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Use of the sensors of a latest generation mobile phone for the three-dimensional reconstruction of an archaeological monument: the survey of the Intihuatana stone in Machu Picchu (Peru')

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Abstract. The survey of archaeological monuments presents particular needs and difficulties. Such surveys must in fact be as complete, geometrically correct and accurately geo-referenced as possible. These needs, however, often face problems of difficult accessibility, the need for rapid timing and complex logistical conditions. The latest generation of mobile phones are equipped with ultra-high resolution cameras up to 100 megapixel. Although they do not have the geometric characteristics of professional cameras, they can be used advantageously for the reconstruction of three-dimensional models using Structure from Motion methodologies . At the same time, the latest mobile phones are equipped with GPS/GNSS chips that allow a postprocessing of their positioning allowing to reach decimetric/centimetric accuracies. The use of sensors integrated in a mobile phone greatly simplify the survey both in terms of transportability but also in terms of authorizations by the competent authorities as the equipment is exactly the same that most tourists who visit the sites themselves bring with them. The approach proposed and made possible by these combined features in a latest generation mobile phone have been tested for a rapid survey of the Intihuatana stone in Machu Picchu (Peru), a site with considerable logistical and organizing complexity.

1. The Intihuatana stones

All the important Inca cities had an Intihuatana 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 none of them are yet uniquely accredited. Giulio Magli [1], an Italian archaeological astronomer, proposes that the Inca ritualistically traveled 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.

Figure 1. View of Machu Picchu, in red circle the position of Intihuatana stone.

In any case, the Spanish invaders, wanting to abolish the Inca religious beliefs, 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 [1].

2. Recent mobile terminals features and their applications to 3d modelling.

The most recent mobile phones have cameras with ever higher resolution until they have recently exceeded the 100 megapixel threshold [2]. 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 the geometric characteristics of a larger photogrammetric camera. In any case, mobile phone images have provided interesting results, especially considering the easy transport of the mobile phones themselves [3, 4]. At the same time the Android operating system has released the possibility to access to raw GNSS measurements on several Android devices, allowing to write phase and/or code observations in a Rinex file as it happens for professional receivers. Mobile phone manufacturers, stimulated by this availability, have made terminals containing dual frequency capable receivers such as GPS/GNSS geodetic receivers. Also in this case the limitations to L1/L5 (GPS) and E1/E5 (Galileo) frequencies alone, combined with GNSS antennas once again of reduced dimensions, do not allow to reach the millimetric accuracies of the geodetic receivers but metric and decimetric accuracies are possible [6, 7].

The combined use of these two possibilities of modern mobile terminals is of particular interest, in fact what is missing from the three-dimensional models obtained by SfM (Structure from Motion) techniques are the correct sizing and georeferencing. This happens because SfM algorithms often 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 with accuracies limited to tens of meters.

The possibility to acquire ground control points (GCPs) with the same devices with potentially decimetric or centimeter accuracy opens new possibilities for expeditious surveys especially in areas with access difficulties such as archaeological ones.

3. The experimentation at Machu Picchu.

The Intihuatana stone of Machu Picchu is still observable and, given its importance and historical and cultural uniqueness, it is now protected, also due to damage caused by tourists in the past. For these reasons access to it for accurate detailed measurements is complex.

The complex logistics to reach the site also makes it difficult to transport traditional equipment. In order to be able to study some of the geometrical characteristics in advance, it was decided to experiment with the possibilities offered by the wide-angle lenses of a latest-generation smartphone terminal in order to reconstruct it using structure from motion algorithms. Moreover, the latest generation terminals allow in fact, using the "pro" mode of the specific Android application, the choice between different optics. The high-end smartphone configuration is to have three optics: a wide angle, a "tele" and an intermediate one. This allows you to always choose the most suitable optics for the specific survey without having to use optical zooms which, by varying the focal length of the lens itself, would vary the calibration parameters making complex the rigorous treatment of the optics itself. In any case, it is necessary to proceed to different calibrations of the different optics available (in the case of the study, three) and verify that the estimated calibration parameters are always correctly applied to each own camera.

