Measurement 178 (2021) 109338

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

A PBeL for training non-experts in mobile-based photogrammetry and accurate 3-D recording of small-size/non-complex objects

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ARTICLE INFO

Keywords:
Photogrammetry
Precision
Measurements
Accuracy
Smartphone
E-learning

ABSTRACT

The high level of automation, user-friendliness and cost-effectiveness of photogrammetry have contributed significantly to its popularisation among amateur users in recent years. Paradoxically, this situation poses challenges when relying on the accuracy of the derived 3-D products requiring control procedures to be implemented. In this context, we present a case study of the *D3Mobile* project: a fully online competition for participants worldwide funded by the International Society of Photogrammetry and Remote Sensing (ISPRS). The aim is for participants to obtain reality-based 3-D models using their own mobile phones and to critically examine the metric accuracy that hides behind the beguiling realism of photogrammetry. The relative precision of the former participants' models reached values around 1:2,000, proportionally to the object size. These results provide an idea of the current level of development of photogrammetry and the potential it offers for any kind of user after proper capacity building and training.

1. Introduction

Photogrammetry is typically defined as the art and science of taking measurements from photographs. Indeed, in addition to its ability to produce reality-based 3-D objects, digital photogrammetry is also an accurate, flexible, and noncontact dimensional measurement tool with multiple professional uses. This technique provides a precise and reliable method for determining geometries, positions and orientations and may also be applicable to monitoring movements and deformations [1–4].

At its beginning, photogrammetry was a specialist discipline using highly specialized equipment and requiring a wide knowledge of the methods [5]. The arrival of personal computers in the 90 s brought digital photogrammetric workstations (DPWs), practical tools much easier to use and teach than old stereoplotters [6]. However, the real revolution in the field occurred with the recent integration of photogrammetry and computer vision, which made it possible to transform tasks that were previously performed manually by skilled operators into fully automated processes, as is the case with SIFT-like algorithms for feature detection [7–11]. These improvements entailed greater flexibility in the image acquisition process (i.e., images with different directions and different distances to the object can be processed simultaneously) and an unprecedented level of automation in workflows. Having enough overlap, the modern SfM (Structure-from-Motion) packages are now capable of reconstructing complex objects and environments from unordered sequences of images in a feasible amount of time with little or no user interaction [12].

Since the appearance of the first phones integrating cameras, such devices have become very interesting options for 3-D scanning in terms of accuracy and flexibility [13]. With the increased affordability of optical systems over the years and the arrival of smartphones embedded with cameras with high-resolution sensors, mobile-based photogrammetry has gained considerable popularity among all types of users. Being light and portable, smartphones have currently become essential tools for the spontaneous capture of 3-D creative content anywhere [14]. Moreover, several related trending technologies have converged in recent years, such as unmanned aerial vehicles (UAVs) [15], VR/AR devices and virtual environments [16,17] or 3-D printers [18], contributing to the popularisation of this technique as a source for obtaining three-dimensional models. If we include the boom of online communities promoting 3-D model sharing (e.g., Thingiverse, Sketchfab, Cults, MyMiniFactory, etc.) and the rising demand for 3-D content in

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https://doi.org/10.1016/j.measurement.2021.109338
Received 1 February 2021; Received in revised form 17 March 2021; Accepted 24 March 2021
Available online 29 March 2021

almost all industries (video games, retail, real state, healthcare, etc.), a favourable ecosystem contributing to widespread interest in photogrammetry is obtained.

1.1. Photogrammetry: A technique accessible to everyone

The term "mass photogrammetry" coined by Stuart Granshaw [19] perfectly reflects what has happened in the last decade since, photogrammetry is no longer a word restricted to geomatics experts but *is a current expression understood by an increasing number of nonspecialists who have an interest in creating 3-D models from their photographs*. Due to its handiness and affordable costs, increasingly more people, often amateur users, are using photogrammetry as a source of their own digital 3-D contents [20]. In addition, increasing efforts are being made in universities to establish geomatic courses in different disciplines (architecture, graphic design, land planning, archaeology, etc.) and update their curricula to properly use photogrammetry and other related techniques to better prepare the next generation of professionals.

In general, photogrammetry is now much cheaper than other competitive remote sensing techniques (e.g., 3-D scanners), as it can be executed with practically any digital camera with sufficient resolution or even with microdevices equipped with mobile phones. This is obviously one of the main reasons why photogrammetry also enjoys such a high level of acceptance among nonexpert users. However, the technique would not have experienced such a great level of popularity among the amateur or semiprofessional public without a parallel development of photogrammetric tools (i.e., software packages/computer vision libraries), available to everyone in a free/open-source format [21–23].

A nonexhaustive list of these open-source programs, both core libraries and programs running complete SfM and Multiview Stereo (MVS) pipelines for general purpose 3-D reconstruction is included in Table 1. Among the items, there are also software and web services that use photogrammetric cloud computing such as Arc3D or the popular Autodesk 123D Catch, allowing users to upload digital images to a remote server and to obtain the output 3-D model back in a few minutes without additional intervention. There is also a group of open solutions specifically oriented to aerial image processing, such as OpenDroneMap. Even some free versions of desktop professional software packages, such as 3DF Zephyr, can be installed, although they have certain limitations of use compared to the full versions but still provide excellent possibilities for amateur use and for training purposes. With the advent of smartphones, many 3-D scanning apps for multiple platforms and mobile operating systems have also been popularized. Some of these apps apply alternative 3-D reconstruction procedures, such as space carving or silhouette-based 3-D reconstructions, to the SfM workflows [31,32]. Free (or almost free) solutions such as SCANN3D are essentially "black boxes" that allow us to scan objects with very few options for controlling the workflow but also without the need for deep technical knowledge [33–35].

Table 1
Open-source software and free mobile applications for photogrammetry.

