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Solutions and limitations of the geomatic survey of an archaeological site in hard to access areas with a latest generation smartphone: the example of the Intihuatana stone in Machu Picchu (Peru)

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ABSTRACT
Archaeological remains need to be geometrically surveyed and set in absolute reference systems in order to allow a "virtual visit" and to create "digital twins" useful in case of deterioration for proper restoration. Some countries (e.g., Peru) have a vast archaeological heritage whose survey requires optimized procedures that allow high productivity while maintaining high standards of geometric accuracy. A large part of Peru's cultural heritage is located in remote areas, at high altitudes and not easily accessible. For this reason, it is of great interest to study the possible applications of easily transportable instruments. In this study it was verified how the capabilities of the latest smartphones in terms of absolute differential positioning and photogrammetric acquisition can allow the acquisition of a geometrically correct and georeferenced three-dimensional model. The experimentation concerned a new survey of the Intihuatana stones at Machu Picchu and its comparison with a previous survey carried out with a much more complex laser scanning instrumentation. It is important to note that both the photogrammetric survey and the GPS/GNSS survey were carried out with the same smartphone taking full advantage of both features of the same mobile phone. Relative comparison to an existing point cloud provided differences of 2 millimeters in mean with an RMSE of 2 cm. The absolute positioning accuracy compared to a very large-scale cartography appears to be of the order of one metre as was expected mainly due to the high distance of the GPS/GNSS permanent stations.

Section: RESEARCH PAPER

Keywords: Intihuatana stone; Machu Picchu; GNSS; GPS; SFM; Xiaomi; DSM

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1. INTRODUCTION

The geomatic survey of archaeological remains is always a difficult task due to the complex accessibility of sites whether they are located in urban or more remote areas. In fact, remains in densely populated areas have problems of accessibility because they are often located in underground areas with limited space [1]. On the other hand, remains in sparsely populated areas are often remote and difficult to reach with bulky equipment [2]-[6]. In the present work we wanted to test the geometric accuracy that can be obtained by creating a three-dimensional point cloud model from images acquired using a latest generation smartphone (Xiaomi Mi9). The three-dimensional model was framed in the geodetic datum WGS84 by means of differential measurements performed with the same smartphone thanks to the recent possibility of writing GNSS RINEX observation files made possible by the Android operating system (from version 7).

1.1. What are Intihuatana stones?

All the important Inca cities had an Intihuatana (or Intiwatana) stone, whose most accredited translation is "the place where the sun binds", it is believed that they indicated in some way the dates of the solstices.

There are many theories concerning the history of the city of Machu Picchu and the meaning of the Intihuatana stone itself, but scholars are yet to reach a consensus. Giulio Magli [7], an Italian archaeological astronomer, proposes that the Inca ritualistically travelled from Cusco to Machu Picchu. The Inca took this pilgrimage to replicate the mythical journey that the first Inca thought their ancestors took from the Island of the Sun in Lake Titicaca. Magli believes that the pilgrimage concluded at the highest peak in the main ruins, the steps leading to the Intihuatana stone.

In any case, the Spanish invaders, wanting to abolish the Inca religious beliefs, soon after their arrival in Peru in the fourteenth century destroyed almost all the Intihuatana stones they found in the various cities except for some of them, including Machu Picchu, probably because of the city's difficult accessibility (Figure 1). This last theory, however, contrasts with the fact that the city of Machu Picchu was never really completely "lost" but only abandoned, the inhabitants of the area have always known its existence and led the first scientific research missions at the beginning of the twentieth century [8].

1.2. Latest smartphone geomatic capabilities

Mobile phone technology is producing cameras with increasing resolution, with some of the latest smartphone models reaching 100 megapixels [9]. It is important to consider that resolution alone is no guarantee of correct photogrammetric reconstruction; the limited size of a mobile phone's camera does not allow to achieve the geometric characteristics of a Digital Single Lens Reflex as well as of a photogrammetric camera. Liquid lens technology is also soon to be released, which will make the optical sensors of smartphones much more versatile but, on the other hand, calibration or self-calibration of the optics will be more complex. In any case, smartphone images have provided interesting results, especially considering their easy transportation [10], [11].

In these and other works in the literature on the use of smartphones for photogrammetry, quite variable precision and accuracy have been observed, ranging from tens of centimetres [10] to a few centimetres [11], the causes of this variability are still being studied by the scientific community. A very important factor is the use of Ground Control Points (GCPs) without which there are poor and uncontrolled results [12], [13]. Other factors that influence the final results can be: the size and shape of the object to be detected, the acquisition distance and, obviously, the quality of the camera optics; it is precisely because of this last factor that it seems that the most recent smartphones are getting closer and closer to the classic professional cameras, which in any case almost always give more accurate results [10].

