CULTURE HERITAGE PRESERVATION WITH OPTICAL CORRELATION SCANNER

J. Reznicek [a], K. Pavelka [b]

[a] Dept. Mapping and Cartography, Tel.: +420224355416, E-mail: jan.reznicek.1@fsv.cvut.cz
[b]Head of Laboratory of Photogrammetry, Tel.: +420224354951, E-mail: pavelka@fsv.cvut.cz

Czech Technical University, Faculty of Civil Engineering
166 29 Thákurova 7, Prague, Czech Republic

Commission V, WG V/2

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ABSTRACT:

There are many culture heritage objects that continue to suffer degradation for many reasons, such as: weather conditions, vandalism, war and even terrorist attacks. With the use of a 3D digitalization technique it is possible at least to preserve the current state of the culture heritage object in a virtual form on computer or even to print the scaled copy with rapid prototyping technique. Nowadays, there are a lot of 3D scanning systems; however the low cost systems are often requested.
This paper is aimed to present the 3D digitalization workflow of the Laboratory of Photogrammetry at the Czech Technical University in Prague, Faculty of Civil Engineering. This low cost system consists of 3D digitalization, software processing and final presentation of a 3D virtual model. In each part of the workflow we pay attention to problematic issues that have not been solved well yet.
The key part of the paper is a brief description of our self-developed 3D digitizer called Optical Correlation Scanner (OKS) based on image correlation techniques from a set of images taken by using calibrated digital cameras and its practical use on three different types of culture heritage objects. The first one is the Gothic-age portal in the church of St. Peter and Paul in the town Bilina, the second one is the Baroque-age relief of the Jesus Christ crucifixion in the town Velenice and the third one is the stone sculpture of the angel by Matyáš Bernard Braun dated in the Baroque era.
The next part of the paper describes the software processing stage. We compare commercial (e. g. Raindrop Geomagic Studio 9) and non-commercial (e. g. Meshlab 1.2) 3D processing software. Special interest is focused to the function of merging point clouds taken from different positions, because here we see the lack of today's software.
Finally we present the possibilities of a virtual 3D model used for historians or restoration specialists. We will compare several types of software (e. g. Adobe Acrobat, Meshlab, CAD), that can be used for measuring and data processing. Special attention will be paid to rapid prototyping technique.

1. INTRODUCTION

This paper is aimed to present the 3D digitalization workflow of the Laboratory of Photogrammetry at the Czech Technical University in Prague, Faculty of Civil Engineering. This low cost system consists of 3D digitalization, software processing and final presentation of a 3D virtual model. In each part of the workflow we pay attention to problematic issues that have not been solved well yet. The structure of the paper is as follows:

1. Description of our self-developed 3D digitizer.
2. Selected projects on culture heritage documentation done with Optical correlation scanner.
3. Comparison of software for processing scan data.
4. Presentation possibilities.

2. OPTICAL CORRELATION SCANNER (OKS)

2.1 Basic principles

Optical correlation scanner (OKS) consists of one calibrated camera, photo-base with moving camera-holder, tripod and software written in Matlab language. OKS was designed to be universal; by changing the base length, it is possible to measure short-distance objects, as well as long-distance (the base is variable up to 1 meter). The images are taken with a very short step (usually 5 or 10 cm) in order to have a good correlation.

Figure 1. Optical Correlation Scanner

The structure of OKS software is divided into several modules. Here, we will mention only two of them: Image rectification module and dense matching module.

2.2 Image rectification module

Epipolar geometry is defined only for one pair of images. For reliable dense matching, more images are needed. For this reason, we developed special algorithm for multiple image matching. Each point is than reconstructed from those images, on which the point can be seen.