	Author/Reference	Type
VisualSFM	Changchang Wu [24,25]	Core library
OpenMVG	Pierre Moulon [26,27]	Core library
Bundler	Noah Snavely [28,29]	Core library
COLMAP	Johannes L. Schönberger [30]	Desktop software
Meshrecon	Zhuoliang Kang [31]	Desktop software
Regard3D	Roman Hiestand [32]	Desktop software
Meshroom	AliceVision[33]	Desktop software
PhoX	Thomas Luhmann [34,35]	Desktop software
GRAPHOS	[36–38]	Desktop software
MicMac	IGN France [39,40]	Desktop software
Arc3d (*)	Luc Van Gool [41–43]	Cloud-based
123D Catch (*)	Autodesk [44,45]	Cloud-based
OpenDroneMap	OpenDroneMap [46]	Desktop / cloud (aerial imagery)
E-foto	[47,48]	Desktop software (aerial imagery)
3DF Zephyr Free (**)	3DFlow [49]	Free version of a commercial software
QLONE (**)	EyeCue Vision Tech. LTD [50]	3-D scanning app for smartphone
SCANN3D (**)	SmartMobileVision [51]	3-D scanning app for smartphone
TRNIO (**)	Trnio [52]	3-D scanning app for smartphone
3D Creator (**)	Sony Mobile Communications [53]	3-D scanning app for smartphone

*Discontinued / **Free version with limited functionality.

Several research works have explored the potential of accessible photogrammetric resources in a number of fields. In recent years, the classical application areas (i.e., topographic mapping [54,55], architecture [56–59] and archaeological and cultural heritage documentation [44,60–64]) have been joined by studies using open source/free resources in apparently unrelated fields. In this sense, applications are now increasingly common in areas such as geology [65,66], lab testing materials [67], and biology [68,69] and even in medical/prosthetic applications [70–74]. All these pioneering works have paved the way for other people who, without necessarily having extensive knowledge of stereoscopic reconstruction methods, could apply this technology in their own fields of interest.

It is also not the first time that participatory approaches using low-cost photogrammetry as a basis for involving the general public in 3-D data capture operations have been proposed. Works such as [75–78], have already experimented with the possibility to infuse of introducing university/high school students and the overall public to the basic competences of the use of photogrammetry in collaborative projects documenting and enhancing of cultural heritage. Additionally, [79] explored the use of collaborative photogrammetry to empower communities hit by urban disasters and to fostering their active participation in recovery by means of registering damaged buildings and structures. These initiatives have shown that the task of training amateur users can be technically challenging depending on the specific needs and subsequent use of the resulting models. The main problem is a general lack of control over the final quality of the outputs since the users, professional or amateur, are more fascinated by the speed and detail of the point clouds/3-D photorealistic models obtained rather than aware of the metric quality of the results obtained. Therefore, the quality of those products can be highly heterogeneous or even unknown [80]. Furthermore, these works also demonstrate the enormous potential generated by crowdsourcing photogrammetry if users are provided with both technical and theoretical awareness of the reliability of the 3-D models obtained. Therefore, it is particularly important to implement educational actions that close the gap between the spread of the technique and its metric rigorous use.

1.2. Education and training in photogrammetry: An overview

In a way that is consistent with this historical evolution, education and training in photogrammetry have formerly occurred at universities due to the complexity of the analytical processes involved in their teaching and the complex instruments used. However, in general, this discipline has never constituted an independent study programme itself anywhere, and its contents have been integrated normally within land surveying, geodesy, GIS or geomatics programmes [81]. With the current level of dissemination, photogrammetry is also quite common as a transversal topic integrated in a range of different courses targeted at intermediate or nonexperts. However, for expert audiences such as academic audiences, the offering are even greater with different study programmes at various levels (i.e., university degrees, postgraduate master courses's, specialized master's schools, advanced courses, etc.) [82].

The demand for skilled people in this field is increasing. In the US, for example, the demand for labour related to the subdisciplines of cartography and photogrammetry is projected to grow 4% over the ten-year period from 2019 to 2029 due to the increasing use of maps and geospatial information in government planning [83]. However, paradoxically, the number of students in engineering subjects such as land surveying and geomatics is decreasing at many universities around the world [84,85]. The reasons are not easy to identify, but children seem to neglect STEM (science, technology, engineering and mathematics) subjects and prefer to escape towards other subjects. This fact has given rise to serious difficulties in finding qualified professionals, generating a recruitment problem for fields related to photogrammetry and 3-D.

Fortunately, e-learning education is also producing a new set of strategies for improving engagement and mastery in photogrammetry. Wide and high-quality online training is now available to facilitate learning and provide more flexible access to content from any place in the world and at any time [34,85–88]. In addition to the courses offered by private institutions and software manufacturers, some of the top universities in the world are also offering massive online open courses (MOOCs) to the wide public. It is true that there are not too many open training initiatives yet presented in the form of free individual courses whose direct theme is photogrammetry [89]. However, photogrammetry is a common topic constituting a unit of specialization within other online massive programs (e.g., “3D Motion and Structure from Multiple Views” belonging to the course “Robotics: Perception” on the Coursera MOOC platform of the University of Pennsylvania).

There is also a clear trend in online education and training towards project-based learning (PBL) or challenge-based learning (CBL) and e-learning or blending learning approaches. PBL represents an active method for knowledge acquisition by means of working with projects and solving specific problems. The key point is to foster active thinking through a continuous cycle of experience and reflection, thus limiting moments of passive reception of content [90,91]. The direct experience of conducting a task allows students to improve their analytical and decision-making skills, internalize their accountability, learn how to handle real-life problems, and develop teamwork and problem-solving skills [80]. Conversely, the e-learning approach implies more autonomy than classical teaching. These kinds of initiatives have also demonstrated their usefulness during the COVID-19 pandemic and subsequent distancing protocols [92,93]. The combination of these learning methodologies in the project-based e-learning (PBeL) approach has proven to increase the benefits and to improve students’ engagement and interest in the proposed topics [94].

The goal of *D3Mobile* is to design a PBeL to present photogrammetry to high school students around the world and test the potential of free resources and online materials, such as those developed here, for training amateur users via e-learning. The proposed activities are intended to highlight the importance of the procedures for controlling the accuracy of the technique, which provides photorealistic results but whose metric quality is often unknown. The accuracy obtained by participants using their smartphones will be analysed according to the results delivered by them. Indirectly, the project also seeks to promote the interest of the young generation in photogrammetry and related sciences, which is also a potential way to keep them engaged with related post-obligatory studies.

2. Materials and methods

The designed PBeL, named “*D3Mobile - Metrology World League*”, started in 2013 with the main aim of showing the possibilities of mobile phones as accurate measurement devices. The material and methods used have varied throughout the different editions; therefore, in the “About the project” section, the general characteristics of the designed PBeL and the method used to investigate its suitability are described. In the “Challenges for assessing accuracy in measurement” section, a more detailed description of the material and methods used to investigate the accuracy obtained by the participants in each edition is presented.

