Spherical photogrammetry for cultural heritage metric documentation: a critical examen six years after the beginning
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1. Introduction
A technique particularly promising for the architectural survey is the so-called Spherical Photogrammetry. It will be indicated from now on PSP (Panoramic Spherical Photogrammetry). The details have been already widely described by [G. Fangi et a. 2007[2], 2009[3], 2010[4], 2011[6],[7]]. The multi-image spherical panoramas are used. They are the cartographic projection of the series of photographs taken from the same point 360° around, downloaded in the computer and then stuck together by any stitching software (Realviz Stitcher, PTgui, Autopano, etc.). The advantages are many: the very high resolution of the images, the speed of takings, the completeness of the documentation, the width of FOV (Field Of View) up to 360°, the absence of photographic distortion, estimated and corrected by the stitching software itself. The stitching technique for digital images was introduced for Apple computers in the years '90 by (Szeliski, Shum, 1997[1]), with the aim to improve the poor (by that time) resolution of existing digital cameras. For the time being the diffusion of the technique of Spherical Photogrammetry is limited for the absence of commercial products and distribution. Unfortunately talking about the technique could seem a self-referential attitude. However now the amplitude of the applications is such that to not allow doubts. And even though the exhibition of the projects may seem an act of self-congratulation, however, the number of the cases now confirmed the effectiveness and serves to validate the method.

1.1. The requirements of the technique of Spherical Photogrammetry
To enable the majority of potential operators to use the technique, in the hope to trying to solve the dramatic problem of the documentation of Cultural Heritage and Architecture, the main requirement to be met is the low-cost of the technique. The equipment must be less expensive than $ 1000-2000. No need for expensive tools such as theodolites, total stations, satellite receivers. No to the signalizations and monumentations, which have been already dismissed by Cipa (International Committee for Cultural Heritage Documentation), due to their temporariness. The technique must be fast in the taking phase and must produce a complete documentation. The only tools are reduced to the camera, the tripod, the spherical head, a longimeter, the computer, the stitching software and the software for orientation of spherical panoramas. All these specifications have been successfully met, as we will see in 2.4.1, table 1.

1.2 The description of the technique
The restitution of the surveyed object takes place by intersection of projective straight lines coming from oriented panoramas. The parameters of orientation of a panorama are six, say the three coordinates of the panorama center, and three angular directions, one of which, the one around the z axis, is the hori-
orizontal bearing $\phi_0 = \alpha_z$, or station constant. Two rotation angles around the horizontal X and Y axes (\(\alpha_x\) and \(\alpha_y\)) must be estimated to correct for the not perfect verticality of the Z axis. To facilitate the orientation, the two correction angles must be small and therefore the suitable panoramas should be quasi-horizontal panoramas. The estimation of the two angular corrections must proceed in two steps, first by putting them equal to 0, and after then, only when all the unknown points coordinates and unknown parameters have been roughly estimated, the correction angles can be computed, leading to a meaningful improvement (see table 1 in 2.4.1). The total view of the object enables a very good understanding and comprehension. Note that the stitching software can estimate and correct the camera lens distortion. The accuracy of the technique is the one typical of monoscopic photogrammetric systems say between 1/1000 and 1/5000 of the camera-object distance. Compared to traditional photogrammetry there is a drastic reduction of the photogrammetric images and models. The limits of the technique are up to now the absence of stereoscopacy and of any automation in the orientation and in the plotting phases.

1.3. Some improvements introduced
Some improvements have been introduced along the time, and they are shortly described here: the block bundle adjustment (with 4 or 6 parameters per panorama), the double taking stations, the geometrical constraints, the monoplotting, the combined use of panoramas with non-metric cameras, the photo-modeling, the combination with points clouds produced by Structure from Motion algorithm.

1.3.1. The Double taking station technique
The panoramas made with short focal length lenses are easy to orient, have a strong geometry, but they have a poor resolution. On the contrary the panoramas made with telephoto lenses have a greater resolution, a bigger average scale, an excellent informative content, but they are difficult to orient and have a very unstable geometry. Then we tried to merge the two types of panoramas to combine the advantages and eliminate the defects of one and the other. From the same point a panorama with wide angle and with telephoto lenses are taken. The coordinates of the projection center of wide-angle pano are the same as the ones of the narrow lens panorama and they can be input in the adjustment. The orientation is carried out with the first type of panoramas while the restitution is done with those of the second type. A project run with this technique is shown in figures 12 and 13. The Santa Maria della Spina church in Pisa is placed along the Arno river. The takings from the northern side have been made at a distance of more than 50 m, and two types of panoramas have been produced, 50 mm focal length and 200 mm focal length.

