GRAPHOS - open-source software for photogrammetric applications

Published Version:
GRAPHOS - open-source software for photogrammetric applications / Gonzalez-Aguilera, D.*; López-Fernández, L.; Rodriguez-Gonzalvez, P.; Hernandez-Lopez, D.; Guerrero, D.; Remondino, F.; Menna, F.; Nocerino, E.; Toschi, I.; Ballabeni, A.; Gaiani, M.. - In: THE PHOTOGRAMMETRIC RECORD. - ISSN 0031-868X. - ELETTRONICO. - 33:161(2018), pp. 11-29. [10.1111/phor.12231]

Availability:
This version is available at: https://hdl.handle.net/11585/632143 since: 2018-03-26

Published:
DOI: http://doi.org/10.1111/phor.12231

(Article begins on next page)

GRAPHOS – OPEN-SOURCE SOFTWARE FOR PHOTOGRAMMETRIC APPLICATIONS

D. Gonzalez-Aguilera* (daguilera@usal.es)
L. López-Fernández (luisloez89@usal.es)
Higher Polytechnic School of Avila, University of Salamanca, Avila, Spain

P. Rodriguez-Gonzalvez (pablorgsf@usal.es)
Higher Polytechnic School of Avila, University of Salamanca, Avila, Spain and *University of León, Ponferrada, Spain*

D. Hernandez-Lopez (david.hernandez@uclm.es)
D. Guerrero (diego.guerrero@uclm.es)
University of Castilla-La Mancha, Albacete, Spain

F. Remondino (remondino@fbk.eu)
F. Menna (fmenna@fbk.eu)
E. Nocerino (nocerino@fbk.eu)
I. Toschi (toschi@fbk.eu)
3D Optical Metrology (3DOM) Unit, Bruno Kessler Foundation (FBK), Trento, Italy

A. Ballabeni (andrea.ballabeni@unibo.it)
M. Gaiani (marco.gaiani@unibo.it)
Department of Architecture, University of Bologna, Bologna, Italy

**Corresponding author*

Abstract

This paper reports the latest developments for the photogrammetric open-source tool called GRAPHOS (inteGRAted PHOtogrammetric Suite). GRAPHOS includes some recent innovations in the image-based 3D reconstruction pipeline, from automatic feature detection/description and network orientation to dense image matching and quality control. GRAPHOS also has a strong educational component beyond its automated processing functions, reinforced with tutorials and didactic explanations about algorithms and performance. The paper highlights recent developments carried out at different levels: graphical user interface (GUI), didactic simulators for image processing, photogrammetric processing with weight parameters, dataset creation and system evaluation.

KEYWORDS: computer-aided teaching (CAT), computer vision, e-learning, open source, photogrammetry, 3D reconstruction

INTRODUCTION

Motivation

PHOTOGRAMMETRY HAS RECENTLY made a comeback as a valuable and reliable 3D surveying solution thanks to new algorithms and methodologies provided by the scientific community for automated image orientation (Hartmann et al., 2016) and dense point-cloud generation (Remondino et al., 2014). However, whereas fully automatic photogrammetric processes have been successful in aerial applications, their reliability and repeatability in close-range applications is still limited due to the nature and requirements of the tasks, complexity of image networks, scale changes and so on. Moreover, most of the existing solutions do not present any educational aspect, with short documentation material limiting full understanding of all functionalities.

With the aim of providing a different solution in this context, an open-source photogrammetric platform, called GRAPHOS (inteGRAted PHOtogrammetric Suite), has been developed within an ISPRS scientific initiative. GRAPHOS allows the processing of aerial and terrestrial sets of images, producing dense metric 3D point clouds. It encompasses a mixture of robust photogrammetric and computer vision algorithms in order to provide:

(1) automated processing;
(2) flexibility in handling any image and type of camera;
(3) quality control and assessment; and
(4) didactic aspects of algorithms and their performance.

Expert users can test different advanced parameters and configurations in order to assess and compare different approaches, whereas non-expert users can be guided by didactic descriptions before and during processing. In González-Aguilera et al. (2016) the initial results of GRAPHOS were presented, whereas this paper reports the latest developments and implemented features.

The main contributions of GRAPHOS in relation to the well-known structure-from-motion (SfM) and multiview-stereo (MVS) solutions are:

(1) *Contrast preserving decolourisation and image enhancement*: two functions to preserve image contrast and deal with low-texture areas in images to improve the relative orientation and bundle adjustment processes (Ballabeni and Gaiani, 2016).
(2) *Smart image analyser*: a tool for radiometric improvement of images in order to ease keypoint extraction with a better distribution, together with enhancing image features important for 3D reconstruction algorithms (Gaiani et al., 2016).
(3) *Various feature extraction and matching strategies*: to test and to compare different detectors/descriptors and matching strategies which have a direct impact on 3D reconstruction results (Apollonio et al., 2014), including a graphical explanation of extracted feature points.
(4) *Different bundle adjustment and self-calibration approaches*: these include statistical output, plots of distortion profiles and conversion tool, offering users the possibility of achieving accurate camera calibration and orientation as a necessary prerequisite for the extraction of precise and reliable 3D metric information (Remondino and Fraser, 2006).

(5) *Quality check for 3D point clouds*: a series of functions to analyse the 3D results obtained and provide adequate statistic parameters to assess the results (Rodriguez-Gonzálvez et al., 2014).
(6) *Educational interface and didactic material*: includes explanations and simulators, trying to overcome the level of abstraction of some steps and methods.

State-of-the-art and Open-source Projects

The image-based processing pipeline, based on the integration of photogrammetric and computer vision algorithms, has become a powerful and valuable approach for 3D reconstruction purposes in recent years. At the beginning of the first decade of this century many researchers and users shifted their attention and interest from photogrammetry and computer vision to laser scanning technologies. Recent years have witnessed the opposite trend with image-based approaches once again very commonly used. Such approaches ensure sufficient automation, low cost, efficient results and ease of use, even for non-expert users.

Over the last decade various authors have provided different contributions within the image-based modelling workflow, from image preprocessing (Maini and Aggarwal, 2010; Verhoeven et al., 2015) and keypoint extraction (Apollonio et al., 2014; Hartmann et al., 2016) to bundle adjustment (Agarwal et al., 2010; Wu et al., 2011; Schönberger and Frahm, 2016) and dense and precise point-cloud generation (Remondino et al., 2014). This progress has led to fully automated SfM and MVS methodologies able to process large image datasets and deliver 3D (both sparse and dense) results with a level of detail and precision varying according to the application (Snavely et al., 2008; Frahm et al., 2010; Rothermel et al., 2012; Crandall et al., 2013; Heinly et al., 2015). However, all these advances can be inefficient when dealing with close-range applications in which geometric and radiometric requirements are critical. Indeed, in these cases the accuracy, precision and reliability of results are far from the standard requirements normally claimed by the photogrammetric community. Nevertheless, recent work by Schöps et al. (2017) and Knapitsch et al. (2017) have presented some 3D reconstruction benchmarks, including both outdoor scenes and indoor environments, that provide very good results in terms of completeness and accuracy.

In contrast to the vision community, where open-source code sharing has been common practice for many years, in the photogrammetric community such participation was almost unheard of. Educational tools were, however, developed such as: sv3DVision (González-Aguilera and Gomez-Lahoz, 2006), which allowed a dimensional analysis of engineering and architectural scenes to be performed; 3D reconstruction using a single image with Arpenteur (Grussenmayer and Drap, 2001); photogrammetric image-based simulation and learning (Piatti and Lerma, 2013); or the PW – Photogrammetry Workbench (González-Aguilera et al., 2012). Arpenteur was a web-based application for architectural photogrammetry, whereas PW represents a real low-cost alternative to laser scanning systems that allows automation and flexibility in the management of any block of images (from vertical stereo to convergent oblique) or type of camera. More recently, the freeware PhoX was developed as a tool for self-learning, including tests and exercises with real photogrammetric data (Luhmann, 2016). The main purpose of this software is data analysis, interactive image measurement, simulation and visualisation of results.

