In search for the perfect method of 3D documentation of cultural heritage

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ABSTRACT: Since 2007 two institutions - Museum of King Jan III's Palace at Wilanów and Institute of Micromechanics and Photonics, Warsaw University of Technology – are developing together a technology for cultural heritage documentation based on precise three-dimensional measurements [1]. In search for "perfect" method they realize different works including: development of robotized positioners, 3D digitization prototype systems and specialized software for measurement and data processing. In this paper, we present this modular system based on example of two 3D documentations of Kings Chinese Cabinet from Wilanów Palace. That measurements were done before (2009) and after (2015) complicated conservation works in this room.

1. INTRODUCTION

It is well known that perfection is impossible to achieve. As Salvador Dali put it: 'Have no fear of perfection – you'll never reach it'. Nevertheless, striving for perfection motivates us to continuously develop currently available methods.

Trying to create the „perfect" method of 3D documentation of cultural heritage objects we must first define our targets on at least few levels. Currently, it is not enough to answer the question what measurement sampling density (MSD) is for us satisfactory in each particular case. Effective documentation of thousands of museum's objects requires the fulfillment of many other criteria such as the automation of measurement processes or implementation the requirements of the conservation.

In 2007 – at the very beginning of the cooperation between Museum of King Jan III's Palace at Wilanów and Warsaw University of Technology, Faculty of Mechatronics – we have defined a group of problems needed to be solved on our way to create a "perfect" measurement method. These include:

- Full automation of the data acquisition process
- Full automation of the data processing
- Construction of measurement systems that a) meet all the requirements of conservation; b) are optimized to the specific requirements of the objects cultural heritage
- Determining the required spatial resolution measurement for different types of surfaces [2]
- Determining the procedures related to the colour acquisition
- Creating the software for visualization of dense point clouds

The path we have chosen allows to create technology which is characterized by a very high level of objectivity in comparison to the other methods of documentation used so far. The end-user is able to freely operate with the three-dimensional data and may take decisions which in classical methods of documentation were taken at the earlier stage of creating the documentation. Within the seven years of cooperation we have built specialized

measurement devices for three-dimensional documentation of different types of objects included in museum collections. Systems differ in the level of automation and measurement sampling density (2500 points per square millimeter for sculptures, 10000 points per square millimeter for easel paintings). They share the measurement method (structured light-based scanning) and the software environment for data processing and applications to visualize the achieved data.
One of the most innovative features of the 3D documentation is the possibility to analyze the changes taking place on the surface of artifacts on the basis of the precise measurements made at intervals. That this reason why we would like to illustrate our search for the ideal documenting procedure taking one of the interiors of the Wilanów residence - King's Chinese Cabinet – as an example.
This unique example of interior decorative art was made using a European lacquer technique in XVIII century and it is attributed to the famous 18th century craftsman Martin Schnell and his workshop [3]. The original color scheme of the cabinet was much different from its state in 2009. A very difficult decision to remove secondary coatings revealing the interior's original character has been made.
Therefore, we have conducted two scans of the whole chamber's surfaces (which are four walls and ceiling) with the resolution 100 points per square millimeter. The first measurement took place in 2009, before the conservators work begun. The second measurement was performed in 2015 with the usage of completely redesigned custom built system.

2. MEASUREMENT METHOD

The measurement method used in both 2009 and 2015 documentation projects were based on structured light illumination [4]. System implementing this method consists of a projector, which displays raster images with a predefined pattern on the surface of the measured object, and a detector, which captures the images of the pattern deformed by the surface of the object. In this particular case the sequence of images consists of a set of sine images shifted in phase [5] and a series of images forming Gray code. Then, using the acquired images, real (x, y, z) coordinates of the surface were calculated for every pixel of the detector. Coordinates of the surface can by calculated only for its part located within the measurement volume. This volume is a part of space defined during the calibration process [6], when a known object, the master, is placed in a number of predefined positions according to a schema. The color of the surface was recorded in the presence of projector illumination with white balance implemented. It allows for relatively good color reproduction but with no uniform light source structure.

3A. MEASUREMENT HEAD USED IN 2009 AND ITS POSITIONING

To speed up measurement process we developed a multidirectional measurement system that allows for sequential measurement without movement. It was reasonable because significant percentage of the surface of the Kings Chinese Cabinet was planar. Four single-directional measurement systems were placed on a common frame (Fig. 1). The measurement systems were positioned with respect to each other so that the adjacent measurement volumes overlapped, forming together one complex measurement volume, which was defined during a common calibration process (Fig. 2).

