Building the Models of Cultural Heritage Objects Using Multiple 3D Scanners

KRZYSZTOF SKABEK a, PRZEMYSŁAW KOWALSKI a

aInstitute of Theoretical and Applied Informatics
Polish Academy of Science
ul. Bałtycka 5, Gliwice, Poland
{kskabek,przemek}@iitis.gliwice.pl

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Abstract: Abstract. Our main goal is building of 3D model of cultural heritage objects using 3D scanners. We have tested four scanners: Konica-Minolta VI-9i, Faro LS880 HE80, Faro Laser ScanArm, and Portable 3dMDface System. Their features were utilized in the multiscanning process and that gives us new possibilities to modelling of complex objects. Scans are processed and integrated using Geomagic Studio (we also relate to Rapid Form, FARO Scene and Gexcel Reconstructor software packages).

The tests give us hints and conclusions about the proper way of usage of the scanners. We also propose the scheme of multi scanning.

Keywords: 3D scanner, 3D mesh, 3D representation, scanning, cultural heritage

1. Introduction

In the article we compare some 3D scanners, and we show how to integrate the scans into one 3D model, to eliminate disadvantages of available scanners. We have tested four scanners: Konica-Minolta VI-9i, Faro LS880 HE80, Faro Laser ScanArm, and Portable 3dMDface System. Two of them – Konica-Minolta VI-9i and Faro Laser ScanArm – are most important for us, because the scanning range best fits to our test objects.

However, there are many commercial systems for 3D object acquisition, the number of them suffer for hardware limitations. Almost each scanner has its own measuring characteristics. Scanners differ in a scanning range, light conditions, scanning precision and manoeuvrability.

Our goal was to prepare procedures for scanning the objects of cultural heritage, so we use such objects, such as a sculpture or a relief to test scanners and integration procedures.
2. 3D Scanners

In the bibliography most of works relate to the usage of a single scanner for cultural heritage objects [1, 2, 5, 7, 9], often with additional photo documentation. The 3D scanners differ in used technology of scanning, parameters, type of the output data. We use 3 laser scanners to model 3D object (see fig. 1): Konica-Minolta VI-9i, Faro Laser ScanArm, Faro LS880 HE80. Further in the article we shortly describe them as well as another facilities for 3D scanning.

![Fig. 1. 3D Scanners: a) Konica-Minolta Vi-9i, b) Faro Laser ScanArm (Hermes statue and Geomagic Studio software in the background), c) Faro LS880 HE80.](image)

2.1. Konica-Minolta VI-9i

*Konica-Minolta VI-9i* (fig. 1a) is an example of a general-purpose device used for wide spectrum of applications. The scanning range is from 0.5 to 2 meters, and distance error is \(\pm 0.05\) mm. The scanner gives a triangle mesh of points and a RGB texture. The error is small (but differs for parts of the scanned area). The main limitations of the scanner results from its limited maneuverability, the measuring distance and the (distance between laser and camera).

Among optional accessories for Minolta Vi-9i there is rotary stage – using it the object can be simply scanned and automatically registered from many directions. Three interchangeable lens (*WIDE, MIDDLE, TELE*) make it possible to obtain the best accuracy for objects of different sizes.
2.2. Faro Laser ScanArm

Faro Laser ScanArm (fig. 1b) consists of the scanning probe mounted on the measurement arm with 7 degrees of freedom. Theoretical accuracy of the laser probe is the same as for Minolta Vi-9i laser scanner: ±0.05 mm, but the final accuracy reflects not only the accuracy of the laser probe, but also accuracy of the arm (for Faro Platinum arm equals ±0.03 mm) – the accuracy of the whole scanning system is ±0.08 mm.

The laser probe works within distance from 9 to 18 cm from the scanned object, but the laser probe is movable (within the sphere with radius 2.4 meter). The output of the scanner is an ordered points cloud.

