light sources are eliminated. Additional advantage of this procedure is that color information is obtained in independent color spaces, CIEXYZ and CIELab, for each point. A modified version of the calibration process developed by Hardeberg [13] was implemented. Each camera-light source pair was calibrated with the X-Rite ColorChecker chart, yielding 12 model matrices. Models are applied to appropriate texture images to calculate CIELab color representation with D65 standard illuminant.

This set of textures becomes the input for the second correction step. Its goal is to recover surface color data in areas suffering from specular reflection. Various techniques for removing specularity from images are available in literature [14] and can be classified into two main categories: single- and multiple-image algorithms. Since multi-image methods do not estimate real values in highlight areas, they are able to preserve the documentary value of acquired scans. Equally important is that multi-image algorithms are generally faster and more robust than single-image methods.

The simplified version of the multi-flash algorithm described in [15] was modified. At this step lightness and a, b color components are analyzed separately. Since the documentary character of scans has to be preserved, neighborhood averaging should be omitted and all calculations are performed per pixel. Output lightness is calculated as median of input lightness values. Specular highlights and shadows (occurring due to self-occlusion) are rejected as max and min outliers. Final values of a and b color components are also calculated as median or simple mean of all input values, which is possible due to low a, b deviation after the first step of color correction (Figure 8.).

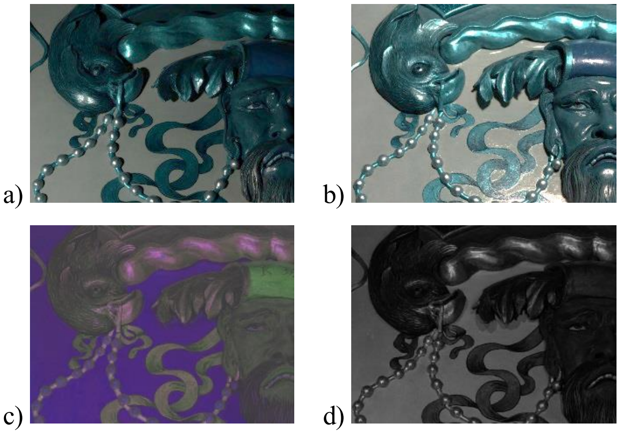

***Figure 8**. Color correction process: a), b) source images with different illumination sources, c) CIELab final image and d) median of lightness calculated from input images.*

Whole surface acquisition

FRAMES was used for management of the whole process of acquisition and data processing. It is a C++ based programming environment that is being developed at Warsaw University of Technology. Its main goal is to effectively process huge datasets (greater than accessible computer memory) with constant visual feedback on the processing results. FRAMES also simplifies development of 3D processing algorithms thanks to a plugin system, which can be used without knowledge about the whole environment. Hierarchical structure of data simplifies working with huge and complex datasets, allowing plugins to work on whole or selected part of the structure.

DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-051

The measurement workflow is divided into following parts:

- single position of measurement platform (PMP),
- single position of robot platform (PRP).

We assume that the measurement process starts from a position arbitrarily selected by the operator. This position defines the first PMP. During the first stage, the system from Figure 4a. is used. It enables acquisition of a whole wall surface up to 3 meters high. Positions of the vertical column are subsequently preset to 0.5, 1.5 and 2.5 meters. In each column position, the PRP process is applied. Next, the operator moves the platform to an adjacent position to document another part of the wall. This process is continued till the whole available surface is documented. Then the robot platform needs to be elevated according to the set-up presented in Figure 4b. and the whole procedure repeats. Finally, a similar strategy is applied to the ceiling.

PRP procedure consists of 25 automated scans with arbitrary robot arm positions distributed equally on the wall's surface. The operator then selects remaining positions manually based on his/her expertise to cover the whole required surface. The targeted viewing position can be selected in the 3D visualization software with a point and click interface.

All measurements from a single PMP are treated as a single structure and need to be initially integrated into the model. Exemplary visualization of this process is presented in Figure 9.


a)
b)

Figure 9. Visualization of measurement process: a) first PRP and b) second PRP added.

Data processing

To process this amount of data in the project, a hierarchical structure is proposed (shown in Figure 10.). This structure allows to easily navigate between scans from one day of acquisition to another (point clouds are given formatted names: YYYYMMDD_HHMMSS) which simplifies finding the interesting fragment of the virtual model.

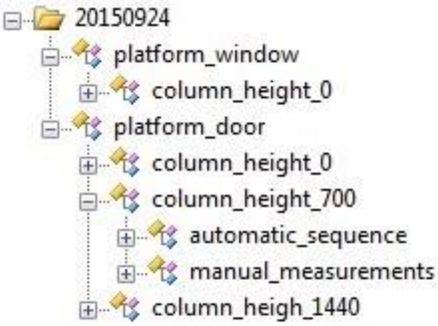
```
⊟ 20150924
  ⊟ platform_window
    ⊞ column_height_0
  ⊟ platform_door
    ⊞ column_height_0
    ⊟ column_height_700
      ⊞ automatic_sequence
      ⊞ manual_measurements
    ⊞ column_heigh_1440
```

Figure 10. Data structure visualization.