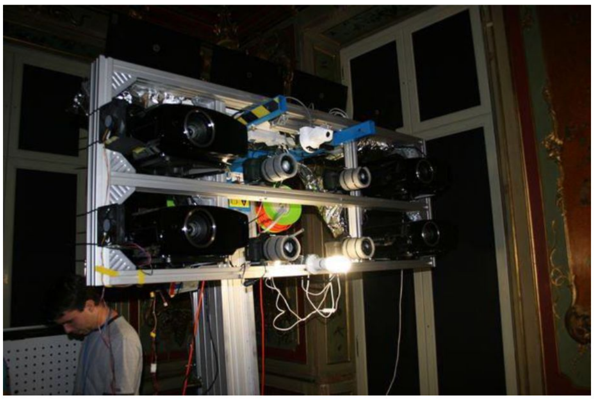


Figure 1: *Multidirectional measurement system*

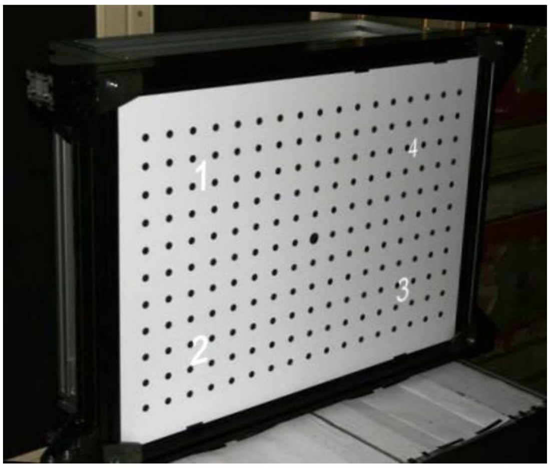


***Figure 2:** Calibration master*

***Figure 3:** Measurement system mounted on the positioning device*

The dimensions of the King's Chinese Cabinet are large in relation to the size of the measurement head volume, which was 0.5 x 0.4 x 0.2 m^3. To create a model of the whole chamber, it was necessary to reposition the system many times. To avoid the problems with changing the position of the measurement system and finding the correspondence between different measurements, a telescopic positioning device was proposed. This device allows to adjust the vertical and horizontal position of the system in a controlled manner and without effort (Fig. 3).

3B. DATA ACQUISITION IN 2009

Scanning process was realized by measurement of parts of geometry in daily basis. We record data of operator and part of measured surface. After each scan data was verified and measurement head was moved to next position. This process had to be done by two persons. After repositioning operator wait about 5 minutes till whole structure was stable and next measurement can be performed. Time efficiency of this process was about 3 measurements per hour. Each measurement produces about 60 millions of points. Whole measurement process takes about two months. Number of directional measurements was about 4000 of directional 3D scans.

3C. DATA PROCESSING IN 2009

The data was processed in 3DMADMAC system in hierarchical manner. First parts of data from each day was integrated by manual rough and color based ICP algorithms. Lately, these data was integrated into models of whole walls and finally model of whole room was created. Due to huge amount of data and semi manual data processing this process takes about six months. Final size of whole model was grated than 4TB of raw data.

4A. MECHANICAL CONSTRUCTION IN 2015

For efficient digitization of historical interiors like Kings Chinese Cabinet system must comply with several requirements. First, with thousands of positions required, the measurement head should be positioned in automatic way. This will significantly speed-up the data acquisition step. Second, scans should be roughly aligned just after the acquisition.

Another challenge was due to the fact, that the room is over 5 meters high. Scanner head to measurement volume distance is approx.