2.1. About the project

D3Mobile is presented as a project-based e-learning (PBeL) initiative to motivate students and introduce them to the application of photogrammetric techniques in dimensional metrology. The intention of the elaboration of the didactic methodology under this learning mode is to make the topic compatible with the daily work in the classroom, either as voluntary or mandatory work, within a given lesson plan of any high school in the world. Under the pedagogical point of view, the *D3Mobile* project may also be considered CBL: the students propose solutions for real-world problems by using everyday technologies such as smartphones and what they already know about the topic of the challenge [86,95]. This framework involves students and teachers engaging to achieve a shared common goal by using both personal and team skills. The format of an international championship encourages teamwork and acts as a source of motivation to keep participants involved in problem solving.

The use of mobile apps and tools for the digitization of reality help teachers to inculcate STEM literacies relevant to participation in future works using 3-D skills. Particularly, the contents of the proposed tests are designed to infuse specific topics of photogrammetry (e.g., rules for image acquisition and stereo-reconstruction principles) and metrology (e.g., error, uncertainty, accuracy vs precision, etc.) into the students’ curricula. These theoretical concepts are otherwise hard to teach without a practical application approach.

Teams are composed of a maximum of four participants led by a teacher. After registration at http://www.d3mobile.es/, each team can sign in their private area on the website. There, teachers and students can find all the information they need to participate. In addition to being up to date with the news of the contest, on this website, teams can find the guidelines for the tests they will have to take. Participants are also provided with a set of auxiliary tools (e.g., discussion forums or video tutorials) to help teachers organize their classrooms.

The competition is divided into different quizzes, with a delivery margin of several weeks to allow the teacher to schedule the activities according to their particular needs during the academic year. Three independent tests have always been proposed during these years, although their content slightly varied: small adjustments have been made to implement improvements but also to allow the same team to participate in several editions without repeating the same quizzes.

The 1st exercise of each annual edition has an introductory nature to provide the basis for the understanding of 3-D digitizing techniques using mobile phones. This test is intended for participants to acquire the knowledge needed to correctly take the images. The configuration of the smartphone camera parameters, the management of the lighting of a scene, the stabilization methods of cameras and the definition of a shooting strategy are some of the points addressed. The results of this test are not scored since the test is simply intended to familiarize all the participants with the photogrammetric technique for scanning a common object.

The 2nd test is the proper application of the concepts acquired in the previous test by digitizing a real object. This exercise starts with the choice of the object, which is selected by the participants, but provides all the information to select a suitable object for the test. In fact, the complexity of the object will greatly influence the results that can be obtained and thus the scoring. In addition, teams are warned that shiny, reflective, transparent, untextured, homogeneous or highly glossy objects can pose problems for 3-D reconstruction. After setting up the scene, the participants captured the images following the shooting strategy that they defined, depending on the type of object.

Once the images are obtained, the teams conduct photogrammetric processing using free software. During these first years of *D3Mobile,* it has been necessary to address changes in the commercial policies of software manufacturers because some initially free apps became paid software. In addition, in some cases, the variety of OSs of devices (i.e., Android, iOS, Linux and Windows) has been a limiting factor for the participants. Therefore, the rules of the test have been made more flexible so that the image processing can be conducted with any type of software (i.e., mobile, desktop or cloud based). The only rules are that open-source or free licenced versions of software are used and that the images must be taken with the camera of a mobile device (tablet or smartphone). However, in each edition, some apps are recommended to participants due to their ease of use and providing text guides and video tutorials. Each team delivers the original photographs that have been used to generate the model along with their final 3-D model. In this way, it is also possible to verify that the methods and equipment used by the participants meet the rules of the contest.

At the end of the project, an opinion survey with scored and open questions was sent to the participating teachers and students to evaluate certain aspects related to the quality of the implemented PBeL and their overall satisfaction with the *D3Mobile* initiative. Some of the general questions seek to analyse how participation in the project can influence interest in technological subjects or whether the initiative could promote the visibility of photogrammetry as a potential field of work for the participants in the future. Another group of questions includes the evaluation of specific aspects of the project: the adequacy of the material used (website, guides, videos, etc.), the satisfaction with the software and apps used, the time required, the perceived level of difficulty, etc.

2.2. Challenges for assessing measurement accuracy

2.2.1. Measuring the coordinates over the faces of a coin (2013 and 2014 ed.)

The 3rd test of *D3Mobile* 2013 was aimed at accurately extracting the X, Y, and Z coordinates of four points over a € 2 Spanish coin (National Euro issuance of 2012). As in this first year, all the participants were Spanish, and a coin was chosen as a standard object. Therefore, any participant could acquire the object and be part of the contest wherever they are located. Due to its size, the coin is a suitable object to be correctly captured by any smartphone camera.

The proposed exercise must be solved using the camera of a user's mobile phones and a photogrammetric application to obtain the 3-D reconstruction of the scene. After obtaining an accurate reconstruction of the model, the participants had to scale the model correctly and determine the coordinates of four characteristic points (M1 to M4) defined by the engraved elements on the coins. The points are located on both sides of the coin; therefore, the participants were forced to use the produced 3-D model for the measures.

The coordinates of the same 4 points were also measured by the CEM (Spanish Center of Metrology) with a high accuracy measurement device (Fig. 1) over 3 different € 2 coins.

The procedure to perform the test in the classroom begins with the preparation of the scene by the participants. Over an open calliper with a fixed measure of 40 mm, the specified € 2 coin is placed vertically, fixing it with some type of adhesive dough to the calliper (Fig. 2a). Using the camera of a smartphone or tablet, the participants captured at least 25 images around the scene. They were asked to move regularly around the coin so that the angle between consecutive images did not exceed 15° and that the overlap between them is adequate for photogrammetric reconstruction. Once the procedure was finished, the images were processed with the 123D Catch photogrammetric software (Autodesk, San Rafael, US). This software allows obtaining a 3-D model with photorealistic textures (Fig. 2b) of the coin on the calliper. The measurement of the calliper introduced in the scene allows the participants to obtain a reliable reference measure to scale the model by picking two points over the Vernier scale. However, the marking of the points on the 3-D model must be performed with the greatest possible rigor. After a first scaling step, the extremes of the upper jaws and the lower jaws of the calliper can also be used as reference points to initially estimate the precision (difference between both distances) and the accuracy (mean value of the distances) of the 3-D model. Based on these measurements, the scale can also be reset to refine the accuracy.