At the same time the Android operating system has recently (August 2016) released the possibility to access to raw Global Navigation Satellite Systems (GNSS) measurements on several (but not all) Android devices, allowing to write phase and/or code observations in a Rinex file similar to the procedure employed by professional receivers, such as it happens for geodetic measurements [14]. Mobile phone manufacturers, stimulated by this availability, have made terminals containing dual frequency capable chips which potentially allow for improved accuracy due to the possibility of estimating, as is known, the delay of the satellite signal due to the crossing of the ionosphere. Unfortunately, till now, double frequency GNSS chips embedded in mobile phone limit this possibility to GPS (“L1/L5” frequencies) and Galilelo constellations (“E1/E5” frequencies) while GLONASS and Beidou, can be observed only in single frequency. This limitation combined with GNSS smart phone antennas once again of reduced dimensions, and other hardware limitations, do not allow to reach the millimetric accuracies of the geodetic receivers but metric and decimetric accuracies are possible [15], [16].

The combined use of these two features of modern mobile terminals is of particular interest, because what most affects the quality of three-dimensional models from photogrammetry is the presence and accuracy of control points that are needed to improve the intrinsic geometry of the camera, to georeference the model and scale it correctly. In other words, without GCPs, the model is generally deformed and only roughly georeferenced and scaled. Structure from Motion (SfM) algorithms typically use the positions that they read on the single frames that are acquired by the cameras through the built-in GPS/GNSS receivers in point positioning mode which produces accuracies in the range of tens of meters.

The possibility to acquire ground control points (GCPs) and SfM images from one single device with potentially decimetric or centimetric accuracy disclose new possibilities for prompt surveys, especially in areas with access difficulties such as archaeological ones.

2. MATERIALS AND SURVEYS PERFORMED

As already mentioned, the Intihuatana stone of Machu Picchu is one of the few that can still be observed, however, given its historical and cultural importance as well as damages caused by tourists in the past, access is restricted.

Furthermore, the site of Machu Picchu is, as is well known, not easy to reach, since it is an entire Inca city within which the accessibility routes are those of the time and obviously cannot be modified. It should be noted (again Figure 1) that the Intihuatana stone is practically at the highest and most central point of the site, and therefore at the most difficult point to reach with heavy instruments. All of the above shows that the survey of such an archaeological remain may require a complex logistical and authorisation process to be carried out using traditional techniques. The interest in studying the geometric characteristics of the Intihuatana stone, and in particular its alignment with respect to the geographic North, suggested that it would be advantageous to use a recently released smartphone, which has photographic and positioning characteristics useful for the reconstruction of an accurate three-dimensional model.

In particular, smartphones with up to five different focal lengths have recently become popular, allowing surveyors to select the most suitable optics for the survey at hand without having to use optical zooms, which require varying calibration parameters, making the process much more complex.

Nevertheless, it is necessary to calibrate the terminal for each of the optics in use and care must be taken to ensure that the specific calibration for that smartphone lens is applied to each acquisition. It is actually quite simple to change the optics, for example in the Android operating system, in the "pro" mode of the camera application, it can be changed instantly between the various optics available (three in the smartphone used in this test, but up to five in more recent smartphones) much more quickly than with traditional cameras.

Figure 1. The Intihuatana stone location in Machu Picchu.

In this regard, it is perhaps worth mentioning the announced (by Xiaomi company) imminent release of the first smartphones with liquid lenses, which promise to significantly improve the quality of leisure photography by allowing different focuses to be used in the same image, but these same features could create difficulties for the correct use of the photogrammetric equations that have traditionally been written for solid-state optics.

Anyway, the latest generation devices allow to set the camera focus mode as well as the aperture and the shooting time like a professional camera, furthermore the latest generation high-end smartphone are equipped with several cameras characterized by different focal length. Such configuration allows to conduct a survey using an adaptive and swift approach, specifically the user can easily modify the focal length switching from a camera to another, in order to choose the suitable one in according to the environment conditions.

The focal length is an important parameter, since it set the Field of View of the camera, moreover, even others camera calibration parameters such as distortion coefficients are strictly related to the focal length [17].

