ISPRS. REPORT OF THE SCIENTIFIC INITIATIVE		
ADVANCES IN THE DEVELOPMENT OF AN ALL-PURPOSE OPEN-SOURCE PHOTOGRAMMETRIC TOOL		
GRAPHOS inteGRAted PHOtogrammetric Suite		
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REPORT OF THE SCIENTIFIC INITIATIVE

1. INTRODUCTION AND PARTNERSHIPS

Photogrammetry is facing new challenges and changes and the Scientific Community is replying with new algorithms and methodologies for the automated processing of imagery. However, such advances are often limited to in-house research activities due to the intrinsic difficulties of reliably and efficiently implementing such solutions and/or the prior theoretical knowledge required for a proper use. Therefore non-expert users outside the field of photogrammetry have difficulties to access these solutions and apply them to their specific applications to support their problem solving and decision making. However, trying to "universalize" the workflow from 2D to 3D from any image acquired in any situation by non-expert users is not an easy task, especially in situations where the geometric constraints and radiometric conditions are complex. Some existing one-click solutions are ideal for non-experts but they lack of transparency, reliability, repeatability and accuracy evaluation.

With the aim of providing a solution in this context, an open photogrammetric platform, called GRAPHOS (inteGRAted PHOtogrammetric Suite), has been developed. GRAPHOS allows to obtain dense and metric 3D point clouds from images and it encloses robust photogrammetric and computer vision algorithms with the following **aims**: (i) increase automation (allowing to get dense 3D point clouds through a friendly and easy-to-use interface); (ii) increase flexibility (working with any type of images and cameras); (iii) improve quality (guaranteeing high accuracy and resolution). Last but not least, the **educational component** has been reinforced with some didactical explanations about algorithms and their performance. In particular, the expert user can test different advanced parameters and configurations in order to assess and compare different approaches.

The project has been led and managed by USAL in collaboration with UCLM, FBK and Bologna University who supported the image preprocessing, photogrammetric processing, dataset creation and system evaluation. The secret of success has been to find a **multidisciplinary and international team** with experience in image analysis and close-range photogrammetry in order to design and develop an efficient and robust pipeline for automated image orientation and dense 3D reconstruction.

2. OBJECTIVES

This **main goal** of the project was to advance with the development of an all-purpose open-source photogrammetric platform. The project aims to bring photogrammetry and computer vision even more closer realizing an open tool which integrates different algorithms and methodologies for automated image orientation and dense 3D reconstruction. Automation is not be the only key-driver of the tool but feature precision, reliability, repeatability and guidelines for non-experts are also considered. The tool wants to provide an easy-to-use and ease-to learn framework for image-based 3D modelling applied to architectural, heritage and engineering applications.

Since the photogrammetric process involves basically three different steps (e.g. extraction and matching of features, camera self-calibration and orientation, dense point cloud generation), the **specifics goals** of the scientific initiative are:

- Add image pre-processing algorithms and strategies for improving the image quality and thus the photogrammetric processes. In particular, *Contrast Preserving Decolorization* and *Wallis filtering* were implemented. In addition, an automatic estimation of sensor size parameters was included for non-expert users and unknown cameras.
- Incorporate further *tie point detectors and descriptors* to improve the image matching phase, paying particular attention to textureless and repeated pattern situations. In particular, SIFT, ASIFT and MSD detectors were combined with SIFT descriptor in order to provide the best keypoint extractor. Furthermore, two different feature-based matching approaches were used: one based on the classical FLANN matcher and the other based on a sequential robust matcher strategy.
- Improve the computational cost exploiting *GPU and parallel computing*. In particular, CUDA programming capabilities were included in order to improve computation times, especially in dense matching.
- Improve the *bundle adjustment performances* using different self-calibration approaches. From a basic calibration which uses just the five inner calibration parameters to a more advanced calibration which includes additional parameters and allows the user to fix some of them.
- Improve the *dense matching methods* with multi-view approaches in order to increase the reliability of the 3D results.

The following figure (Figure 1) outlines the proposed pipeline (main GRAPHO) including the different algorithms and techniques.

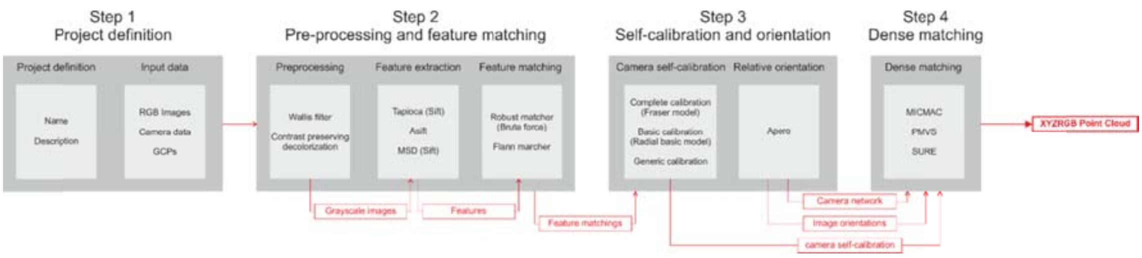

Figure 1. Workflow with the main GRAPHO highlighted.