With the model definitively scaled, the origin of coordinates can be translated to point M1 (0,0,0), and the axes can be rotated until the X-axis passes through M3 (X_{M3},0,0) and the Y-axis belongs to the plane defined by M1-M2-M3 (i.e., with M2 coordinates (X_{M2},Y_{M2},0)). Once the coordinate system is correctly located, the coordinates of the four singular points (M1 to M4, Fig. 2c) can be measured (Fig. 2d). Participants were asked to complete the entire process twice (making a new session of photos) and send the values of the coordinates obtained by both measurements for evaluation.

2.2.2. Measuring the coordinates over a scanned calliper (2015 and 2016 ed.)

The 2014 edition was the first time people from all over the world were targeted. However, paradoxically, participation declined significantly compared to the previous year in the metrology test. The main reason has been the difficulty of many of the teams to find the specific coin (even in Spain) and the problems in receiving it by mail. Therefore, a new methodology was proposed for 2015 and 2016 using the same procedure.

The new test consisted of the 3-D scanning of a calliper and the extraction of the coordinates of some points marked on it (Fig. 3a). For the previous test, two photo sessions were conducted by the participants

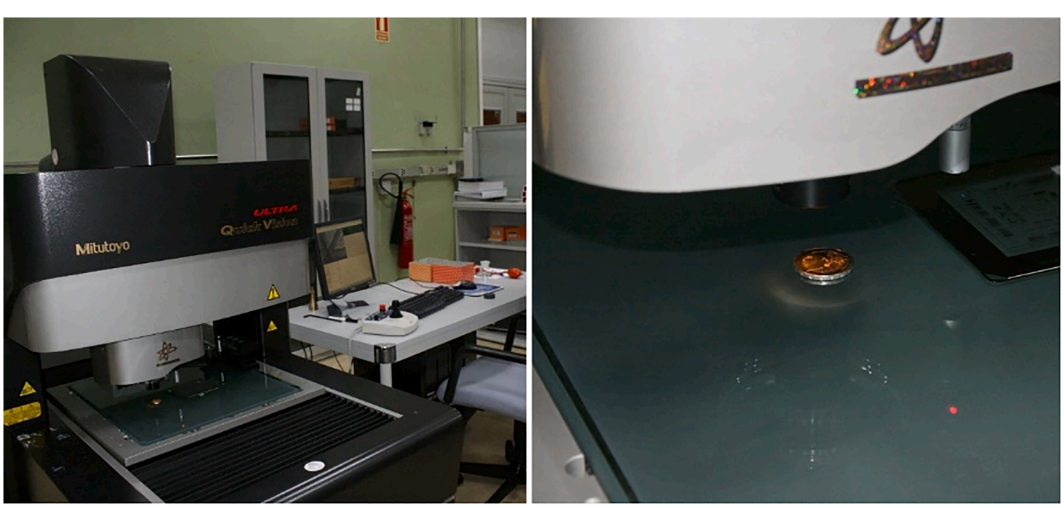

Fig. 1. The three-axis Mitutoyo Ultra Quick Vision measuring four point coordinates in a 2€ coin.

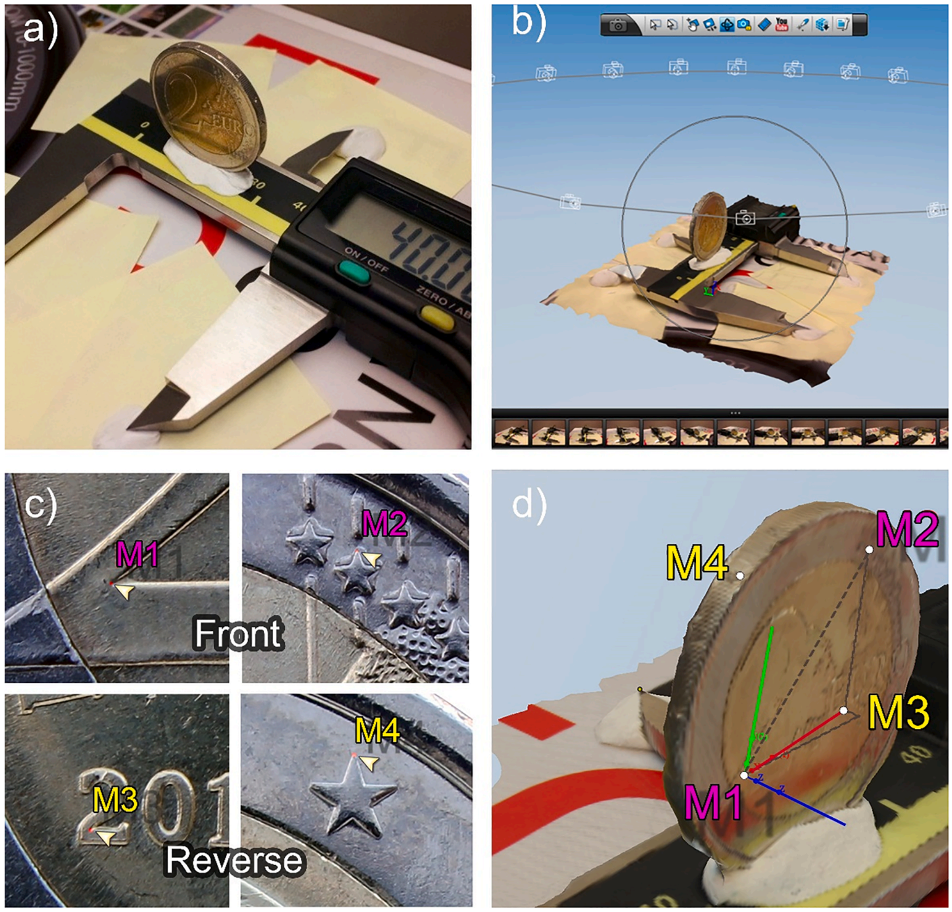

Fig. 2. 1st test of metrology in D3Mobile 2013 and 2014 editions.