75cm, that means that we have to lift measurement head 5 meters above the ground to capture the top-most parts of the room. Whole construction should be stable, rigid and safe. Measured objects are priceless, there is no room for error. Used system consists of the motorized vertical column with robotic arm (Fanuc LRMate 200i of 700 mm range), that holds 3D measurement head. Column is placed on a wheeled platform, which allows the free movement of the structure inside the Cabinet. Vertical column is high enough to reach the top-most parts of the Cabinet ceiling (Fig.4)

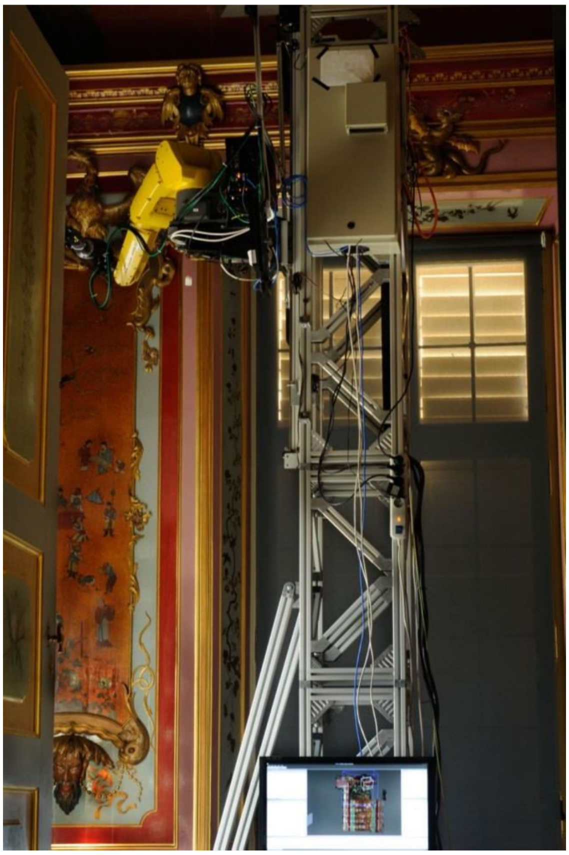


***Figure 4:** Mechanical construction with robotic arm*

4B. MEASUREMENT HEAD IN 2015

To meet conservators' requirements (measuring surfaces with light-sensitive pigments) no ultraviolet nor infrared radiation emission in the direction of measured object is allowed. We decided to use commercially available DLP projector Optoma ML-750e with LED light source. Measurement head uses two cameras Point Grey 9MPixel cameras on both sides of the projector, observing the same measurement area. That helps us to scan shiny parts of the object. In most cases, if the specular reflection is visible with one camera, the same part should be well-measured with the second one (Fig.5)

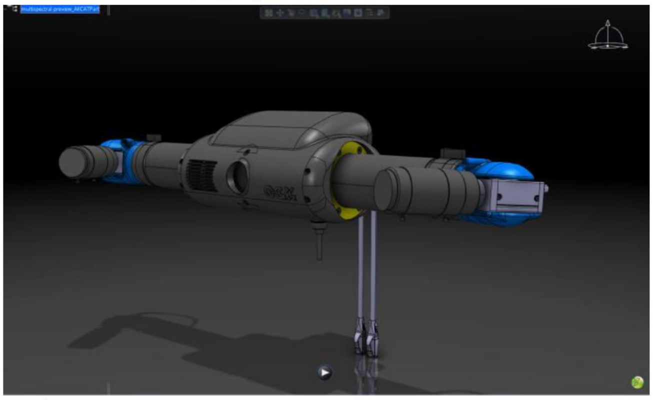


***Figure 5:** Final concept of the measurement head*

Additionally, head has to be lighter than 5kg so it can be easily lifted by robotic arm. 3D printing technology and carbon fiber parts were used to build a final version of the device. The head used the calibration method [7], which allowed to achieve a working volume of size 200x280x200mm and resolution of 0.1mm, measured as the average distance between points in the captured cloud.

4C. ADDITIONAL LIGHTING EQUIPMENT

Stitching final 3D model from separate scans, each one captured with different scanner-head position results in non-uniform color of final model. Additionally, some specific parts of Kings Chinese Cabinet ere extremely shiny, resulting in unpleasant highlights visible on final model (Fig. 6). To achieve uniform brightness for model we should use shadow-less lighting system, not moving during the whole digitization process. That is impossible due to lack of space and system self-shadowing resulting from limited 3D-scanner to measurement volume distance. To resolve this problem we capture images with few additional lights and run color-correction procedure.