A Xiaomi Mi9 terminal was used for this experiment, which is equipped with Sony 48 MPix ultra wide-angle AI triple camera: a 48 Mpix primary camera with a pixel size of 0.8 μm $f/1.75$ aperture, 12 Mpix telephoto camera with a pixel size of 1.0 μm $f/2.2$ aperture and a16 Mpix Ultra wide-angle lens with a pixel size of 1.0 μm $f/2.2$ aperture [18].

At the time of the present experimentation (April 2019) this camera was considered at the top range of mobile phone cameras, although it has been overtaken by other models in recent months [9]. Its size (157.5 x 74.7 x 7.6 mm) and weight (173 g.) do not generate any transportation problems and it is even possible to take more than one terminal with you for specific needs. At the time of experimentation its cost was that of an average mobile phone, just over 500 euros, but now it is possible to buy it refurbished for less than 300 euros, to give an idea of the investment required, which is certainly lower than that of other instruments that could be certainly more accurate.

In the present experiment, the feature of interest was recorded

Figure 2. Three-dimensional model of Intihuatana stone, acquired and georeferenced with Xiaomi Mi9 smart phone.

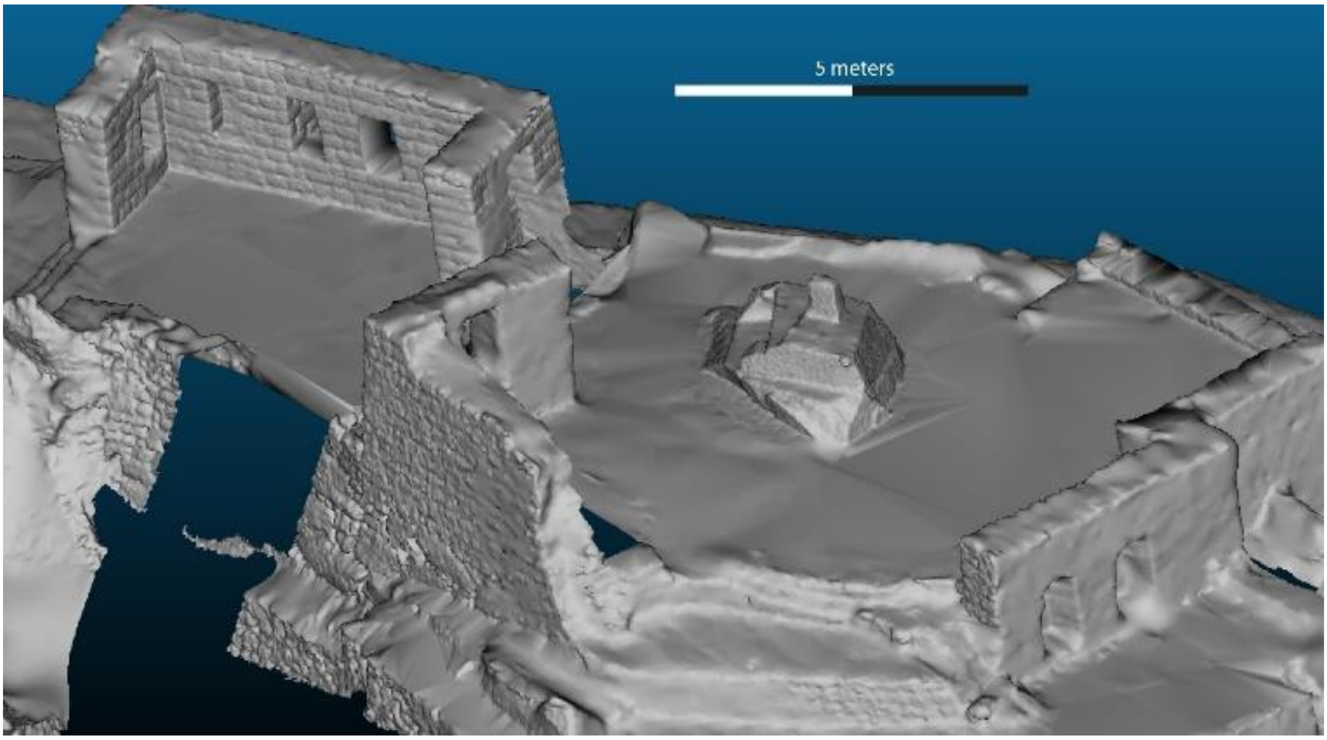

Figure 3. Reference laser scanning model.

in its entirety with intermediate optics. Additional images were acquired using wide angle optics for comparison. The geometry and sequence of the images to be acquired for correct photogrammetric reconstruction using smartphones is the subject of lively debate in the scientific community, which has also developed useful guidelines [19]. For this experiment, the authors have decided to proceed according to their experience gained in previous experiments [1], [2], [10] and therefore to use mainly the intermediate focal length with a single horizontal strip, maintaining an overlap between one frame and the next never minor than 60 % in the longitudinal direction.