The open-source MicMac tools (MicMac, 2017) have been developed by Marc Pierrot-Deseilligny since 2005, integrating various scientific developments for satellite, aerial, unmanned aerial vehicle (UAV) and terrestrial photogrammetry in order to produce digital elevation models (DEMs), dense point clouds and ortho-images (Pierrot-Deseilligny and Paparoditis, 2006; Pierrot Deseilligny and Clery, 2011; Nony et al., 2012; Rosu et al, 2015). However, the main limitation of this initiative is the lack of a user-friendly graphical user interface (GUI) for non-experts, its data structure and a clean code for further developments.

Other open-source and freeware solutions, frequently with a GUI, for image-based 3D modelling exist, but they do not guarantee accuracy and reliability in the results, lacking georeferencing procedures (namely ground control points (GCPs) included in the bundle adjustment as observations) and spatial data creation. Some examples are VisualSFM (Wu, 2011), PMVS (Furukawa and Ponce, 2010), Bundler (Wu et al., 2011), Python Photogrammetry Toolbox (Arc-Team, 2017), Open Drone Map (Waechter et al., 2014) and so on. More recently, interesting tools such as MVE (Fuhrmann et al., 2015), Theia (Sweeney, 2016) and COLMAP (Schönberger et al., 2016) were developed. MVE (Multi-View Environment) integrates the Bundler SfM approach adding multiple variations on each step of the pipeline. Theia includes recent implementations of both incremental and global SfM pipelines. COLMAP follows the incremental SfM approach used in Bundler but integrates additional verification, outlier filtering and model selection techniques that increase the robustness of each processing stage.

Considering all the aforementioned solutions, GRAPHOS was introduced at the 23rd ISPRS Congress in Prague (González-Aguilera et al., 2016) with the aim of providing an integral open-source photogrammetric platform with a GUI for close-range applications (terrestrial and UAV), able to perform all steps of the 3D image-processing pipeline and to deal with different types of sensors and images (such as red/green/blue (RGB), near infrared (NIR), thermal infrared (TIR) and so on). This establishes GRAPHOS as a complete and reliable open-source photogrammetric software, within reach of various educational materials for teaching purposes. Table I summarises GRAPHOS features compared with other existing open-source solutions for 3D image processing.

This paper is structured as follows. After this introduction, the next section describes in detail the main workflow for data processing, showing the main features of the open-source tool developed. A final section presents the main conclusions and future perspectives.

inteGRAted PHOtogrammetric Suite: GRAPHOS

GRAPHOS (Fig. 1) encloses a photogrammetric pipeline divided into five main steps applied sequentially:

(1) image preprocessing;
(2) feature extraction and matching;
(3) self-calibration and bundle adjustment (or image triangulation);
(4) dense image matching; and
(5) quality control.

Each step features different parameters that can be set up by the (expert) user, allowing the testing of the various implemented algorithms. Although GRAPHOS requires user interaction in each step, some automatic batch processes can be created, allowing the whole pipeline to be performed in an automated way, especially for non-expert users.

Image Preprocessing

Image preprocessing is an important initial step to aid better feature extraction and matching, in particular in cases of low texture or unfavourable image quality. Successful

TABLE I. Summary of the most common open-source/freeware image-based 3D reconstruction tools. Georeferencing refers to the use of ground control points (GCPs) as observations in the bundle adjustment.

Reconstruction tool	*Calibration and orientation*	*Georeferencing*[a]	*Datum definition with GCPs*	*Dense image matching*	*Surface reconstruction*	*Orthophoto*	*Quality control*	*GUI*	*Didactic simulators*	*Operating system*
MicMac	X	X	X	X	–	X		X[b]	–	Linux, Windows
					http://micmac.ensg.eu					
VisualSFM	X	X	–	–	–	–	–	X	–	Linux, Windows
					http://ccwu.me/vsfm/vsfm.pdf					
Bundler	X	–	–	–	–	–	–	–	–	Windows
					http://www.cs.cornell.edu/~snavely/bundler/					
PhoX	X	X	X	–	–	X		X	X	Windows
					http://iapg.jade-hs.de/phox/index.php					
Theia	X	X	–	–	–	–	–	X	–	Linux, Windows
					http://www.theia-sfm.org/index.html					
COLMAP	X	X	–	X	X	X	–	X	–	Linux, Windows
					https://colmap.github.io/					
PMVS	–	–	–	X	–	–	–	–	–	Linux, Windows
					http://www.di.ens.fr/pmvs/					
MVE	X	–	–	X	X	–		X	–	Linux, Windows
					http://www.gcc.tu-darmstadt.de/home/proj/mve/					
GRAPHOS	X	X	X	X	X	–[c]	X	X	X	Windows
					https://github.com/itos3d/GRAPHOS					

[a]Post-bundle adjustment transformation. [b]Not in the standard version. [c]Under development.

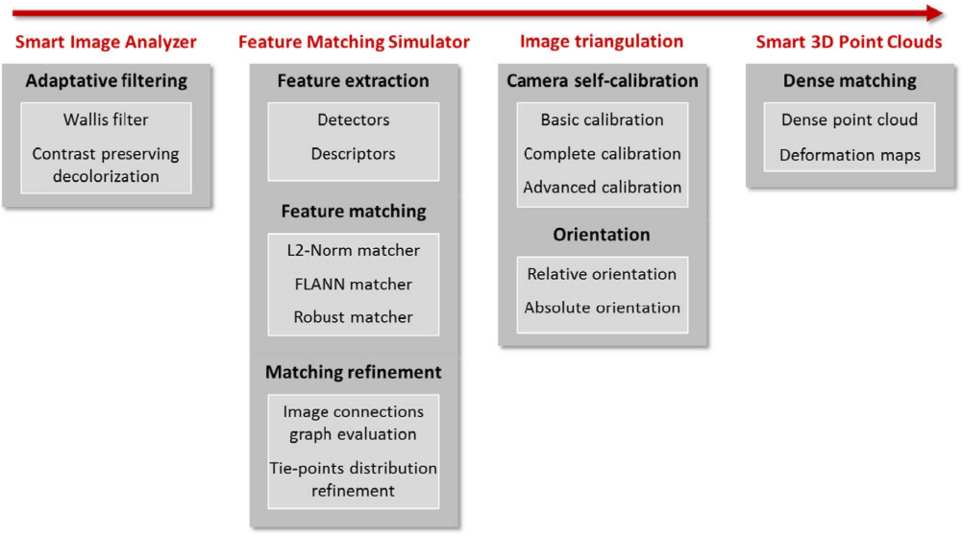

FIG. 1. GRAPHOS workflow, from image preprocessing to dense point-cloud generation.

preprocessing can indeed improve significantly the number and spatial distribution of features extracted by the keypoint detector and thus improve the relative orientation and bundle adjustment processes (Ballabeni and Gaiani, 2016).

