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A low-cost automatic acquisition system for photogrammetry

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Abstract—Photogrammetry is a non-destructive technique commonly employed in the cultural heritage field for reconstructing a 3D virtual replica of an artifact by simply taking several photos of the artifact itself from different points of view. The 3D model can be used either for documenting the artifact or for preserving its geometrical information and appearance. Moreover, by using a digital 3D model is extremely easy sharing information with the public and researchers without physically moving the artifact, and this represents a unique opportunity which cannot be achieved with traditional methods. Unfortunately most systems already present on the market are complex and costly both due to their hardware and software. This paper presents a novel acquisition system which is extremely cheap and can be easily arranged in any conservation laboratory. The solution is based on a simple acquisition system designed with the aim of providing researchers with a user-friendly and low-cost platform for the reconstruction of an artifact 3D model. The proposed system can be virtually interfaced to every commercial camera and can be integrated with several 3D reconstruction software. As an example, the authors employed a free open-source software referred to as Meshroom.

Index Terms—Photogrammetry, Acquisition system, Cultural heritage, Open source, Non-destructive techniques

I. Introduction

Digitalization of cultural heritage artifacts is a widely diffused practice to preserve them for the posterity. As a matter of fact, the creation of a 3D virtual replica of an artifact brings with it a great amount of advantages. Among many of them, it is worth to underline the importance of documentation of an historical object as means of preserving it. Several effective practices are commonly employed to preserve artifacts, such as restoration and conservation under optimal conditions [1], [2]. Nevertheless, a virtual model can store valuable information regarding an artifact conservation state, providing useful tools for its preservation [3]–[5].

3D digital tools are useful also in high-risk areas because of natural catastrophes or wars, in which these techniques can be used to create virtual replicas of endangered heritage [6].

Indeed, 3D models can be easily shared with the public, that can visit an item from all over the world. 3D models can be also easily shared with researchers located in different places and they can be also employed for educational purposes [5]. In addition, 3D models can be very useful for the creation of innovative exhibitions, as virtual museum experiences, or provide accessibility also to people with physical disability. For instance, a virtual replica of an artifact can be 3D printed to create tactile experience for blind people in museums [7].

Several digitalizing methodologies are nowadays available, but photogrammetry is a simple technique that allows the creation of 3D models at different scales. Moreover, photogrammetry can be an accessible technique both in term of costs and of the obtained results. The technique potential and versatility have been proven by many authors [5], [8], [9]. Several different software and algorithms for photogrammetry have been recently designed for working under different operative systems, such as Macintosh, Windows and Linux, and they are available both as proprietary and open-source solutions [5], [10].

The general workflow that has to be followed to obtain a 3D model through photogrammetry is well known and described in literature [4], [11], [12], and it can be summarized in the following fundamental steps:

- image capture with a digital camera;
- images importation into the 3D reconstruction software;
- image alignment with subsequent feature detection, matching and triangulation;
- sparse reconstruction (point cloud computing);
- dense correspondence matching (dense cloud computing);
- mesh creation;
- texture creation.

Nevertheless, digitalization requires a relevant amount of time and expertise. Indeed, fine results can be achieved only if suitable images are acquired and if the reconstruction

Fig. 1. A typical setup of the proposed acquisition system. The tent front-cover is normally closed during photo acquisition in order to avoid any interference from the environmental light.

parameters are properly configured. Therefore, an effective and reliable setup for photogrammetry is extremely important, being the image acquisition one of the most important phases of 3D models creation. As a matter of fact, the quality of the final 3D model greatly depends on the quality of the acquired images: any mistake in this phase cannot be overcome through image processing. In addition, in the field of cultural heritage, the access to an item for research purposes is time-limited and it is usually possible only during restoration and documentation phases. Taking into consideration this latter aspect, the acquisition phase has to be seen as an almost unique chance and, therefore, this process had to be carried out with extreme attention.

Different works presenting automated acquiring systems for digitization are present in literature, ranging from very complex systems [3], [13] to simpler ones [9]. However, the above mentioned systems are often expensive and not always easy to operate by non-expert users. Moreover, they usually require more than one software for carrying out all the required steps.

Trying to overcome such limitations, the proposed system has been developed with the main aim of achieving a low-cost, integrated, fully-automated and user-friendly solution able to carry out all the photogammetry steps, from image acquisition to model and texture computation.

The system is basically composed by a rotating platform and a dedicated control application, and it can be successfully employed for the creation of 3D models of small and medium-scale artifacts (up to about $40\ \mathrm{cm}\ \times\ 40\ \mathrm{cm}\ \times\ 40\ \mathrm{cm}$ of

dimension and $2\ \mathrm{kg}$ of weight).