A Xiaomi Mi9 terminal was used for this experiment, which is equipped with Sony 48MPix ultra wide-angle AI triple camera: a 48MPix primary camera with a pixel size of 0.8µm $f/1.75$ aperture, 12MPix telephoto camera with a pixel size of 1.0µm $f/2.2$ aperture and a16MPix Ultra wide-angle lens with a pixel size of 1.0µm $f/2.2$ aperture [8]

At the time of the experimentation (April 2019) this camera was considered the front end of the mobile phone cameras but the situation has changed further in recent months [2].In the present experiment, some images were acquired with the intermediate optics and a complete coverage with the wide-angle optics to make a comparison between the two optics.

The images taken from different points of view, along the entire accessible area near the Intihuatana stone, were subsequently processed with Agisoft Metashape software ver. 1.5.0 [10], obtaining a complete three-dimensional modeling of the visible part of the stone itself (Fig.2).

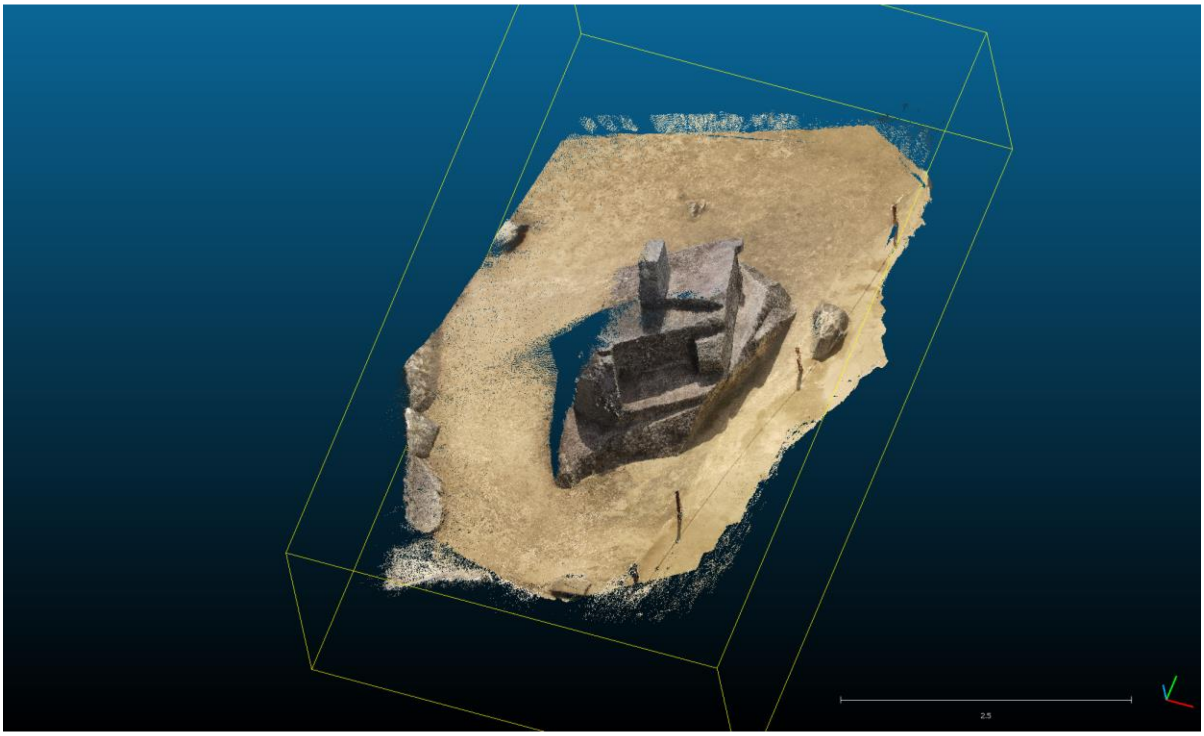

Figure 2. Three-dimensional model of Intihuatana stone, acquired and georeferenced with the same cellular phone.

