

THE PROCESS OF AUTOMATED DIGITISATION OF SHAPE AND COLOUR OF OUTDOOR HISTORIC OBJECTS

Case study – Baroque vases from the Museum of King Jan III's Palace at Wilanów

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ABSTRACT:

The process of complete digitisation of shape and colour of cultural heritage objects is intricate and complex. It requires much preparation, especially when digitisation has to be of the highest quality. The complexity of the tasks increases significantly when the object to be digitised is located outdoors, as the conditions for taking measurements are very different from those found in a laboratory. The paper presents a case study in automated digitisation of shape and colour of Baroque vases (radius about 0.5m, height 2m) in the gardens of King Jan III's Palace Museum in Wilanów, Warsaw. The two vases were digitised by a robotised structured-light scanning system with spatial resolution of 0.02 mm (2,500 points per square millimetre), with about 4,500 directional measurements each. Each vase took almost 30 days to measure. The Authors discuss different challenges encountered during the course of scanning, and remark on data processing and visualisation of such dense data.

1. INTRODUCTION

Much work on 3D documentation of cultural heritage objects has been done in recent years (Pierracini *et al.* 2001, Sansoni *et al.* 2009). Owing to the improvement of the quality and accuracy of hardware, many obtained 3D models can be considered by conservators and historians as comprehensive documentation data (Bunsch 2010). Nevertheless, for this purpose, heritage objects have to be digitised in high resolution that is sufficient to capture important details of the surface. Much work has been devoted to establishing resolution standards required for objects made from various materials. It is generally agreed that 2,500 points per square millimetre is sufficient to capture details of objects made of sandstone (Bunsch *et al.* 2011), while higher resolution of 10,000 pts/mm² is required for fine materials such as porcelain (Figures 1 and 2).



Figure 1. Examples of 3D models digitised at 2,500 pts/mm². From left: a copy of the 2nd-century BC Kybele statue; Gargoyle from the Mont Saint Michel (a modern souvenir); a copy of the 2nd-century AD Roman votive altar; a Greek red-figured hydria, 4th century BC.

Such precise measurements are possible with various full-field optical devices, such as close-range laser scanners, close-range photogrammetry (either passive or active) and structured-light-based scanners. All these methods have their pros and cons (Blais 2004). Structured-light systems are amongst the best suited devices for high-resolution shape acquisition (Sansoni *et al.* 2009, Bunsch *et al.* 2011).



Figure 2. Examples of 3D models digitised at 10,000 pts/mm². Four biscuits in the collection of King Jan III's Palace Museum in Wilanów.

Alongside accurate measurement devices, high-resolution digitisation requires maintaining controlled environmental conditions to ensure that the results are not distorted by a change in the object shape, due to the changing ambient temperature, or by other factors. Such control is certainly possible in a laboratory, but large monuments, such as façades of buildings, and other cultural heritage objects cannot be moved to a laboratory. Baroque residences have usually beautifully decorated façades and parks with sculptures. Notable examples include the Château de Versailles in France, Schloss

Sanssouci in Germany, Schloss Schoenbrunn in Austria and many other palaces and castles that are members of the Association of European Royal Residences. It is therefore important to assess whether such significant cultural heritage objects can be digitised with high precision and resolution.

In this paper we present our efforts to digitise two Baroque vases, some 2 metres high and 0.5 metre in diameter, in the gardens of King Jan III's Palace Museum in Wilanów, Poland. The vases are made of sandstone. The scanning resolution was 2,500 points/mm².

The paper is organised as follows: in the next section, general requirements for obtaining high-resolution 3D models during digitisation are described. The test objects are presented in section 3, alongside the description of problems encountered in the preparation stage of the digitisation process, and the solutions adopted. The fourth section of the paper contains details about the digitisation process, as well as some comments concerning the planning of automated measurements and data processing. Results of digitisation are presented in the fifth section, alongside their comparison to a 3D model obtained with a Time-of-Flight scanner. The final section consists of conclusions drawn from our experiences, as well as the directions planned for the future work.