Two preprocessing functions are available in GRAPHOS:

(1) *Contrast preserving decolourisation*: this applies decolourisation (RGB to grey) to an image, preserving its contrast (Lu et al., 2012). In contrast to other methods which simply use the green channel of each image, this delivers better images for the successive feature extraction and matching steps (Gaiani et al., 2016).
(2) *Wallis filter*: this image enhancement method (Wallis, 1974) is applied in the case of textureless images or those with a homogeneous texture, improving the keypoint extraction and matching steps. The filter works with window patches, employing a user-defined mean and standard deviation of the pixels. It thus adjusts the brightness and contrast of pixels according to a weighted average, achieving more contrast in the images.

Both functions are provided with a didactic explanation about the meaning of each parameter and its role during image preprocessing. Furthermore, a *smart image analyser* is available to evaluate the degree of texture variation (Fig. 2). It converts each image into the hue–saturation–value (HSV) colour model. Then, for a given HSV image, the dispersion coefficients based on the hue and saturation components are computed to provide a score; the median value of such scores is used to characterise the textural variation in the image. Based on an empirical qualitative threshold, the final median score is converted to a recommendation, which suggests the application of a texture enhancement or, conversely, avoids its application since it could add noise to the image content, thus deteriorating the keypoint extraction and matching phases.

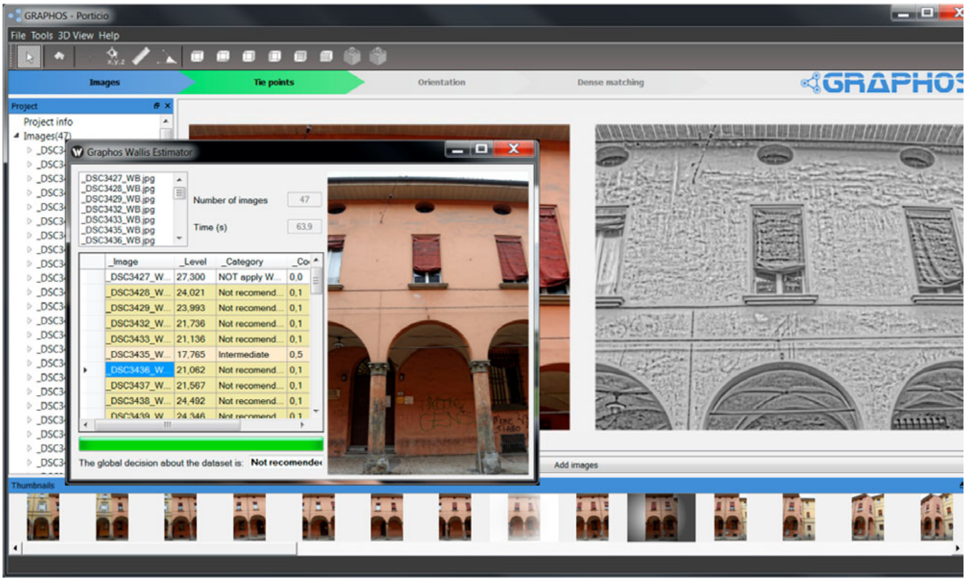

FIG. 2. Smart image analyser: image preprocessing using a Wallis filter and the values provided by the smart image analyser.

Feature Extraction and Matching

GRAPHOS includes different methods to extract features (or keypoints) based on the most recent and outperforming feature detectors/descriptors (Apollonio et al., 2014; Hartmann et al., 2016; Schönberger et al., 2017): scale-invariant feature transform (SIFT) (Lowe, 2001), affine SIFT (ASIFT) (Morel and Yu, 2009) and maximal self-dissimilarities (MSD) (Tombari and Di Stefano, 2014). In the latter the maximal self-dissimilarity concept replaces the classical self-dissimilarity concept used in most popular interest point detectors (such as the Moravec and Förstner operator based on a local self-dissimilarity or the 1-nearest neighbour (1-NN) search problem) with a contextual self-dissimilarity notion, the k-NN nearest neighbours search problem. The most recent addition in GRAPHOS is the affine MSD (AMSD) detector, which is a variant of MSD. In a similar way to ASIFT, AMSD includes the main perspective geometric parameters, namely the angles defining the camera axis orientation (ω, φ):

$$\mathbf{A_F} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} = H_\lambda \mathbf{R}_1(\kappa)\mathbf{T}_1\mathbf{R}_2(\varpi) = \lambda \begin{bmatrix} \cos\kappa & -\sin\kappa \\ \sin\kappa & \cos\kappa \end{bmatrix} \cdot \begin{bmatrix} t & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\varpi & -\sin\varpi \\ \sin\varpi & \cos\varpi \end{bmatrix} \quad (1)$$

where $\mathbf{A_F}$ is the affinity transformation that contains: the scale λ; rotation κ around the optical axis (swing); the perspective parameters that correspond to the inclination of the camera optical axis φ (tilt) or the vertical angle between the optical axis and the normal to the image plane expressed as $t = \sec(\varphi)$ and ϖ (axis); and the horizontal angle between the optical axis and the fixed vertical plane. In this manner, AMSD finds maximal self-dissimilarities in images that have a large scale and rotational difference, which are common in close-range scenarios. The result is an invariant detector that supports the hypothesis that image patches which are highly dissimilar over a relatively large extent of their surroundings hold the property of being repeatable and distinctive. AMSD is coupled with the SIFT descriptor in order to provide the features necessary to identify image correspondences.

Last but not least, GRAPHOS includes a didactic explanation of the main detectors and descriptors. For instance, the concept of the SIFT operator has been visualised through an interactive graphic, so the user can understand better the performance of the SIFT operator. This interactive graphic (Fig. 3) shows the concept of the SIFT descriptor through a 128-dimensional vector (in greyscale) which includes the individual L2 norm values (in pseudocolour) for the 8 orientations (columns) and the 16 cells (rows).

FIG. 3. AMSD feature extraction results on very diverse image scales (top) and among multimodal images (bottom). The graphical representation of the extracted feature points is also shown.

Once keypoints are extracted in all images, a matching strategy should be applied to identify the correct image correspondences. GRAPHOS contains different matching strategies: (i) the classical L2-norm matching strategy (Bhattacharyya, 1943; Kullback and Leibler, 1951); (ii) the efficient fast library for the approximate nearest neighbours (FLANN) strategy (Muja and Lowe, 2009), which is independent of the image acquisition protocol; and (iii) a *robust matching approach* providing considerable improvements with respect to the other methods. In particular, the robust matching approach applies a brute-force matching strategy based on the L2-norm distance but adding the following twofold filtering process:

(1) For each keypoint, the *distance ratio* between candidate pairs is compared with a threshold. Generally, a high distance ratio represents an ambiguous or incorrect match. According to the probability distribution function, a threshold higher than 0·8 provides a good separation between correct and incorrect matches. The greater the ratio's value, the greater the number of matched points.

(2) The remaining matched points ("putative correspondences") are filtered by a parameter which expresses the *discrepancy between descriptors*. This parameter is established as an interval [0, 100]. The computation is established as a maximum descriptor distance (for whole matched pairs) multiplied by a K factor. The matched pairs whose distance is greater than that value are rejected. This is equivalent to sorting all the matches in the ascending order of their distances, so that the best matches (with a low distance or lower than $1 - K$) come to the front. A $K = 1$ factor implies that no refinement is done (all matches are kept).

As a result, the final set of putative correspondences is used to compute the relative orientation (fundamental matrix) between image pairs by means of robust estimators (such as the random sample consensus (RANSAC)) and iterative processing. Additionally, if the number of matched points is high, filtering which selects the n-best points according to their quality ranking (twofold filtering process) can be applied, making the successive bundle adjustment easier and more robust (Buoncompagni et al., 2015).

