The Analysis, Accuracy and Utilization of Open-Source Photogrammetric Software

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Summary

A multi-image orientation is one of the most important tasks in photogrammetry and 3D modelling in computer vision. The accuracy of image orientation and camera calibration significantly influences the quality of all consecutive processes, such as a determination of spatial coordinates of individual points or 3D modelling. Therefore, orientation and calibration are an essential prerequisite for several applications. In the last years, various types of algorithms and software provided as an open-source software that allow to perform these processes with varying degrees of user interventions and settings have begun to appear and be used. The aim of this work is to focus on the most accessible and potentially the most suitable types of such software (or web services) and to compare their reliability, quality of spatial object reconstruction into digital spatial data and the quality of photo-texture, provided by them. For this purpose, a testing solid body made of a suitable material and with a suitable shape and dimensions, whose images were acquired by a DSLR camera, was used. Subsequently, these images were used for testing and comparison of individual open-source photogrammetric software.

Keywords: open-source software, digital photogrammetry, testing body

Introduction

Currently, there are several technologies and methods, by which it is possible to obtain spatial data on any real-world objects and to generate accurate and high-quality 3D digital models from them. Especially two technologies can be classified as the most appropriate, accurate and most commonly used – laser scanning and digital photogrammetry. We have a wide range of available instruments that can be used, from relatively low cost and accessible digital SLR cameras to expensive semi-metric and metric cameras in the case of photogrammetric procedures; from triangulation scanners (laboratory, portable) to terrestrial scanners (stationary, mobile, aerial) in the case of laser scanning.

Both technologies have their advantages (but also disadvantages), whether it is the final accuracy for different distances of scanning vs. imaging, mobility, quality of the final point cloud (radiometric and geometric resolution), or purchasing costs. Nowadays, just the achieving of low purchasing costs for obtaining reliable results is one of the trends in the area of computer vision and 3D modelling (Kersten, 2012). Primarily the high accuracy, level of detail, complexity and reliability of data, which in turn must have a geometric and visual quality with effective collection and low volume of data, may be included among the current requirements on the final data, often represented by 3D models. Present technologies and methods of laser scanning and digital photogrammetry meet these requirements, but the costs of hardware and software are several times higher for laser scanning than digital photogrammetry, where, however, the cost of software may still be relatively high, especially when compared to the cost of hardware (DSLR camera ~ 1000 EUR).

Also for these reasons, a lot of effort was spent on the development of new approaches for computer modelling from photographic images and display of 3D models in the area of computer vision in recent years. Based on that, a number of algorithms and software dealing with a reconstruction of surfaces from images began to emerge progressively, even though a detailed procedure for solving the problem of fully automated, accurate and reliable matching between a set of multiple images was introduced as early as 1988 (Gruen – Baltsavias, 1988). In most cases, it is a software based on the principle of the SfM method (Structure from Motion), which includes a simultaneous determination of parameters of interior and exterior orientation and a reconstruction of 3D structure captured in images, resp. the MVS method (Multi-View Stereo), representing a matching algorithm for a set of multiple image stereopairs. In the past years, reconstructions based on these methods were generally usable mainly for visualisation and not for the purposes of mapping and photogrammetry. But nowadays, thanks to advances in computer technology and enhancing the performance of computers, a large number of images can be automatically oriented in an arbitrary defined coordinate system by using different algorithms.

Open-source software and web services

The following open-source software solutions dealing with the multi-image orientation can be classified among the current and best-known: the SIFT algorithm (Lowe, 2004) for obtaining distinctive invariant features from images, which can be further used for reliable matching between these images; the system for generating 3D digital models from images (Pollefeys, 2004); the MicMac software (Pierrot-Deseilligny, 2006); the SfM system Bundler (Snavely, 2010) that is based on the previous project PhotoTourism (Snavely, 2006); the PMVS2 software for generating dense point clouds and CMVS for the splitting of very large files of images into smaller clusters (Furukawa, 2010); the CMPMVS software for reconstruction of textured MESH models from input images and parameters of interior and exterior orientation of a camera (Jancosek, 2011) or the GUI application VisualSFM for a 3D reconstruction of objects from images using the SfM method (Wu, 2012) and others.