3. DATASETS

Some dataset related were created and used to test the capabilities and scope of the developed tool. Different case studies and geometric configurations were considered. Additionally, smartphone and tablet sensors were tested in order to assess the flexibility of the tool in data acquisition. As a result, **38 case studies** were used and evaluated in GRAPHOS (Figure 2 and Table 1).

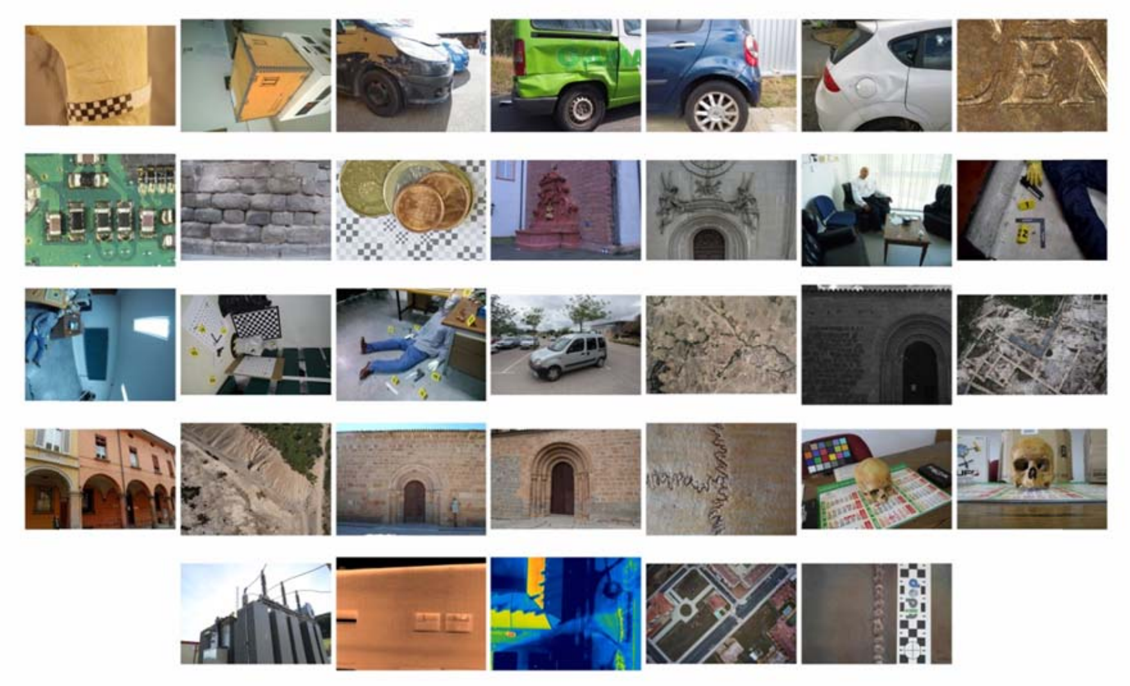

Figure 2. Some of the images of the dataset used in the testing of technology.

Dataset	Case	Difficulty	Nº of images	Dimensions		Size (Mp)	Sensor	Focal
Bones	Forensic	MEDIUM	12	4752	3168	15.1	Canon 500D	46 mm
Box_Smartphone	Others	MEDIUM	18	2048	1536	3.1	Lumia 1020*	-
Car_Black	Automotive	VERY HIGH	15	4032	3024	12.2	E-PM1	14 mm
Car_Green_Damage	Automotive	LOW	9	4608	3456	15.9	E-PM2	14 mm
Car_Lumia	Automotive	MEDIUM	6	7152	5360	38.3	Lumia 1020	7.2 mm
Car_SeatLeon_Lumia_5Mp	Automotive	HIGH	5	2592	1936	5.0	Lumia 1020*	-
Cent	Others	VERY HIGH	9	2560	1920	4.9	Cam	unknown
Chip_2	Others	VERY HIGH	5	2560	1920	4.9	Cam	unknown
Cimorro_Facade	Architecture	MEDIUM	4	3872	2592	10.0	Nikon D80	18 mm
Coins	Others	VERY HIGH	6	4752	3168	15.1	Canon 500D	300 mm
DenseMVS	Architecture	MEDIUM	11	3072	2048	6.3	EOS D60	20 mm
Facade	Architecture	LOW	27	2256	1504	3.4	EOS 450D	20 mm
Forensic	Forensic	VERY HIGH	23	4032	3024	12.2	E-PM1	14 mm
Forensic_Gun	Forensic	LOW	5	4752	3168	15.1	Canon 500D	17 mm
Forensic_Homogeneus	Forensic	VERY HIGH	48	4608	3456	15.9	E-PM2	fisheye 7.5 mm
Forensic_Sony_XperiaL	Forensic	HIGH	15	3264	2448	8.0	XperiaL	3 mm
Kangoo	Automotive	HIGH	48	5616	3744	21.0	EOS 5D mkII	20 mm
LaCoba	Aerial archaeology	MEDIUM	5	11310	17310	195.8	UltraCamXp	100.5 mm
Multispectral	Others	VERY	30	1280	1024	1.3	MCA6	9.6 mm