The proposed solution does not require any additional proprietary software and it employs exclusively open-source resources. The control application, by means of a dedicated socket interface, can be integrated with several 3D reconstruction software. As an example, the authors used Meshroom [14] and Mic Mac [15], ending up with Meshroom which proved to be the easiest solution. In any case, no specific license is required for using the proposed system and this contributes to maintain its cost lower than about 200 USD (plus of course the costs of the digital camera and the processing computer).

II. THE PROPOSED SYSTEM

The proposed solution allows the operators to automatize the photo acquisition process for small and medium-sized artifacts and it can be interfaced to several 3D reconstruction software in order to automatically load the acquired photos and process them. Taking advantage from a modular architecture, the proposed system makes it possible to easily interface different cameras and integrate several 3D reconstruction software without modifying the whole system structure. This provides great flexibility and enables users to adapt their acquisition setup to any specific requirement. Fig. 1 shows a typical setup for the acquisition system with a test object.

A. The Proposed Setup

As above mentioned, setup cost is extremely limited with a total amount lower than 200 USD, so that it can be easily arranged by any research laboratory.

Lightning conditions of the artifact must remain stable during the whole image acquisition procedure. Moreover, the illumination has to be diffused and uniform in order to avoid the creation of bright and shadow areas on the object. Therefore,the setup includes a low-cost foldable photographic tent whose internal sizes are about $63.5\ \mathrm{cm} \times 76.0\ \mathrm{cm} \times 63.5\ \mathrm{cm}$ [16]. Such kind of tents, which usually provide a front-cover with dedicated camera openings and internal LED light sources, are commonly employed in photogrammetric setups in order to reduce the effects of environmental illumination and provide an internal, uniform and controllable lighting. Moreover, tents help users to acquire all photo-set with a uniform background, significantly improving the subsequent 3D reconstruction process.

A low-cost camera tripod is included in the setup as well, with the aim of maintaining the camera orientation fixed.

The setup includes an automatic photo-taking rotating platform and a control software application running on the computer together with the 3D reconstruction software. The main components of the system, shown in Fig. 2, are:

- A *rotating platform*, properly controlled by the system, which provides a stable support for placing the artifact and acquiring photos at different views. The platform has been realized by cutting a plywood laminate and painting it with a white varnish similar to the tent in order to unify the photo background.
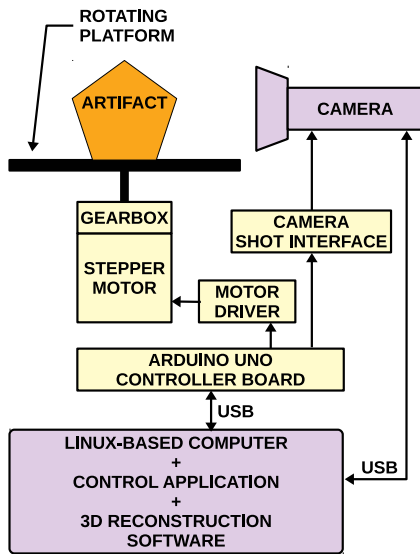
Fig. 2. Block diagram of the proposed acquisition system. The digital camera and the processing computer can be selected accordingly the users' necessity.

- A *stepper motor*, mechanically coupled to the rotating platform by means of a *reducing gearbox*, which is used to turn the rotating platform of the required angle. The gearbox reduces the angular velocity during platform rotation with the benefit of increasing the angular resolution. At the same time, the gearbox increases the available torque so that also artifacts weighting few kilograms can be moved without affecting rotation accuracy. The authors employed a NEMA 17 motor and a 1:18 reducing gearbox, both allocated inside a 3D-printed enclosure, to provide a rotation resolution of $0.1°$ and a maximum error of $1°$, but other step motor can be used as well provided that they have suitable resolution and torque.
- A *motor driver* which is required to drive the step motor. Any driver can be used for this purpose. The authors employed a driver based on an A4988 chip, manufactured by Allegro MicroSystems. This driver, which has a very low cost, is used to drive the stepper motor by means of a simple digital interface for selecting both the rotation direction and the angular displacement. The driver is also able to control the motor current up to 2 A, so that it is possible to employ a wide range of stepper motors and select the most appropriate torque.
- A *camera shot interface*, which allows the system to connect with the employed camera in order to take photos synchronously with the platform rotation. The interface technology change, of course, with the selected camera. The experimental setup described in this paper employs a NIKON D3100 camera. Such camera provides a simple analog interface for triggering the focus and shot actions by means of two dedicated digital inputs with integrated pull-ups. Therefore, two open-drain buffers are included inside the camera interface to generate two positive edges