In addition to those software, also a variety of web services and applications, providing the possibility of generating point clouds or directly 3D MESH model from images, often without the need of installation of additional software on a computer of the end user, began to occur. Currently, there are a number of them, for example 123D Catch by Autodesk, Photosynth by Microsoft, My3DScanner, ARC3D and more. However, for some of these services (e.g. Photosynth, My3DScanner) a fully automated approach is a big disadvantage, since they provide no possibility of user intervention in the reconstruction process, no information on the accuracy of calibration, orientation of images and the final model, nor any tools for data transformation into the reference coordinate system. As a result, such services are becoming unusable for creating sufficiently accurate and quality documentation.

The automation of individual processes and procedures based on the processing of images on the internet can basically help to save manpower in the processing of data, but on the other hand, they offer no guarantees on the quality of 3D models and protection of private data. Therefore, it is important to get the assessment of accuracy and reliability of these algorithms and software used for photogrammetric work, which would also certainly help laymen dealing with a 3D reconstruction from images.

The selection of software

From a various types of open-source software and web services, the following were selected as the most suitable, based on their analysis and image processing method:

1. *VisualSFM* (Wu, 2012) – an open-source software (Fig. 1); basically it is a GUI application for a 3D reconstruction of objects from images into a point cloud using the SfM system. It is an upgraded version of author's previous projects enhanced by the Sift-GPU and Multicore Bundle Adjustment algorithms. In addition, this software provides an interface to run tools like PMVS/CMVS, or it can prepare data for the CMP-MVS software.
2. *OSM-Bundler* (Bundler + CMVS/PMVS2) – an open-source software, it includes a set of tools that enable to run a 3D reconstruction of objects from images, using the Python programming language. The key tools of this system are as follows:
   - *Bundler* – the SfM system for a calibration, bundle adjustment and reconstruction of sparse point cloud (Snavely, 2012);
   - *PMVS2* – generation of dense point cloud (Furukawa, 2010);
   - *CMVS* – dividing images into individual clusters for rational use of computer memory, especially for large set of images (Furukawa, 2010).
3. *Microsoft Photosynth* – a free web tool that automatically combines a set of images capturing the same scene into a single, 3D interactive output that can be shared with anyone on the internet directly through this service. One of the tools for creating a 3D output is a "Synth". The Synth is basically a set of overlapping images of a specific object or scene that was automatically reconstructed into a spatial model. The process generating this model uses the principle of natural stereoscopic vision and algorithms similar to those used by the OSM-Bundler toolkit (SIFT, Bundler). However, a detailed description of algorithms used by this tools is not publicly available.
4. *Photosynth Toolkit* (Photosynth (Fig. 1) + CMVS/PMVS2) – it is a combination of the Photosynth web service and the CMVS/PMVS2 software, where Photosynth performs a calibration on the basis of a set of overlapping images of a specific object or scene, subsequently realizes the orientation of these images in space and finally it generates a reconstruction of that object or scene in the form of a sparse point cloud. Afterwards, the CMVS/PMVS2 software is used for its extension, densification and filtration into the resulting point cloud.
5. *Autodesk 123D Catch* – it is also a freely available web service that allows to generate a digital spatial model from images capturing an object or a scene from different positions. Same as for the Photosynth service, detailed descriptions of algorithms and

image processing procedures are not publicly available. But the processing clearly involves the use of SfM method with an initial identification of common image features using an algorithm similar to the SIFT algorithm.

In order to compare individual outputs with a commercial photogrammetric software, also the Photomodeler Scanner (PMSC) software was included to the processing and comparing the results.