The images taken from different points of view, along the entire accessible area near the Intihuatana stone, were subsequently processed with Agisoft Metashape software version 1.5.0 [20], obtaining a complete three-dimensional model of the visible part of the stone itself (Figure 2).

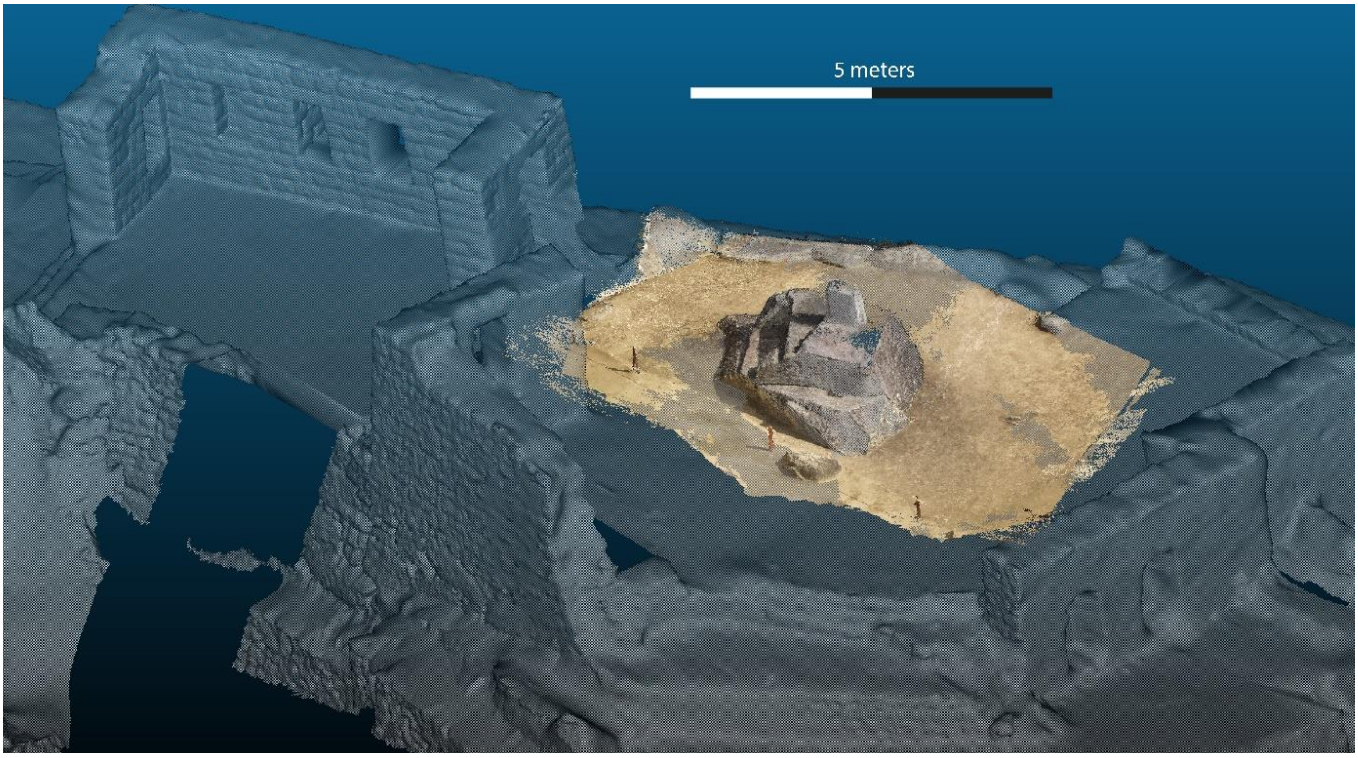

Figure 4. Reference laser scanning model and photogrammetric model co-registered.

