RC-HELI AND STRUCTURE & MOTION TECHNIQUES FOR THE 3-D RECONSTRUCTION OF A MILAN DOME SPIRE

M. Scaioni, L. Barazzetti, R. Brumana, B. Cuca, F. Fassi, F. Prandi

Politecnico di Milano, Dept. BEST/SITE Group, piazza L. da Vinci 32, 20133 Milano, Italy
e-mail: {marco.scaioni; luigi.barazzetti; raffaella.brumana; branka.cuca; francesco.fassi; federico.prandi}@polimi.it

KEY WORDS: Cultural Heritage, 3-D Reconstruction, Structure and Motion, UAV

ABSTRACT:

The paper describes a complete workflow for the 3-D photogrammetric surveying and modeling of complex architectonical objects. The application is focused to the major spire of the Dome of Milan, that is characterized by the well known striking vertical geometry and a high level of complexity. Because no positions from which capturing images and scans exists, a 5 kg payload model helicopter has been used to lift and carry a calibrated digital camera, which has been adopted to capture images for the reconstruction of highest part of the spire. The huge quantity of image data has been partially oriented with a new algorithm able to detect automatically corresponding tie points among the overlapping images by using a Structure & Motion approach, but extended to blocks with a generic shape. The algorithm can identify homologous points with the SIFT operator alternated to a robust estimation of camera poses to remove wrong correspondences. Then a progressive resection alternated with triangulation is carried out to determine the orientation parameters of each image. Finally a photogrammetric bundle adjustment is computed to derive final exterior orientation parameters.

1. INTRODUCTION

1.1 UAV: a new paradigm for photogrammetry

In the latest five years one of the most emerging technology in photogrammetry is undoubtedly represented by *unmanned aerial vehicles* or *UAVs* (van Blyenburg, 1999). The interest for these flying platforms in motivated by several grounds related to several fields of possible application. In aerial survey, they allow a high resolution image acquisition, because of the possibility to fly at very low height on the ground with respect to manned aircraft and helicopters. The possibility of mounting sensors in tilted position can be exploited for imaging some kinds of objects which are difficult to capture in standard aerial imagery. Typical examples of this are building façades, waterfronts or vertical rock faces (Eisenbeiss, 2008). So far, digital or video-cameras have been installed for the most on UAVs, even though multi-spectral sensors have been already tried (Nebiker *et al.*, 2008) and their use is increasing on such vehicles.

The presence of on-board navigation/positioning systems enable the most evoluted UAV to follow a predefined flight-plan and to record orientation parameters. These sensor are usually based on GPS/INS technology, but alternative solution integrating other kinds of data (scans, images) have been explored (Eugster & Nebiker, 2008; Steffen and Förstner, 2008; Wang *et al.*, 2008).

UAVs can be deployed with ease and require a small plot of land for take off and landing, properties that encourage their use for data acquisition just after anthropogenic or natural disasters. Thus they are an ideal platform to capture images needed in emergency response (Kerle *et al.,* 2008), without any risk for operators.

Studies and efforts to improve autonomous flying capability, data acquisition and control make this platform capable of reducing cost and time for production of mapping products (Zongjian, 2008). The new scenario that UAV are opening is so relevant that Colomina *et al.* (2008) state that a new paradigm for photogrammetry is forthcoming, following aerial and satellite ones. Agriculture represents another potential field for the extensive use of UAVs (Grenzdörffer, 2008).

But also in large-scale or close-range applications of photogrammetry (e.g. for Cultural and Environmental Heritage documentation and conservation), the UAV technology might solve many problems that currently cannot be coped with effectively by using terrestrial or aerial surveys. UAVs were successfully applied to map archaeological sites, where other surveying techniques were not suitable (see e.g. Eisenbeiss, 2004; Bendea *et al.*, 2007).