The same terminal, having double frequency GNSS chips, has allowed, in a second moment, the survey in static mode of the GCP on the only natural points measurable and collimable on the three-dimensional model obtained by SfM which were the tops of the fence posts (Figure 2). This 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.

The terminal tested here has a limitation because it cannot write phase observations in the RINEX file but only code observations: this limitation affects only some terminals but, for example, not its predecessor Xiaomi MI8 [10]. For this reason it was only possible to process RINEX data in post processing as code difference. The post processing was performed using the open source software RTKLIB 2.4.2 [12] which allows to easily process the four GNSS constellations using all available frequencies.

Due to the reduced availability of official permanent GNSS stations in Peru [13] the processing of GNSS data in post processing has been were carried out with respect to the permanent stations of the Instituto Geográfico Nacional (National topographic service) of Peru (IGN), in particular the permanent stations in the cities of Abancay (AP01) and Cusco (CS01), both about 80 km away. Using both stations it was possible to differentiate the data with expected precision between 80 cm. and one metre. Given the high distance and the availability of only code information and the relatively short duration of the surveys (20 minutes per point) the results can be considered satisfactory.

4. Comparison with existing surveys.

At this stage it has been decided to compare the results obtained mainly with the available free data.

The verification of the data covered both surveying techniques: the reconstruction of the point cloud and the GNSS differential survey.

For point cloud, it was possible to compare the results obtained with those obtained using an *Optech ILRIS-3D* laser scanner between 2006 and 2009 [14].

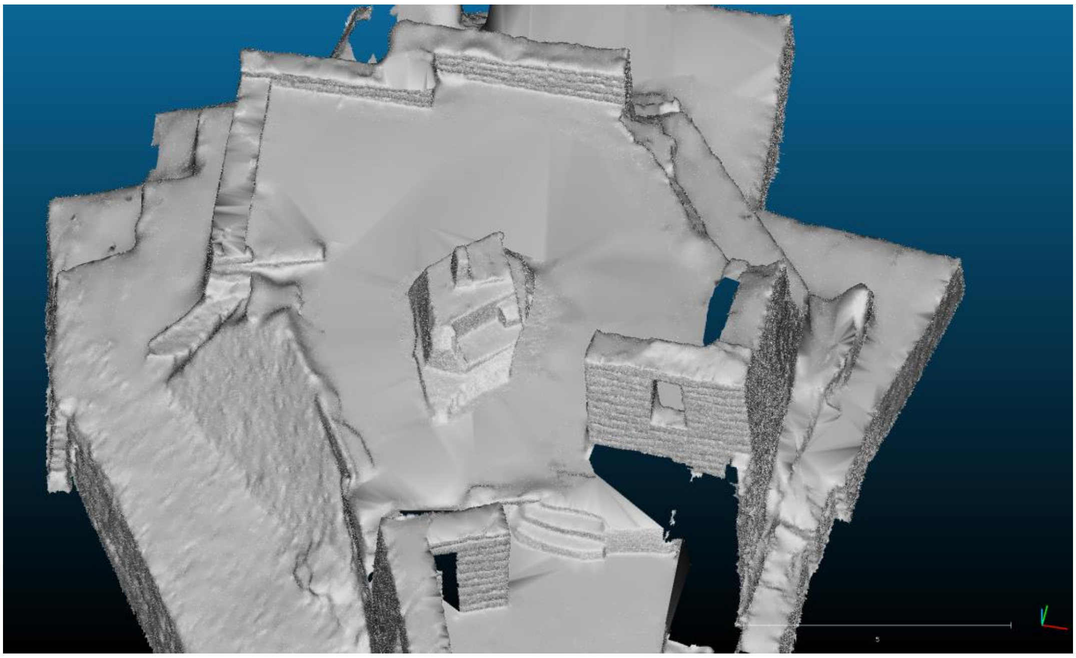

Figure 3. Reference laser scanning model.