1.3.2. Geometric Constraints
To obtain the orientation of a block of panoramas the minimum requirement is one fixed point, one direction one distance to know the scale of the model and at least one geometric constraint on the verticality or horizontality of a line. In this manner one can avoid to use the traditional photogrammetric control
points, difficult to obtain and expensive in the production, either signalized or not. The correlation among the unknowns in the variance-covariance matrix are reduced and the quality of the geometrical block improved [Fangi, 2010, 4].

1.3.3. The Monoplotting
Due to the absence of stereoscopy, the complicated details cannot be plotted. In case that the details lay on a plane, it is possible to plot just by intersecting the projective rays coming from one panorama only with the known plane, (monoplotting) (fig.1).

Fig.1 – Cagli, Italy, the façade of the city hall, the rectified photomosaic as background of the line plot (orange), where many details came from monoplotting (restitution Livia Piermattei)

1.3.4. PSP in combination with non-metric cameras
The joint orientation and plotting of spherical panoramas and non-metric photographs improves the potential of the technique. For example in case of restitution of internal domes, the vision offered by the spherical panoramas can be sometime difficult. A better vision is given by the zenithal views that can be also the photo-mosaics obtained with the same photographs of the spherical panorama: the control points needed for the orientation of the non-metric cameras are obtained from the panorama orientation and used as input for the orientation of no-metric-cameras with the Direct Linear Transformation.

1.3.5. The photo-modeling
When the surfaces of the object are rough, uneven, it is difficult to distinguish the corresponding points in the different panoramas. The number of the suitable points for plotting are very limited. The following procedure can be helpful. The oriented panoramas are imported in a CAD environment (like 3D Studio). The known orientation parameters can be input there so the operator can
1) build a rough model
2) project the panoramas over the rough model
3) edit, modify, improve the model until it fits, at the best possible, with the panoramas projection.
Fig.2 - Petra, Jordan, Ad-Deir - The Orientated panoramas were projected over the rough model produced by PSP, enabling the editing (E.d’Annibale) and the formation of the textured model

1.3.6. In combination with Structure from Motion
As an alternative to photo modelling there are possibilities to produce point clouds by matching a series of photographs with the algorithm SFM (Structure From Motion). There exist web-services like Photosynth by Microsoft [10]: the operator must first register and then send the images. He receives back the points cloud, in an unknown scale and orientation. Better than this web-service one can download a stand-alone software package like PMVS2 by Furukawa (2006, [9]). He can use it to orient the bulk of photographs and produce the point cloud. The point cloud, in an unknown scale and orientation, can be rotated, translated scaled and linked, by means of some common points, to the wire-frame model produced by PSP. (fig.15 Notre Dame du Haut), see 2.4.

2. Some example projects
After some unsuccessful experiments of this technique of survey, finally we got some satisfactory results. By that time, six years ago, the image coordinates were taken by hand, written in a paper and later on transferred to the computer. When the method seemed to work, professional software for data collection has been ordered to a profession software house. Up to now about some 500 architectural emergencies have been documented. Unfortunately, the application of PSP for archeology has had little success: in almost all surveys we had great difficulty in orientation. Among the attempts let’s remind a segment of the Great Wall of China in Badalin, the bridge Manlio in Cagli, Italy, the Roman baths in Vininacium (Bosnia). The reason for the difficulties consists in the absence of easily identifiable points in the different views, due to uneven surfaces. In the case of the Chinese wall in addition to this reason, one more reason was the extremely difficult accessibility of the sites. Never the less there are successful projects in archaeology, say the ancient roman theaters of Sabratha and Leptis Magna, Libya, and the one in Bosra, Syria.