2. REQUIREMENTS FOR HIGH-RESOLUTION DIGITISATION

During high-resolution digitisation, some environmental conditions have to be maintained to ensure high accuracy of the resulting 3D model. Otherwise, it is impossible to assess whether features visible on the surface of the digitised object have been measured correctly (due to, for example, the impact of thermal shape changes). Moreover, the presence of even minute vibrations, will be visible in the 3D data as noise. When the noise level is comparable to allowed inaccuracy, the digitisation output is not suitable for professional use. Therefore, the digitisation process should be performed in carefully stabilised conditions, with controlled temperature and humidity. The measuring device, 3D scanner, as well as the digitised object should be protected from vibrations. Digitisation should normally take place in the darkness, because changing lighting conditions also impact on the quality of results. For example, in our typical, laboratory environment we maintain:

- Stabilised temperature (20°C);
- Stabilised humidity (RH = 50 +/-5 %);
- Darkness (less than 20 lux).

Another issue related to high-resolution digitisation results directly from the relation between the resolution of commonly available detectors, used in digitisation systems, and the number of points required on the surface. A great number of directional measurements has to be taken. For average targets of 10,000 points per square millimetre digitisation (biscuit figurines – Figure 2), which are between 200 and 500mm high, up to several hundred measurements have to be taken (each of about 40mm x 40mm x 12mm). As carrying out such a task is very difficult for human operators, we use robotised

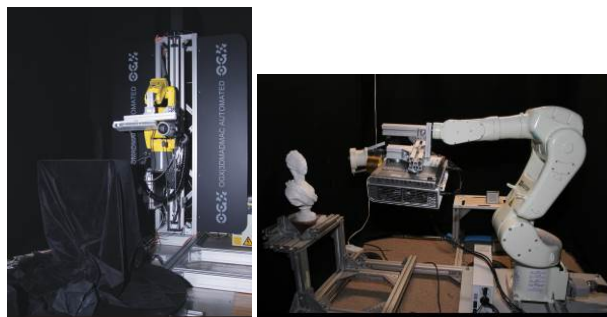


Figure 3. Examples of automated digitisation systems.

systems for automated digitisation, such as those presented in Figure 3.

Our automated systems have been operational in the laboratories within King Jan III's Palace Museum in Wilanów for a few years. We also became interested if such high resolution scanning could be performed outside the laboratory. This question is important because many valuable cultural heritage objects are not moveable and cannot be taken to the laboratory, because they are too large, too heavy or too fragile. Some interesting sculptures may, for example, be part of the decoration of a building's façade and cannot be removed. To test the possibility of high resolution digitisation *in situ*, and identify problems arising during this process, we selected a few objects located in the gardens of King Jan III's Palace Museum in Wilanów.

3. TEST OBJECTS, PROBLEMS AND SOLUTIONS

Two sandstone vases in the gardens of the Museum were chosen due to their unique decoration (Figure 4). They were made by J. A. Karinger and J. A. Siegwitz in the 18th century. Both vases are similar in shape, 2000mm high and have the radius of about 500mm. One is similar in shape to a cask (Figure 4b) and has a smooth surface decorated in low-relief, and a highly ornamental pedestal, while the other (Figure 4a) is rather slender and decorated with cannelures, approx. 15mm deep. The latter vase is also covered in low-reliefs. As both objects are located outdoors, the effects of weather and time are clearly visible. Both vases are made of sandstone, therefore the 3D scanner with 2,500 points per square millimetre has been chosen for digitisation.

The scanner used was a structured-light based device. As mentioned in the first section of this paper, many different devices are suitable for the task, however as we specialise in building 3D structured-light scanners (both in terms of hardware and software), we selected one of our typical setups, the 3dmac device (Sitnik 2005). This device allows for fast, accurate measurements and returns results as clouds of points with geometrical XYZ coordinates and colour (RGB) data. It is important that the detector (DSLR camera) used for acquiring images of deformed fringe patterns (which are used for shape calculation) is also used for acquiring the RGB data. Therefore, the mapping of colour data onto points in the obtained clouds is perfect. For resolution of 2,500 pts/mm² the inaccuracy of the measurement is within +/- 10um (Skladek 2011).