Figure 6: Highlights and brightness non-uniformity visible on separate scans

Six LED light sources are used to capture additional images. Two smaller LED panels are attached directly to the scanner head next to cameras. Position of these two light changes with cameras and DLP projector. Four bigger panels are attached directly to the lift of vertical column and are arranged in square layout with dimensions 1,2x1,2m. Bigger lights are further than 2m meters from the currently measured surface and move only when the level of vertical column is changed. This four lights can produce constant lightning conditions for all are measurements captured in the single platform position, except when robot arm obscures individual panels. All lights produce soft, diffuse daylight with color temperature of 5650K. Additionally panels are certified for ability of faithful color reproduction of illuminated objects with CRI Ra>95 [8].

4D. DATA ACQUISITION IN 2015

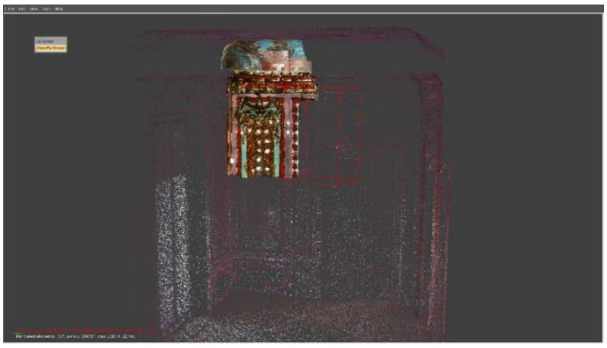
With measurement volume of single scan of 200x280x200mm and 50% overlap between consecutive scans to cover the whole area of Kings Chinese Cabinet, more than 12000 scans were captured from 6000 separate head positions.

consecutive platform positions		50
vertical column different positions (3 levels for each platform position)		150
different measurement head positions	automatic sequence (25 per column level)	3750
	semi-automatic additional measurements (approx. 15 per column level)	2250
TOTAL number of scans		**12000**

Table 1: Number of scans required to cover the Cabinets walls and ceiling.

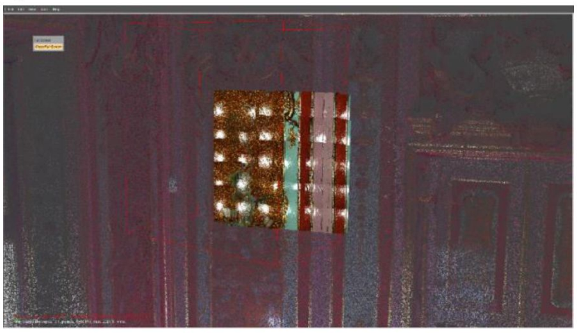
At single platform position, robot arm is lifted at 3 different levels above the ground. On each level operator starts automatic sequence with 25 different scanning-head positions, covering area of approx. 0,8x0,8m. When automatic sequence completes, we can start with semi-automatic measurements of parts with more complex shape, where defects appeared. Using the next-best view algorithm described in [9] operator just has to point the area where next scan should be performed. If calculated measurement head position is reachable, robotic arm starts movement. Scan starts immediately after reaching requested position.
Thanks to robot arm and vertical column calibration all the scans are roughly aligned in local coordinate system related with the current platform position. When the lower part of the Cabinet was measured, vertical column was extended and the process was repeated for upper-part and ceiling of the Cabinet.
Images acquisition takes approx. 20 seconds. With additional time for calculation of point cloud, saving data, next-best view procedure and robot movement, next measurement can be performed after approximately 3 minutes. Two scans are captured and calculated simultaneously, for both left and right detector. Finally the process of scanning the whole Cabinet last 6 weeks, with approximately 400 scans per day.

a)

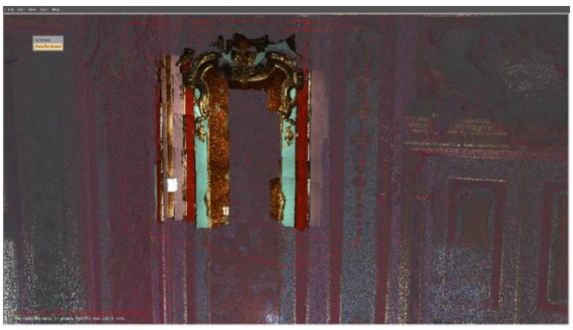


b)