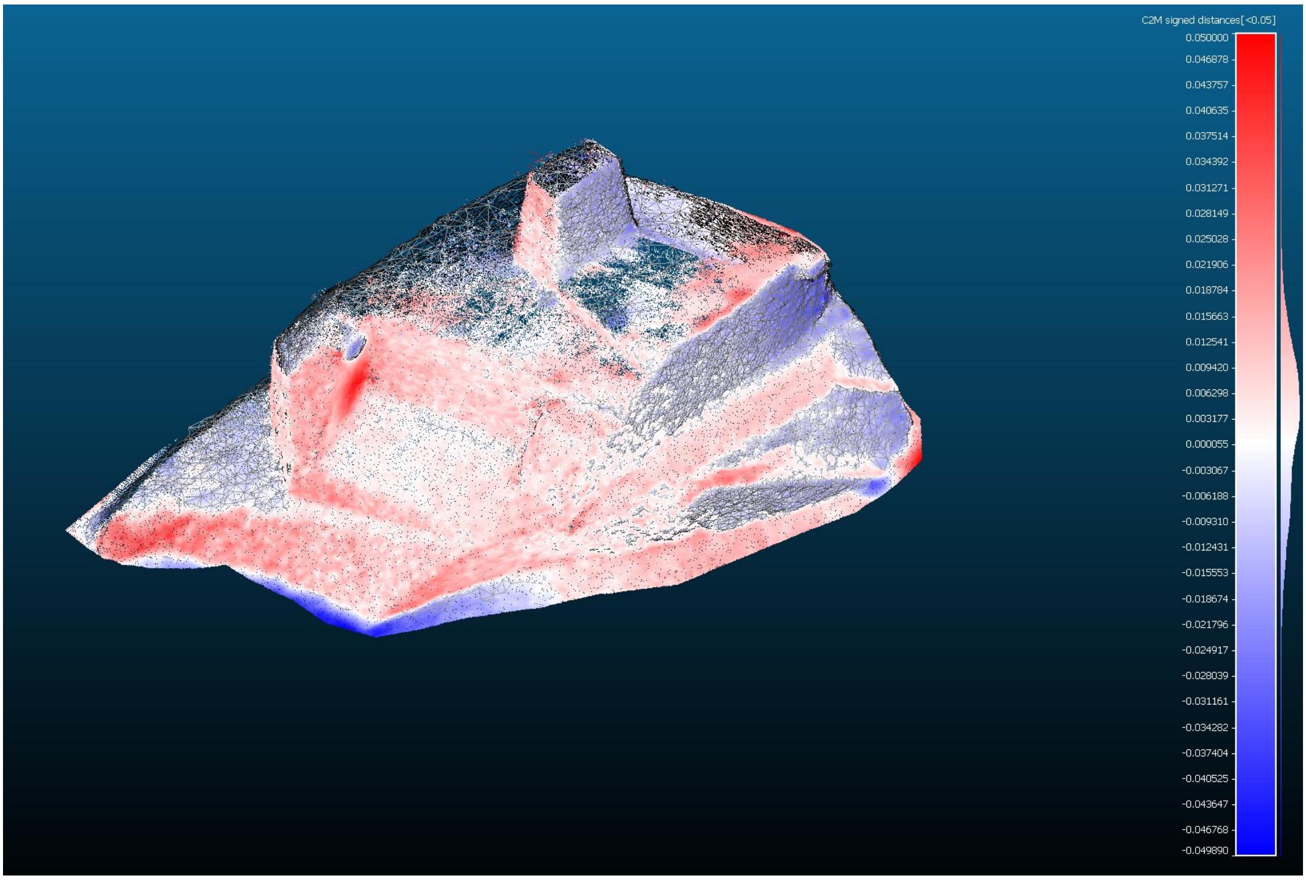

Figure 5. Reference laser scanning model and photogrammetric model compared with C2M distance signed tool (distances are in metres).

Image processing in the Metashape software requires personnel with at least basic photogrammetric knowledge, but many of the functions are automated, so the time required by the operator is reduced to a few hours, while processing time can be up to a few days on average performing hardware and for very detailed models. Obviously, one of the most important factors for processing time is the number and resolution of the images.

The smartphone itself was used in static mode to collect ground control points from the only natural points measurable on the 3D-model obtained by SfM which were the tops of the fence posts (Figure 2). We used three points on the fences; the fourth point had in fact a less extensive view of the sky and gave results that were not entirely congruent with the other three and is a likely outlier; it is therefore only included in the photogrammetric software as a Check Point (CP) and consequently not used to estimate the rototranslation of the model. We could not use artificially marked points because this would have required specific permissions and the blocking of tourist flow. Of course, from a photogrammetric point of view, it is much more correct to survey points all around the monument even with artificial targets but in this case, it was not possible. However, we decided to carry out the experimentation even in these unfavourable conditions because they are very similar to those encountered in real field situations due to access difficulties or morphologies that are unfavourable for GPS/GNSS surveying, such as the presence of steep slopes near the monuments to be surveyed due to excavation works. The results are nevertheless interesting despite the less-than-optimal geometry of the points.