over the two inputs with the required delays, so that the camera can complete the autofocus operation (if enabled) before taking the photo.
- A *control board*, which is based on the Arduino Uno development platform [17]. The Arduino Uno is programmed with a firmware which is designed to control both the platform rotation and the photo shot triggering. The Arduino receives commands and configuration parameters from the processing computer over its USB Interface configured as a virtual serial port. All pictures are directly transferred to the PC directly from the camera, thus no manual intervention is required in this phase.
- A linux-based *processing computer* running both the control application and the 3D reconstruction software. Among the available 3D reconstruction software, the authors selected Meshroom for this experimental setup because of its good performance and the quite high flexibility. Since, such software is open-source, this contributes to decrease the overall cost of the system and makes it possible to modify the software itself in order to fully integrate it with the acquisition system. Anyway the proposed solution is easily configurable to work with other reconstruction software and different operative systems. No specific constraints are required in general for the computer. However, if the Meshroom software is used, a CUDA-compatible NVIDIA graphic card is required (level ≥ 2.0) [18]. In fact, Meshroom employs the graphics card to create the 3D reconstruction and it can take advantage from the Cuda Parallel Computing Technology for decreasing the processing time and improving the 3D model quality. Of course, the higher are the performance of the computer the shorter is the reconstruction time for a given artifact, which may range from few minutes to several hours. The computer requirements may differ if other types of reconstruction software are employed.

The camera is connected to the processing computer in order to transfer the acquired photos and processing them. Most of the commercial cameras provides a standard USB interface and they are mounted by the linux operative system as a *removable media* which can be accessed directly without the necessity of installing specific drivers or applications. This makes the photo transfer process quite straightforward for the control application independent from the specific model of camera employed in the setup.

B. Control Application

A dedicated control application has been developed in the open-source Python Programming Language and wxPython with the aim of providing a user-friendly Graphical User Interface (GUI) to configure the rotating platform and the photo transfer (Fig. 3). The application directly communicates with the control board in order to drive the platform, take the photos and, at the same time, it looks for the acquired photos in the camera folder, imports all the new ones and transfer
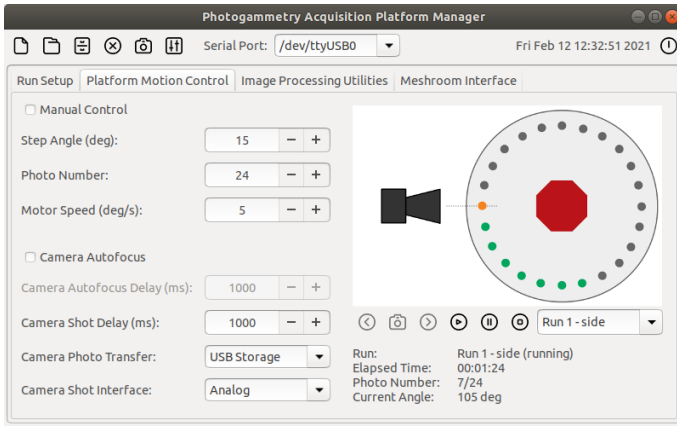
Fig. 3. Grafical User Interface (GUI) of the proposed dedicated control application.

TABLE I
ACQUISITION PARAMETERS EMPLOYED DURING THE TEST

IMAGE SIZE	4608×3072 pixels
SENSOR SIZE/TYPE	23.1 mm $\times$ 15.4 mm/CMOS
PIXEL SIZE	$4.94 \mu m \times 4.94 \ \mu m$
IMAGES FORMAT	RAW
ISO	400
FOCAL LENGTH	18 mm
APERTURE	$f/22$
SHUTTER SPEED	1/20 s
STEP ANGLE	10°
ACQUIRED IMAGES	72 (2 revolutions of 36 images)

them in the project directory. In this way, the reconstruction software can process the images, also in *live mode* during the photo-set acquisition.

The application, organized in several tabs, allows users to create and configure a reconstruction project on the processing computer. All the platform parameters, such as motor speed, number of steps and shot delays can be configured from a dedicated tab.

Taking advantage from the open-source library OpenCV [19] and its python bindings, the application is also able to perform a pre-processing on the acquired photos. This is carried out by calling specified OpenCV functions with a set of parameters that can be configured directly from the GUI.