The image correspondences found can be assessed with a didactic assistant which graphically displays their spatial distribution on the camera sensor. Indeed, an asymmetric distribution of tie points will negatively affect the correct determination of all camera parameters. Therefore, if the matching points do not cover an area of more than two-thirds of the camera sensor format, the user will be alerted in order to modify the detector and descriptor parameters (Fig. 4).

Self-calibration and Bundle Adjustment

The bundle adjustment step in GRAPHOS integrates routines available in Bundler (Snavely et al., 2008) and APERO (Pierrot Deseilligny and Clery, 2011). This step has been didactically supported by the integration of computer vision and photogrammetry based on the relationships between the Longuet-Higgins (1981) method and the coplanarity condition (Hartley and Zisserman, 2003); and the direct linear transformation (DLT) (Abdel-Aziz and Karara, 1971) and the collinearity condition (Kraus et al., 1997). The adjustment can be performed with internal constraints (a free network) or with external constraints (for example, using GCPs). An interface for the manual identification of GCPs or scale distances is available.

GRAPHOS allows the use of three different types of self-calibration models:

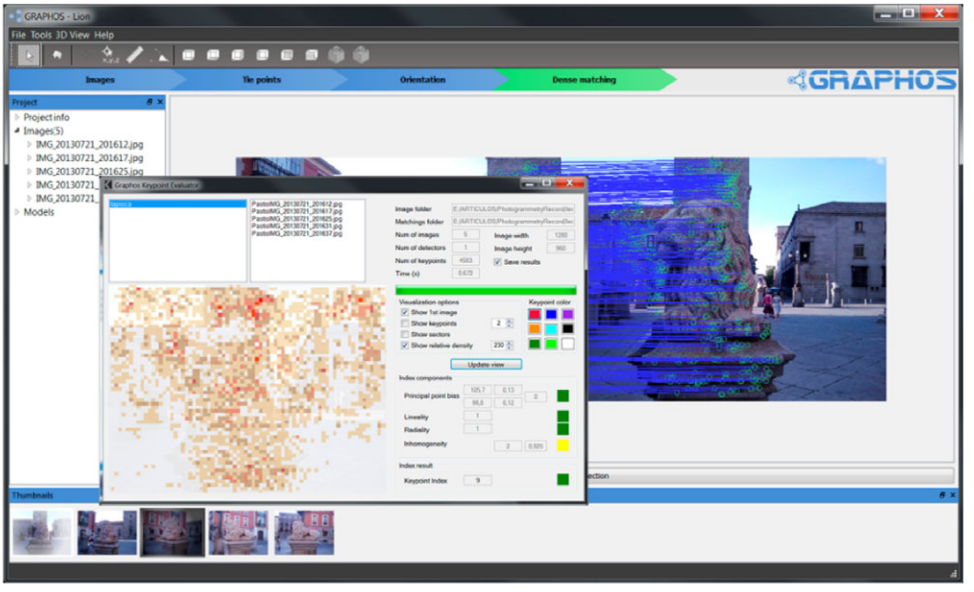

FIG. 4. Quality control function for the extracted tie points in order to analyse the spatial distribution of the image correspondences.

(1) *Basic calibration*: five interior orientation parameters (principal distance f, principal point of symmetry (x_0, y_0) and radial lens distortion parameters k_1, k_2) are used (Kukelova and Pajdla, 2007). This model is suitable when using unknown cameras or with cameras with lower quality (such as smartphones or tablets), or when the image network is not very suitable for camera calibration.
(2) *Complete calibration*: this implements the Fraser calibration model (Fraser, 1980; El-Hakim, 1986) with 12 parameters (f, x_0, y_0, principal point offsets x_1, y_1, radial lens distortion k_1, k_2, k_3, and decentring distortion p_1, p_2 (scaling and affinity factors)).
(3) *Advanced calibration*: this allows the user to fix or keep variable the different additional parameters of the previous calibration models.

All three self-calibration models and their parameters are didactically explained through different documents and examples. Moreover, the results of the bundle adjustment are available in a detailed log file, while orientation results are accessible in the 3D viewer as sparse point clouds with image pyramids (Fig. 5). Additionally, the bundle module of GRAPHOS includes: (i) different radial distortion profiles (such as Gaussian or balanced) and (ii) a converter to transform the calibration results among the most common photogrammetric commercial tools (for example, PhotoScan, PhotoModeler), which allows the analysis of calibration parameters in a more didactic way.

Dense Image Matching

Recent pixel-based matching solutions (Pierrot-Deseilligny and Paparoditis, 2006; Hirschmüller, 2008; Furukawa and Ponce, 2010; Rothermel et al., 2012) allow dense and colourised 3D point clouds to be obtained with a stereo or multiview approach (Remondino

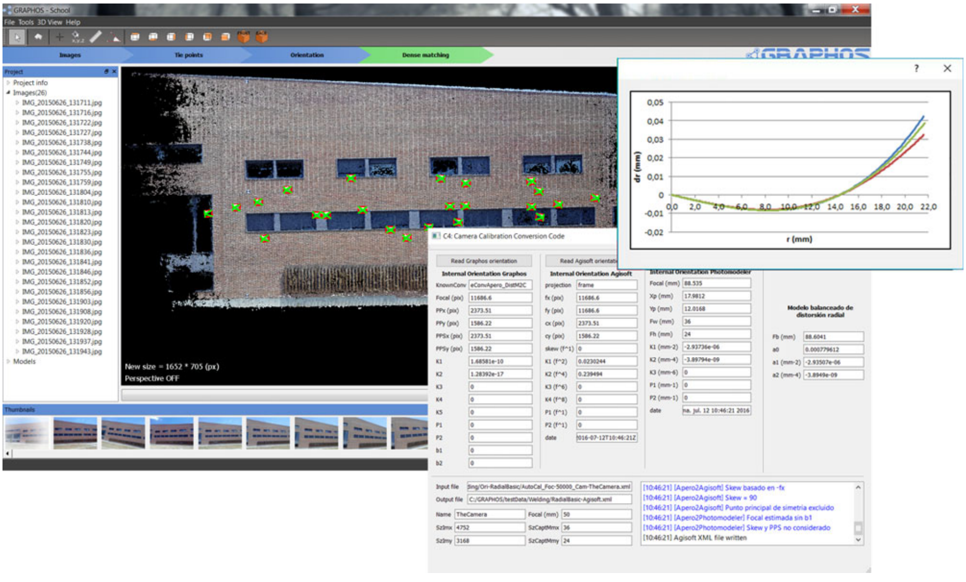

FIG. 5. Bundle adjustment interface with the conversion functions for orientation parameters and the plot of lens distortion curves.

et al., 2014). These strategies, supported by precise external and internal orientations as well as epipolar images, are focused on the minimisation of an energy function. GRAPHOS includes the multiview MicMac (2017) algorithm. This strategy consists of minimising an energy function E (equation (2)) throughout the eight basic directions that a pixel can take (45° separation). This function is composed of a cost function M (the pixel correspondence cost) that reflects the degree of the similarity D of the pixels between two images, together with two constraints, P_1 and P_2, to consider the possible presence of gross errors in the matching process:

$$E(D) = \sum_{x} \left(M(x, D_x) + \sum_{x' \in N_x} P_1 T[|D_x - D_{x'}| = 1] + \sum_{x' \in N_x} P_2 T[|D_x - D_{x'}| > 1] \right). \qquad (2)$$

Trying to reinforce the role of dense image matching in modern photogrammetry, some didactic documents and graphics have been included to support its performance: from the relationship between depth and parallax to the generation of disparity maps using global or semi-global methods and the stereopair to the multiview approach.