2.3. Faro LS880 HE80

*Faro Range Laser Scanner LS880 HE80* (fig. 1c) is a device for outward and inward scanning of large areas within a distance less than 76 meters. Its distance error is ±3 mm at each 25 meters. The scanner gives measures of distance points with the reflectance (for infrared light) and collects it in a point-cloud grid. The measurement error is relatively small (as for such distances), but for small objects the accuracy is pretty poor. In fact for small objects the measurement error is much bigger than for Minolta VI-9i or Faro Laser ScanArm, that makes comparison of the output almost impossible (see fig. 3).

2.4. Portable 3dMDface System

*Portable 3dMDface System* (fig. 2) is a system specialized for scanning the human faces. It uses four graylevel cameras to capture the depth map and two RGB cameras to obtain the texture. A special flashes of structure light are also used. The scanner does not use a laser light, so it can be utilized for medical diagnosis.

Fig. 2. Portable 3dMDface System.

The accuracy of the scanner is ±0.15 mm, but the main advantage is the time of images acquisition – it takes 1.5 msec. In fact the image processing takes much more time, but it can be performed after scanning without concerning the attention of patients. This way the method is insensitive for natural human movements (such as breathing, eye
blinking, facial expression) during the scanning process. The output of the scanner is a triangle mesh with a color texture.

2.5. Another Scanning Systems

We tested four scanners, but there are many other facilities like that – for example Zoller+Fröhlich models IMAGER 5003, IMAGER 5006 are similar to the Faro LS880 HE80. The differences concern mainly the scanning precision. Another example is QT Sculpture (Polygon Technology) with the performance similar to the Minolta Vi-9i scanner. The difference concerns the scanning procedure. QT Sculpture uses structural light, and operates better in darker rooms. It takes more time to obtain each scan.

2.6. Data types

Almost each 3D scanner has its own data format, but in fact, the number of data types is not numerous. We have two types of output data (with additional type of flat, 2D bitmap image for texture):

- unstructured point clouds
- structured point clouds (used in both Faro scanners);
- triangle meshes (used in Minolta VI-9i and Portable 3dMDface System).

In fact the data type depends on the scanning technique. For Faro LS880, where the laser beam is deflected in a rotating Galvano mirror and the scanner measures shifts of the incoming light waves, the obtained points are independent. For Faro Laser ScanArm we have a set of laser beams forming a stripe light. In this case positions of the laser probe are independent, so the meshing is quite a complicated problem.

Typical triangulation scanners, such as Konica-Minolta VI-9i emits the stripe light that is vertically deviated using a Galvano mirror and a 3D image data of the object is obtained. Preparing the mesh is relatively easy in this case as the output data has a grid form. Portable 3dMDface System acquires a set of well calibrated photographs of the object (e.g. face) covered with a structure light. The mesh is computed from the shifts in these photographs. In these case the output mesh is composed of two views and covers the extent of 180°.

2.7. Usage of scanners

Each type of scanners has its specific applications: architecture (relatively big areas), medium objects, complex medium objects and moving or deformable parts (such as human body). Sometimes one scanner is able to substitute a scanner of another type. Especially, scanning probe on the arm can substitute the universal scanner, and vice versa. The cooperation of these two scanners is a particularly interesting task, as both are designed for the object of the same size, but differ in the scanning scope and conditions.
The differences in the scanning conditions are a motivation for using both devices for scanning the same object and, after that, integrate the scanning data [6].

3. Stages of processing the scanned data

In fact, the main stages of scanning objects of cultural heritage are the same for all kinds of scanners and objects [7]. The stages of scan processing contain: scanning, removing additional objects (accidentally scanned), removing redundant data, removing spikes, reducing noise, execution of a manual and global registration. The whole pipeline of 3D Model Acquisition is presented in [3].

The further actions depend on the used software. For Geomagic and RapidForm we need to merge scans into one model, transform to the manifold, convert the polygon model into the shape model, detect contours, construct patches, construct grids, and fit NURBS surfaces into patch template. The patch template can be used for 3D comparison of models.