Methodology of testing

To compare the quality of reconstruction and accuracy of individual open-source photogrammetric software and web service, a testing using images of suitably chosen testing solid body was performed, by comparing the outputs of these software with the reference model. For the analysis of individual outputs obtained using this testing body, a method of comparison based on the volume of geometric body approximated to the final point cloud acquired from each software (alignment of a geometric body to the point cloud) was used, while 1 reference volume of the testing body acquired by laboratory measurements was compared against the average volume obtained from 10 independently generated point clouds for every single tested software. As a next step, the behaviour of points in individual point clouds and their copying of the surface and shape of the testing body was analysed.

In order the image processing and subsequent comparison of outputs to be meaningful and practical, it is necessary that this body meets certain conditions relating to the:

1. shape – a regular geometric shape,
2. dimensions – possibilities of manufacturing and transportation,
3. material – the type of texture and surface treatment.

Based on the real possibilities of manufacture of such bodies, a granite cuboid with an edge length of approx. 7 cm was made (Fig. 2a).

Imaging

Imaging of the testing body was performed in exterior with a clouded sky and constant light conditions, guaranteeing uniform illumination from all sides and minimization of unwanted shadows that could lead to wrong matches between individual images and therefore reducing the quality and accuracy of the subsequent image orientation. The body was placed on the stone tile with varying texture, which helps in the selection of distinctive invariant features from images, while these features are consequently used for reliable image matching (Fig. 2b).

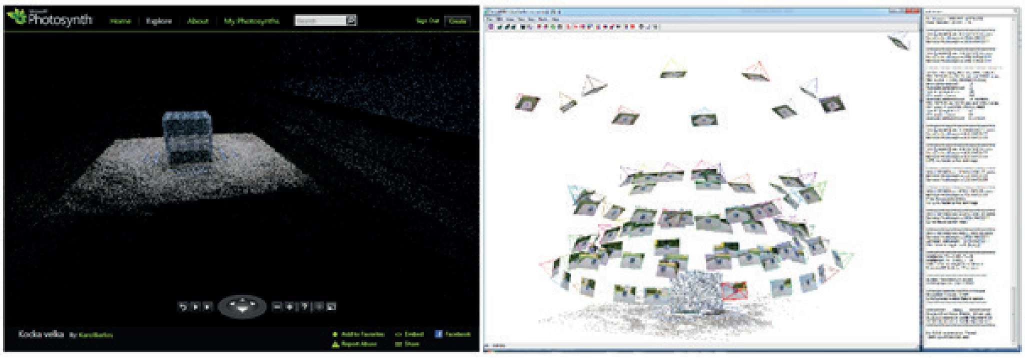

Fig. 1 a) Web service Microsoft Photosynth; b) VisualSFM – workplace

Rys. 1 a) Web Microsoft Photosynth; b) VisualSFM - miejsce pracy

Fig. 2 a) the testing solid body – cuboid; b) imaging

Rys. 2 a) badane ciało stałe - prostopadłościan; b) obrazowanie

All images were acquired by the digital SLR Pentax K-5 with the lens SMC Pentax DA 4/15mm ED AL Limited, mounted on the solid carbon tripod using the 12 second self-timer, in order to eliminate the image blur due to the camera movement.

Since these open-source software and web services works only with images in JPEG format (only Autodesk 123D Catch also supports the TIFF format), thus images in the RAW format were converted to the JPEG format with a minimum compression and radiometric resolution of 8 bits per each RGB channel.

12-bit coded targets, placed directly on the testing body and also in its surroundings on the stone tile, were used as ground control points for transformation of the final point cloud based on reference distances and for the automated orientation of images in the PMSC software. Reference distances were measured by a calliper as distances of centres of two coded targets on opposing sides of the testing body.