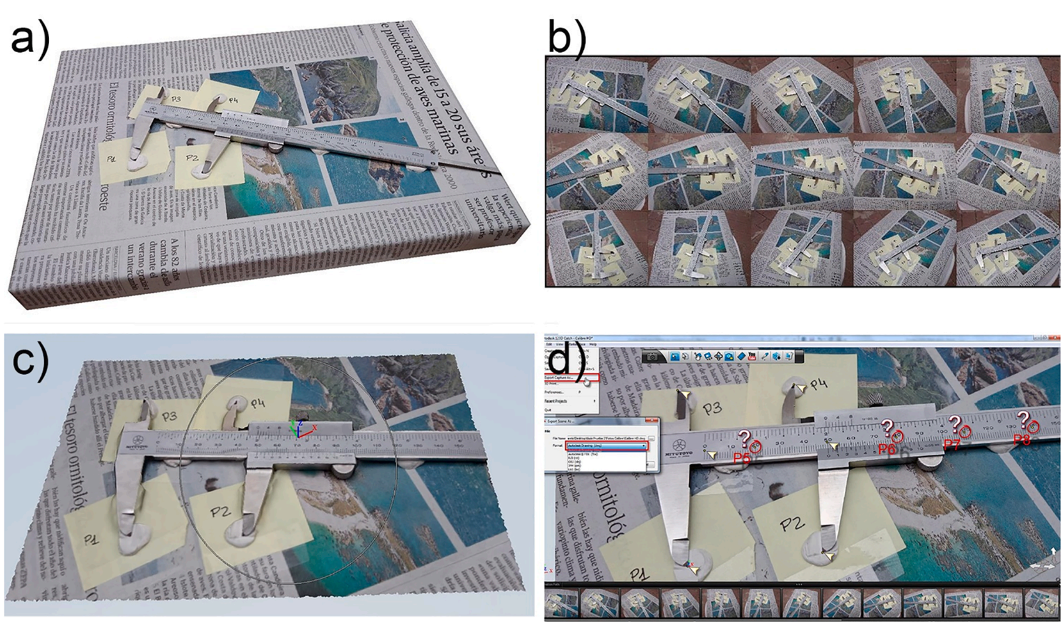

Fig. 3. 2nd test of metrology in D3Mobile 2015 and 2016 editions.

(Fig. 3b) to build twice the 3-D models, thus having duplicate results for a quality check. The evaluation system is analogous to that of the previous test with the coin. Once the scene is scanned (Fig. 3c), the fixed calliper measure is used to scale the 3-D model. The participants had to send the XYZ coordinates of four aligned points (Fig. 3d). The particularity of the proposed problem is that the four points belong to a line parallel to the X-axis.

The system to evaluate the measurement quality of the model based on this parallelism serves to avoid cheating. It should be remembered that to modify the position of a point in the 123D Catch software, it is necessary to move it in one of the photos in which it has been marked. In this way, if any team wants to modify the distances to match the theoretical values, the parallelism of the adjusted line will also be modified, thus making the changes detectable by the organizers. Therefore, the possibility of cheating using this software was significantly reduced. It also must be noted that all the participants are requested to deliver the project files and the photos, and the results are carefully reviewed by the project staff.

The measurement quality is evaluated from the differences observed in the coordinates of each point for both repetitions.

2.2.3. Coordinate measurement over a scanned object (2017 to 2020 ed.)

The latest variant of the metrology test was implemented in 2017. Although many schools use callipers as didactic tools, not all the participating schools around the world may have these tools available for the classroom to perform the test. Furthermore, Autodesk 123D Catch was discontinued in 2016, which required an alternative program. The existing free software at that time did not work with all the major operating systems (Windows, Linux and iOS) or did not allow for coordinates to be measured directly. To address these problems, a new test was designed, aiming for participants to extract 20 accurate distance measurements from a common 3-D model.

Participants are provided with an arbitrarily scaled 3-D model of an object (Fig. 4a) with reference distances indicated using a calliper in the scene. This 3-D model is entirely produced by the *D3Mobile* staff (including the image set collection and processing steps) and is made available in *.obj* format through the website so that all participants work with the same file in this 3rd test. Four reference points and 40 other randomly located points are materialized in the scene with cross targets (noncoded). The ground truth coordinates of these points can therefore be automatically extracted by the organizers during the photogrammetric processing of the model in Photoscan (Agisoft, Saint Petersburg, RU), a former version of Metashape. It should be noted that the accuracy of the automatic measurements is estimated in a quarter pixel, which clearly surpasses the accuracy of hand-operated measurements [70,71]. Additionally, some coded targets are introduced in the scene in order to improve the accuracy of camera calibration and orientation processes.

The participants used open-source Meshlab (ISTI, Pisa, IT) software to open the randomly scaled *.*obj* model, measure the reference coordinates (with manually picked points) and apply the correct scale factor. As in the previous trials, after having the correctly scaled model, participants were asked to measure the coordinates of 40 points on the surface of the object.