For Gexcel Reconstructor the main type of data is in form of grid point cloud. This software is dedicated for range scanners such as Faro LS or Zoller+Fröhlich, and most of the procedures are specially designed for them. We should start with preprocessing; next we go to pre-registration (equivalent of manual registration in Geomagic) and registration. The following step is converting the grid point cloud into a triangle mesh and, finally, add texture (if we have proper photographs).

The accuracy of the scanners is subject of many works; our experiments were described in proceedings [6].

3.1. Scanning with Konica-Minolta VI-9i

The scans were taken using Konica-Minolta VI-9i scanner and Polygon Editing Tool (software produced by Konica-Minolta). We use the Konica-Minolta scanner with TELE lens (input range in X: 93 mm, in Y: 69 mm and in Z direction: 26 mm) and in one test MIDDLE lens were used. The Polygon Editing Tool was used not only for scanning but sometimes also for the manual registration. The scans were converted into ASCI STL format and transformed into Geomagic or RapidForm.

3.2. Scanning with Faro Laser ScanArm

The scans were taken using Faro Laser Scan Arm mounted on the arm Faro Platinum (with arm span: 2.4 m) and the Geomagic software (with Faro plug-in). In plug-in we set some parameters (including the range of scanning angle). The whole scan processing was performed in Geomagic. Scan data can be imported into Geomagic in two different forms. Faro Laser ScanArm acquires ordered points or unordered points, but the second
representation is less useful because of triangulation problems. Such representation is further cleaned and converted into the polygon model.

3.3. Scanning with Faro LS

Faro LS is equipped with an internal computer, but the efficient solution is to use an external workstation with the Faro Scene software. The software makes it possible to integrate scans. This process can be facilitated by special balls located in the scanned area. We can also use previously prepared cards for more accurate registration.

In fact we had a problem with registration of Faro LS scans with scans prepared using the other tested scanners (see fig. 3b), because of the big difference in scanning range and precision, as Faro LS is dedicated for large area scanning.

Fig. 3. The Hermes statue: a) photograph, b) comparison of a single scan prepared using Faro Laser ScanArm (darker area) and a scan prepared using Faro LS (brighter area).

3.4. Scanning with the Portable 3dMDface System

Portable 3dMDface System is very specialized system – the parameters of the scanner and software procedures are dedicated to the face analysis. The dedicated software for Portable 3dMDface System is used only for scanning and exporting the data to WRL file.

3.5. Further Processing for Comparison of the Models

We may register scans before converting them into the polygon model (using either Polygon Editing Tool or Geomagic Studio). If the scans are still not registered we can do it using polygon models.

For the base model (i.e. the model to be compared to another models) we have to: fill holes (model is almost always incomplete), make manifold open (i.e. delete non-manifold triangles), convert copy of the model into the shape model. The shape
model is further converted into the patch template, because the patch template is the only representation in Geomagic that can be used as a template for scan comparison.

The original data (structured points or mesh) are stored as a base for comparison, because registration is limited to two models of the same type and without registration the position of the models is not proper. On the other hand, 3D compare procedure from Geomagic gives us the maximum distance (positive and negative), the average distance (positive and negative), the standard deviation and the color map of distances between both models (see fig. 4b and 5b).

4. Tests

The idea of data integration is easy – the data formats are convertible and can be transferred between software packages. Data sets can be integrated using the manual registration first. In fact there are some problems:

- What exactly is the advantage of the used scanner?
- How similar are the scans?
- Which is the best way for data integration?

We have tested both Konica-Minolta and Faro scanners using three objects. The chosen objects represent different types of cultural heritage objects.

- The Hermes statue is an example of statue – free form objects, with some flat (or curved but simple) surfaces. The statue is white (matt) and rather not complicated.

- The Polish national emblem is an example of an embossed sign. Theoretically the embossed sign is an easy example (and some works are limited to 3D scanning of embossed signs or bas-reliefs [4]) because of the few occluded parts, but there are still problems with small details.