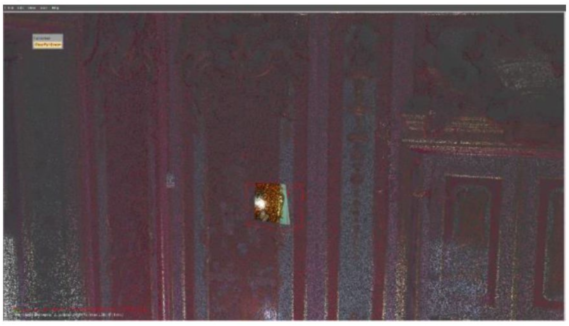
c)



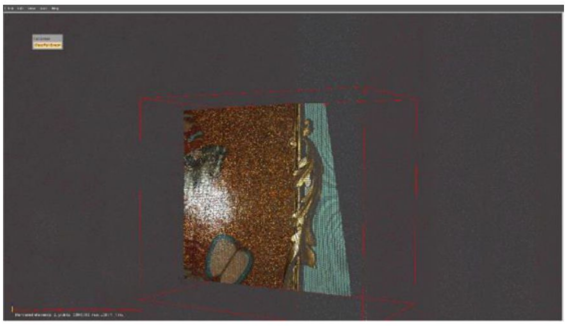
d)



e)



f)



g)

Figure 7: Simplified scanning results at each step: a) whole Cabinet, b) single platform position, c) single column level, d) automatic 25-sequence, e) semi-automatic next-best – view measurements, f) single scan, h) single scan close-up

4E. MODEL COLOR CORRECTION AND EQUALIZATION

In the first step of correction we use images acquired with additional lights described in the previous chapter and we can treat each scan individually. First, images captured with two small LED panels attached directly to the measurement head are blended together using maxima-suppressing averaging filter. Simple minimum filter is good enough for most cases. Due to head geometry and maxima-suppressing averaging virtually all specular reflections will be removed at this step.

Both cameras where white-balanced on the gray card illuminated with small LED lamps, with high CRI index. That is why we can treat blended image as color reference. In the next step, we convert all images to HSV color space. Hue and saturation from blended image are copied directly to an output image. Value channel is calculated as an average from 4 images lit with big panels. Several scenarios of averaging can be applied. In most cases, maxima-suppressing average between images lit with upper and lower lamps is calculated. Than these two images are simply mixed. Final value is copied to output V channel and after back-conversion to RGB color space, color of single scan can be overwritten.

In the next step between-clouds averaging can be performed. Due to double-camera setup and 50% overlap between consecutive scans major part of the model is reconstructed with 8 overlapping scans. Color for each point is computed as an average of colors of its closest neighbors from overlapping clouds. At the final step additional color segmentation and Gaussian-blur smoothing with specified radius within segments can be applied.