The calibration of digital camera was performed separately for each set of images. For the PMSC software, it is represented by the „Full Field Calibration“ method, for the tested open-source software - parameters of interior orientation are determined during the image processing individually for each image (only VisualSFM allows the use of uniform fixed calibration for all images in a project), while each of these software determines the focal length and two parameters of radial distortion. The calibration procedure is questionable in the case of web services, since the procedure of image processing is not directly available.

Each of the open-source software (but not web services) provides certain setup options of the basic parameters affecting the quality of the final reconstruction (size of the correlation window; texture type; raster density; change of image resolution during processing; a number of images in which the point is visible, so that its spatial position can be reconstructed). However, these settings are not completely identical in the case of open-source software and PMSC. In order to achieve comparable results, the same values of parameters common to all software were set.

Imaging parameters:

- acquired 80 images in 4 height levels:
  - 56 convergent images
  - 12 image stereopairs
- + 4 images from arbitrary stations around the testing body,
- baseline of image stereopairs – 15 cm,
- 5 reference distances.

Comparison of results

A set of points defined by their spatial coordinates XYZ and radiometric data RGB – a point cloud, is the final result of image processing of the testing body by the chosen software (Fig. 3). In the first step, these outputs were compared in terms of the reconstruction density, completeness of the point cloud and quality of the photo-texture.

As one can see at the first sight, the Microsoft Photosynth web service gives an output of very poor quality – the point cloud contains many outliers and is overly sparse, which also implies the quality of photo-texture that would be of very poor quality in the case of further processing (e.g. to a MESH model). OSM-Bundler software provides denser and less noisy reconstruction with higher quality photo-texture, but the point cloud is not homogeneous and contains several small holes. A sufficiently dense point cloud is the result of image processing in the VisualSFM, this software was able to deal with the texture of material in a better way – the point cloud is compact and does not contain any holes, however it had some problems in the reconstruction of coded targets with a white surface (which can be expected due to the uniform white texture of a paper). Photosynth Toolkit software and web service 123D Catch provide a sufficiently

Tab. 1 Parameters of imaging and image processing

Tab. 1 Parametry obrazowania i przetwarzania obrazu

Number of images	Imaging distance	GSD[1]	Number of reconstructed points	m_{XYZ} [mm][2]	
84	20 - 30 cm	0,06 mm	1 899 000	0,01	***PM Scanner***
			961 000	0,33	***VisualSFM***
			160 000	0,11	***OSM-Bundler***
			10 000	0,32	***Microsoft Photosynth***
			669 000	0,32	***Photosynth Toolkit***
			1 747 000	-	***Autodesk 123D Catch***

[1] *__G__round __S__ampling __D__istance - represents a spatial resolution of image record, expresses the pixel size in the imaged area*

[2] *total mean error, indicates the accuracy in the reference system*

dense reconstruction with low noise (the point cloud from 123D Catch almost no noise, Ph. Toolkit slightly higher), without holes and gaps. In both cases, they are point clouds with a quality photo-texture, which is slightly worse in the case of Ph. Toolkit. The biggest disadvantage of the 123D Catch web service is that the quality of photo-texture is somewhat different every time it generates a 3D reconstruction from same images. Consequently, the user can never be sure whether the final model will be usable for further processing.

The comparison by volume

To compare results of reconstruction obtained by individual software, comparison based on the volume of geometric body approximated to the final point cloud was chosen. However, before the actual approximation and determination of volumes, it was necessary to consider the effect of paper thickness of coded targets. Considering the paper thickness of 0,1 mm, its overall used surface and a cuboid with an edge length of 70 mm, the volume difference between the body with coded targets and without them will be approximately 2000 cm3 (0,002 dm3), representing too big difference for the purpose of this comparison. Therefore, areas containing the paper of coded targets were cut from each point cloud before further processing.

Subsequently, individual volumes were compared to the reference volume acquired by the independent laboratory measurement (Tab. 2). For this purpose, a hydrostatic method of measuring a density of solid was used, consisting of double weighting the body in the air and in a liquid of known density with subsequent determination of the body volume.