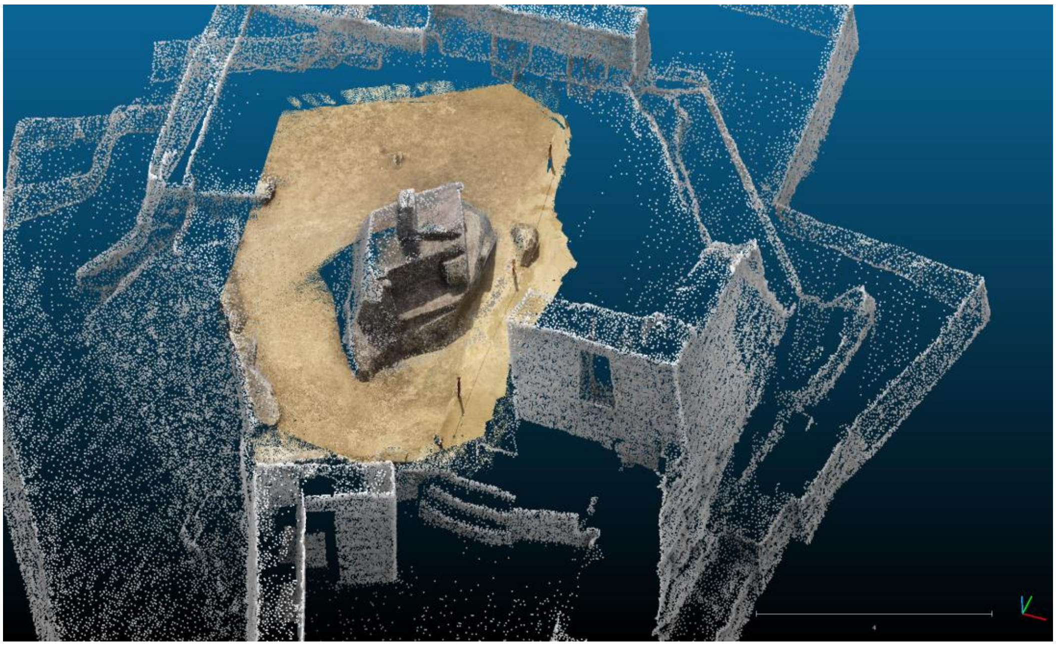

Figure 4. Reference laser scanning model and photogrammetric model co-registered.

The georeferencing of this model (figure 3) is not known but the scale should be reliable so the two clouds were compared after co-registration (figure 4) in the open source software CloudCompare ver. 2.10.3 [15]. This allowed to make a comparison between the two models using the M3C2 CloudCompare

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command considering only the points deduced from the LASER Mesh of the common area only (figure 5).