		HIGH						
Paraglider Tolmo	Aerial archaeology	LOW	58	5616	3744	21.0	EOS 5D mkII	5 0mm
Portico	Architecture	MEDIUM	48	4608	3072	14.2	Nikon D3100	18 mm
Presa_Lodos	Aerial engimeering	LOW	27	4032	3024	12.2	E-P1	14 mm
SanNicolas	Architecture	VERY LOW	6	4032	3024	12.2	E-P1	14 mm
SanSegundo	Architecture	VERY LOW	4	4752	3168	15.1	Canon 500D	17 mm
Skull_Fontanela	Forensic	LOW	15	4608	3456	15.9	E-PM2	42 mm
Skull_Ring	Forensic	HIGH	43	4752	3168	15.1	Canon 500D	19 mm
Skull_Stripe	Forensic	LOW	7	4752	3168	15.1	Canon 500D	17 mm
Subtation	Engineering	VERY HIGH	24	4752	3168	15.1	Canon 500D	17 mm
Thermal_EPSA	Others	VERY HIGH	17	640	480	0.3	NEC TH9260	41.7 mm
Thermal_Roofs	Others	VERY HIGH	7	640	480	0.3	FLIR SC655	24.6 mm
UX5	Urban aerial	LOW	21	3264	4912	16.0	NEX-5R	15 mm
Welding	Engineering	LOW	25	4752	3168	15.1	Canon 500D	50 mm
Primiero	Urban aerial	LOW	9	6048	4032	24.4	Nikon D3x	50 mm
Muro	Architecture	VERY LOW	24	4608	3072	14.1	Nikon D3100	35 mm
Column	Architecture	LOW	14	2816	2112	5.9	DSC-W30	6.3 mm
Chigi	Architecture	VERY LOW	26	4416	3312	14.6	Canon G10	6.1 mm
Ventimiglia	Aerial archaeology	MEDIUM	80	6048	4032	24.4	Nikon D3x	50 mm

	Width (mm)	Height (mm)
E-PM1	17.3333	13
E-PM2	17.3333	13
Lumia 1020	8.8	6.6
Cam	unknown	unknown
Canon 500D	22.35	14.9
EOS D60	22.35	14.9
XperiaL	5.72	4.29
EOS 450D	22.2	14.8
EOS 5D mkII	36.0	24.0
UltraCamXp	67.86	103.86
MCA6	6.66	5.32
Nikon D3100	23.1	15.4
E-P1	17.3333	13
NEC TH9260	16	12
FLIR SC655	10.88	8.16
NEX-5R	23.4	15.6
Nikon D3x	36	24
Canon G10	7.44	5.58
DSC-W30	5.8	4.3

Table 2. Sensor dimensions of the different cameras used for data acquisition.

The last 5 case studies included a ground truth by means of control points, check points and laser scanning point cloud.

4. IMAGE ACQUISITION PROTOCOL

Concerning the photogrammetric procedure, one of the greatest barriers for non-expert users is the data acquisition. However, whilst it may be technically simple, the protocol shows several rules (e.g. geometrical and radiometric restrictions or camera calibration) which make difficult the data acquisition and, thus, determine the quality of the final result. In this sense, some **basic rules** have been created to help non-expert users who want to create a 3D object/scene from some images (through conventional cameras and even smartphones).

Regarding the image acquisition rules, there are two protocols which can be used by the user:

- **Parallel protocol**. Ideal for detailed reconstructions in specific areas of an object. In this case, the user needs to capture between five-nine images following a cross shape as shown (Figure 3, left).The overlap between images needs to be at least 80%. The master image or central image (shown in red) will capture the area of interest. The remaining photos (four) have a complementary nature and should be taken from the left, right (shown in purple), top and bottom (indicated in green) with respect to the central image. These photos should adopt a certain degree of perspective, turning the camera towards the middle of the interest area. It should be noted that, with the purpose of a complete reconstruction, each photo needs to capture the whole area of interest.

- **Convergent protocol**. Presents an ideal behavior in the reconstruction of a 360º object (e.g. statue, column, etc.). In this case, the user should capture the images following a ring path (keeping an approximate constant distance from the object). It is necessary to ensure a good overlap between images (>80%) (Figure 3, right). In the situations where the object cannot be captured with a unique ring it is possible to adopt a similar procedure based on multiple rings or a half ring.