The survey with raw GPS/GNSS data acquisition has been possible thanks to the app Rinex ON version 1.3; Rinex ON utilizes the measurements of the new Android Raw Measurements API to produce RINEX Observation and Navigation Message Files. The app was written by NSL as part of the FLAMINGO project [21]. It should be noted that, as mentioned above, the dual frequency is only observable for Galileo satellites (E5 frequency) and the latest generation GPS satellites (L5 frequency). In addition, at least on the terminal we used, the possibility of writing phase observations in the post-processing files seems to be disabled, limiting the possibilities of processing observations both in "classic" post-processing mode and in "Precise Point Positioning" (PPP) mode, which would be very useful in these areas given the great distance from the permanent stations of the Peruvian correction network. In other words, since only code observations can be recorded, acquisition times have to be prudently extended, the achievable accuracy is reduced to about 1 metre and the usefulness of the dual frequency is practically lost [22]. This limitation is even more incomprehensible given that it was possible to write phase observations with the previous model "Xiaomi Mi8" [23] of which the "Mi9" is the evolution. This determined the necessity to process the RINEX files in post processing code using the open-source software RTKLIB 2.4.2 [24], which would have potentially allowed to process all four GNSS constellations. Unfortunately, since it was only possible to operate the code difference relative to the permanent stations of the national geodetic network of Peru, it was necessary to limit ourselves to the use of only the GPS and GLONASS constellations. In particular, the observations were differentiated with respect to the stations of Abancay (AP01) and Cusco (CS01), both about 80 km away with significant differences in altitude [25]. By differentiating with respect to both stations, results were