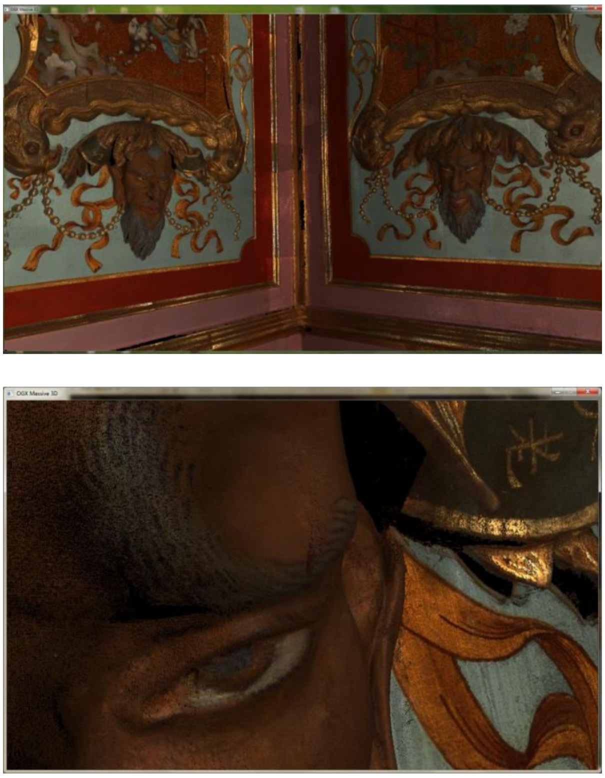


Figure 8: *Scanning results*

5A. IMPLEMENTATION OF ALGORITHMS FOR DATA POSTPROCESSING IN 2015

To facilitate a processing of huge amount of data, the hierarchical structure is proposed (Tab. 2). A node connected with a certain date is divided into sub-nodes representing positions of a scanning system. Next, each of them contains sub-nodes connected with different heights of a scanning device. On the lowest level scans are organized in two groups: automatic sequence and manual measurements. Automatic sequence consists of 25 directional measurements collected by a measurement head positioned automatically with a robotic arm. Additionally, each measurement is represented as a pair of initially aligned point clouds, as a consequence of a construction of a measurement head with two cameras. Because of a risk of damage, some details are impossible to be measured automatically. In those parts the measurement head is positioned manually. Measurements got names in format YYYYMMDD_HHMMSS – for example 20150904_174152_right_sim).

Due to applying the mechanical manipulators to position the measurement head, the output point clouds within the automatic sequence are initially aligned. However, an inaccuracy of manipulators causes slight misalignment between point clouds and additional refinement processing is essential. In order to decrease time of processing, algorithms operate on lower level of details.

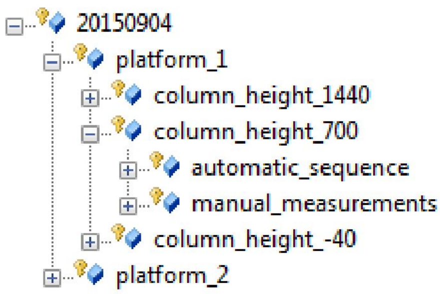


Table 2: Data structure

5B. ALGORITHMS

Two different procedures are developed for integration of scans from for the automatic sequence and manually added to the model. Procedure used for automatic alignment of a sequence with 25 directional measurements is divided into three parts. First, a copy of the whole automatic sequence node is created and new empty node, to store scans after alignment is added. Next, scans within a sequence are arranged in the order of execution.

In second step, Iterative Closest Point (ICP) [10][11][12] algorithms are used to refine the alignment between point clouds. According to the type of a data, there are different modifications of ICP applied: initial ICP, main ICP, ICP with data layer, detailed ICP. 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. The algorithm iteratively revises the transformation (combination of translation and rotation) needed to minimize the distance from the source to the reference point cloud.

Initial ICP is used, when scans are misaligned significantly, and in such case, the algorithm is running with large searching radius. Usually next step is to calculate Main ICP, standard version of point-to-plane algorithm. In this method ICP is running with average searching radius until error is below fixed threshold.

ICP with data layer is used, when scans are mostly flat and texture feature must be used to extract correspondences between two datasets. We propose to recalculate color information from RGB to HSL color system (HSL stands for hue, saturation, and lightness) and then according to saturation values calculate Difference of Gaussians (DoG) with fixed radius (Fig. 9). Thereby, we receive a data layer which is much more independent from the noise in texture.

Detailed ICP, the last part of the algorithm running iteratively with small radius.

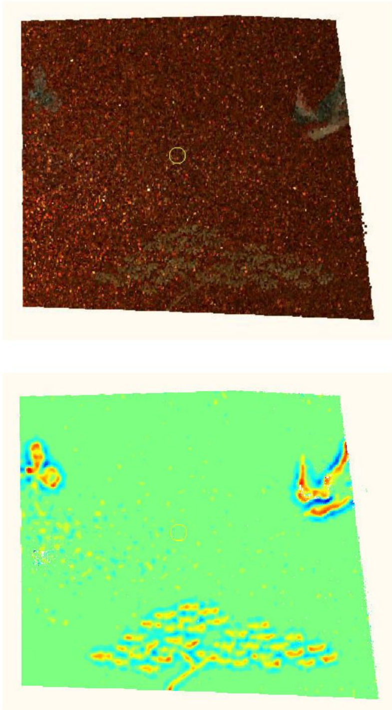


Figure 9: *Original cloud point texture and calculated data layer*

After second step is finished, newly aligned scan is moved to the node with fitted measurements. Whole sequence is repeated until all scans are calculated. Algorithm made for manual measurements differs only in the first step. Here you set up fixed node as stable, usually automatic sequence node. Algorithm then check, if earliest scan from manual node is adjacent to any scan from stable node, if yes, aligns them one by one to the automatic sequence using the analogous ICP algorithms. Algorithm repeats until there is no scan in manual measurement node. In final step we match well-fitted sequence with manual scans to 3D point cloud of whole room from 3D laser scan system. This allows us to create full 3D representation of Chinese Cabinet from 12 000 scans.