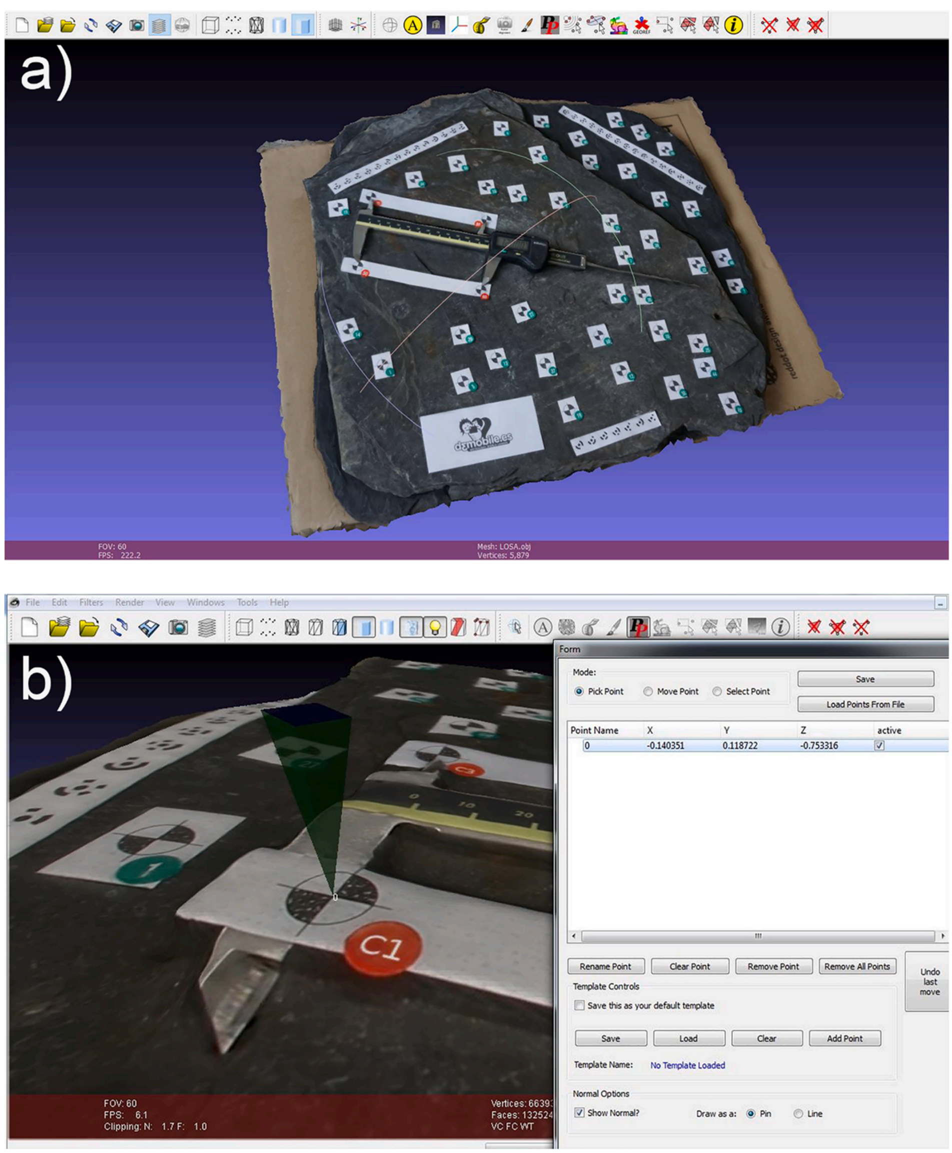

Fig. 4. 3rd test of metrology in D3Mobile 2017 to 2020 editions.

3. Results and discussion

3.1. The project-based e-learning approach

3.1.1. 3-D models

Smartphone apps for 3-D scanning have been demonstrated to be a great way for any nonexpert user to start with photogrammetry. The experiences of these eight years of *D3Mobile* have shown that "learning by doing" constitutes an effective way of practically transferring 3-D skills and know-how. A previous short explanatory theory contained in a text guide or in a video tutorial, complemented with the support of a teacher, is in most cases sufficient for participants to start scanning real objects. Some of the final reality-based 3-D models look convincingly lifelike (Fig. 5), which usually exceeds the initial expectations of the participants. The map of the winners from all previous editions (http://d3mobile.es/ganadores_2020.php) and the entire list of 3-D models (https://sketchfab.com/d3 mobile-m world league) can be found online.

3.1.2. Feedback from the participants

Furthermore, the project also sought to allow students to approach metrology science and photogrammetry from a more practical and less theoretical perspective by means of the integration of different challenges. Based on the feedback provided by the participants (Fig. 6), the project is believed to meet its initial expectations as a training action.

Fewer participants' responses to open questions were of a *meta*-analytical nature, and most of them tended to express specific complaints such as short deadlines, the difficulty of some quizzes or software compatibility issues. However, it is also gratifying to see that participants generally recognize that they have learned about "metrology", "photogrammetry" and "3-D". These are some typical quotes:

> "We believe that the project is well planned since it is accessible to everyone who wants to participate and opens up new possibilities for many young people who want to know more about 3D scanning with mobile phones."
> "We enjoyed doing this activity because we think it encourages teamwork and it allows us to learn about metrology in a more pleasant way."
> "I think it's an excellent initiative to promote photogrammetry. I loved knowing the process of 3D modelling and its applications."

Overall, the response of teachers to the project is also very positive. A better understanding of traditional "hard-to-teach concepts" (e.g., accuracy, precision, and uncertainty) compared to those of nonparticipating peers has been highlighted. They also agree that the kids showed a particular "striving for accuracy" with thoroughness and attention to detail in every measurement procedure (Fig. 7).

The current level of development of digital close-range photogrammetry has enormous educational and scientific value for amateurs who can use online free didactic materials and low-cost software. To date, several works have successfully proven various utilities and training approaches targeted at different interest groups, including researchers, semiprofessional users and academics with expertise in geomatics or other technical careers [34,86] and even high school students approximately 16–17 years old [75]. The *D3Mobile* project proves that with proper training methodologies, even 13 year old children can be effectively instructed in the use of 3-D reconstruction techniques using e-learning resources.

3.2. Precision assessment

While evaluating the potential of the PBeL to present the basic procedures of photogrammetry to amateur users is one of the objectives of this project, it is also crucial to emphasize the importance of assessing the metric quality of the resulting 3-D models. Therefore, the results of the 3rd test constitute important feedback for both the participants and for us. Although precision in photogrammetry is dependent on multiple factors, the results presented in this section for each edition provide an interesting estimation of the limits of the precision achievable by amateurs by using smartphone-based photogrammetry and simple small-sized objects.

3.2.1. 2013–2014 editions

The measures of 4 point coordinates over 3 different coins performed by the CEM resulted in a standard deviation (Std Dev) less than 0.067 mm (Table 2). As point M1 has been established as the coordinate origin, there is no deviation for it. The same occurs for the Z coordinates of M2 because it is contained on the XZ plane and with coordinates Y and Z of point M3 that belongs to the X-axis.

With Std Dev values lower than 0.07 mm for the coin measurements, these results can be considered reference values for coordinates. It should be noted that the precision obtained with photogrammetry can be initially estimated to be ten or more times lower.

Fig. 5. Samples of objects scanned by participants.