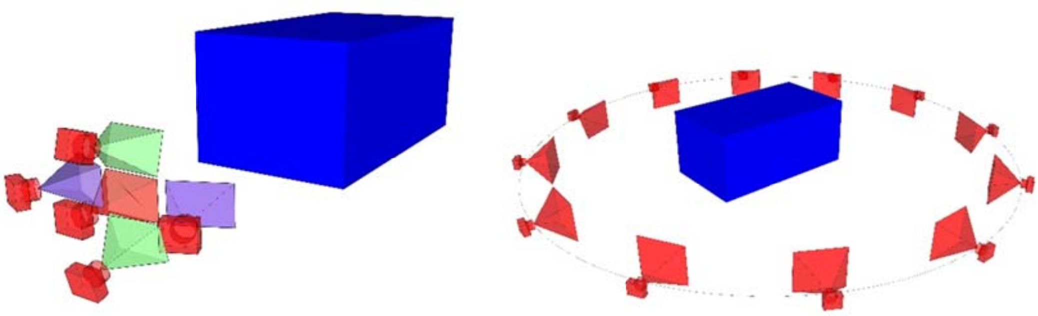

Figure 3. Different adopted acquisition protocols. Parallel protocol (left) and convergent protocol (right).

5. WORKFLOW FOR DATA PROCESSING

GRAPHOS encloses a photogrammetric pipeline divided in five main steps applied sequentially:

1) project definition, 2) pre-processing, 3) tie point extraction and matching, 4) self-calibration/orientation and 5) dense matching 6) Geo-referencing and quality control.

The result of each step will affect the quality of the next one, so achieve good results in each step will be crucial in order to get a good dense 3D point cloud. Although GRAPHOS requires that the user interacts in each step, some automatic batch process can be generated allowing to perform the whole pipeline in an easy-to-use way, especially for non-expert users.

1. **Project definition**. The user defines a project's name and description. Next, the images of the project are selected and can be examined together with the camera used. GRAPHOS provides an automatic estimation of sensor parameters (format size) for those unknown cameras.

2. **Pre-processing**. The image pre-processing is an important step since it can provide a better feature extraction and matching, in particular in those cases where the texture quality is unfavorable. Two pre-processing functions are available in GRAPHOS:
   - Contrast Preserving Decolorization: it applies a decolorization (i.e. RGB to Gray) to the images preserving contrast (Lu et al., 2012). Contrary to other methods, it delivers better images for the successive feature extraction and matching steps (Figure 4).

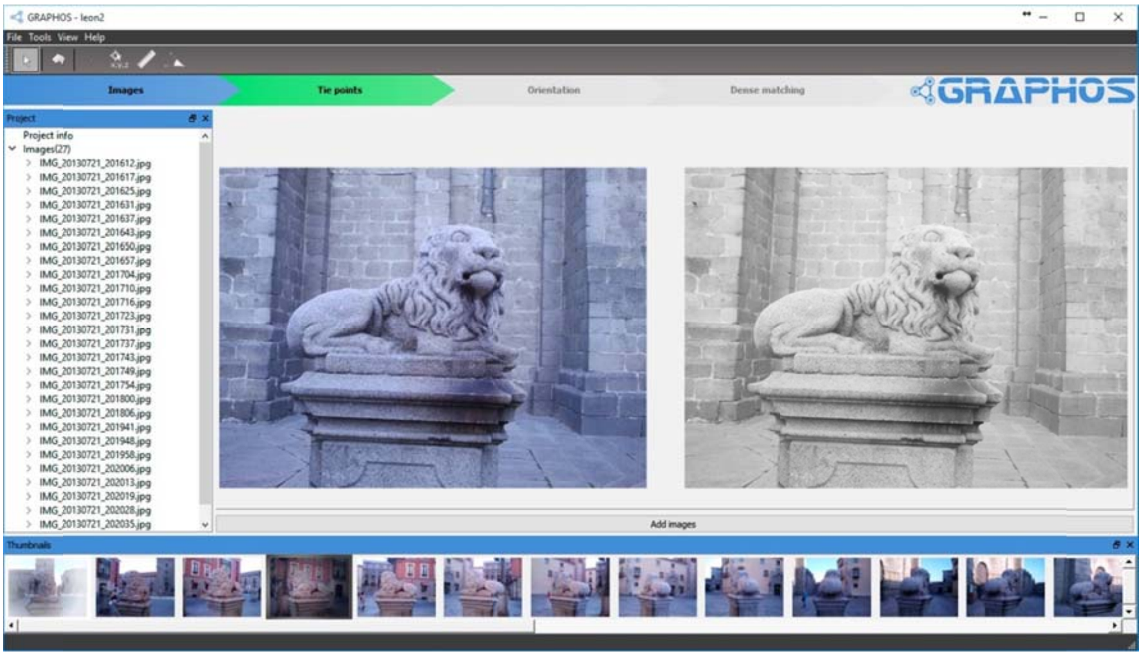

Figure 4. Decolorization (RGB to Gray) of the images.

   - Wallis filter: this enhancement algorithm (Wallis, 1976) is available for those textureless images or images with homogeneous texture, improving the keypoint extraction and matching steps. In particular, the Wallis filter adjusts brightness and contrast of the pixels that lie in certain areas where it is necessary, according to a weighted average. As a result, the filter provides a weighted combination of the average and the standard deviation of the original image. Although default parameters are defined in GRAPHOS, the average contrast, brightness, standard deviation and window size can be introduced by the user (as advanced parameters) in case the default values are not suitable (Figure 5).