2.1. Elmina castle, Ghana, The block adjustment with the largest number of panoramas
For Irvine California University we carried out the survey of the Elmina castle in Ghana. Elmina castle is the most noticeable of the many castles built by Portugueses for their trade from Africa along the sea coastline, starting from
XVI c to XVIII.
The survey was executed on June 5-6, 2011. We used a Canon 60D equipped with a 28 and 50 mm lenses, a tripod and a spherical head. For the distances measurements a Disto Leica distantiometer was used. To be able to depict any possible point of the castle from at least two panoramas more than 100 panoramas were taken. The collection of panoramas was subdivided into one main network and 4 sub-projects. The restitution consists of the construction of the wire-frame of the model, including points, lines, and primitives, such as arcs, circles, and so on. From the wire-frame we form the solid model by connecting the points in the closed polygons and adding surfaces to the model. On the solid model textures are now applied to the surfaces. To improve the realism, the original photographs were glued on the walls (Fig.4).

2.2. The largest project: The Vietnam Cham towers
The Università Politecnica delle Marche, Ancona, Italy, is carrying out a research on the Cham towers in Vietnam. The kingdom of Champa existed from the 2nd to the 17th century A.D. in Vietnam and it was located near the coast of the southern part of the Vietnam. The ancient Cham people created a developed culture expressed in the architecture in the so-called towers, which were baddish temples. Near Hué, the ancient Vietnam capital, there is the most northern tower is My Khanh near the sea side visited the 28th -08, latitude 16°,50', while the most southern is PHO HAI 10°.57', visited the 04th -09-12.

In figure 5 one panorama of the Hoa-Lai tower is depicted and in figure 6 its line restitution as wire-frame. The line plot must be integrated because many rough parts are not easy to plot. The top of the tower is always hardly visible. Probably laser scanning would have been the most suitable instrument for this type of survey. But there are difficulties to bring in Vietnam such an expensive instrument.

2.3. The most ambitious project: The Bahia project
The Università Politecnica delle Marche, Italy and UFBA, the Universidade Federal de Bahia, are carrying out a joint research project for the metric documentation of Bahia Cultural Heritage. Here some example of this quick metric documentation of Bahia CH is presented. They are the Largo do Pelourinho, and the facade of the Igreja Nossa Senhora do Conceicao da Prahia. The
Fig. 5 - Vietnam – Hoa-Lai tower; Fig. - The line plotting of Hao-Lai tower (restitution by M. Ripanti, Veronica, Sara, Miranda)

Fig. 7, 8 – Bahia, Largo do Pelourinho (restitution by Elisa Bronzini)

Fig. 9, 10 – Salvador do Bahia – Igreja de Nossa Senhora da Conceição da Praia, left the restitution of the facade on the right the central of the three panoramas (restitution G. Fangi)
surveys have been carried out in two separated missions in 2012. The aim is to build up an archive of historic houses, buildings, architectural emergencies, churches.

2.4. The most meaningful project: Notre Dame du Haut, Ronchamp, France

Notre dame du Haut is a Church of Contemporary Architecture, designed by Le Corbusier in 1950 and built in 1954. This is a pilgrimage destination and perhaps the most important project by Le Corbusier. The most difficult part to be plotted is for sure the roof, realized in the shape of a shell; its strange profile makes the survey a challenging test. In May 2011 we went to Ronchamp and we made 37 panoramas of the exterior and 9 of the interior of the Church. The panoramas have been successfully oriented and then the restitution begun. We had already a topographic control network of about 100 natural points, created by G. Fangi for a thesis project in the nineties (figure 32). So we oriented the photogrammetric models using this control network, reaching centimeter accuracy. This phase of the work ended with the restitution of all the recognizable points of the buildings that allowed creating a wire model.

2.4.1. Quality control

From the block adjustment the estimated correction angles $\alpha x$ and $\alpha y$ have values up to almost 2 gon also.

<table>
<thead>
<tr>
<th>Sigma-naught (radians)</th>
<th>$\alpha x = \alpha y = 0$</th>
<th>$\alpha x \neq \alpha y \neq 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>89 control points</td>
<td>0.002384</td>
<td>0.001302</td>
</tr>
<tr>
<td>3 control points</td>
<td>0.002195</td>
<td>0.001250</td>
</tr>
</tbody>
</table>

Table 1- Results of the block adjustment of the panoramas

Due to the large amount of the available control points, we made also the following test: in the global adjustment we regarded as fixed points only the control points 101, 102, 116 placed at the limit of the network. We compared
the values of the adjusted coordinates of all the other points with the already known coordinates in practice as they were check points. The average module of the differences in the three directions is 0.014 m of 86 check points. Probably there is a gross error for point 114 in elevation. In table 1 are shown the results of the bundle adjustment with 89 Control Points, the results of the adjustment with 3 Control Points only, in the two different cases $\alpha_x = \alpha_y = 0$ and $\alpha_x \neq \alpha_y \neq 0$.