Based on the values given in the Tab. 2, one can see which software shows the lowest (blue) or the biggest (red) difference in the volume compared to the volume obtained by laboratory measurement. Generally, we can state that VisualSFM software achieved the smallest deviations on average and contrary 123D Catch and Photosynth web services the highest. This comparison demonstrates especially the fact that VisualSFM software achieved even better results than commercial PMSC, i.e. the volume difference of only 0,07% compared to 0,79%.

The comparison by cross-sections

For the analysis of point's behaviour in individual point clouds and their copying of the surface and shape of the testing body, 2 mm wide cross-sections at two locations – the wall and edge of the body, were led through each point cloud. Subsequently, individual cross-sections were displayed in a side view in colour according to individual software (Fig. 4 and Fig. 5).

The above images show that surface and shape of the testing body is the most ideal represented by 123D Catch web service. VisualSFM software also relatively well copies this surface and scattering of points is even smaller than in the case of point cloud from PMSC. On the contrary, Photosynth Toolkit shows the largest dispersion of points. The point cloud generated by Photosynth web service proves to be entirely unsuitable. It should be noted that it is a 2 mm wide cross-section displayed in a 2D plane, so single points are at different distances from the cutting plane and it is questionable, to what extent this point dispersion represents noise in a point cloud and to what extent it

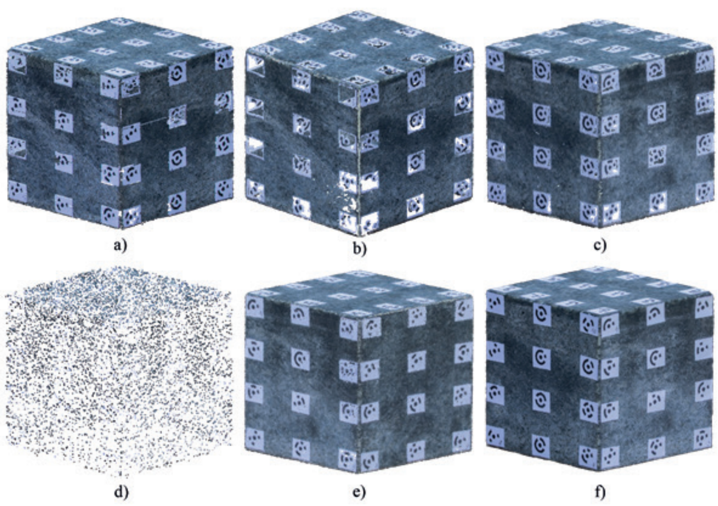

Fig. 3 The testing body – point clouds from a) PMSC, b) VisualSFM, c) OSM-Bundler, d) Microsoft Photosynth, e) Photosynth Toolkit, f) Autodesk 123D Catch

Rys. 3 Badane ciało - z chmury punktów a) PMSC, b) VisualSFM, c) OSM-Bundler, d) Microsoft Photosynth, e) Photosynth Toolkit, f) Autodesk 123D Catch can be caused by roughness of the body material. Also for these reasons, we can assume that 123D Catch web service uses some degree of generalization in the generation of final model and therefore this, at first sight, ideal copying of the body shape may not necessarily represents the reality.

Conclusion

The use of low-cost and open-source photogrammetric software, whose fundamental principle is the SfM method of surface reconstruction, is among the current trends in the field of photogrammetry. Initially, they were developed in the field of computer vision, but they are also slowly finding an application in the photogrammetry, whether for documentation of cultural heritage, but also for obtaining topographic data, and other applications. To obtain high-quality data, it is necessary that the used software fulfil certain criteria relating to the accuracy of calibration, image orientation and dense surface reconstruction.