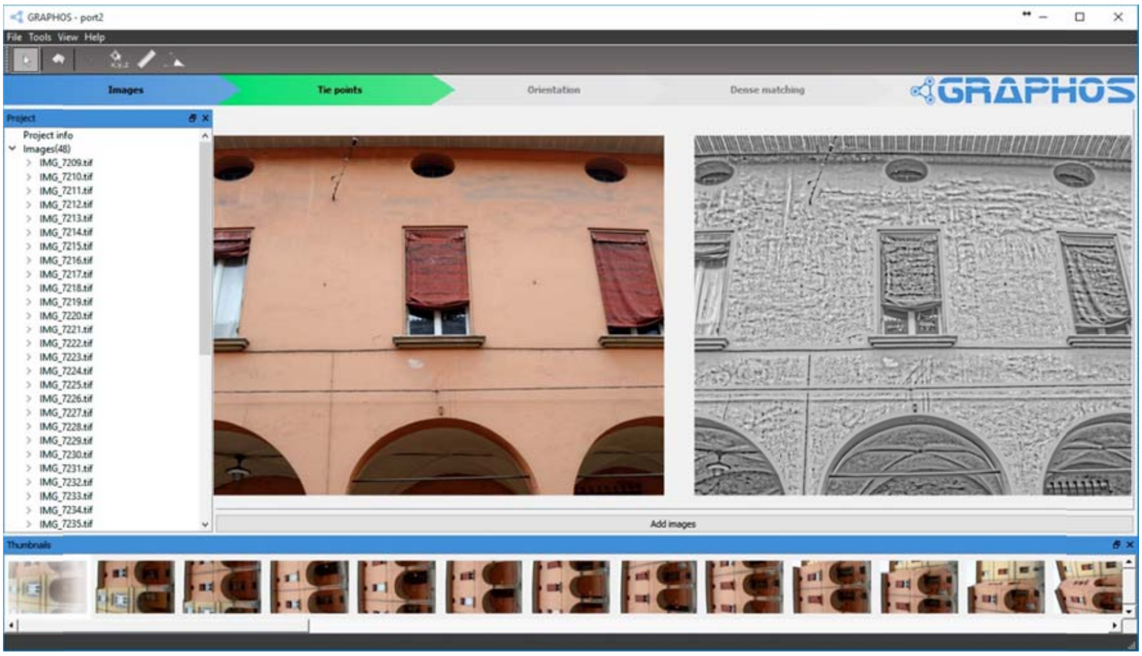

Figure 5. Wallis filtering results.

3. **Feature extraction and matching (tie point extraction)**. GRAPHOS includes three algorithms coming from the computer vision community which can be combined and used with different types of data acquisition (parallel and oblique acquisitions) (Figure 6).

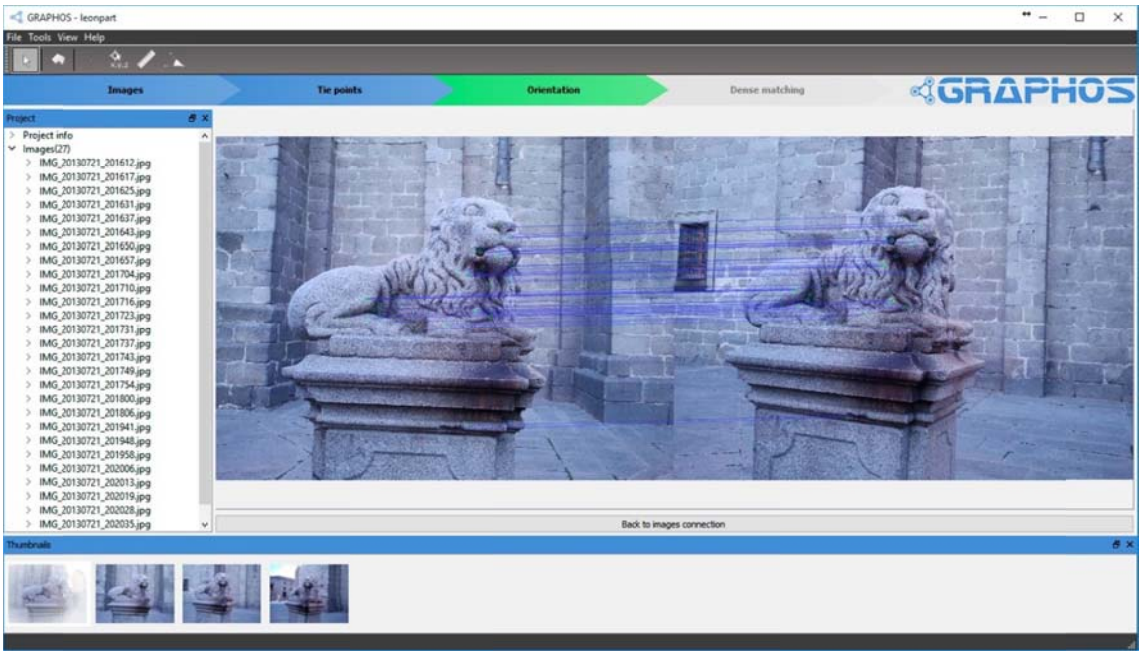

Figure 6. Feature extraction and matching for the tie point extraction step.