Figure 4a, b. Sandstone vases in the gardens of King Jan III's Palace Museum in Wilanów. Photo © Wojciech Holnicki.

Digitisation of those two vases poses many challenges when compared to our usual procedures. The placement of the targets, the fact that they are fixed to the ground and, last but not least, their size compared to the measurement volume of the 2,500 pts/mm² 3D scanner (about 50mm x 50mm x 20mm), make the digitisation task very complicated. It was expected that the number of directional measurements required for a full 3D model of the vase would be no less than 3,000. Clearly, we needed an automated system for such a process.

In our typical digitisation tasks that involve small objects, which can be easily moved to the laboratory, we usually use a turntable, on which the object is placed. The scanning device is fixed to a robotic arm. This configuration gives us a positioning system with 7 degrees of freedom, which allows us to digitise the whole object easily. As the vases are fixed to the ground, we obviously could not put them on any type of turntable, instead we had to move the robot arm around them. Moreover, the range of our typical robot arms is not long enough (about 700mm). Therefore, we had to use another type of robot, with a range of about 2,000mm enabling coverage of the vase from the bottom to the top. For this task we chose a Kawasaki FS20N (Kawasaki 2014) robot arm (Figure 5a). The operating range of this device allowed us to measure more than 25 per cent of the vase surface from one fixed position of the robot base. To digitise the entire vase, we chose to move this robot arm around using a special carriage (Figure 5b) which, after positioning, is put on the extendable supports with a large touch surface (not visible on the photo).

The introduction of a manually positioned robotic platform, of course, requires the need to integrate directional measurements. Fortunately, as for each vase there are only four positions available on this platform, the integration is not complicated, because the overlap between datasets obtained from different directions is large.



Figure 5. Positioning devices: a) Kawasaki FS20N robotic arm, b) Platform for the robot arm.

After completing the positioning system, we tried to emulate the conditions as close to the laboratory environment as possible. As mentioned, not only controlled temperature and humidity are required, but the environment must be free from vibration, as well as dark. For this reason, we chose to construct a tent around the subject vase. The material was carefully selected to reflect the sun's rays (to protect the interior from heating). Another layer of material was added inside to provide an additional screen against the light coming from outside. To maintain stable temperature conditions inside, we used highly efficient air-conditioning-units which allowed us to keep the temperature at 20°C +/- 2°C and humidity at about 50% RH +/- 10%. Those conditions are not as stable as in a laboratory. However, we considered them good enough. Vibrations were not present because the platform supporting the robot was placed on soft ground, efficiently dampening any vibrations which could happen in the vicinity of the measurement system.



Figure 6. The tent covering the object and measurement system during digitisation.

4. THE DIGITISATION PROCESS

The digitisation process was started after all preparations had been completed (Figure 7). It can be described as follows:

- The measuring head used for digitisation was a structured-light 3d madmac scanner, with a resolution of 2,500 points per square millimetre. This system has the measurement volume of about 50mm x 50mm x 20mm;
- Each vase was measured from four positions of the robotic platform. The platform was moved manually after the surface reachable by the robot had been fully digitised;
- Measurements were performed automatically within each of the four positions;
- The simple collision avoidance was applied due to the simple global object shape;

- Manual supervision was necessary, because the system was an untested prototype;
- Manual checking of the results was necessary to ensure good quality from the obtained model;
- The digitisation process ran 24 hours a day, 7 days a week;
- The accuracy of the measuring head was checked daily, with a high-quality calibration unit.



Figure 7. The measurement system during digitisation of the first vase.

As stated above, within each quarter, directional measurements were performed automatically. The process was started after the operator had directed the robot's measuring head to a place from which any part of the vase could have been measured (i.e. within the measurement volume of the scanner). After this part of the object was digitised, the next scanner position and orientation were calculated by the so called next-best-view algorithm (NBV) (Karaszewski *et al.* 2012). The scanning head was then moved to the proposed position (with collision-avoiding procedures) by the robot and the next measurement was taken. The process continued until the whole available (i.e. reachable from current platform position) surface of the vase was digitised. Some parts of the surface which could not be measured (for example, due to occlusions or collision-threatening robot configurations) were scanned with the operator's assistance. The average time of one directional measurement was about 6 minutes, with half of this time spent on the measurement itself (projecting fringe patterns, acquiring and downloading images, XYZ calculation), while the remaining time – on data processing (denoising, saving, simplifying for NBV calculation), the next scanner position calculations and finally on the positioning.