Fig. 6 shows examples of 3D dense image matching at different scales: details of architectonic elements and façade (Figs. 6(a) and (b)); sub-millimetre reconstruction of welds (Fig. 6(c)); archaeological remains and site (Figs. 6(d) and (e)); and a reconstruction of an urban area from helicopter images (Fig. 6(f)).

Quality Control

GRAPHOS includes various tools for performing analyses and quality checks on the dense point clouds produced. First, it is possible to compute deformation maps (Fig. 7)

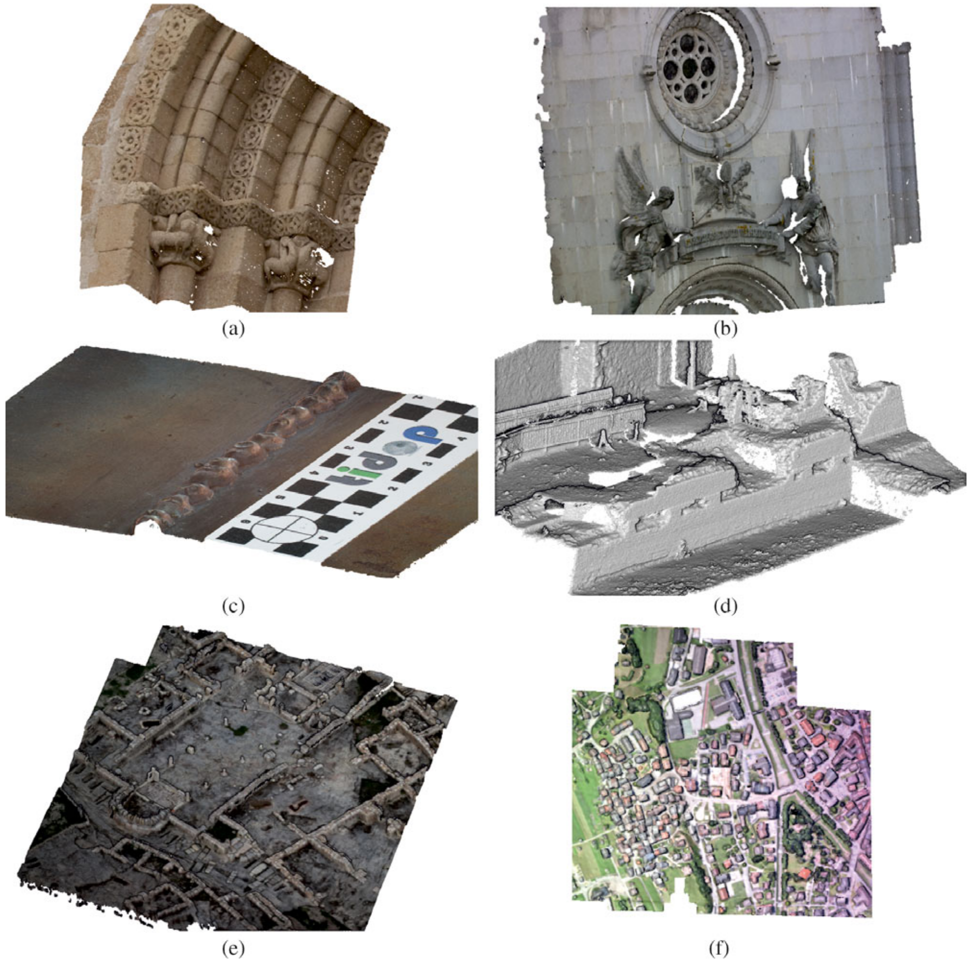

FIG. 6. Examples of dense matching results achieved with GRAPHOS using terrestrial (a, c), UAV (b, d, e) and aerial (f) datasets. (a) Detail of San Segundo church portal, Spain. (b) Façade of São Torcato church, Portugal. (c) Welding. (d) Detail of the stage walls (frontal scene) of Ventimiglia theatre, Italy. (e) Part of the archaeological site of Tolmo de Minateda, Spain. (f) Urban area in Primiero, Italy.

using two approaches: (i) from a single point cloud using a semi-automatic process based on a convex hull (O'Rourke, 1994); or (ii) from multitemporal point clouds using an automatic co-registration strategy (Makadia et al., 2006). Second, point-based quality analyses can be performed by picking points or measuring distances (scale bar checks) and angles (verticality checks) directly on the point cloud.

Finally, given a point cloud set as a reference, it can be imported and co-registered with the aim of providing an accuracy assessment. To this end, several 3D detectors (such as VoxelGrid and Harris3D) and descriptors (for example, SHOT and PFH) have been included to co-register point clouds automatically (Fig. 8). The accuracy assessment is carried out according to the methodology shown in Rodríguez-Gonzálvez et al. (2015).

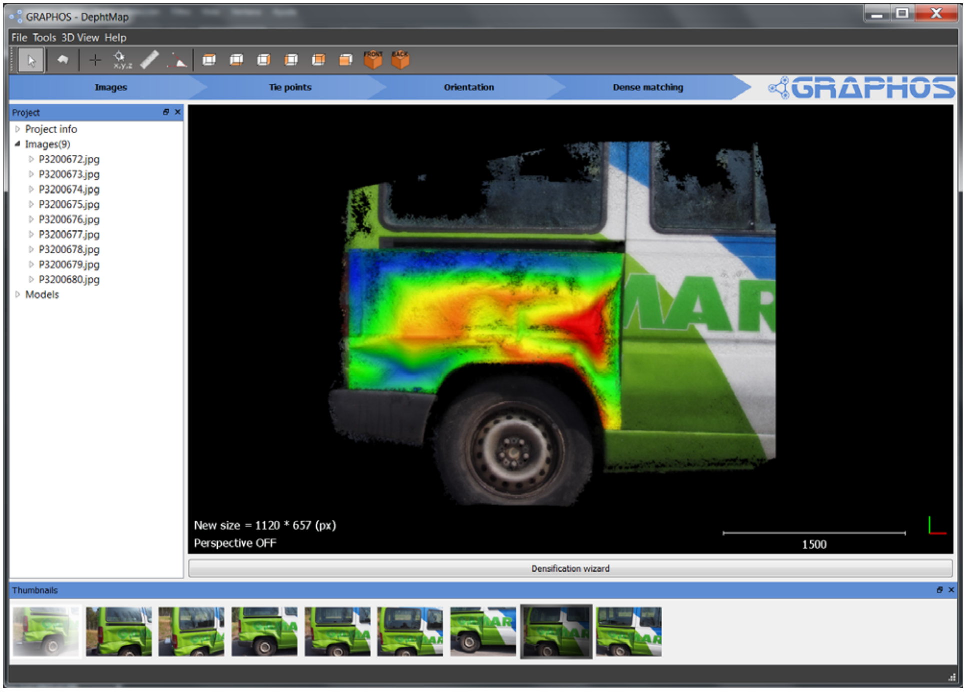

FIG. 7. Dense matching results based on a multiview algorithm. Deformation/comparison map applied to the inspection of car accidents.

To dismiss the uncertainties associated with global coordinate georeferencing, a registration phase using the iterative closest point (ICP) technique (Besl and McKay, 1992) is carried out, prior to the point-cloud evaluation. Only errors affecting the 3D point cloud are thus analysed.