Tapioca: It is a combined keypoint detector, descriptor and matching strategy. The keypoint detection and description strategy is based on the SIFT algorithm developed by (Lowe, 1999) which allows a scale invariant feature transform.

ASIFT: It is a keypoint detector developed by (Yu and Morel, 2011). ASIFT considers two additional parameters that control the presence of images with different scales and rotations. In this manner, the ASIFT algorithm can cope with images displaying a high scale and rotation difference, common in oblique scenes. The result is an invariant algorithm that considers changes in scale, rotations and movements between images.

MSD: It is a keypoint detector developed by (Tombari and Di Stefano, 2014) which finds maximal self-dissimilarities. In particular, it supports the hypothesis that image patches highly dissimilar over a relatively large extent of their surroundings hold the property of being repeatable and distinctive.

Once the keypoint are extracted, a matching strategy should be applied to identify the correct image correspondences. GRAPHOS contains three different matching strategies, independently from the protocol followed in data acquisition:

- Tapioca: The matching strategy of this method applies a classical matching strategy based on the L2-Norm to find the point with the closest descriptor for each keypoint extracted in the initial image. Moreover Tapioca allows two select two strategies: (i) for unordered image datasets, the keypoint matching is recursively calculated for all possible image pairs; (ii) for linearly structured image datasets, the matching strategy can check only between n-adjacent images.

- Robust matcher approach: In this case a brute force matching strategy is used in a two-fold process: (i) first, for each extracted point the distance ratio between the two best candidates in the other image is compared with a threshold; (ii) second, those remaining pairs of candidates are filtered by a threshold which expresses the discrepancy between descriptors. As result, the final set of matching points is used to compute the relative orientation (fundamental matrix) between both images, re-computing the process in order to achieve optimal results. Additionally, and if the number of matched points is high, a filtering based on the *n*-best according to their quality ranking can be applied, making easy and more robust the next step of self-calibration and orientation.

- FLANN: this is optimal and alternative method useful in those cases where the number of extracted keypoints is pretty high. It similar to the previous method but it optimizes the computation time.

4. **Self-calibration / Orientation.** Self-calibration and image orientation are fundamental pre-requisite for the successive dense point cloud generation. Additionally, GRAPHOS includes different well-known radial distortion profiles (i.e. Gaussian, Balanced) together with a conversor to export the calibration results to the most common close-range commercial tools such as PhotoScan and PhotoModeler. As a result, different comparisons and analysis can be carried out through different tools.

The **image orientation** is performed through a combination between computer vision and photogrammetric strategies included in the open-source tool APERO (Deseilligny and Clery, 2011). This combination is fed by the previously extracted tie points. In a first step, an approximation of the external orientation of the cameras is calculated following a fundamental matrix approach. Later, everything is refined by a bundle adjustment solution based on Gauss-Newton method (Figure 7). During the processing, the user can run also self-calibration to simultaneously compute also the interior camera parameters. GRAPHOS allows to use three different types of self-calibration models:

- **Basic calibration**: five interior parameters (*f-focal length,* x_0,y_0*-principal point of symmetry,* k_1*,* k_2*-radial distortion*) are used (Kukelova and Pajdla, 2007). This model is suitable when using unknown cameras or with cameras with less quality (such as smartphones or tablets) or when the image network is not very suitable for camera calibration.
- **Complete calibration**: it implements the Fraser calibration model (Fraser, 1980) with 12 parameters (*f,* x_0,y_0*,* x_1,y_1 *- distortion center,* k_1,k_2,k_3*,* p_1,p_2*, scaling and affinity factors).*
- **Advanced calibration**, which allows the user to fix or unfix the different additional parameters of the previous calibration model.

The results of the bundle adjustment are available in detail in a log file, while image orientation results are immediately accessible in the 3D frame of the graphical user interface in the form of a sparse point cloud and image pyramids.