First, we compute epipolar geometry for each pair of neighbour images and get **n** homographies (Pollefeys).

$$\mathbf{H}^{\pi 1}{}_i \sim \mathbf{A}^1{}_i - a^1{}_i \boldsymbol{\pi}^T, \quad \mathbf{H}^{\pi 12}{}_i = \mathbf{H}^{\pi 1}{}_i\, \mathbf{H}^{\pi 2}{}_i{}^{-1} \qquad (1)$$

where $\mathbf{H}^{\pi 12}{}_i$ is homography between images induced by world plane $\boldsymbol{\pi}$.
$\mathbf{P}_i = [\mathbf{A}_i|a_i]$ is camera projection matrix.
im is a number of images, **n** is a number of homogr.
i = 1:**n**, **n = im** – 1, j = 1:**im**

Then, we generate (using $\mathbf{H}^{\pi 2}{}_i$) all right-side epipolar images ($im^{EPI}{}_i$) from all pairs (but left and right from the first pair). In this solution, epipolar images do not fulfil the basic rule, that points on the left image lies in the same row as in the right image, because no right image was generated (except the first one). For this reason, we generate **n** look up table matrices (LUTrow) in which the information about corresponding rows is stored.

$$\mathbf{LUTrow}\{i=2{:}n\} = (\mathbf{H}^{\pi 1}{}_{i-1})^{-1}\, \mathbf{H}^{\pi 2}{}_i\, \mathbf{x} \qquad (2)$$

where **x** is a matrix of all image pixels coordinates.

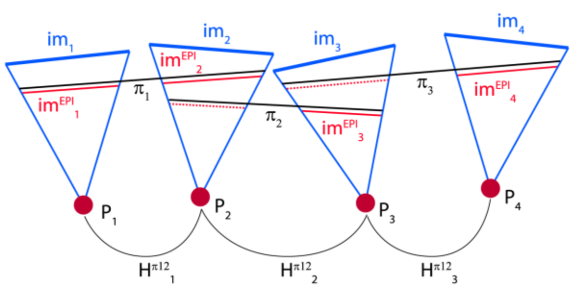

Figure 2. Image rectification scheme

The corresponding row is stored in LUTrow matrix and the one-dimensional searching is preserved:

$$\mathbf{row}_i = \mathbf{LUTrow}\{i\}\, (\mathbf{x}^{uv}{}_j) \qquad (3)$$

This method is great for saving ram memory, because it is not needed to generate each pair of epipolar images. The right one is sufficient.

Generating epipolar images is not an unambiguous task. There is several approaches of how to compute the optimal homography. More information can be found for example in (Sandr, 2009).

2.3 Multi-view stereo dense matching algorithm

Here, we describe the dense matching algorithm. The basic idea of our approach is such that each point should be matched on more than two images. Given two image point correspondence only, we have no control of good estimate. The third image point correspondence is necessary for validating the correctness of point match. More image point correspondences increase the total precision and reliability of point match. As we use bundle adjustment method for each point reconstruction, we can simply detect outlier by analyzing covariance matrix. This is not possible in simple pair-wise matching and therefore the final model is less reliable. The process of point correspondence validation consists of a several more steps which will be described in more detail in chapter 2.4.

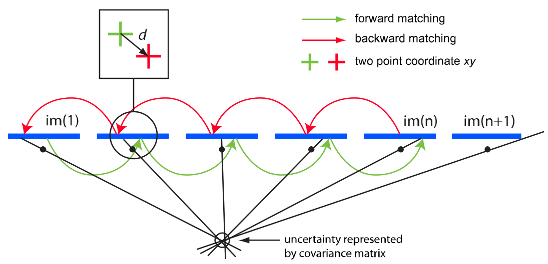

Figure 3. Multi-view stereo matching scheme

The process of multi-view point matching is as follows:

The forward-initial (FI) point is continuously searched on next images until one of the two options happens:

1. The searched band in (**n**+1)th image is out the predefined range.
2. The correspondence validation on (**n**+1)th image is negative.

Then, the last good point match (image **n**) is taken as a backward-initial (BI) point and the algorithm repeats in backward order until one of the two options happens:

1. The matching algorithm successfully reaches the FI point (with validated difference **d**).
2. The matching algorithm stops (because of negative validation) before reaching the FI point.