After all the data were collected, the post-processing was performed. It consisted of fine clouds alignment by Iterative Closest Point algorithm (Besl, McKay 1992). This step was required because of inaccuracies within the positioning system itself and of calibration of the relation between the robot and scanner coordinate systems. The ICP fitting took about one week. Once the fine-aligned model was obtained, it was optimised for visualisation in

real time by our specialist application, Massive3D. Those calculations consisted mostly of generating levels of detail of the cloud. Due to the large size of the model (about 1TB) it took about five days to complete. All processing was done on a computer with 4-core 2.4 GHz Intel Xeon Processor with 96GB RAM, controlled by Microsoft Windows Server 2008 R2.

During the measurements we encountered a few phenomena which we had not thought of before. One of them was the presence of various insects, especially mosquitoes, moths and flies, which were attracted in the evenings by the relatively high temperature inside the tent. Beside their obviously negative influence on the human operators, they tended to sit on the measured surface (probably because it was the brightest spot in the tent) causing errors in the measurements. The only way to overcome this problem was to use an electrical discharge insect control system, which can be seen in Figure 7.

The dampness of the ground was another problem. The vases are displayed in the Museum gardens, in an area which is significantly lower than the surrounding terrain. Therefore, especially after heavy rains, much of the fall was flowing near the fieldwork area. For this reason, the ground around was very damp and soft. This phenomenon caused instability of the platform supporting the robotic arm. Even the high-area supports used for its stabilisation did not prevent it from sinking into the soil, especially when the robot was working close to its maximum range. The tilting of the platform was not apparently visible by operators, but its effect could be clearly seen in the initially aligned 3D model. The alignment was based solely on the information about the position of the robotic arm, without any fine fitting. Those additional errors had to be corrected in the course of data post-processing (with the fine alignment performed with Iterative Closest Point-based algorithms). Another problem caused by the water was that the high dampness of the ground, darkness and stillness of the air inside the tent caused the grass to decay, emitting a rather unpleasant odour.

Regardless of all these problems we have managed to obtain high resolution models of the two vases.

5. RESULTS

It took 23 days to measure the first object; 4451 directional measurements were needed. Total number of points was about $3 * 10^{10}$. The results are presented in Figure 8.

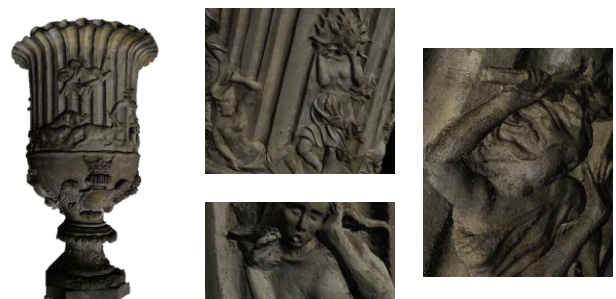


Figure 8. Computer model of the first vase.

The second vase (Figure 4b) was digitised in 26 days, during which 4822 measurements were taken. Total number of points for the model was also approx. $3 \cdot 10^{10}$. Figure 9 presents the results of the digitisation process.