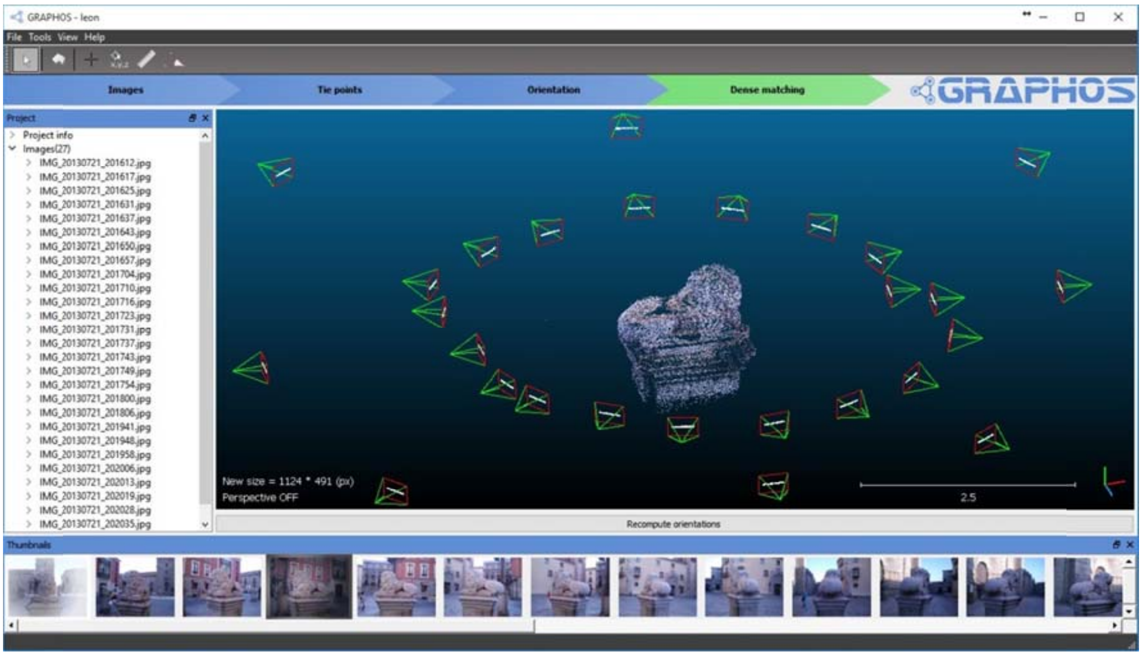

Figure 7. Retrieved camera poses of a dataset with 27 images.

5. **Dense matching.** GRAPHOS offers the possibility to derive dense point clouds (Figure 8) with various methods:
   - MicMac algorithm (Micmac website), more suited for the parallel protocol;
   - PMVS-PatchBased algorithm (Furukawa and Ponce, 2012);

- SURE (Rothermel et al., 2012), based on the SGM algorithm (Hirschmüller, 2008).

GRAPHOS also includes some export functionalities in order to work with various point clouds formats (e.g. LAS, LAZ, PLY, etc.).

In order to open the tool to expert users, the different approaches remarked above can be setup with advanced parameters.

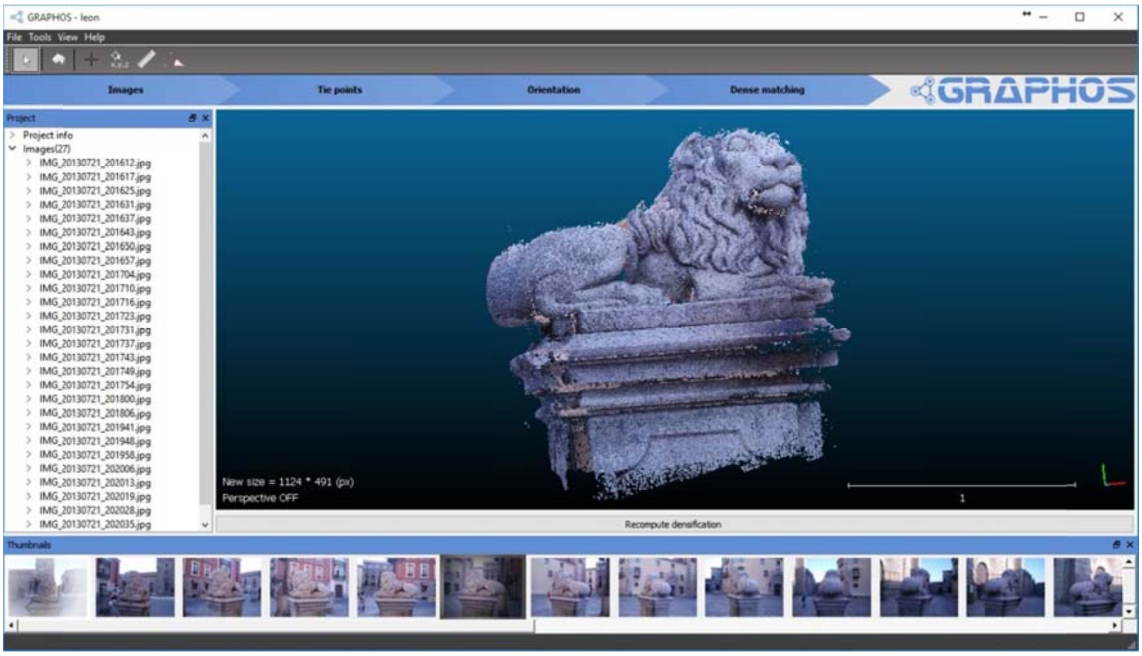

Figure 8. Dense matching results based on a multi-view algorithm.

6. **Geo-referencing and quality control.** GRAPHOS includes a tool for geo-referencing the point cloud in a Cartesian reference system through 3D control points. The tool is accessible under the Tools menu after performing image orientation. The user is asked to load two files containing the 2d image coordinates and the 3D coordinates of at least three points of the object. For performing further analysis and quality checks, tools for picking points as well as measuring distances (scale bars checks) and angles (verticality checks) on the point cloud are available too.