Let us consider for example the completion of the 3-D survey of a construction, where the roof is to be capture at high resolution as well, or when a high-rising building has to be imaged in its top. In many cases, suitable images cannot be taken neither from the ground, nor from other buildings or scaffoldings. On the other hand, aerial imagery might not be suitable due to the insufficient scale, while the used of manned helicopter usually is largely expensive. The availability of a micro or mini UAV (see Bento, 2008 for classification of UAVs) equipped with a high resolution digital camera enables one to capture images from unconventional point-of-views and to respond to the above-mentioned critical requirements.

The application described in this paper just belongs to this category and it will further analysed in the next Sub-section.

1.2 Project overview

The inquired “object” is the major spire of the Milano (Italy) Cathedral (see Fig. 1) that is characterized by the well known striking vertical geometry and a high level of complexity. Information on the Cathedral can be found at Veneranda Fabbrica del Duomo di Milano (2009). The 3-D geometric measurement of this object cannot be done with a combination of classical topography and manual survey, because the density of architectural and structural details and the richness of decorations make this approach very intricate, time consuming and in some cases also impracticable. For example total station measurements require the creation of a complex geodetic network and the collection of a huge number of measured points. The manual survey would be possible only by building a series of high and heavy scaffoldings on the dome's roof to reach all inquired zones. Photogrammetry and *terrestrial laser scanning* (TLS) represent the ideal solution to cope with such a subject. Unfortunately, no positions from which capturing images and scans exist, being the peak of the main spire is more than 50 m over its basement on the roof of the Cathedral.

Figure 1. Some images of the Milan Dome Cathedral, showing the high-rising character and the architectural complexity of this gothic building.

1.3 A solution with a RC-UAV and automatic image orientation

To overcome the drawback typical of traditional photogrammetric surveying, a 5 kg payload model helicopter has been used to lift and carry a calibrated digital camera, which has been adopted to capture images for the reconstruction of highest part of the spire. A micro-camera was used to control from the ground the shooting angles and the overlay among the single shots. The images are taken considering an incidence angle of circa 60 deg, so that it is possible to model the scene with a close-range photogrammetric software. This helicopter, classified as *micro-UAV*, is not equipped with GPS and IMU unit, so the image orientation is performed through *aerial triangulation*. Currently, the helicopter is remotely controlled, as presented in the description at subsection 2.1. In next months, a new UAV with a higher capacity pay-load and with on-board navigation tools will be used (Subsec. 2.2).

The use of the helicopter model find its place inside a interdisciplinary research project that has the aim to create an integrated system build up especially for architectonical and environmental heritage surveying and modeling. This system would like to integrate an UAV platform, different kinds of surveying sensors and a software package for automatic photo orientation, feature extraction and Speedy Orthophoto creation. The whole system would be able to speed-up not only the surveying phase but also the orientation and the processing stages.

The described application will be the first experience to set up the flying hardware, a capture device and some modules of the correlated software. In addition, some preliminary results will be reported.

Automation is an important key aspect of this project, requiring the acquisition of thousand images of the exterior of the Cathedral. Its main spire will be interested by relevant restoration works that will last about 3 years, so a complete documentation has to be achieved before starting of works. Some images will be used for the photogrammetric reconstruction, some others for documentation purpose only. In addition, a photogrammetric coverage of the interior of the main dome of the Cathedral will be repeated periodically in order to monitor the fissuration state by visual inspection of the images. Disregarding the aim they are captured, all images need to be oriented to allow the information to be georeferenced. The automation of exterior orientation is an issue still open in close-range photogrammetry. In fact, many photogrammetric digital stations have tools for automatic detection of homologous points (without targets) but they generally work with images in normal configuration only. Thus, they can orient an aerial block but often fail with convergent images (Remondino & Ressl, 2006). On the other hand, targets cannot be put in the most locations of the Cathedral, neither indoor nor outdoor.

To cope with the huge amount of image data, an automatic algorithm based on a Structure and Motion (S&M) strategy has been tested on one of the first datasets. As described in Sec. 3, the S&M algorithm might extract corresponding tie-points among the overlapping images, then are used to compute a photogrammetric bundle adjustment to derive the final exterior orientation parameters.

The 3-D model of the main structures will be created in a close-range photogrammetric environment. Some tests have been performed so far by adopting Photomodeler 6 Scanner (Sec. 4).