In case of the second option, the FI point is not discarded yet. We take (**n**–1)th image point as a BI point and the same process is repeated until successful match. In case of reaching minimum number of views (2 or more) without successful match, the point is definitely discarded.

Matching windows and other parameters (e.g. sub-pixel shift – see chapter 2.7) are temporary stored in memory in case of repeating the matching algorithm with (**n**–1) images.

2.4 Point correspondence validation

In order to exclude the outliers, each pair-wise correspondence has to pass the three different validation steps:

Correlation coefficient threshold: Correlation coefficient should be higher than threshold (usually 0.8).

Bundle adjustment: Standard deviation computed from covariance matrix should be higher than threshold.

Point coordination difference (uniqueness constraint): Each point coordination has two values. The first one is derived from the forward part of the matching algorithm, while the second one is the result of the backward computing. The distance between those two image points should be less than predefined threshold.

2.5 Extension of the multi-view stereo dense matching algorithm to infinite stripe of images

The multi-view stereo dense matching algorithm described in chapter 2.3 can be extended to infinite stripe of images (e.g. aerial photogrammetry). Our approach is very simple. After matching all points (FI points) belonging to the first image, we set the next one as a new start image and the process of matching repeats until the end of image stripe. From the previous computing, we have a lot of already matched points in image 2 which we do not need to compute again. In order to skip these points, we use raster maps (fig. 4) of same size as epipolar images in which each pixel (point) has two states – matched (1), not matched (0).

Figure 4. Epipolar image (left) and raster map (right)

Theoretically, it is not needed to set up the limit (**N**) of how far the matching algorithm can try to search FI point, because it is already limited by predefined minimum and maximum object distance. In practice, we sometimes want to set this limit manually. For example, we prefer the speed prior to accuracy. Another reason could be limited memory in computer (fig. 5).

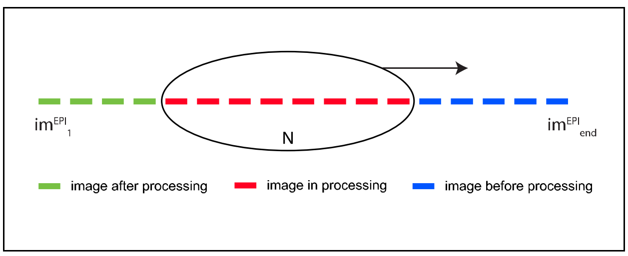

Figure 5. Extension of multi-view stereo matching scheme

2.6 Correlation coefficient

For evaluation of the similarity of a candidate pair of image points, we use technique (cross-correlation coefficient) based on the idea that each point neighbour should be unique. Feature-based methods are probably more stable but it is not suitable for dense matching. Increasing the size of the correlation window, the algorithm finds more points but the accuracy is lower. For this reason, we use two sizes of correlation window. Larger for the pixel-precision mode, smaller for the sub-pixel mode (in most cases, we use 21x21/11x11 – 8 Mpix image).

2.7 Sub-pixel accuracy

The precision of correlation-based matching is limited by the pixel size. The sub-pixel accuracy can be achieved in two ways. The first option is to use the phase-based correlation method, which is invariant to image sampling (Cech, 2005). We use simpler method. It is based on interpolation the sub-pixel value from the map of correlation coefficients computed in close neighbour of the highest value. The sub-pixel shift has to be stored in memory also for next matching (between image 2–3), because the correlation window is generated around the integer value of the highest correlation coefficient in image 2. We could of course interpolate the right correlation window around the sub-pixel value, but it is time consuming process. Image coordination in sub-pixel precision is than computed from equation:

$$\mathbf{xy}_{i+1} = \mathbf{xy}_i^0 + \mathbf{dsub}_i + \mathbf{dsub}_{i+1} \quad (4)$$

where $\mathbf{xy}_{i+1}$ is a final sub-pixel image coordination on image **i**+1,
$\mathbf{xy}_i^0$ is an integer image coordination on image **i**+1,
$\mathbf{dsub}_i$ is a sub-pixel shift taken from previous matching ($\mathbf{dsub}_1 = 0$),
$\mathbf{dsub}_{i+1}$ is a sub-pixel shift from actual matching.