The discrepancies between point clouds can be computed by means of unsigned or signed distances. In the first case, there is no information about any bias in the data, and the central tendency error is related to the error module. Since an absolute error distribution does not provide complete insight into the data, the signed discrepancies have to be computed. The results obtained from photogrammetric processing rarely follow a Gaussian error distribution. This wrong assumption about the error function could lead to a biased accuracy assessment and false conclusions about the data. In order to check the normality assumption there are several numerical methods, but they are limited to small sample sizes. In the case of large photogrammetric point clouds, it is necessary to employ visual methods such us a quantile–quantile plot of the distribution of the signed differences (Höhle, 2011). If the normality assumption is not verified, either due to the presence of outliers or because a different error function, the classical Gaussian statistic parameters are replaced by non-parametric ones. Central tendency and dispersion of the error sample is assessed by means of the median m and the median absolute deviation (MAD), respectively. MAD is defined as the median m of the absolute deviations from the data's median m_x:

$$\mathrm{MAD} = m(|x_i - m_x|), \tag{3}$$

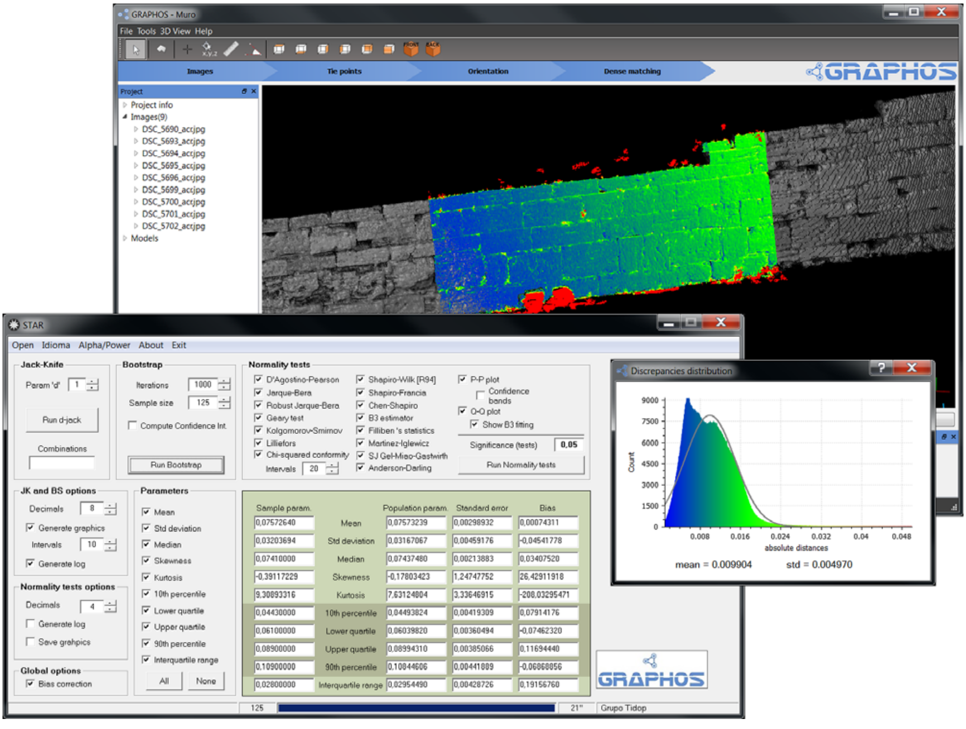

FIG. 8. Quality control based on parametric and non-parametric statistics.

where the x_i values come from the discrepancies (Euclidean distance) between both point clouds. MAD will lead to different results than the standard deviation in normally distributed error samples. So for comparison, a normalisation factor of about 1/0·6745 is applied (according to an inverse cumulative distribution function of 3/4).

All the different parametric and non-parametric statistical approaches are didactically explained through tutorials and graphical examples, so the non-expert user can analyse the accuracy results obtained.

CONCLUSIONS

The paper has presented the latest development within the GRAPHOS project, an open-source photogrammetric tool which goes beyond the usual SfM and MVS solutions based on fully automated approaches. GRAPHOS has the potential of being widely employed across a broad range of 3D applications (such as architectural, heritage and engineering applications) which usually exhibit geometric and radiometric complexity.

The presented tool encloses an important educational component supporting each step of the image-processing pipeline with different tutorials and simulators. GRAPHOS is currently being used to support theoretical classes for bachelor and master students in Spain and Italy; it also provides a research platform for PhD students. GRAPHOS guarantees:

(1) *Automation*: allowing dense 3D point clouds to be generated through a friendly and easy-to-use interface.

(2) *Flexibility*: working with any type of imagery, scenarios and cameras.
(3) *Quality*: allowing the assessment of the accuracy and reliability of the results.

GRAPHOS (and some datasets for testing and evaluation) is distributed as an open-source platform (https://github.com/itos3d/GRAPHOS) for research and educational purposes. It should be remarked that, currently, there is no other open-source photogrammetric package with a GUI which integrates the entire 3D reconstruction pipeline with didactic simulators, as well as a quality-control tool based on parametric and non-parametric statistics.

Future investigations will be focused on performing comparisons using the recent benchmarks presented at the latest SIGGRAPH/CVPR 2017 and larger image datasets. Moreover, an aim is to further optimise computational costs, especially in tie-point extraction and dense matching steps, as well as to cope with new learned feature descriptors (for example, Schönberger et al., 2017). Speed and computational time have not been a priority so far as developments have focused more on assembling the various algorithms and on the educational aspects of the processing pipeline. Furthermore, new MicMac algorithms and other third-party tools, such as DGAP (DGAP, 2017), will be evaluated and included in the current implementation. In general, any outstanding innovation introduced by the scientific community will also be analysed and implemented according to its effectiveness and efficiency results.

Acknowledgements

This work has been supported by ISPRS through the 2016 Scientific Initiative entitled "Advances in the Development of an Open-source Photogrammetric Tool".

References

Abdel-Aziz, Y. I. and Karara, H. M., 1971. Direct linear transformation from comparator coordinates into object-space coordinates in close-range photogrammetry. *American Society of Photogrammetry Symposium on Close-Range Photogrammetry*, Falls Church, Virginia, USA. 18 pages.

Agarwal, S., Snavely, N., Seitz, S. M. and Szeliski, R., 2010. Bundle adjustment in the large. *Lecture Notes in Computer Science*, 6312(2): 29–42.

Apollonio, F. I., Ballabeni, A., Gaiani, M. and Remondino, F., 2014. Evaluation of feature-based methods for automated network orientation. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5): 47–54.

Arc-Team, 2017. http://184.106.205.13/arcteam/ppt.php [Accessed: 12th August 2017].

Ballabeni, A. and Gaiani, M., 2016. Intensity histogram equalisation, a colour-to-grey conversion strategy improving photogrammetric reconstruction of urban architectural heritage. *Journal of the International Colour Association*, 16: 2–23.

Besl, P. J. and McKay, N. D., 1992. A method for registration of 3-D shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 14(2): 239–256.

Bhattacharyya, A., 1943. On a measure of divergence between two statistical populations defined by probability distributions. *Bulletin of the Calcutta Mathematical Society*, 35: 99–109.

Buoncompagni, S., Maio, D., Maltoni, D. and Papi, S., 2015. Saliency-based keypoint selection for fast object detection and matching. *Pattern Recognition Letters*, 62: 32–40.

Crandall, D. J., Owens, A., Snavely, N. and Huttenlocher, D. P., 2013. SfM with MRFs: discrete-continuous optimization for large-scale structure from motion. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 35(12): 2841–2853.

DGAP, 2017. http://www.ifp.uni-stuttgart.de/publications/software/openbundle/index.en.html [Accessed: 12th August 2017].

El-Hakim, S. F., 1986. Real-time image metrology with CCD cameras. *Photogrammetric Engineering & Remote Sensing*, 52(11): 1757–1766.