In several parts of the Cathedral exterior, the use of a "phase-shift" TLS (Leica HDS6000) has been possible, because the instrument could be placed on the Cathedral roof (see an example in Fig, 2). 3-D models of complex details or artistic decorations will be recorded by using a hand-held triangulation scanner. These will be acquired in a second stage, when scaffolds have been installed around the spire in order to start restoration works.

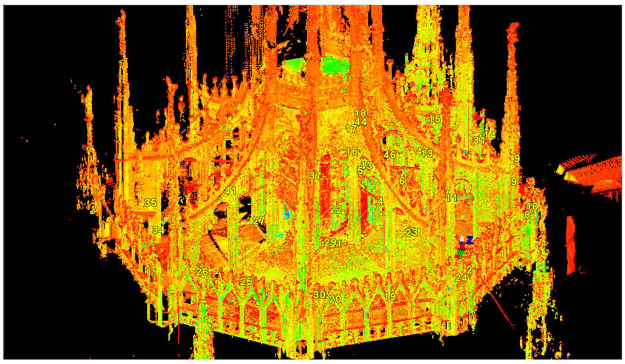


Figure 2. Laser scans taken over the main dome roof, after registration.

The integration of photogrammetric data and different scale scans will be carried out on the basis of GCPs referred to the same reference system. This allows one to build up a multi-scale and complex 3-D model of the whole major spire. In a next stage, drawings (profiles, cross-sections, prospects, plans) for the documentation and restoration purpose have been derived from the whole 3-D model.

2. THE DATA ACQUISITION PLATFORM

The project involved the use of two different UAV platforms. The first one is a simple Remotely Controlled Helicopter without any autonomous navigation capability. This has been used for the acquisition of first datasets that have been captured so far. On the other hand, a second platform with higher performances and a INS/GPS system on board is under development at our institute. The urgency required by survey of the Milan Dome spire and the need to operate with a platform allowing to shot the images from a low altitude flying vehicle, motivated the use of the RC-Helicopter. In following subsections both heli platforms will be addressed and discussed.

2.1 The current RC-helicopter platform

The first UAV platform adopted for acquisition of all image blocks described in their paper is a RC model helicopter Hirobo "sst-eagle Freya" with a pay-load up to 5 kg (see a picture in Fig. 3). According to the classification of UAV reported in literature (see e.g. Bento, 2008), this vehicle is addressed to as *micro-UAV*. Currently it carries a digital camera Nikon D200 with a 20 mm lens, suspended by elastic wires in order reduce the effect of engine vibration. The sensor is forward oriented in fixed position. In Table 4 some characteristics of the micro-helicopter are reported.

Figure 3. The current RC-Helicopter based on a RC model Hirobo "sst-eagle Freya", which has been adopted for the photogrammetric surveying of the Dome spire.

On the other hand, three main drawbacks have been coped with to operate with this RC helicopter. The first one is the absence of a navigation/positioning sensor, resulting in the possibility to follow a flight-plan. In reality, the most applications of UAVs for Cultural Heritage concern the acquisition of nadiral blocks. Here the verticality of all involved structures resulted in designing blocks with a more complex shape, and comprehending convergent images as well. The use of INS/GPS systems might give problems due to occlusions, poor satellite visibility, and frequent losses of GPS signal. In order to help the image acquisition, an ancillary micro video-camera has been installed, giving in real-time to the ground operator a similar overview as the main Nikon D200 camera . The unavailability of a direct positioning sensor is supplied by the use of an automatic procedure for image orientation, as presented in Section 3.

Helicopter	**Hirobo sst-eagle Freya**	**Vario Benzin-Trainer**
Classification	Micro-UAV	Mini-UAV
Length×width×height (mm)	1395×200×435	1630×200×520
Main rotor diameter	1500	1564
Overall weight (kg)	5.2	7.3
Pay-load (kg)	5	7
Engine (cc)	19	23
Endurance (min)	15	30

Table 4. Main technical features of 2 model helicopters adopted as UAV platforms in this project.