As a matter of fact, once the acquisition is complete and before passing the acquired images to the software, it is fundamental to control the image quality and exclude blurred and low-quality images. Images might be stored in any format compatible with the reconstruction software. However, the RAW format is often the best solution both to avoid any compression loss and to store all the information related to the acquisition parameters within the images themselves. In facts, such information are typically loaded by the 3D software and employed to improve the reconstruction process [12].

Typically, pre-processing of the original RAW images includes:

- White and color correction, to compensate for light source chromatic value. As an example, several white LED sources feature a blue-rich light emission which modifies the appearance of the artifact. In order to compensate such an issue and to assure color fidelity, it is possible to take a photo with a reference color chart and automatically correcting all the acquired photos by using the OpenCV Color Correction Matrix (CCM).
- Contrast and brightness normalization, to avoid under or over exposure and to have similar images. This can help to improve details and edge detection in the 3D reconstruction process.

- Photo cropping, to eliminate empty area of a photo, thus reducing memory usage and computation time during the reconstruction process.
- Resolution down-scaling for obtaining draft models with very short processing time to check for the acquisition correctness.

Such kind of pre-processing can significantly improve the subsequent reconstruction process allowing one to achieve higher-quality models with reduced computation time. The developed control application allows users to easily configure such pre-processing and to automatically apply it to each acquired photo.

C. 3D Model Reconstruction

Meshroom [14], is based on the AliceVision Framework, and it was the selected software for the described experimental setup. This decision is due to the fact that it is a complete and open-source solution which allows one to perform all the photogrammetry pipeline and obtain a textured 3D model within a single application.

It is also worth to notice that Meshroom has embedded a particular feature called *live reconstruction*. Such a function allows one to carry out an iterative reconstruction process: images can be added to the reconstruction process while they are acquired to augment the *Structure-from-Motion* (SfM) coverage. This way it is possible to have a live result and to decide if more images are necessary to achieve a complete coverage. In this way, it is possible to avoid the addition of redundant photos which would not improve model quality but would only increase computing time.

Meshroom has an embedded pipeline, that can be run without the necessity of manual intervention by the user, and can be configured and controlled by means of sockets or by a common command line. This way, the reconstruction process and its configuration parameters, can be partially controlled by the control application when necessary. The pipeline is created by connecting basic processing blocks together accordingly to the desired reconstruction steps.

Optional processing blocks, including special filters, can be added when required by the specific application. After the 3D model has been reconstructed, mesh and texture can be exported in several format and, optionally, processed manually with an external software, such as Meshlab [20].

III. EXPERIMENTAL VALIDATION

The proposed solution was validated with a test object (set figure Lego(TM), Wall-e [21]) for assessing if the system was able to work reliably in all the steps of the pipeline from the image acquisition to the final 3D reconstruction. The test object, shown in Fig. 4-(A) and Fig. 4-(B), is quite complex, with an irregular shape and full of small parts and holes. This represents an additional difficulty for the 3D reconstruction software and, therefore, this test is a valid way to evaluate the overall performance of the proposed solution.

The images were acquired with a NIKON D3100 digital camera together with an AF-S DX ZOOM-NIKKOR 18-55mm f/3.5-5.6G ED lens. Table I summarizes the main parameters employed in the test acquisition. Reconstruction was carried out by using Meshroom in *Live Reconstruction Mode* by adding four images at time. A first set of images was acquired frontally the test object with a angular step of $10°$. In fact, thanks to the live mode, a number of 36 images proved to be enough to obtain a satisfactory coverage of the object. Subsequently, a second set of 36 images was taken from above the object with the aim of improving the reconstruction of the object top part. Therefore, a total of 72 images was acquired and imported in Meshroom by means of the dedicated control application.

A standard Meshroom pipeline was set for the project. In particular, the pipeline was composed by the following steps: Camera Initialization, Natural Feature Extraction, Image Matching, Features Matching, Structure From Motion (SfM) Creation, Prepare Dense Scene, Depth Map Estimation, Depth Map Filtering, Meshing, Meshing Filtering, Texturing. All the steps parameters were set to default values.

Reconstruction took a total processing time of less than 2 h on a quite cheap processing computer (intel i7-9750H CPU, 16GB RAM, NVIDIA GTX2060-6GB). After the 3D model was fully reconstructed and textured, its mesh was exported in the *obj format* and properly scaled by employing the open-source software Meshlab. Scaling was carried out taking measurement of three dimensions of the object and computing the mean scaling factor between them. The ultimate model, shown in Fig. 5, featured about 514000 vertices and about 1020000 faces.