It is evident that:

- there is a very good improvement when the corrections of the verticality of the pano-spheres axis are enabled ($\alpha_x \neq \alpha_y \neq 0$)
- the amount of control points is completely irrelevant on the final result, the control points network can be limited to three points as it is already done in many projects, (Pisa et al. 2011, [6]).

This result is very important. In fact it means that to reach the best accuracy there is no need to use sophisticated and expensive instruments like theodolites, total stations or GPS.

Conclusions

A constant of our research was always to enable everybody to make an architectural survey metrically correct, everywhere with simple and chap means. PSP seems to be able to achieve this task. Some conclusions can be drawn from all these projects. Up to now, 6 years after the introduction of PSP, some 500 small or large projects have been run, buildings, facades, churches have been documented, totally or partially, making use of this technique. PSP is suitable mainly for architecture, less for archaeology. The reason for that is simple, say the need to identify the same object point in the different images, that makes the architecture the ideal operational field, the architecture being though in the design phase as a collection of isolated points connected by lines, while in the archaeology the shape of the items are less appropriate, as...
they are normally rough surfaces. Laser scanning would be indeed the ideal instrument for the archaeological survey. The only concern up to now is the fact that all PSP projects were carried out by the laboratory of our department and that almost no other operator has used the technique, although the software has been distributed to many university laboratories. The problem of limited diffusion can be traced back to several causes: the introduction of the laser scanner, which has greatly reduced the interest for photogrammetry, and consequently for PSP also, the lack of automation in the orientation and restitution processes, and above all the absence, up to now, of a commercial product.

Acknowledgements

References
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http://photosynth.net/
Abstract
In the recent years the introduction of laser scanning has improved the quality of the architectural surveys, giving ease to many professional operators to make reliable and accurate surveys in reasonable times. The traditional architectural photogrammetries, both stereoscopic and convergent, have reduced their impact and are almost out of use. Nevertheless new types of photogrammetry have been introduced. Dense points cloud produced with the algorithm SFM (Structure From Motion) added new horizons to close-range survey since SFM builds 3-D models in an unknown scale and orientation, supplying a (dense) set of images taken in different locations. The process is simple from the point of view of the operator since it is fully automatic. The point cloud can be rotated translated and scaled with a tradition 7 parameters s_transformation giving at least three not aligned knows control points. In addition another type of photogrammetry has been proposed, the so-called PSP (Panoramic Spherical Photogrammetry). This photogrammetric technique, is particularly suitable for architectural survey. The multi-image spherical panoramas are used. They are the digital images obtained as cartographic representation of the sphere where the images taken 360° of view around, from the same point and partly overlapping, have been projected (Szeliski, Shum, 1997). Such representations can be produced by means of the many stitching software packages available on the market. The advantages are many: the speed of execution, the drastic reduction of the traditional photogrammetric models, the completeness of the documentation, the FOV can be 360° wide, the absence of distortion, and mainly the low-cost, enabling people to make a photogrammetric survey, fast, complete, accurate and in an inexpensive way. The stitching technique for digital images was introduced by (Szelisky, Shaum) for Apple computers in the years '90, with the aim to increase the poor (by that time) resolution of digital cameras. The Spherical Photogrammetry could be defined as “metric documentation” enabling the access in very short times and at cost almost equal to zero to a computerized archive documentation of whole monuments with centimeter accuracies, including the details. A technique that could achieve the goal to finish the catalogue of ICR (Istituto Centrale del Restauro), in very short times and at a coast almost equal to zero. After the exposition of the principles of the PSP technique, a few examples are shown. Up to now some 500 projects have been run ranging from the very initial phase, the photographic taking, to the final rendered model. The procedure is very quick in the taking phase, on the contrary is time consuming in the orientation phase and mainly in the restitution, being fully manual up to now. Only few projects have been finished, but this is just the aim of the technique, to build up an archive of oriented images (panoramas) to be retrieved, observed, used when the need will require.