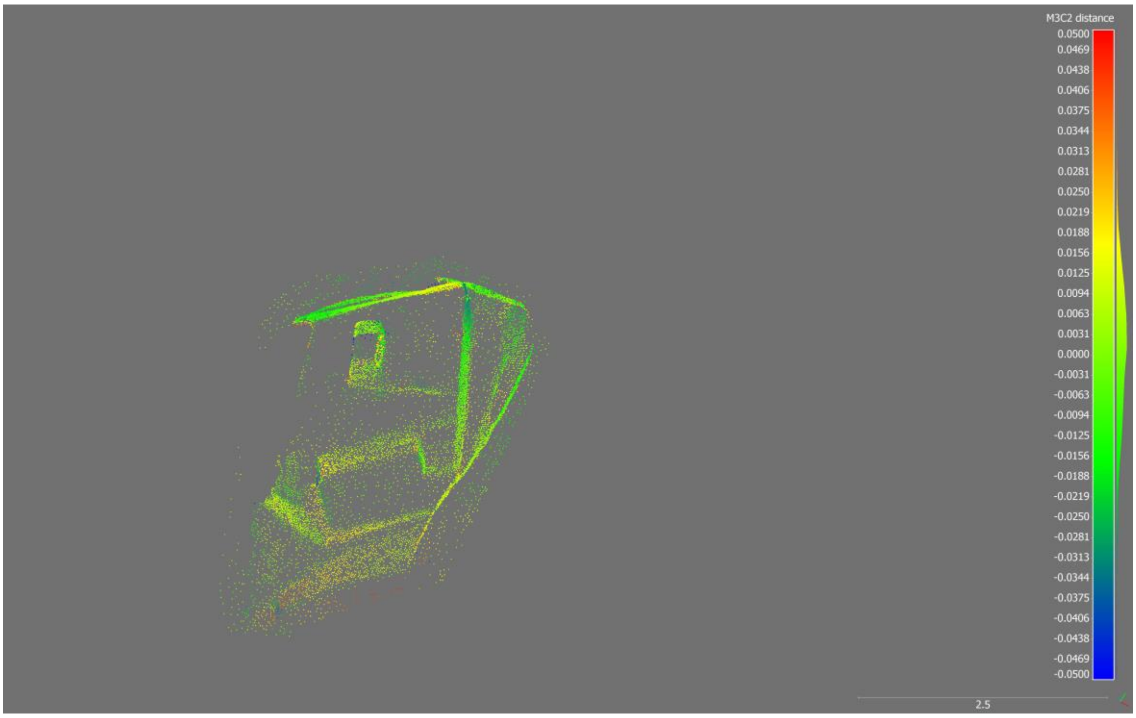

Figure 5. Reference laser scanning model and photogrammetric model compared with M3C2 command.

The comparison between the two models showed a remarkable agreement (figure 6) always keeping in mind that the models themselves have been co-registered.

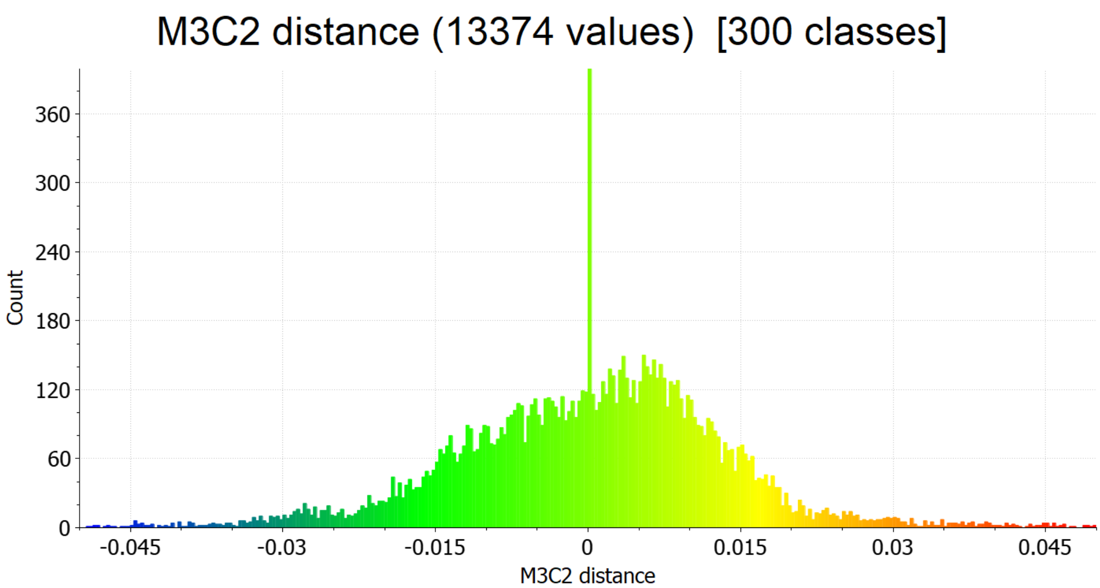

Figure 6. Histogram of differences between reference laser scanning model and photogrammetric model compared with M3C2 command.