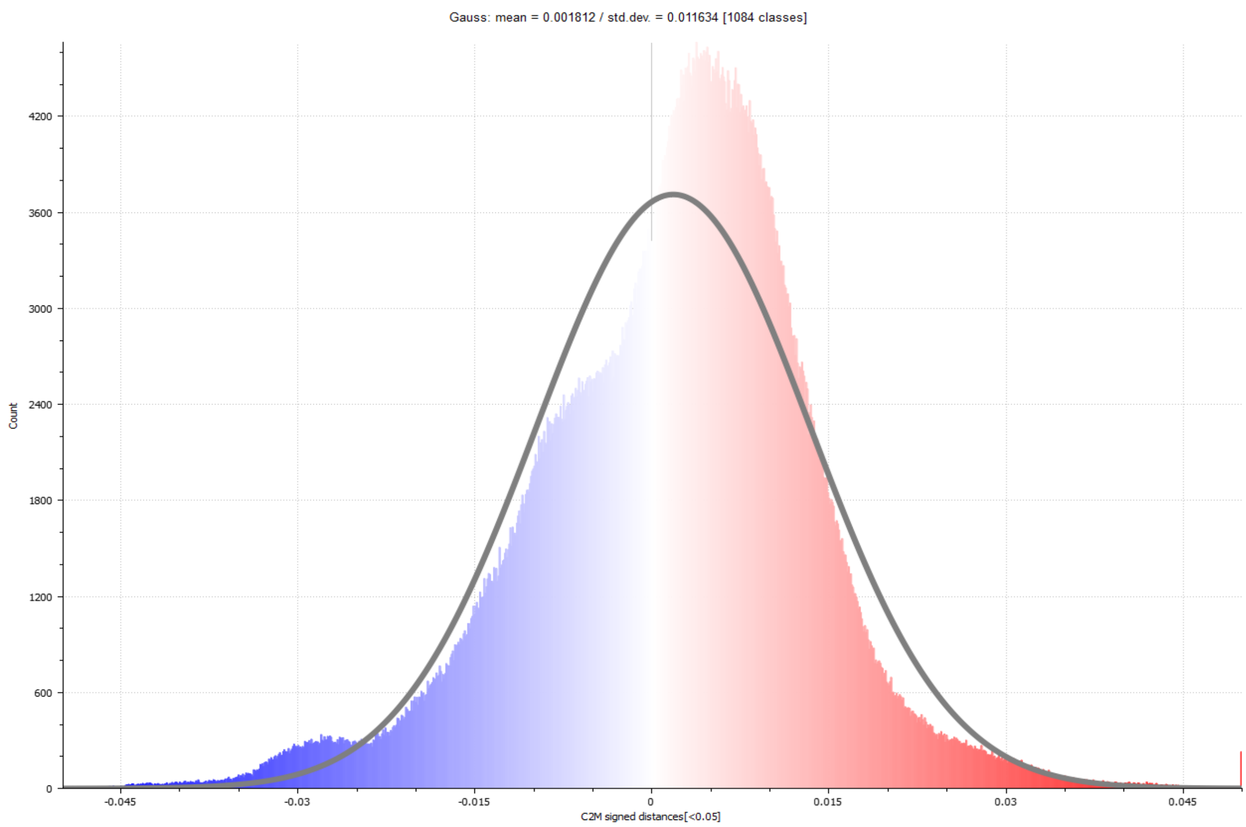

Figure 6. Histogram of differences between reference laser scanning model and photogrammetric model compared with C2M tool and the fitted gaussian curve computed (distances are in metres).

obtained with an estimated accuracy of 0.8 - 1 metre, which, considering the relatively short measurement sessions possible (so as not to hinder the flow of tourists) of about 20 minutes and the distance from the permanent stations can be considered absolutely satisfactory.

The whole survey took less than an hour and a half, most of which was spent surveying the GPS/GNSS points, while the photogrammetric survey took less than ten minutes. In this regard, it must be further specified that according to recent research [26] such times could be considerably shortened (about 5 minutes per point) if permanent real time GPS/GNSS stations (RTK) were available, as for example in Europe; on the other hand, in areas even more remote than those under study, it would be necessary to use PPP techniques [27] which require about one hour per point. All survey operations do not require any particular specialisation and can be carried out by one person.

3. RESULTS AND DISCUSSION

In order to check the results obtained from the smartphone device a comparison between the photogrammetric model and a 3D model from a LiDAR survey was performed. Indeed, the University of Arkansas [28] has released on the web a 3D model of the archaeological site of Machu Picchu performed using an Optech ILRIS-3D laser scanner, that is a long-range LiDAR (Figure 3). The laser scanner survey can be considered as reference, to estimate the accuracy as well as the completeness achieved by the photogrammetric solution.

Unfortunately, the LiDAR model (Figure 3) is not georeferenced, indeed, it is linked to a local reference system while the scale is correct. However, from the University of Arkansas web page for the specific project [29] it can be seen that the scanning resolution was set at 3 cm and that at that distance the estimated accuracy is 7 mm.

Using the classical ICP (Iterative Closest Point) technique the two models have been registered in a common reference system (Figure 4). Therefore, a comparison between the two models was performed using the tool C2M present in the open-source software CloudCompare ver. 2.10.3 [30]. For each 3D point extracted by the photogrammetric procedure was computed the signed distance from the surface derived by the LiDAR survey. The result is reported in Figure 5 using a coloured map.

A statistical analysis, of the result obtained from the comparison between the two models, was conducted. The computed distance showed a remarkable agreement as reported in the histogram of the Figure 6. Specifically, a gaussian curve fitting was carried out to the signed distance, obtaining a curve with a mean of 2 millimetres and a standard deviation of 1 centimetre.

However, it can be observed that the average is very close to zero (although there is a small amount of systematic shift), that the maximum deviations are below 5 centimetres and that most of these are in the 2.5 cm range. These results are absolutely interesting, particularly when compared with previous research [10]-[12], but it should be noted that in our case the LiDAR cloud was adapted to the photogrammetric cloud because the lidar cloud was not georeferenced. These results can therefore confirm a relative coherence between the two clouds, but not absolute.

Finally, we wanted to evaluate the possibilities of some software to reconstruct missing parts, in particular SCANN3D [31] in Android environment and TRNIO [32] in IOS environment. This evaluation was interesting in this case because the accessibility to the monument was not complete all around the monument itself due to the already mentioned protection needs. The 3D model obtained by the use of the first software was unsatisfactory and is not shown here; on the other hand, the result obtained with TRNIO is shown in Figure 4 where also some parts that are badly reconstructed can be easily detected.