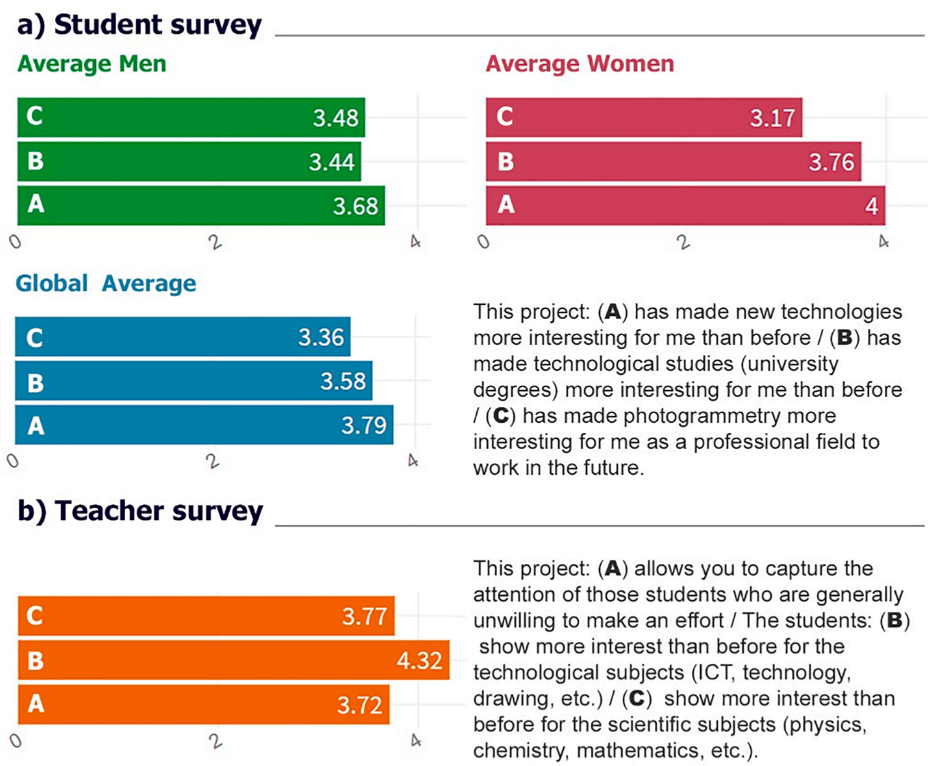

Fig. 6. Some questions of the survey after participating in D3Mobile 2020. The ratings range from 1(strongly disagree) to 5(strongly agree).

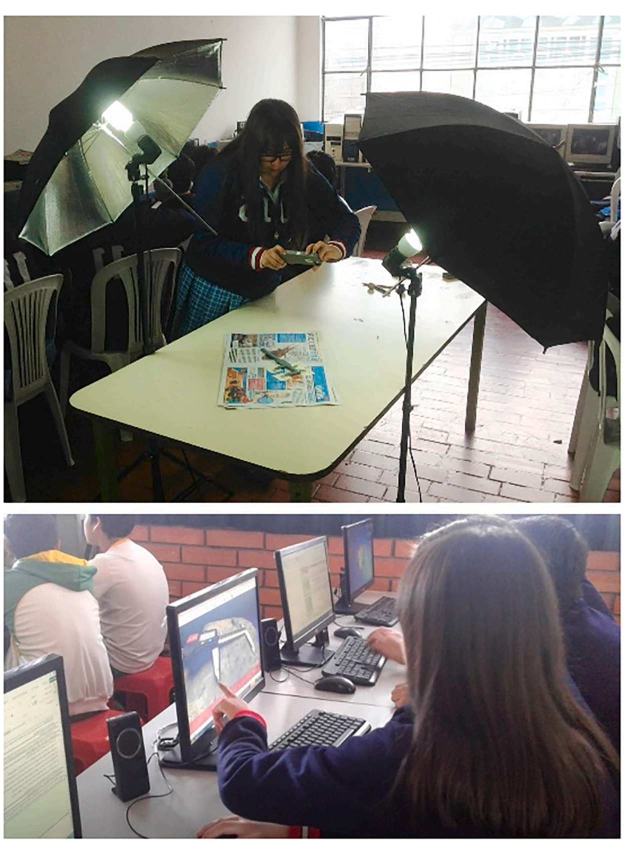

Fig. 7. Participants working in the 3rd test learned to measure with the calliper and their mobile phones.

The differences between the results obtained by the participants when directly measuring the 3-D reconstructed model and the measurements obtained by the CEM are shown in Table 3. These results correspond to the differences of the reference coordinate measurements and those equivalent values submitted by the 56 teams participating in the 3rd test in 2013 and 19 teams in 2014.

3.2.2. 2015–2016 editions

In these editions, the XYZ coordinates of points P1 to P4 were measured by every team. The results obtained by the participants are shown in Table 4.

The extreme values of the deviation are due to errors made by the participants, probably because they picked a different point than the one requested. When these points are marked over a calliper, it is relatively easy to make such mistakes. The guidelines recommend repeating each measurement twice just to avoid this situation. In any case, these data are part of the analysis.

Establishing comparisons from the data obtained in these two editions is only feasible if relative precisions are used to express the results since in photogrammetry the error is also dependent on the size of the scene. A hypothetical camera system with a 1:k precision could distinguish measurements down to 1 mm across a k-mm-long scene [4]. Therefore, the results should be expressed in proportion 1:k, where k is the size of the diagonal of the scene divided by the reported standard error.

The standard error of the mean (SEM) is

$$(\sigma\overline{x}) = \frac{\sigma}{\sqrt{n}} \tag{1}$$

where:

$\overline{x}$ = the samplés mean

σ = Std Dev

n = the sample size

The metric 1:k presented in Table 5 has no inherent scale and is only a rough estimate of the true precision, which is actually variable within

Table 2
Deviations in the coordinates over 3 coins with Mitutoyo Ultra Quick Vision (CEM).

Coord (mm)	X_{M1}	Y_{M1}	Z_{M1}	X_{M2}	Y_{M2}	Z_{M2}	X_{M3}	Y_{M3}	Z_{M3}	X_{M4}	Y_{M4}	Z_{M4}
Std Dev (mm)	0.000	0.000	0.000	0.050	0.055	0.000	0.052	0.000	0.000	0.035	0.067	0.027

Table 3
Deviations in the coordinate measurements over the faces of the coins in D3Mobile 2013 and 2014.

Year	Max. (mm)	Min. (mm)	Mean (mm)	Std Dev (mm)
2013 n = 56	3.542	0.002	0.178	0.229
2014 n = 19	1.703	0.006	0.027	0.237

Table 4
Deviation in 4-point coordinates over the calliper in D3Mobile 2015 and 2016.

Year	Max. (mm)	Min. (mm)	Mean (mm)	Std Dev (mm)
2015 n = 18	29.880	0.003	0.408	3.491
2016 n = 28	26.176	0.001	0.432	3.648

Table 5
Relative precision of the D3Mobile test measurements with mobile phones.

Year	Std Dev (mm)	n	SEM (mm)	Scene (mm)	1:k
2013 (1)	0.300	56	0.040	100	1:2494
2014 (1)	0.297	19	0.068	100	1:1467
2015 (2)	1.478	18	0.348	500	1:1722
2016 (2)	1.180	28	0.223	500	1:2690

(1) Coin test, and (2) Calliper test.

every image [96]. Despite this, it can be useful to estimate the relative precision achievable with photogrammetry using a mobile phone camera. The results obtained by the group of amateur users participating in this challenge are approximately 1:1400–1:2600. These precisions are comparable to some experiments performed by researchers or expert users using DSLR cameras (e.g., Mokroš et al. [97] achieved a relative precision of ~ 1:2000 in tree diameter measurement (~0.5–0.8 cm) and Castagnetti et al. [98] obtained ~ 1:1300 when applying SfM to rock art documentation in scenes ~ 3 m in size).