- The car model has two important features for us:
  - The car is a die-cast model and Geomagic has special procedures for such shapes; we wanted to test these procedures.
  - The car is the two-color model (with small decoration color details) – that gives us possibility of testing the multicolored objects.

The objects were scanned using both scanners (Konica-Minolta VI-9i and Faro Laser ScanArm), processed, converted to the common data type and then compared. Tests were performed not only for comparison of both scanners but also for comparison of different scans taken by the same scanner. Such comparison can be used for verification of the scanner reliability.

The further actions depend on the used software and were described above (chapter 3).
4.1. The Hermes Statue

The Hermes statue (size: 94 × 223 × 150 mm, see fig. 1b, 3) was scanned using both scanners. For Minolta Vi-9i scanner problems concerned: scanning of the small partially occluded parts (like curled hairs, armpits, etc.). The model was registered easily using the rotary stage and the geometry of the whole model was undisturbed. Advantages of Konica-Minolta VI-9i are: good quality and stable geometry of the model. Disadvantage: relatively big area of occluded parts.

For the Faro Laser ScanArm the problems concerned: scanning of the occluded parts (but the parts are smaller in comparison with Konica-Minolta), range of the scanning angle (not bigger than 90°) limiting scanning areas (and consequently, we must prepare more scans to cover the whole object). In the stage of scan processing the important problem occurred: improper registration of curved surfaces disturbed the shape of the scanned object).

Advantage of Faro Laser ScanArm is accessibility to small parts of the sculpture. On the other hand, the main disadvantage is unstable geometry of the statue and problems with proper registration.

The differences between scans made by both scanners are small; they differ only in small parts.

The best way to data integration is to start scanning with Konica-Minolta VI-9i (it gives us the stable and almost complete model of the object) and to use Faro Laser ScanArm to fill holes in the existing model.

4.2. The Polish National Emblem

Size of this embossed sign (fig. 4a) is 189 × 13 × 176 mm (in fact thickness of the sign is even smaller – this value results from its leaning).

Fig. 4. The Polish national emblem: a) photograph of the original object, b) comparison of the scanned meshes – grey levels represent differences between two scans.
The emblem was the easiest to scan – both scanners have no problems with it. Faro Laser ScanArm gives us slightly more possibilities for scanning edges; Konica-Minolta VI-9i gives the model slightly more geometrically stable.

In fig. 4b, the difference map between two scan of the sign is presented – we can see relatively big differences on the edges of feathers and talons, because these parts were hardly accessible. There were no great problems with the geometry of the whole object, except of left wing (but there are still pretty small differences).

4.3. The Car Model

The die-cast model of Ford Capri RS (scale 1:24, size: 161 × 48 × 60 mm) was in fact most interesting of the objects (see fig. 5a). It was the first colorful model. It was also a model with flat surfaces and many hidden details.

![Fig. 5. The toy car: a) die-cast model photograph, b) differences between scan and model built using scans.](image)

In fig. 5b we can see the biggest problem for scanning our car model – the differences between scans (it means that scans aren’t reliable for this parts) located on the wheels (especially front wheels – it is caused by their mobility), car windows (in this example, only edges of the windows area) and most of the sharp edges in the object.

4.3.1. Scanning the Colourful Model

There are problems with scanning multicolour objects and also shining or changing the albedo [3]. It was very difficult to scan colourful model using Konica-Minolta VI-9i scanner, especially because of problems with scanning black surfaces. Better results give us scanning using Faro Laser ScanArm – almost the whole model was scanned properly. For the second scanner the output of the scanning procedure was almost the same for the colourful and bleached model. The problem considered: the ambiguity of scanning partially transparent surfaces (e.g. dirty windows), reflective parts, transitions between
the silver body and the black chassis (body and chassis cannot be scanned using one set of scanning parameters – luckily the scanner sets proper parameters automatically, with a small delay only), open windows (car interior is almost occluded, but an uncompleted interior is a problem for software), partially occluded parts with many details.