Results of this work show that each of tested software using SfM algorithms provide different results, either in quality of reconstruction, quality of phototexture or degree of deviations from a reference data. OSM-Bundler and Ph. Toolkit software provide relatively good results, but their reliability is very poor. This might be caused by the fact that they determine a specific set of parameters of interior orientation for each image in the process of calibration, which may lead to unstable results. VisualSFM software appears

Fig. 4 The cross-section through point clouds across the wall of the testing body

Rys. 4 Przekrój poprzeczny przez chmury punktów na ściance korpusu testowania

Fig. 5 The cross-section through point clouds across the edge of the testing body

Rys. 5 Przekrój przez chmury punktów na krawędzi korpusu testowania

Tab. 2 The comparison of volumes obtained from software

Tab. 2: Porównanie uzyskanych wielkości

Software	Tested volumes	Approximation accuracy				Reference volume	Volume difference (V_T - V_R)	
	$\overline{V}_T$ [dm³]	$\overline{ME}$[1] [mm]	$\overline{\sigma}$[2] [mm]	$\overline{MAE}$[3] [mm]	$\overline{AE}_{max}$[4] [mm]	V_R [dm³]	$\overline{\Delta}_V$ [dm³]	$\overline{\Delta}_V$ [%]
PM Scanner	0,33542	-0,0006	0,17	0,13	0,97	0,33281	-0,0026	-0,79
VisualSFM	0,33305	-0,0018	0,13	0,20	0,88		-0,0002	-0,07
OSM-Bundler	0,33615	-0,0033	0,14	0,11	1,01		-0,0033	-1,01
M. Photosynth	0,34186	0,0028	0,86	0,56	2,55		-0,0091	-2,72
Ph. Toolkit	0,33111	-0,0029	0,16	0,12	0,85		0,0017	0,51
123D Catch	0,33809	-0,0025	0,11	0,08	0,91		-0,0053	-1,59

[1]**ME** (Mean Error) – mean distance between points and surface of geometric body for all the points
[2]**σ** – standard deviation of distances between points and surface of geometric body
[3]**MAE** (Mean Absolute Error) – mean absolute distance between points and surface for all the points
[4]**AE_{max}** (Maximum Absolute Error) – the maximum absolute distance between points and surface

to be the most suitable for the needs of photogrammetry, since it provides the possibility of using a fixed calibration, detailed settings of parameters affecting the reconstruction and reliable results in contrast to other software and moreover it demonstrated the smallest deviations from the reference model within the testing of these software.

Therefore, we can say that the current state of the art SfM algorithms began to achieve the quality of commercial photogrammetric software and in some specific cases they have already achieved it. However, prior to their using for professional applications in photogrammetry, more detailed analysis of individual processing steps and especially improvements in the calibration process would be necessary, which would help to increase their accuracy and quality of reconstruction.

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Streszczenie

Orientacja multi-obrazów jest jednym z najważniejszych zadań w fotogrametrii i modelowaniu 3D. Dokładność orientacji obrazu i kalibracji aparatu znacząco wpływa na jakość wszystkich kolejnych procesów, takich jak określenie współrzędnych przestrzennych poszczególnych punktów lub modeli 3D. Dlatego, orientacja i kalibracja, są niezbędne w wielu zastosowaniach. W ostatnich latach pojawiły się różne algorytmy i programy określonych jako oprogramowanie open-source. Celem artykułu jest zwrócenie uwagi na najbardziej dostępne i potencjalnie najbardziej odpowiednie rodzaje takiego oprogramowania (lub usług internetowych) i porównanie ich niezawodności, jakości odwzorowana obiektu przestrzennego do cyfrowych danych przestrzennych i jakości zdjęć. W tym celu badania przeprowadzono na modelu w postaci stałej wykonanego z odpowiedniego materiału i o odpowiednim kształcie i wymiarach, którego obrazy zostały wykonane za pomocą lusrtzanki. Następnie zdjęcia te były używane do testowania i porównywania poszczególnych programów fotogrametrycznych open-source.

Słowa kluczowe: oprogramowanie open-source, fotogrametria cyfrowa, materiał badawczy