Proposed method preserves the sub-pixel accuracy throughout the multi-view correspondence matching.

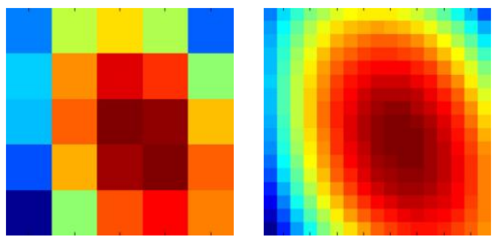

Figure 6. Interpolation for sub-pixel accuracy

3. CULTURE HERITAGE 3D DOCUMENTATION WITH OPTICAL CORRELATION SCANNER

3.1 Gothic-age portal in the church of St. Peter and Paul in the town Bílina

Portal of church in Bílina (Nord Bohemia) artefact from beginning 15th century was found in the north part of the church. The 3D virtual model of the portal helps historians in research.

The portal was measured from sixteen stations that were close to each other. Each station has 6–11 views. The scene was lighted with two 500W photo lamps. The images were taken with calibrated Canon 20D camera (8 Mpix), 10–22 mm Canon and 50 mm Canon lenses. The noise of the images is reduced by averaging three images taken from the same view with a different exposure. The distance between two views is 5 or 10 cm. All images except the first station have a landscape orientation. The scan resolution is 2 pixels.

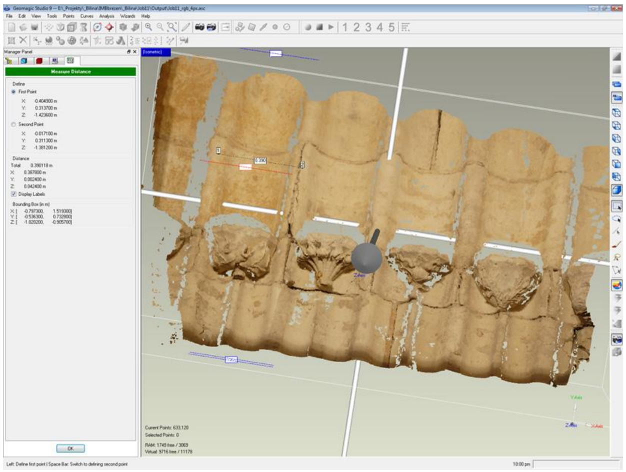

Figure 7. Scan of the Gothic-age portal in Geomagic Studio

station	number of views	number of points [thousands]	Overall computing time [hours]
1	11	3 511	133
2	9	3 246	169
3	9	4 736	199
4	8	2 914	98
5	9	2 600	52
6	7	2 294	72
7	7	2 487	39
8	9	3 038	57
9	9	3 508	192
10	9	3 204	106
11	9	2 850	67
12	9	2 629	62
13	9	3 022	50
14	6	1 521	33
15	6	1 629	28
16	9	2 991	47

Table 1. Overview on processing in OKS (Gothic-age portal)

3.2 Baroque-age relief of the Jesus Christ crucifixion in the town Velenice

The Jesus Christ Crucifixion rock chapel is situated 400 meters east of the town Velenice. In 1710–1711 it is decorated with sculptures and reliefs carved into the sandstone rocks probably by one of the folk artist named Schill, who lived in town Velenice. The primary purpose of the chapel was to replace the church which was built later in 1735. In later years, the chapel became a popular pilgrimage site.

The chapel is inside divided into three small rooms. The middle one is open to wide entrance portal. In the opposite direction of the entrance is carved altar with a casket for storing the body of Christ. In the other rooms, lighted by two windows, are folk relief scenes from the Easter (passion) cycle.