2.2 The forthcoming helicopter platform

The current helicopter will be replaced by a more advance platform, based on a model Vario "Benzin-Trainer" (see Fig. 5). In Table 4 its main technical features are reported.

Apart the bigger pay-load, which enable to mount other kinds of sensors or a camera-pair, this UAV will be equipped with an autonomous flying systems. This should enable to follow a flight plan and to capture images at predefined positions, also when flying on vertical paths like those required in architectural applications.

Navigation and positioning will be assisted by a GPS operating in RTK with reference to a ground master station. The attitude is provided by a triaxial gyro. However, the presence of a direct orientation system is aimed to:

1. provide a good approximate exterior orientation useful for real-time applications (for example for emergency response, damage assessment,…);
2. provide initial orientation values to improve automatic orientation procedures already implemented in the current processing workflow.

Figure 5. The new helicopter Vario "Benzin-Trainer."

The digital camera will be installed on a stabilized and turnable pay-load to capture images along different directions. A radio connections will transmit all images to the ground station.

3. STRATEGY FOR IMAGE ORIENTATION

3.1 Overview on automatic image orientation

The UAV vehicles adopted during this project should operate in several conditions and environments, which might feature completely different scenarios. Even though the platform with autonomous flight capability is still under development, high-precision photogrammetric projects cannot simply rely on direct orientation through GPS/INS sensors. A procedure to solve this task plays a key-role in the processing workflow, even more at the current stage.

As already mentioned in the introduction (Subsec. 1.3), *automatic orientation* is a completely solved task in Aerial Photogrammetry, but not in Close-range. Some low-cost software can solve for the orientation of a generic image block but using *coded targets* (e.g. iWitness, PhotoModeler). Unfortunately, targeting requires temporary application of markers on the object to survey, operation that in some cases is complicated or impossible. The survey of Milan Dome spire is a typical case when this happens.

Automatic orientation of marker-less image block is then an still open issue in Photogrammetry, but also in Computer Vision (CV). Both disciplines afford the same problem but with a different mathematic and methodological approach. Also the used sensors can be really different: in Photogrammetry high resolution images are adopted, while in CV video-cameras are employed and a huge number of short baseline frames must be analyzed. Another difference is calibration: CV algorithms are “uncalibrated”, that means that inner orientation parameter are not necessary, while photogrammetric application need sensor calibration.

In this paper a method integrating techniques of both disciplines is presented. It makes use of photogrammetric procedures during the image orientation phase, in order to provide an accurate solution, but it also implements CV methods to automate the procedure. In fact, a conjunct use of the methods of both disciplines allows the resolution of some typical problems of one with the other, and vice versa. Calibration parameters must be known for the correct running of the algorithm.

Either an image sequence or a generic image block can be processed. The former case requires the acquisition of images in a way that each image presents an overlap with the next two images. The latter case is instead carried out with unorganized images. The main difference between both cases is the computational time: a sequence analysis is faster because the order of images is a priori given, while in a generic block it must be estimated with an exhaustive research in the whole block. In the next sections both procedure are described.

The implemented strategy is referred to in literature as Structure and Motion (S&M) or Structure from Motion. It is based on the use of sequences made up of single images (likewise the present application) or stereo-pairs (e.g. in MMT applications), captured by a camera or a video camera. Consequent images in a sequence usually show small differences between them, fact that makes easier the search of corresponding points by image matching algorithms. Homologous points are firstly searched in close images by using geometric models typical of CV (*fundamental matrix*, *essential matrix*, *trifocal tensor*); high break-down robust estimator are applied at this stage to cope with outliers (Rousseeuw & Leroy, 1987). In a second stage, if needed, tie points are transferred along more images of the sequence in order to find manifold points and to improve the block reliability.

3.2 Sequence orientation with S&M algorithm

The automatic orientation of a sequence requires that each image (*i*) presents an overlap with the next two ones (*i*+1, *i*+2). This condition can be easily respected when a video is acquired, while particular attention must be paid in case a camera is used.