On top of this structure there is a root node with current date. Next level is divided into sub-nodes representing positions of the scanning system. Subsequently, each of them contains sub-nodes labeled with different heights of the vertical platform. Deeper are two groups of nodes: automatic sequence and manual measurements.

An additional refinement process is required after scanning due to the inaccuracy of manipulators. All point clouds are slightly misaligned with respect to each other, as it is shown in Figure 11.

Figure 11. Visualization of misalignments between directional clouds of points.

Two different algorithms are used for integration of scans: one for the automatic sequence and second for scans manually added to the model. The procedure used for automatic sequence alignment is divided into three parts. In the first step a copy of the automatic sequence node is made and a new empty node is created, where scans will be stored after alignment.

In the second step, we propose a group of Iterative Closest Point (ICP) algorithms. Iterative Closest Point is an algorithm employed to minimize the distance between two point clouds. In the algorithm, one point cloud, the reference, or target, is fixed, while the other one, the source, is transformed to best match the reference.

©2016 Society for Imaging Science and Technology
DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-051

The algorithm iteratively revises the transformation (combination of translation and rotation) needed to minimize the distance from the source to the reference point cloud [16-18].

As mentioned above, we use different modifications of ICP algorithms:

- initial,
- main,
- data layer and
- detailed ICP.

When scans are misaligned significantly, we use initial ICP running with large searching radius. Main ICP – in this method ICP is running until calculated error is below fixed threshold. Next one is Data Layer ICP. This algorithm is used in special scenario, when scans are mostly flat and texture feature must be used to connect two datasets. Because of noise in texture, we had to use slightly different representation of texture. In our modification, we create an additional data layer in which we assign value for each point in point cloud. This value is calculated in few steps. First, we change color representation from RGB color model to HSL (HSL stands for hue, saturation, and lightness), then based on saturation values we calculate Difference of Gaussians on fixed radius. After that we obtain a data layer which is strongly independent from any noise in texture. Last algorithm is the standard ICP running iteratively with small radius.

After the second step is finished, we move the transformed scan to the newly created node. The whole procedure is repeated until all scans are aligned.

The procedure applied for manually added scans is similar, but instead of creating a new node, we use previously aligned automatic sequence node. Manual scans are connected to automatic sequence one by one using the analogous ICP algorithms.

Exemplary results

Below the results for each step of data processing are presented. The result of precise integration algorithms for data from Figure 11. is shown in Figure 12.

Figure 12. *Result of data integration.*

Figure 13. *Results of color data integration: a) data before and b) after processing.*

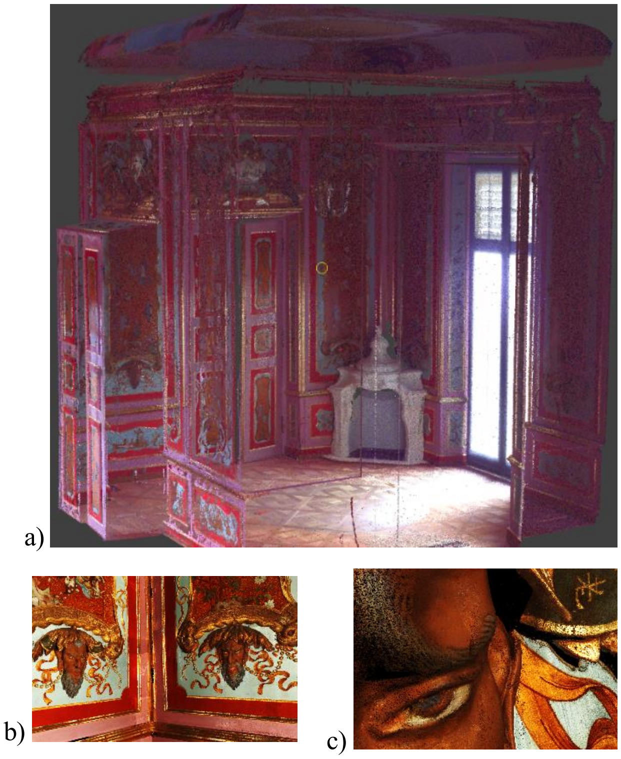

Figure 14. *Final model visualization: a) whole model, b) large fragment and c) small area.*

DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-051

For the final color processing we propose averaging of data between separate measurements or segmentation and smoothing with specified radius within specific segments. This final step reduces lightness non-uniformity and improves the final visual effect but should be omitted if reliable data without any misrepresentations is required. Exemplary results of color processing are presented in Figure 13. The final model with two fragments is shown in Figure 14.

Conclusions

We have developed the 3DMADMAC system specialized for high resolution 3D documentation of large surfaces. The system supports measurement of 3D geometry and color representation in CIELab color space. Measurement method is adjusted for partially reflective surfaces by adopting the HDR technique. We also support partial automation in acquisition and data processing for generation of the final 3D model.