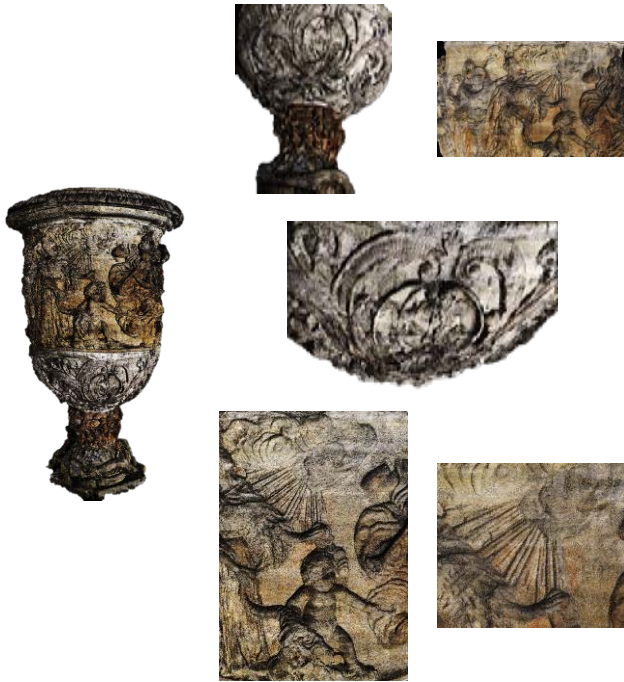


Figure 9. 3D computer model of the second vase.

Unfortunately we could not compare the high-resolution data with measurements obtained with other scanners. We were unable to obtain such devices at the time of digitisation. The vases are in a garden which is open to visitors. We had to take the tent and air-conditioners down as quickly as possible. For this reason, we can only assume that our dense data are correct based on control measurements of our calibration unit (performed frequently during the digitisation process). This unit, by Edmund Optics, is a plane with 2,501 black dots, spaced 1.0mm +/- 2um, radius 0.5mm +/- 2um. It has an overall flatness inaccuracy of +/- 1um. Results of the control measurements were always within the declared range of scanner accuracy, so it can be assumed that the system maintained its metrological properties.

Both vases were also measured with the laser scanner Faro Photon 120 of +/- 2mm accuracy (Faro 2014). While we were certain of the quality of our scanning head in directional measurements, we wanted to test also the quality of the global model. The comparison between the global shape of our models and those obtained with a laser scanner shows, that despite the subsidence of the robotic platform, we managed to maintain high accuracy of the global shape of the model (the distance between our results and the Faro ones are smaller than the accuracy of the laser scanner), Figure 10. The greatest differences between the models are visible near sharp edges (especially the cannelures of the second vase), which in the laser scans were very significantly rounded due to the smoothing of data proprietary to the software controlling the scanner.

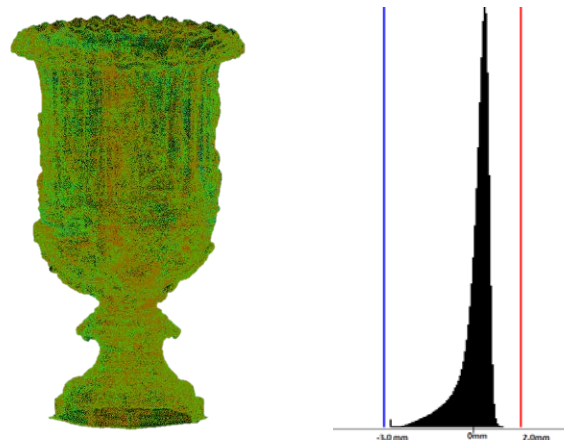


Figure 10. Visualisation of shape differences between our model and the one obtained with a laser scanner.

6. CONCLUSIONS

The experiment of high accuracy measuring of outdoor objects was conducted successfully. In spite of some errors, the results achieved are of high quality and accuracy. The comparison of the results to the laser scans confirm this, at least within the accuracy offered by a laser scanner. Unfortunately, we do not have a more accurate system, which would be suitable for digitising large parts of the test objects (significantly larger than working volume of our structured-light scanner), therefore we cannot evaluate the global accuracy more precisely. However, we have proved that high accuracy scanning is possible outside laboratories under some particular conditions, especially when temperature and humidity can be controlled.

In cultural heritage documentation there is a need for precise, dense digitisation of objects which cannot be moved to a laboratory. We rest assured by the result of the trial digitisation process described in this paper that this is possible and we plan to construct a mobile station for precise outdoor digitisation. The station would make it possible to digitise large monuments and façades of buildings with hitherto unprecedented resolution.

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