FRAHM, J.-M., FITE-GEORGEL, P., GALLUP, D., JOHNSON, T., RAGURAM, R., WU, C., JEN, Y. H., DUNN, E., CLIPP, B., LAZEBNIK, S. and POLLEFEYS, M., 2010. Building Rome on a cloudless day. *European Conference on Computer Vision*, Heraklion, Crete, Greece. Pages 368–381.

FRASER, C. S., 1980. Multiple focal setting self-calibration of close-range metric cameras. *Photogrammetric Engineering & Remote Sensing*, 46(9): 1161–1171.

FUHRMANN, S., LANGGUTH, F., MOEHRLE, N., WAECHTER, M. and GOESELE, M., 2015. MVE – an image-based reconstruction environment. *Computers & Graphics*, 53(4): 44–53.

FURUKAWA, Y. and PONCE, J., 2010. Accurate, dense, and robust multiview stereopsis. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 32(8): 1362–1376.

GAIANI, M., REMONDINO, F., APOLLONIO, F. and BALLABENI, A., 2016. An advanced pre-processing pipeline to improve automated photogrammetric reconstructions of architectural scenes. *Remote Sensing*, 8(3): 178. https://doi.org/10.3390/458030178.

GONZÁLEZ-AGUILERA, D. and GOMEZ-LAHOZ, J., 2006. sv3DVision: didactical photogrammetric software for single image-based modeling. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36(6): 171–178.

GONZÁLEZ-AGUILERA, D., GUERRERO, D., HERNÁNDEZ LÓPEZ, D., RODRÍGUEZ-GONZÁLVEZ, P., PIERROT, M. and FERNÁNDEZ-HERNÁNDEZ, J., 2012. PW, Photogrammetry Workbench. CATCON Silver Award, ISPRS WG VI/2. *Proceedings of the 22nd ISPRS Congress*, Melbourne, Australia.

GONZÁLEZ-AGUILERA, D., LÓPEZ-FERNÁNDEZ, L., RODRIGUEZ-GONZALVEZ, P., GUERRERO, D., HERNANDEZ-LOPEZ, D., REMONDINO, F., MENNA, F., NOCERINO, E., TOSCHI, I., BALLABENI, A. and GAIANI, M., 2016. Development of an all-purpose free photogrammetric tool. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 41(B6): 31–38.

GRUSSENMAYER, P. and DRAP, P., 2001. Possibilities and limits of Web photogrammetry. Experiences with the ARPENTEUR web based tool. *Photogrammetric Week*, 2001: 275–282.

HARTLEY, R. and ZISSERMAN, A., 2003. *Multiple View Geometry in Computer Vision*. Second edition. Cambridge University Press, New York, USA. 655 pages.

HARTMANN, W., HAVLENA, M. and SCHINDLER, K., 2016. Recent developments in large-scale tie-point matching. *ISPRS Journal of Photogrammetry and Remote Sensing*, 115: 47–62.

HEINLY, J., SCHÖNBERGER, J. L., DUNN, E. and FRAHM, J.-M., 2015. Reconstructing the world in six days. *IEEE Conference on Computer Vision and Pattern Recognition*, Boston, Massachusetts, USA. Pages 3287–3295.

HIRSCHMÜLLER, H., 2008. Stereo processing by semiglobal matching and mutual information. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 30(2): 328–342.

HÖHLE, J., 2011. The assessment of the absolute planimetric accuracy of airborne laserscanning. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38(5/W12): 145–150.

KNAPITSCH, A., PARK, J., ZHOU, Q.-Y. and KOLTUN, V., 2017. Tanks and temples: benchmarking large-scale scene reconstruction. *ACM Transactions on Graphics*, 36(4): article no. 78.

KRAUS, K., JANSA, J. and KAGER, H., 1997. *Photogrammetry: Advanced Methods and Applications*. Volume 2, Fourth edition. Dümmler, Bonn, Germany. 466 pages.

KUKELOVA, Z. and PAJDLA, T., 2007. A minimal solution to the autocalibration of radial distortion. *IEEE Conference on Computer Vision and Pattern Recognition*, Minneapolis, Minnesota, USA. 7 pages.

KULLBACK, S. and LEIBLER, R. A., 1951. On information and sufficiency. *The Annals of Mathematical Statistics*, 22(1): 79–86.

LONGUET-HIGGINS, H. C., 1981. A computer algorithm for reconstructing a scene from two projections. *Nature*, 293: 133–135.

LOWE, D. G., 2001. Local feature view clustering for 3D object recognition. *IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Kauai Marriott, Hawaii, USA*, 1: 682–688.

LU, C., XU, L. and JIA, J., 2012. Contrast preserving decolorization. *IEEE International Conference on Computational Photography*, Seattle, Washington, USA. 7 pages.

LUHMANN, T., 2016. Learning photogrammetry with interactive software tool PhoX. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 41(B6): 39–44.

MAINI, R. and AGGARWAL, H., 2010. A comprehensive review of image enhancement techniques. *Journal of Computing*, 2(3): 8–13.

MAKADIA, A., PATTERSON, A. and DANIILIDIS, K., 2006. Fully automatic registration of 3D point clouds. *IEEE Computer Society Conference on Computer Vision and Pattern Recognition, New York, USA*, 1: 1297–1304.

MICMAC, 2017. http://www.tapenade.gamsau.archi.fr/TAPEnADe/Tools.html [Accessed: 18th September 2017].

MOREL, J.-M. and YU, G., 2009. ASIFT: a new framework for fully affine invariant image comparison. *SIAM Journal on Imaging Sciences*, 2(2): 438–469.

Muja, M. and Lowe, D. G., 2009. Fast approximate nearest neighbors with automatic algorithm configuration. *International Conference on Computer Vision Theory and Applications*, Lisbon, Portugal. Pages 331–340.

Nony, N., De Luca, L., Godet, A., Pierrot-Deseilligny, M., Remondino, F., van Dongen, A. and Vincitore, M., 2012. Protocols and assisted tools for effective image-based modeling of architectural elements. *Lecture Notes in Computer Science*, 7616: 432–439.

O'Rourke, J., 1994. *Computational Geometry in C*. Cambridge University Press, Cambridge, UK. 346 pages.

Piatti, E. J. and Lerma, J. L., 2013. Virtual worlds for photogrammetric image-based simulation and learning. *Photogrammetric Record*, 28(141): 27–42.

Pierrot-Deseilligny, M. and Paparoditis, N., 2006. A multiresolution and optimization-based image matching approach: an application to surface reconstruction from SPOT5-HRS stereo imagery. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36(1/W41): 5 pages (on CD-ROM).

Pierrot Deseilligny, M. and Clery, I., 2011. APERO, an open source bundle adjustment software for automatic calibration and orientation of set of images. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38(5/W16): 269–276.

Remondino, F. and Fraser, C., 2006. Digital camera calibration methods: considerations and comparisons. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36(5): 266–272.

Remondino, F., Spera, M. G., Nocerino, E., Menna, F. and Nex, F., 2014. State of the art in high density image matching. *Photogrammetric Record*, 29(146): 144–166.

Rodríguez-Gonzálvez, P., Garcia-Gago, J., Gomez-Lahoz, J. and González-Aguilera, D., 2014. Confronting passive and active sensors with non-Gaussian statistics. *Sensors*, 14(8): 13759–13777.

Rodríguez-Gonzálvez, P., González-Aguilera, D., Hernández-López, D. and González-Jorge, H., 2015. Accuracy assessment of airborne laser scanner dataset by means of parametric and non-parametric statistical methods. *IET Science, Measurement and Technology*, 9(4): 505–513.