Additional tests suggested that the greatest problems with Faro Laser ScanArm were caused by shiny black surfaces and reflective surfaces. Scanner operator should take into consideration problems with transitions between different colours – the lines looks like convex or concave, although they lie on a plain surface. The example is presented on the fig. 6, it is the scan of a book cover. The cover is flat, but still there are visible a distinguishable convexities on the 3D scan in place of changing colours – inscriptions (a), a black line (b), a part of the contrast image on the cover (c). We can also see problems with precision of the Faro Arm and instability of our workspace (d) – some parts of the scan are shifted in relation to the others.

Fig. 6. The example of scanned book cover.

4.3.2. Scanning of the Bleached Model

The model was bleached using developer Bycotest D30A and the window holes were closed, so that the interior part of the car was invisible.

The main problem for Konica-Minolta VI-9i scanner is an angle of scanning – some objects are represented inaccurate – it is especially visible in respect of convex inscription on the chassis. But the scans are much better than for colourful model.
5. How to Scan Model Using More Than One Scanner?

Some works suggest proper scanning procedure for one scanner [7, 4] (even if there are more scanners, e.g. in [8], it is not mentioned of data integration and quality of the scans) – the main scheme seems to be obvious, but it is easy to forget some preparation steps.

The both described above scanners can be used for the same model. Our procedure starts with scanning using Konica-Minolta VI-9i scanner. The scans give us reliable object geometry with well represented main surfaces. The model built using Minolta scanner does not give us information about parts of the object that were scanned improperly (especially small parts, and parts partially occluded, sometimes also parts with improper albedo or color). For example – we scanned the miniature statue of Friedrich Wilhelm Great Elector of Brandenburg and Duke of Prussia by Andreas Schlüter (fig. 8a, the miniature comes from Foundary Art Department of Museum in Gliwice and the original statue is situated in Charlottenburg). The size of the miniature is: 532×670×463 mm.

The scanned model is the basis for scanning using Faro Laser ScanArm. We use the following scanning procedure: 1. Find parts of the object that were not scanned (or parts not properly scanned). 2. Find optimal angle of scanning for the chosen parts. 3. Do the scan using optimal angle ±45° – in the same scanning tour scan also the visible surrounding parts for further registration. 4. If there are no scanned or accessible parts of the object, go to 1. 5. In many cases not previously scanned parts must be scanned twice or thrice – each time for different angle range.

While we scanned the miniature statue of the “Great Elector” for the second time, we fixed our attention on the uncovered parts on the belly of the horse and details of the human forms on the pedestal. We tried to register scans simultaneously to the procedure of model scanning. The registered scans gave us actual information of parts that were still not scanned.
Scans from both scanners were used to build the resultant output model. We did the merging using Geomagic Studio – the procedure is similar to that used for comparison and only the final result is different. The expected result is a model, but in this case we needed the integrated shape model only, so we did not proceed to the template building stage.

The complete algorithm for model integration in Geomagic Studio (or using equivalent procedures in another software package) is:

1. Chose the first scan to integration (the preliminary model from Konica-Minolta scanner gives us the proper geometry at the beginning; start with the Faro Laser ScanArm is easy, because we use the same software for preprocessing). The scan will be simultaneously integrated to the existing model.
2. Import new scans (process them if it is necessary). Attention: the scans must have common surfaces with the actual model.
3. Register the new scan to the existing model manually.
4. Check the quality of the actual model (process the model if it is necessary).
5. If there are still differences between scans (surfaces are not perfectly aligned, but almost parallel to each other), use the global registration.
6. If there are still scans to integration, return to 2.

(Optionalally) Merge the scans into one shape model. In short the complete scheme of scanning is presented on fig. 13.