Finally, we wanted to evaluate the possibilities of some software to reconstruct missing parts, in particular SCANN3D [16] in Android environment and TRNIO [17] 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 results of the first software with our model were unsatisfactory and are not shown here while TRNIO was able to reconstruct a complete and plausible model even if not metrically reliable in the reconstructed areas (figure 7).

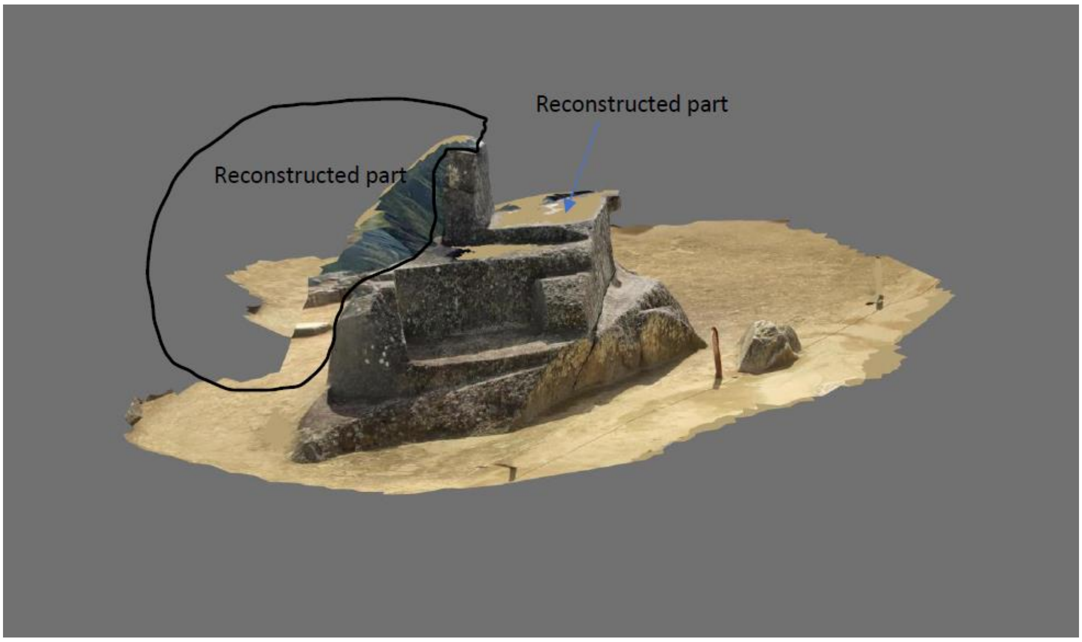

Figure 7. Photogrammetric model completed with reconstructed parts.

Figure 8. GNSS surveyed points (red) over 1:750 existing map.

The verification of the GNSS survey was instead more difficult due to the reduced accuracy of the maps we were able to access. In the site there is actually a reference point nearby but it was not possible to identify it with certainty during the survey campaign and therefore it was not considered. Compared to the various Google Earth images, even high planimetric deviations have been observed on the measured points, but probably they are mainly due to the known limits of planimetric accuracy of Google Earth [18]. The only document with comparable declared accuracy was a 1:750 scale map made by the Ministry of Culture of Peru in 2014: the comparison showed a good agreement even if the measured points cannot be identified with certainty because they didn't exist six years ago and the planimetric accuracy of the map is not explicitly declared (Figure 8). However, the result seems satisfactory and compatible with previous experiments [6, 7].

5. Conclusions and further developments

The purpose of this experiment was to verify the operational feasibility of a complete archaeological survey carried out only with the sensors available on a latest generation mobile phone. Further tests can be carried out with terminals that allow the acquisition of the phase signal in double frequency or with even more advanced optical casings. These terminals will also allow to test the possibilities of Precise Point Positioning processing, useful for rover and reference stations far away from permanent stations.

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