In order to assess the quality and the uncertainty of the final model, the method proposed in [10] was applied. A set of 18 distances, highlighted in Fig. 4-(A) and Fig. 4-(B), was defined taking care of including all feature types of the artifact (flat and rough surfaces, circular features, holes and small relief parts). Moreover, the selected distances were distributed around all the artifact volume with the aim to effectively assess the dimensional quality of the reconstructed model. Such distances were measured directly on the test object by means of a caliper (sensitivity of $50~\mu$m). Subsequently, the homologous distances were evaluated on the reconstructed 3D model by means of the open-source Wings3D software [22]. Both the measurements of the test object and of the model are reported in Table II, together with their absolute and relative errors.
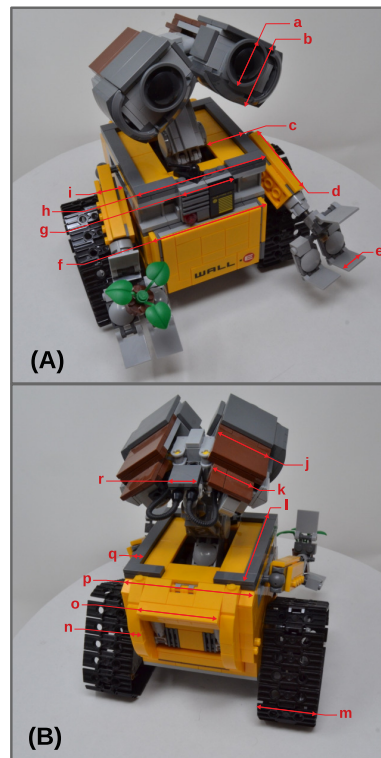

Fig. 4. Experimental validation: (A) and (B), two original images of the test artifact with validation measurement points.

In particular, maximum deviation between the object and the model was 1.37 mm (distance f) and the maximum relative deviation was 4.51% (distance r). It is possible to observe that the model was properly and accurately reconstructed and scaled with a mean difference between object and model of 0.57 mm (relative deviation of 1.18%) and a standard deviation of 0.67 mm.

Even though such errors are surely not negligible, the achieved results are very promising and new system settings are under investigation in order to improve the 3D reconstruction accuracy. In any case, the proposed system has proven to be a valid integrated solution for the complete photogrammetric reconstruction of an artifact.

IV. CONCLUSIONS

The developed automatic acquisition system presented in this paper is a user-friendly, flexible and low-cost solution for the photogrammetry-based reconstruction of 3D models of small and medium-scale artifacts. As a matter of fact, the proposed solution allows users to carry out the whole reconstruction pipeline automatically with a minimal user intervention. In particular, the solution assists the users during all the steps: artifact image acquisition, importing and pre-processing of the acquired images, control and configuration of the 3D reconstruction software, up to obtain a complete textured model. The system features high flexibility in interfacing any model of digital camera and can be fully integrated in different reconstruction software.

TABLE II

UNCERTAINTY ESTIMATION OF THE RECONSTRUCTED 3D MODEL.
MAXIMUM ERRORS ARE HIGHLIGHTED IN BOLDFACE.

Dimension	Artifact [mm]	3D Model [mm]	δ [mm]	ϵ [%]
a	24.80	24.05	0.75	3.02
b	34.90	35.32	0.42	1.20
c	23.70	24.27	0.57	2.41
d	47.90	47.50	0.40	0.84
e	15.70	16.08	0.38	2.42
f	**73.65**	**72.28**	**1.37**	**1.86**
g	31.80	31.65	0.15	0.47
h	79.75	79.14	0.61	0.76
i	15.95	16.49	0.54	3.39
j	31.80	30.87	0.93	2.92
k	23.90	23.45	0.45	1.88
l	79.55	78.79	0.76	0.96
m	37.90	37.08	0.82	2.16
n	7.80	7.85	0.05	0.64
o	47.70	47.13	0.57	1.19
p	79.75	79.01	0.74	0.93
q	7.80	7.85	0.05	0.64
r	**15.95**	**15.23**	**0.72**	**4.51**

Fig. 5. Experimental validation: 3D reconstructed model of the test artifact.

The proposed solution, integrated with Meshroom, has been validated by carrying out a complete reconstruction process of a complex test object. The obtained model was compared with the object itself resulting in an average accuracy of about half millimeter and a standard deviation of 0.67 mm. Therefore, the described integrated system, thanks to the good performance, its low cost, and the high capabilities of integration with several reconstruction software, can be considered a valid solution in the photogrammetry field. Several improvements are under development, including a Bluetooth support which will allows users to interface smartphones and wireless cameras, and the integration of 3D printing systems inside the reconstruction pipeline, so that it will be possible starting from an artifact, to achieve its 3D digital model and its 3D-printed replica within a single integrated solution.

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