Scanning the greater objects, we should start with the scanner for greater areas – it is helpful if we can obtain the rough model of the whole object and then use it as the preliminary model.
6. Summary

Scanning using more than one scanner can be very helpful for building models of cultural heritage objects. Integration of scans made by different scanners can give us more complete and more accurate models.

For such task we can use universal software packages for 3D scan processing. The main problem is not a software, but hardware – parameters of the scanners, monitoring of model completeness, and the strategy of scanning. In the article we present proposition of the scanning procedure, but the main part of scanning still relies on experience of operators.

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References

Artykuł podejmuje problem skanowania obiektów dziedzictwa kulturowego przy pomocy skanerów przestrzennych. Obiekty dziedzictwa kulturowego stanowią szeroką klasę obiektów przestrzennych: rzeźby, płaskorzeźby, obiekty architektoniczne. Obiekty te różnią się wielkością, złożonością i dostępnością. Zakładamy, że obiekty nie zmieniają swojego kształtu w czasie skanowania. Ograniczenia w digitalizacji takich obiektów związane są m.in. z brakiem możliwości nanoszenia dodatkowych warstw matowiących. Istotnym czynnikiem jest konieczność akwizycji tekstury powierzchni w wielu analizowanych przypadkach.

W swoich badaniach ograniczyliśmy się do obiektów stosunkowo niewielkich (o wymiarach rdzenia kilkadziesiąt centymetrów w każdym wymiarze), co pozwalało prowadzić czasochłonne testy w laboratorium.

Testom poddano cztery różne skanery przestrzenne: Konica-Minolta VI-9i, Faro LS880 HE80, Faro Laser ScanArm, oraz Portable 3dMDface System. Zastosowanie
poszczególnych skanerów odpowiada charakterowi zadań, do których zostały zbudowane – najwyrazistsze przykłady to: Faro LS880 HE80, przeznaczony do skanowania dużych przestrzeni (do odległości ok. 76 m), co jednak wiąże się z mniejszą dokładnością i gęstości próbkowania i utrudnia łączenie skanów z tego skanera z innymi testowanymi urządzeniami; Portable 3dMDface System, którego główną zaletą jest szybkie wykonanie skanu 3D, co pozwala na minimalizację błędów skanowania związanych z odkształcaniem obiektu (system przystosowany do skanowania twarzy). W przypadku dwóch pozostałych skanerów – Minolta Vi-9i i Faro Laser ScanArm zakres skanowanego obszaru się nakłada, choć różnią się dostępnością do szczegółów obiektu i dokładnością. Pierwszy z nich pozwala lepiej odwzorować ogólną geometrię skanowanego obiektu, drugi jest bardziej mobilny i cechuje się większą tolerancją na barwę i albedo powierzchni.

 Każdy z testowanych obiektów: popiersie Hermesa, odcisk godła Polski, oraz model samochodu stanowi odrębny przypadek, ze względu na możliwe do stosowania metody – wybór obiektów testowych miał umożliwić weryfikację funkcjonowania skanerów i oprogramowania w zastosowaniu do typowych obiektów dziedzictwa kulturowego, jak też wypracowanie schematów postępowania.

 Zaproponowano schemat skanowania obiektu w oparciu o kilka skanerów:

 1. Wybierz pierwszy skan do integracji (rozpoczynając od skanowania skanerem Minolta, ze względu na jego charakterystykę). Tak pozyskany skan stanowi nasz tymczasowy model.
 2. Importuj kolejne skany (przetwarzając je w miarę potrzeby). Uwaga: skany muszą posiadać wspólne częki z istniejącym modelem.
 3. Dokonaj manualnej rejestracji nowego skanu z istniejącym modelem.
 6. Opcjonalnie łączymy skany w jeden model.

 Procedura łączenia różnych skanerów podczas skanowania tego samego obiektu poprawia zeskanowany obszar, mimo jednak zaproponowania w artykule schematu postępowania dla skanowania wielu skanerami, wciąż sama procedura w znacznej mierze zależy od doświadczenia operatorów skanerów.