5B. EXAMPLES OF RESULTS OF THE ALGORITHM

In this section we will show data samples before and after applying the algorithm. Scans within the sequence are initially aligned (Fig. 10), but at close range (Fig. 11) many mismatches between scans are observed. In order to show misalignment between scans, the cross-sections along the red lines are presented.

Figure 10: *Scan sequence*

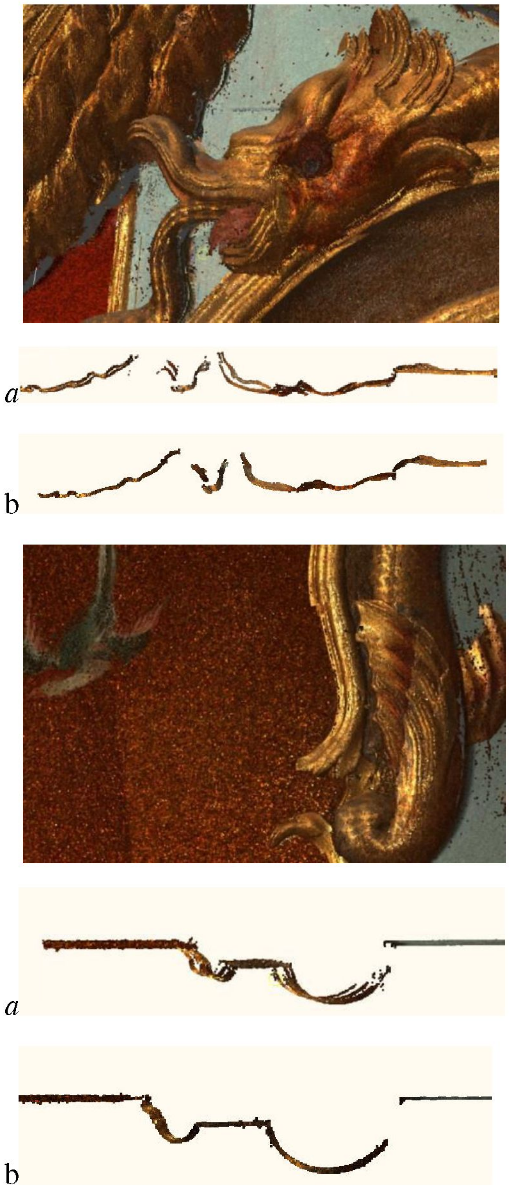


Figure 11: *Two spots observed at close range before (a) and after (b) applying algorithm*

Error values	Minimal	Average	Maximal
Before	3,27 [mm]	5,01 [mm]	6,63 [mm]
After	0,27 [mm]	0,33 [mm]	0,51 [mm]

Table 3: Error statistic for a sequence of 25 scans from Fig.9

Error values are calculated using distance between randomly selected points from overlapping parts of adjacent scans and RMS (Root Mean Square Error) formula (Tab.3). The entire model consists of approximately 12 000 point clouds. Each simplified cloud of points has approximately 300 000 points. This gives us massive amount of data to process. One iteration of the algorithm takes about 300 sec. Usually we needed to run this three times plus algorithm used for manual measurements. To sum up, the creation of the whole model took ~855000 sec, which gives us approximately 238 hours.

6. CONCLUSION

The cultural heritage is a mankind legacy – it perpetually whispers us our own history, it allows us to connect with the past. Thus it should be handed over to successive generations unchanged. In the same time, the case of the King’s Chinese Cabinet presents that all artifacts are in a constant state of transformation due to the different factors. The fact is, that this splendid interior in Wilanów will never be as it once was. This shows that our historical treasures need a documentation method as close to the perfection as possible. The authors of this article believe that proposed approach brings us one step closer to solving this problem. While putting the developed methodology into the practice we constantly face obstacles, but the imperfections fruit with progress. All things considered, the perfection is a long-term project.

7. FUTURE WORKS

In the future we will still focus on software for data processing, visualization and analysis. We believe that only the acceleration and automation of the whole process will allow mass 3D digitization of cultural heritage artefacts with reasonable quality supporting reuse of 3D data in the future. We also focus on extending classical 3D geometry measurement with multispectral color and BRDF modalities for better documentation.

8. ACKNOWLEDGMENT

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