The entire sequence is divided into triplets (images *i*, *i*+1, *i*+2 - *i*+1, *i*+2, *i*+3 - …) and a *feature-based matching* (FBM) with SIFT (Lowe, 2004) is carried out to identify homologous points inside each triplet. Any mistakes that might remain is removed by the robust estimation of the *fundamental matrix* (Hartley & Zisserman, 2004) with Least Median of Squares technique (Rousseeuw & Leroy, 1987). Details of this task can be found in Scaioni (2000). The FBM with SIFT is highly time consuming, then it is opportune to use only compressed images (less than 1 Mpx) in order to speed up the process (see Fig. 6). From these image coordinates, a refining with *Least Squares matching* (LSM - Gruen, 1985) is carried out in order to use also full resolution images and to improve the estimation of image coordinates.

The orientation procedure is based on a progressive resection alternated to intersection in order to concatenate all images to a initial reconstruction of an image triplet assumed as reference (generally the first one). This procedure is completely based on collinearity equations and no CV orientation techniques are used. This approach looks like the standard S&M procedure, but the mathematical approach makes use of photogrammetric methods. Further details about this algorithm can be found in Barazzetti & Scaioni (2009).

Camera poses and 3-D points computed with this technique are shown in figure 7. In this case only 11 images were analyzed and some problems were found during the S&M approach because these images do not form an ordered and regular sequence. Indeed, the sequence analysis algorithm can present some problems during processing of a block made up of several strips. In fact, the procedure is useful when a sequence has a “ring” shape, while it is complicated to determine homologous points between non-consecutive images. The matching between images of different strips is carried out by means of a search in the object space and presents problems when the strips are not regular, like in this case. This is the reason why a tool for generic image block was implemented.

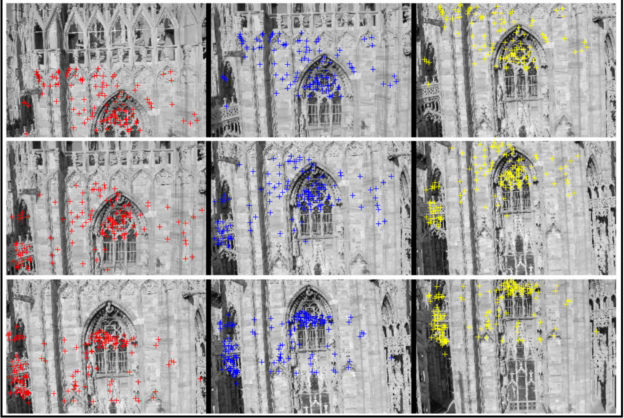


Figure 6. Matching between 3 consecutive triplets with SIFT.

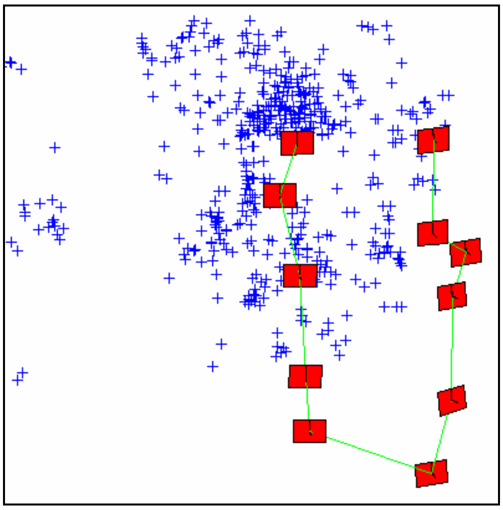


Figure 7. Camera poses with the implemented algorithm for image sequence analysis.

3.3 Orientation with the algorithm for generic image blocks

The tool for generic image blocks makes use of an exhaustive search of tie points between all possible image pair combinations. In particular, a FBM with SIFT is carried out between compressed image pairs, then a LSM refining is carried out to use original full resolution images.