It was much more complex to verify GNSS measurements accuracy, defined as the difference between the results obtained and the actual values of the same point coordinates. In order to be able to calculate this statistical parameter it is in fact, as is well known, necessary to know the true values with an accuracy higher than that expected for the measurement system on a suitable set of points. Usually, in geomatics and geodesy, such verifications are carried out using trigonometric points whose coordinates are known a priori with geodetic accuracy. Unfortunately, at the Machu Picchu site there is only one trigonometric point on maps, but it is not unambiguously identifiable in the field, which suggests that it may have been removed, as often happens at archaeological sites of considerable interest. It is obviously not possible to compare with the coverage available on the web such as Google Earth whose estimated planimetric accuracies are generally lower than those expected for our survey methodology [33].

Official large-scale cartographies of the area are not available, with the exception of a 1:750 nominal scale map produced by the Ministry of Culture of Peru in 2014 (Figure 7); considering a graphic error of 0.2 mm, its planimetric accuracy could be 15 cm, but since there are no metadata of the cartography itself, this must be considered only as a hypothesis. In any case, the comparison with this cartography showed a good agreement in line with what was verified in previous experiments [10], [11], [12], [13] even if the measured points cannot be identified with certainty because they didn't exist in 2014 and so they are not reported on the map.

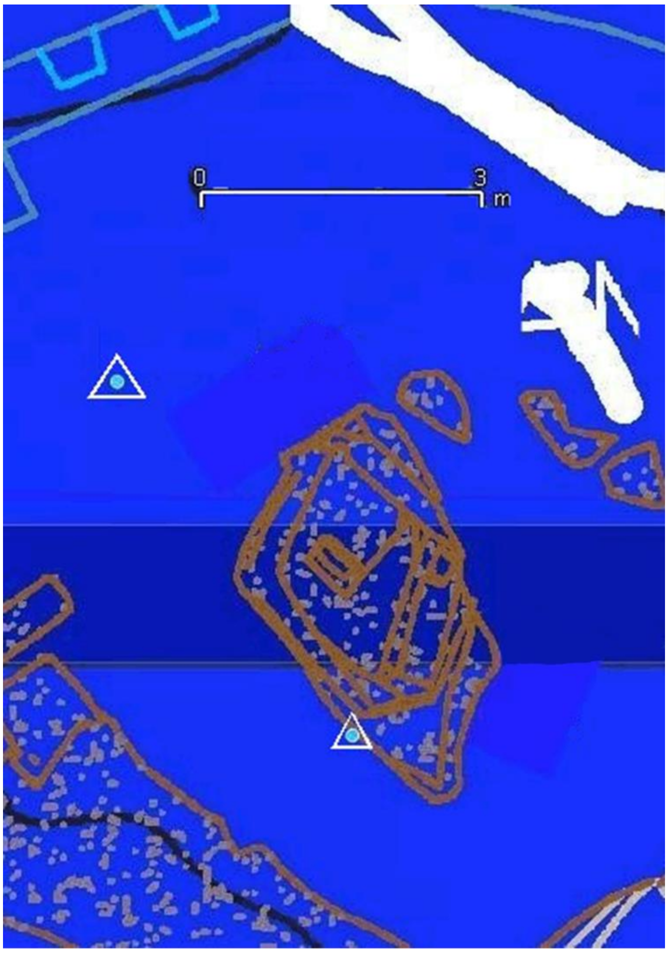

Figure 7. The Intihuatana stone location in 1:750 map and position of two of the four surveyed points (triangles).

4. CONCLUSIONS AND FUTURE PERSPECTIVES

The present experimentation has shown that it is possible to carry out a complete and expeditious georeferenced geomatic survey with the latest generation smartphone. The ease of transport and the simplicity of the operations greatly facilitates the survey work both in terms of logistics and authorisation. The final results are at least comparable with those previously carried out on the same site with laser scanning. The possible applications of such surveys are numerous, ranging from rapid and efficient documentation to the valorisation of sites that are difficult for the general public to access, but also to true photogrammetric surveys where logistical situations make it very costly or impossible to survey with more rigorous instruments.

It is interesting to study in the future the possibilities offered by smartphones that also acquire dual frequency phase GNSS observations; this would also allow the application of PPP post-processing, which could prove to be the most appropriate in such remote sites. There is also interest in studying smartphones with even more advanced optics, with particular interest in liquid optics, which are expected to be released soon.

In this experiment, the GPS/GNSS sensor and the camera of the same mobile phone were used, which allowed the minimum possible encumbrance of the instrumentation. More generally, it is not necessary that the reference points and the photogrammetric survey are acquired by the same device, also considering that the overall dimensions of the mobile phones are very small and do not create any logistical or transport problems.

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