The measurement system was tested on the King's Chinese Cabinet in Museum of King Jan III's Palace at Wilanów. The tests can be summarized with:

- 28 days (8 hours per day) of 3D scanning with single operator assistance,
- 5043 directional measurements (approximately 180 measurements per day),
- around 14 billion measurement points.

The novelty of our 3DMADMAC solution could be recognized in the following areas:

- custom 3D measurement head with additional, synchronized light sources and algorithms for CIELab calculation at each data point,
- semi-automation of the measurement process with use of a robot arm and automated integration of coordinate systems,
- operator-supported data processing for filtering and view integration of the whole measured 3D dataset.

Acknowledgements

This work has been partially supported by the Ministry of Culture and National Heritage (Poland) by KULTURA+ framework, the project "Revitalization and digitalization Wilanów the only Baroque royal residence in Polnad" co-financed by the European Union within the Infrastructure and Environment Operational Programme and Statutory Work of Warsaw University of Technology.

References

[1] K. Ikeuchi, D. Miyazaki, Digitally Archiving Cultural Objects, Springer, ISBN: 978-0-387-75806-0, 2008.

[2] F. Remondino, "Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning" Remote Sensing, vol. 2011, no. 3, pp. 1104-1138, 2011.

[3] H. Eisenbeiss, L. Zhang, "COMPARISON OF DSMs GENERATED FROM MINI UAV IMAGERY AND TERRESTRIAL LASER SCANNER IN A CULTURAL HERITAGE APPLICATION " in n V Symposium 'Image Engineering and Vision Metrology', Dresden, 2006.

[4] P. Santos, M. Ritz, R. Tausch, H. Schmedt, R. Monroy, A. Stefano, O. Posniak, C. Fuhrmann, D. Fellner, "CultLab3D - On the Verge of 3D Mass Digitization" in GCH 2014 - Eurographics Workshop on Graphics and Cultural Heritage, ISBN 978-3-905674-63-7, ISSN 2312-6124, 2014.

[5] M. Karaszewski, "Automated full-3D digitization system for documentation of paintings" in SPIE Optical Metrology 2013, International Society for Optics and Photonics, 2013.

[6] E. Bunsch, R. Sitnik, J. Krzesłowski, "Precise 3D-documentation of Cultural Heritage within The Polish Long-term Government Programme Culture+ between 2010 and 2014" in EVA Berlin, pp.56-63, 2014.

[7] M. Koplin, A. Kwiatkowska, Chinois. Dresdener Lackkunst in Schloss Wilanów, Münster, 2005.

[8] G. Sharma, C. E. Rodrıguez-Pardo, "The Dark Side of CIELAB" in Proc. SPIE Vol. 8292, 82920, 2012.

[9] F. Remondino, S. Campana, "3D Recording and Modelling in Archaeology and Cultural Heritage - Theory and Best Practices" in Archaeo press, BAR Publication Series 2598, ISBN 9781407312309, 2014.

[10] J. Geng, "Structured-light 3D surface imaging: a tutorial", Advances in Optics and Photonics. vol. 3, pp. 128-160, 2011.

[11] M. Karaszewski, R. Sitnik, E. Bunsch, "On-line, collision-free positioning of a scanner during fully automated three-dimensional measurement of cultural heritage objects", Robotics and Autonomous Systems vol. 60, no. 9, pp. 1205-1219, 2012.

[12] R. Sitnik, "New method of structure light measurement system calibration based on adaptive and effective evaluation of 3D-phase distribution" in Proc. SPIE, 5856, pp. 109-117, 2005.

[13] J. Hardeberg, Acquisition and reproduction of color images: colorimetric and multispectral approaches, Universal-Publishers, 1999.

[14] A. Artusi, F. Banterle, D. Chetverikov, "A survey of specularity removal methods" in Computer Graphics Forum, vol. 30, no. 8, pp. 2208-2230, Blackwell Publishing Ltd., 2011.

[15] R. Feris, R. Raskar, K. H. Tan, "Specular reflection reduction with multi-flash imaging" in Computer Graphics and Image Processing, 2004 Proceedings, pp. 316-321, 2004.

[16] P. J. Besl, N.D. McKay, "A Method for Registration of 3-D Shapes" in IEEE Trans. on Pattern Analysis and Machine Intelligence, Los Alamitos, vol. 14, no. 2, pp. 239–256, 1992.

[17] Y. Chen, G. Medioni, "Object modelling by registration of multiple range images" in Image Vision Comput., Newton, Butterworth-Heinemann, pp. 145–155, 1991.

[18] Z. Zhang, "Iterative point matching for registration of free-form curves and surfaces" in International Journal of Computer Vision (Springer) 13 (12): 119–152, 1994.

Author Biography

Robert Sitnik (Member of SPIE) received his MSc Eng (1999), PhD (2002) in applied optics from the Warsaw University of Technology. He has authored and co-authored more than hundred scientific papers. His interests are structured light shape measurement (3D/4D), triangulation methods, digital image processing, computer graphics, animation software development and virtual reality techniques. He has been a leader of projects from various fields like 3D optical metrology, virtual and augmented reality and supporting medical diagnosis by opto-numerical solutions. He is head of Virtual Reality Techniques Division at WUT.