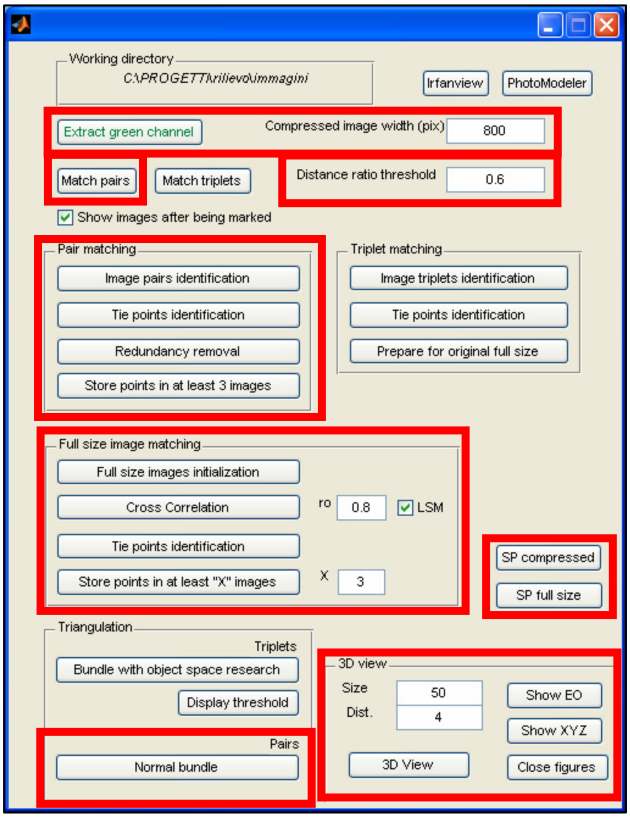
For a block of n images, this search strategy results in $(n^2\text{-}n)/2$ tries. With a sequence made up of 50 images compressed into VGA quality, the algorithm needs 1.7 hours for the matching phase. In case images form an ordered sequence, the time for the same block is 4 minutes only due to its linear computational cost with respect to the image number. This is the reason why when images are taken with a “ring” configuration the algorithm of section 3.2 results faster.

The graphical user interface of the algorithm is shown in figure 8. The code is developed in Fortran (LSM algorithm), standard C (FBM) and MATLAB®. The parts selected with a red rectangle on the GUI form the generic image block algorithm.

The block analyzed with the proposed method is composed of 78 images. The matching phase needed 4 hours roughly and more than 16000 points were automatically matched. Also in this case, mismatched points were removed with the robust estimation of the fundamental matrix. In figure 9 results before the outlier removal are shown: with the Lowe descriptor 120 matches were found, while the robust estimation of the epipolar geometry selected 89 points. Figure 10 reports the estimated camera poses with compressed images

A bundle adjustment was carried out with compressed images only, in order to check the quality of the FBM. The algorithm used in this step is the same PhotoModeler bundle procedure. In fact PhotoModeler can be used in a Dynamic Data Exchange modality. This means that it is sufficient to develop a code which enables one to control the software for using all main capabilities of PhotoModeler with a remote connection.

Manual operations are thus not necessary. In any case, this bundle algorithm is only a temporary solution. However, it gave useful results for many applications and the only limit is the lack of a complete statistical output. In addition, PhotoModeler offers an user friendly interface for visual analysis and allows one to save the data in several formats.



Working directory C:\PROGETTI\rilievo\immagini

Compressed image width (pix) 800

Distance ratio threshold 0.6

☑ Show images after being marked

ro 0.8 ☑ LSM

X 3

Size 50

Dist. 4

Figure 8. The GUI of the algorithm. In red the function concerning a generic image block.

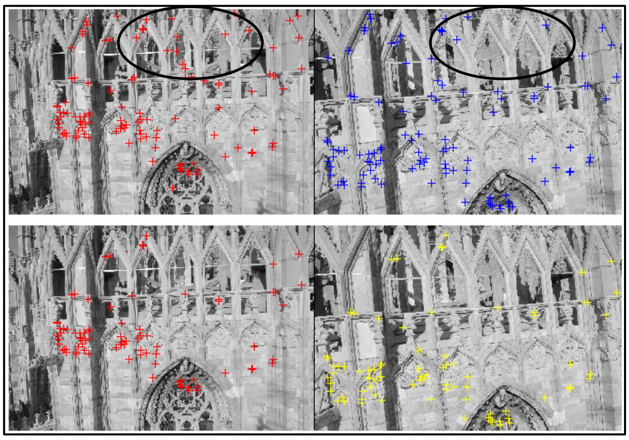


Figure 9. An image pair before (top) and after (bottom) the robust estimation of camera poses: many outliers have been correctly removed.