There are some comparative works such as Wrózyński et al. [99] that have found no significant differences in accuracy between the 3-D models generated with compact cameras and current mobile devices. These results are derived from two different scale tests; however, not all previous studies agree with this equivalence. Micheletti et al. [66] compared the accuracy of photogrammetry models of a river bank at close-range (10 m or less) using smartphone imaging technology (iPhone 4 with a 5 MP camera) vs. a semiprofessional Nikon D7000 camera (16.2 MP) and commercial software (Eos Systems Inc. PhotoModeler) vs. a free tool for processing the images (Autodesk 123D Catch). The reported results of their study show a significant loss of accuracy using smartphones and the free cloud-based processing of 123D Catch. However, the application of the same methods to an entire alluvial fan system showed a linear degradation of precision with the image scale. Authors such as Lerma et al. [62] and Remondino et al. [100] also suggested that neither the low-cost nor freeware services that were analysed by them (i.e., Apero, Bundler/PMVS2, Photosynth, Visual SFM, 123D Catch, etc.) can be considered completely reliable for the digitization of complex and very large datasets and have poor repeatability. It should be noted that when using absolute errors or even using relative precisions, the reported results of different studies and scenes are hardly comparable. Nonetheless, the objects scanned by the participants of D3Mobile are generally quite small and simple; therefore, the geometry of the scene also has little complexity and, generally, can be covered using few photos taken in circular paths. The 3-D reconstruction of more complex objects or larger structures may also require complex processing steps (i.e., a rigorous process of camera calibration and optimization, ground control point (GCP) marking, multiblock alignment, etc.) [101]. The object selection in D3Mobile is driven by the organizers' suggestions, thus avoiding too complex of objects and scenes to be digitized and simplifying the problems related to object and scene complexity as much as possible. Moreover, they have a recommended limited object size (~1.5 m) in the guidelines, although the digitization of very small objects is often not simple at all but not comparable to buildings or the environment. Furthermore, it is also important to state that usually the participant can control the scene characteristics (if indoor), such as illumination. Most likely, all these issues also have a significant impact on achieving relative precisions very similar to those of studies using commercial software and DSLR cameras.

3.2.3. 2017–2020 editions

In the most recent editions of the project, the reconstructed 3-D model was already delivered to the participants at the beginning of the test. The distances measured by the participants after scaling the model are compared with distances between the markers automatically detected by the software used by the staff (Table 6).

Beyond quantitative results, with this exercise, the participants became aware that photogrammetry itself is a scaleless method. The reconstructed 3-D models and the translational component of camera motion are defined up to an unknown scale factor. Since the object and the camera poses from the epipolar geometry are scaled together, it is not possible to calculate the scale factor exclusively from the images without any other external knowledge [102]. A simple and commonly adopted method in photogrammetric registration is to introduce some object with known dimensions (e.g., scale bars) into the scene being photographed [59], and this is exactly what the participants do in the 3rd test. However, in addition to the error due to the estimation of camera poses, the method introduces two new sources of error in the final scaled model, whose accuracy also relies on the accuracy of the reference distances and the accuracy with which those corresponding distances are selected in the model.

The deviations obtained when measuring reference distances (Table 5) after rescaling a model of a given object (~60 cm) demonstrate that the rigorousness of the scaling procedure becomes crucial when seeking to accurately scale small objects. Thus, nonexpert users are aware of the reliability that can be obtained with this method and understand that it is better suited to large-scale reconstructions for which the measurement error can be negligible compared to the distance being measured.

4. Conclusions

The popularisation of photogrammetry as a measurement tool requires training actions directed to a wide range of nonspecialist and amateur users who may use this technique while not being aware of its principles and rigorous use.

Table 6
Deviations of 20 distances measured over the 3-D model.

Year	Max. (mm)	Min. (mm)	Mean (mm)	Std Dev (mm)
2017 n = 18	2.415	0.005	0.455	0.473
2018 n = 25	2.469	0.001	0.014	0.237
2019 n = 26	2.951	0.002	0.039	0.234
2020 n = 18	1.977	0.001	0.234	0.332

The participants of the *D3Mobile* project were provided with the basic photogrammetric principles to start scanning using their own mobile phones and with the technical capability to understand and objectively evaluate the accuracy of the results. The designed PBeL approach allowed participants to become more motivated by actively engaging them in the process of learning and gaining different types of skills and taking responsibility for their own learning. The accuracy assessment of the participantś models demonstrates that significant metric quality (~0.1 mm error or ~1:2,000 relative precision) can be achievable for noncomplex/small-sized (<1.5 m) objects when a rule-based procedure is followed.

The analysis of the achieved accuracies and the feedback provided by the participants taught us very valuable lessons in the design of further training actions and STEM projects for efficient educational outreach in photogrammetry and metrology. This initiative present new methods of teaching in those fields and encourages students from early ages to pursue related postobligatory studies. Furthermore, this work also highlights the potential of low-cost photogrammetry using a smartphone for any type of amateur user trained via e-learning.

CRediT authorship contribution statement

J. Ortiz-Sanz: Conceptualization, Methodology, Funding acquisition. **M. Gil-Docampo:** Supervision, Methodology, Investigation. **T. Rego-Sanmartín:** Conceptualization, Software, Validation. **M. Arza-García:** Investigation, Software. **G. Tucci:** Conceptualization, Methodology, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thankfully acknowledge the financial support from ISPRS Education and Capacity Building Initiatives 2020 and the Xunta de Galicia through the grant for the Consolidation and Structuring of Competitive Research Units within the Galician University System 2020-22 (ED431B 2020/25) and FECYT—Ministerio de Economía y Competitividad (FCT 12-3495, FCT 13-5961, FCT 14-8038, and FCT 15-9481). We would also like to thank our sponsors and collaborators: Universia, BQ, Autodesk, National Geographic Institute (IGN), City Council of Lugo, Provincial Council of Lugo, Spanish Center of Metrology (CEM), Vodafone Foundation, CEAPA, City Council of La Coruña, Fundación Barrié, ANPE, CSI-F, Comforp Foundation, PCE, Univ. Tecnológica Nacional (Argentina), Fundación Mujeres, and EDUCACION 3.0, among others.

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