Rosu, A. M., Pierrot-Deseilligny, M., Delorme, A., Binet, R. and Klinger, Y., 2015. Measurement of ground displacement from optical satellite image correlation using the free open-source software MicMac. *ISPRS Journal of Photogrammetry and Remote Sensing*, 100: 48–59.

Rothermel, M., Wenzel, K., Fritsch, D. and Haala, N., 2012. SURE: photogrammetric surface reconstruction from imagery. *Low-Cost 3D Workshop*, Berlin, Germany. 9 pages.

Schöenberger, J. L. and Frahm, J.-M., 2016. Structure-from-motion revisited. *IEEE Conference on Computer Vision and Pattern Recognition*, Las Vegas, Nevada, USA. Pages 4104–4113.

Schönberger, J. L., Zheng, E., Frahm, J.-M. and Pollefeys, M., 2016. Pixelwise view selection for unstructured multi-view stereo. *Lecture Notes in Computer Science*, 9907: 501–518.

Schönberger, J. L., Hardmeier, H., Sattler, T. and Pollefeys, M., 2017. Comparative evaluation of hand-crafted and learned local features. *IEEE Conference on Computer Vision and Pattern Recognition*, Honolulu, Hawaii, USA. Pages 6959–6968.

Schöps, T., Schönberger, J. L., Galliani, S., Sattler, T., Schindler, K., Pollefeys, M. and Geiger, A., 2017. A multi-view stereo benchmark with high-resolution images and multi-camera videos. *IEEE Conference on Computer Vision and Pattern Recognition*, Honolulu, Hawaii, USA. Pages 2538–2547.

Snavely, N., Seitz, S. M. and Szeliski, R., 2008. Modeling the world from Internet photo collections. *International Journal of Computer Vision*, 80(2): 189–210.

Sweeney, C., 2016. http://theia-sfm.org [Accessed: 12th August 2017].

Tombari, F. and Di Stefano, L., 2014. Interest points via maximal self-dissimilarities. *Lecture Notes in Computer Science*, 9004: 586–600.

Verhoeven, G., Karel, W., Štuhec, S., Doneus, M., Trinks, I. and Pfeifer, N., 2015. Mind your grey tones – examining the influence of decolourization methods on interest point extraction and matching for architectural image-based modelling. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W4): 307–314.

Waechter, M., Moehrle, N. and Goesele, M., 2014. Let there be color! Large-scale texturing of 3D reconstructions. *European Conference on Computer Vision*, Zurich, Switzerland. Pages 836–850.

Wallis, K. F., 1974. Seasonal adjustment and relations between variables. *Journal of the American Statistical Association*, 69(345): 18–31.

Wu, C., 2011. *VisualSFM: a Visual Structure from Motion System*. http://ccwu.me/vsfm/ [Accessed: 20th September 2017].

Wu, C., Agarwal, S., Curless, B. and Seitz, S. M., 2011. Multicore bundle adjustment. *IEEE Conference on Computer Vision and Pattern Recognition*, Colorado Springs, Colorado, USA. Pages 3057–3064.

Résumé

La photogrammétrie est actuellement confrontée à des défis et des changements liés principalement à l'automatisation, au traitement et à la variété des applications. Cet article présente un outil photogrammétrique à source ouverte appelé GRAPHOS (inteGRAted PHOtogrammetric Suite) destiné à la communauté scientifique pour la restitution 3D dans des applications rapprochées. Il englobe des algorithmes photogrammétriques et de vision par ordinateur avec les objectifs suivants: (i) accroître l'automatisation, permettant d'obtenir des nuages denses de points 3D grâce à une interface conviviale; (ii) accroître la flexibilité en travaillant avec tout type d'image, de scénario et de caméra; (iii) améliorer la qualité, garantissant une haute précision et une haute résolution; (iv) préserver la fiabilité photogrammétrique et la répétabilité. Enfin et ce n'est pas le moins important, GRAPHOS dispose également d'une composante éducative qui va au-delà des solutions les plus courantes pour le traitement d'images et la génération de nuages de points 3D, et renforcée par des simulations et des explications didactiques sur les algorithmes et leur fonctionnement. Les développements ont été réalisés à différents niveaux: réalisation d'interface utilisateur graphique (GUI), simulateurs didactiques pour le traitement d'images, traitement photogrammétrique avec paramètres avancés, création d'un jeu de données public et contrôle de la qualité des résultats.

Zusammenfassung

Die Photogrammetrie steht derzeit vor einigen Herausforderungen und Veränderungen, die sich hauptsächlich auf Automatisierung, ubiquitäre Verarbeitung und vielfältige Anwendungen beziehen. Durch dieses Papier wurde ein photogrammetrisches Open-Source-Tool namens GRAPHOS (inteGRAted PHOtogrammetric Suite) entwickelt, um die bildbasierte Verarbeitung von 2D- zu 3D-Daten in Nahbereichsanwendungen für die Scientific Community zu öffnen. Es umfasst robuste photogrammetrische und Computer-Vision-Algorithmen mit den folgenden Zielen: (i) Erhöhung der Automatisierung, so dass dichte 3D-Punktwolken durch eine freundliche und einfach zu bedienende Benutzeroberfläche erhalten werden; (ii) Erhöhung der Flexibilität, um mit jeglichen Arten von Bildern, Szenarien und Kameras arbeiten zu können; (iii) Verbesserung der Qualität und Gewährleistung hoher Genauigkeit und Auflösung; (iv) Sicherstellung der photogrammetrische Zuverlässigkeit und Wiederholbarkeit. Nicht zuletzt hat GRAPHOS auch eine pädagogische Komponente jenseits der gängigsten Black-Box-Lösungen für die 3D-Bildverarbeitung und Punktwolkenerzeugung, verstärkt mit einigen Simulatoren und didaktischen Erklärungen zu Algorithmen und deren Performance. Die Entwicklungen wurden auf verschiedenen Ebenen durchgeführt: grafische Benutzeroberfläche (GUI), didaktische Simulatoren für die Bildverarbeitung, photogrammetrische Verarbeitung mit Gewichtsparametern, Erstellung von Datensätzen und Systemauswertung.

Resumen

Este artículo presenta los últimos desarrollos de la herramienta fotogramétrica de código abierto llamada GRAPHOS (inteGRAted PHOtogrammetric Suite). GRAPHOS incluye algunas innovaciones recientes en el proceso de generación 3D basada en imágenes, desde los detectores/descriptores de características automáticos y la orientación de la red fotogramétrica a herramientas de correspondencia densa y de control de calidad. GRAPHOS tiene también un componente educativo que va más allá de las soluciones habituales para el procesamiento automático, reforzado con tutoriales y explicaciones didácticas sobre los algoritmos y su funcionamiento. Se destacan los desarrollos llevados a cabo en diferentes niveles: interfaz gráfico de usuario (GUI), simuladores didácticos para el procesamiento de imágenes, procesamiento fotogramétrico con parámetros avanzados, creación de un conjunto de datos y evaluación de los resultados.

摘要

本文描述了一个名为GRAPHOS (嵌入式摄影测量组件) 的开源摄影测量工具的最新进展。GRAPHOS包含了基于影像进行三维重建的若干技术革新，如自动特征提取与特征描述、影像网络定向、密集匹配、以及质量控制。除了其自动化的处理功能外，GRAPHOS 还具备强大的教学功能，包括辅导材料、算法与性能的细致解释等。本文着重描述了其各个层面的最新发展：包括图形用户界面、用于图像处理的教学仿真器、具有权重参数的摄影测量处理, 数据集创建和系统评估。