The relief was measured from ten different stations (fig. 10). Each station has 6–11 views. The scene was lighted with two external flash lights. The images were taken with calibrated Nikon D200 camera (10 Mpix) and 14 mm Nikkor lens. The noise of the images is reduced by averaging four images taken from the same view and with the same settings. The distance between two views is 10 cm. Images taken on stations 4–9 have portrait orientations, other stations are landscape oriented. The scan resolution is 4 pixels.

station	number of views	number of points [thousands]	Overall computing time [hours]
1	11	967	13
2	11	999	14
3	11	993	14
4	11	933	13
5	11	998	14
6	11	974	14
7	8	807	11
8	6	601	8
9	7	678	9
10	6	682	9

Table 2. Overview on processing in OKS (Baroque-age relief)

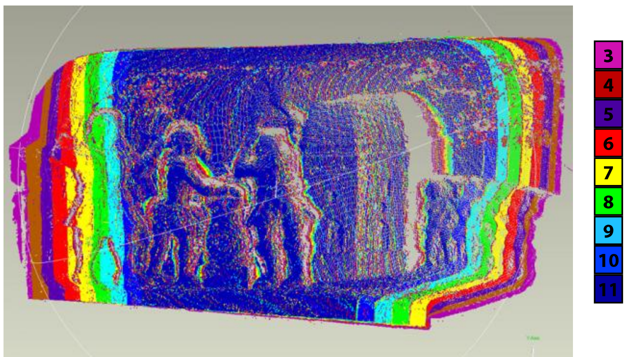

Figure 8. Colour visualisation of points based on the number of views (right column). Baroque-age relief, Velenice.

Figure 9. Final 3D model of one part of the relief with texture

Figure 10. The stations placement in the chapel.

4. SOFTWARE FOR PROCESSING LARGE DATASET FROM SCANNERS

In culture heritage documentation, our goal is to get a precise virtual model of scanned object represented as a high quality mesh with a good texture. Following this statement, we will focus only on software and its functions, which are suitable for this specific workflow (unorganized set of point clouds –> continuous, watertight clean mesh).

In Laboratory of Photogrammetry, we have a long time experience with many types of commercial scanners (Konica-Minolta Vivid VIi, Creaform Exascan, Callidus, Optech Ilris, Leica Scanstation, Riegl, Photomodeler scanner, Menci Zscan) and even with scholar prototypes (our self-developed OKS (Reznicek, 2008a), LORS (Koska, 2006), SICK, ARC 3D Webservice (Vergauwen, 2006) etc.). Based on this experience, we can say, that scanning process itself is very easy and there is almost nothing that could be improved. No matter what kind of hardware we use. Real task is a processing stage in suitable software.

The problem of processing point cloud data and setting the right workflow is still a big issue. Hardly accomplished precision of scanner machine is much decreased by unsuitable processing the data. Outliers, over-smoothed point cloud, poor registration, intersecting triangles, non-uniform data distribution, poor texture and specially overlapping regions are nightmares for operator. The quality of processing software could be measured by implemented functions that should suppress all of the above mentioned difficulties. The second criterion asks on how is the software optimized for speed and working with large datasets (ram memory use, multi-threaded functions, 64bit system support etc.). From this point of view, there is not much software left that we can talk about.

In next section we will compare software Raindrop Geomagic Studio 9, Meshlab 1.2.1, VripPack (Curless, 1996) and VxScan.

4.1 Raindrop Geomagic Studio

Raindrop Geomagic Studio is well known software for processing data from all kind of 3D digitizers. It has a number of sophisticated functions for working with points and polygons. Our experience with this software is very positive. It is very stable, 64bit system support and the menu with functions is perfectly and logically organized. Geomagic has no options for defining the parameters of used 3D digitizer. This seems to be an advantage, because we can process all kind of dataset with unknown origin. On the other hand, we lost important information that significantly help improves the processing. For example, knowing the origin coordinates and the geometry of scanning, it is possible to use faster 2D triangulation algorithm that results in perfect mesh with no intersecting triangles (Reznicek, 2008b).