7. FURTHER EXAMPLES

In the following figures some other results achieved with GRAPHOS are presented. The tool works under Window OS and will be soon available for download.

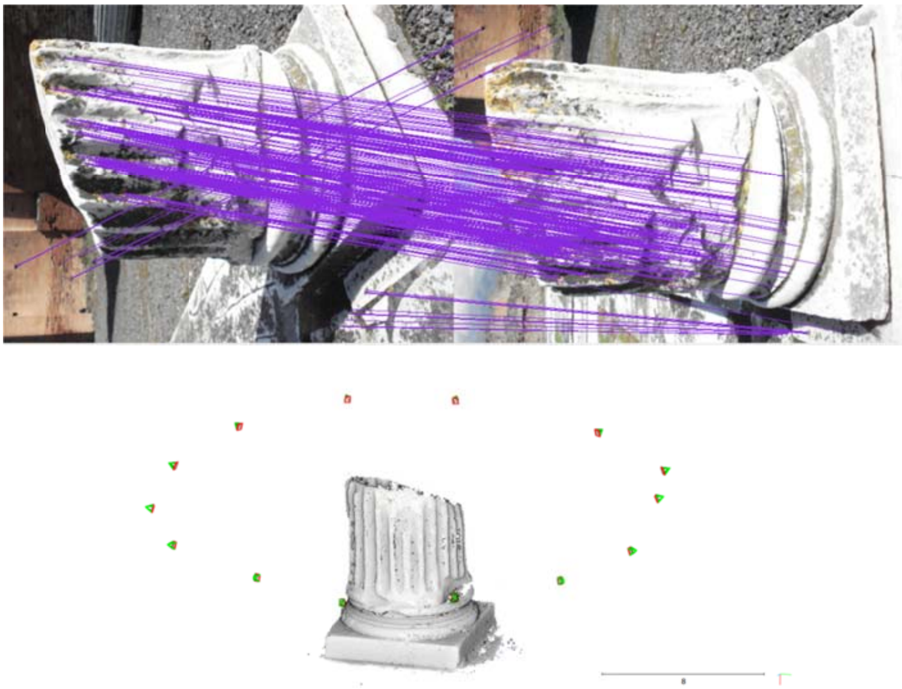

Figure 9. Matching example (up) and external orientation (below) of 'Column' dataset.

Figure 10. Dense matching result of 'Chigi' dataset. Color (left) and shaded (right).

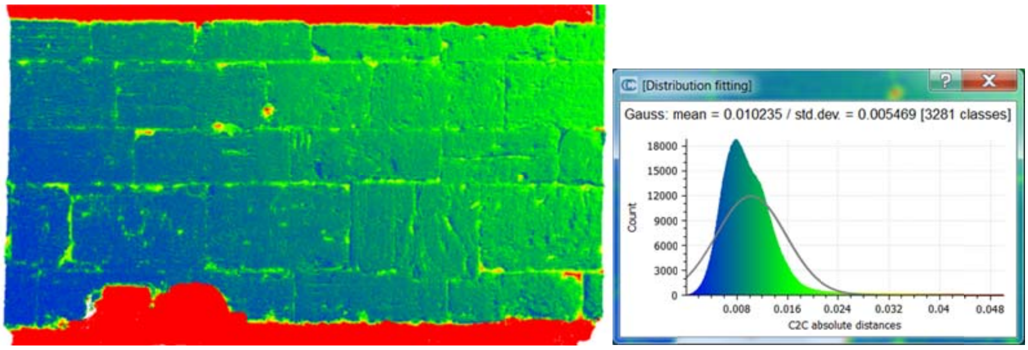

Figure 11. Dense matching model (up) and comparison between GRAPHOS results and ground truth (below) of 'Muro' case.

8. DISSEMINATION

The Scientific Initiative has been already advertised during some scientific events held in 2015 such as the ISPRS 3DARCH in Avila (Spain) and CIPA Symposium in Taipei (Taiwan). In these events, the involved researchers got the opportunity to show the project aims during the opening or demo sessions.

The partners have extensively tested the tool and used external testers (e.g. students) for dissemination and evaluation purposes. Last but not least, several impact factor papers have been published using this tool and pipeline.

Currently, GRAPHOS is being refined to be presented at **CATCON contest** in the ISPRS International Congress in Prague. In addition, some of the case studies tested with GRAPHOS will be presented as a full paper submitted by USAL at the incoming ISPRS Congress.

9. SCIENTIFIC INITIATIVE BUDGET

Grant provided by ISPRS: 6000 CHF (5735.34 EUR)

Total grant: **5735,347 EUR**

Expenses - incl. 21% VAT:

- Staff costs - implementation and validation: 3827.90 €
- Open access journal publications: 2439.32 €
- Travels: 529.22 €

Total expenses: **6796.44 EUR**

USAL - as PI and manager of the SI funds – has co-financed the missing funds.

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