The price of Raindrop Geomagic Studio is about 10–30.000 Euro.

4.2 Meshlab v1.2.1

"MeshLab is an open source, portable, and extensible system for the processing and editing of unstructured 3D triangular meshes" (http://meshlab.sourceforge.net/). From this definition, it is obvious that Meshlab is not designed for processing point cloud data. But there are some functions (e.g. triangulation) that works with points.

Meshlab is a great solution for testing purposes, or as a advanced 3D data viewer. It has a function for scan registration based on ICP algorithm. But we don't recommended it as a full software solution due to unexpected results in many functions, poor stability, unorganized and unlogical menu, and for missing important functions (e.g. more selection functions).

What is interesting on Meshlab, is a support of universal 3D format (U3D) that can be attached to Adobe documents (version 7 and above). The software also support Stanford University format PLY, which uses quality parameter for each point or triangle. There are many sophisticated and useful functions for different kind of visualisation. It is possible to generate the quality parameters for each triangle or point.

Meshlab is distributed as open source software.

4.3 VripPack (Brian Curless and Marc Levoy)

"VripPack is a package for volumetrically merging a set of range images. It is based on a new approach to surface reconstruction from range images." (Curless, 1996). This command-line type of scholar software gives unbelievably good results. The main reason is that this software takes into account the geometry of used scanner and also introduces the weighted point cloud. Due to the different precision of scanning in the coverage area, some points (e.g. border points) should have a smaller weight. Unfortunately, it is not possible to process large dataset (millions of points) with a high precision. VripPack is written for PLY format. We think that this is the best solution for merging point clouds into a one final clean mesh.

VripPack is being made available for research and commercial use, free of charge. The software is covered by a new General Software License, which is based on the BSD license.

4.4 VxScan (Creaform)

VxScan is the data acquisition software developed by Creaform for the whole line of portable, self-positioning handheld scanners. It is not standard software for processing point cloud data.

This software is very interesting, because it directly generates the high quality continuous mesh and not the point cloud. Because the handyscan is a portable, self-positioning system, the object scanning is continuous and we get the whole model at once. The processing stage is than very simple. Basically, we only fill the holes.

We mentioned here this software, because it seems that the basic idea and algorithms are similar to VripPack software. It would be very interesting, to try convert the geometry of static scans of selected object that was scaned with other type of machine (e.g. Konica-Minolta Vivid) as it would be like from handyscan. This procedure would lead directly to a clean and uniform mesh.

5. PRESENTATION POSSIBILITIES OF THE 3D VIRTUAL MODELS

For sculptor, the simple 3D model helps for right stone size selection and for space conception of the carved copy that he can make. Artists and restoration specialists are not ordinarily the specialists in 3D modelling or animation. They don't use special software for 3D scan analyzing and presentation. The possibility of simple 3D measurement is often demanded – a simple solution in this area provides the Adobe Acrobat with 3D functions or the Meshlab. Especially welcomed is a real 3D copy of scanned object made by Rapid prototyping technology.

5.1 Adobe Acrobat 3D

In the Adobe Acrobat 3D product, many kinds of measurements can be made. Especially useful is the section profiles function. This software is very easy to use and satisfies most of the needs of historians and restoration specialists. This solves a very frequent question of non-specialist on laser scanning: on which non-expensive and easy software we can utilize the measured and processed 3D data.

5.2 Rapid prototyping technology

Rapid prototyping is technology of printing real 3D models of scanned objects. At Laboratory of Photogrammetry, CTU in Prague, we have a ZPrinter 450 from Zcorporation. This type of 3D printer use standard inkjet printing technology to create parts layer-by-layer by depositing a liquid binder onto thin layers of powder.

Figure 11. Real 3D colour model from rapid prototyping machine (ZPrinter 450). Stone sculpture of the angel from Mary's pillar by Matyáš Bernard Braun dated in the Baroque era.

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