Figure 10 also shows an image redundancy. For this reason only 29 images were selected for further next elaborations. The LSM refining allowed one to use full resolution images and 6000 points were matched.

The bundle adjustment with these image coordinates allowed a free net analysis of the block and a scale factor was then fixed. The model was roto-translated to set the axis x and y (y is vertical) on the façade, while z represents the depth.

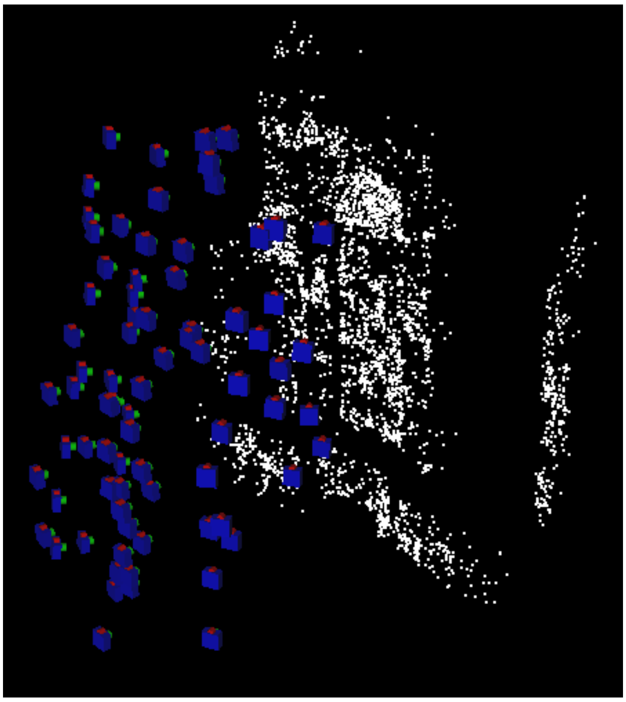


Figure 10. Orientation result of compressed images.

In any case, the procedure cannot be considered now completely automatic. In fact after the bundle adjustment few points were manually removed. This manual correction required no more than few minutes to identify these gross errors, but in any case was necessary. Globally 10-15 points were classified as outliers. The bundle adjustment was also performed by using image points which belong to 4 images (at least). This choice is motivated by the large overlap of this image block and made more reliable the block.

In future development of the algorithm a benchmarking technique on the bundle adjustment result will be implemented (Dickscheid *et al.*, 2008).

The average theoretical precision of this survey is $\sigma_x = \pm 2.4$ mm, $\sigma_y = \pm 1.6$ mm and $\sigma_z = \pm 7.5$ mm and 486 object points were found.

4. OBJETC RECONSTRUCTION

4.1 Point cloud creation with PhotoModeler

The last version of PhotoModeler 6 has a “Scanner” (Eos Systems, 2009) tool for point cloud extraction with *dense matching* algorithm. This tool works with image pairs only but seems to be able to provide a good dense point cloud.

In this sense, PhotoModeler Scanner is the first low-cost photogrammetric package which allows the point cloud extraction from images (see. figure 11). Although very slow, results are good (especially if compared with the prize of other more expensive commercial packages capable to create and manage point clouds). The reconstruction is often good where planar elements are located, while some problem occurs in correspondence of more complex elements. Sometimes systematic errors are found.

Figure 11. Some example of point clouds created with PhotoModeler 6 Scanner. Point spacing varies from 5 to 10 mm.

5. FINAL CONSIDERATIONS AND FUTURE WORKS

5.1 Considerations on the achieved results and future work

The paper presented the current photogrammetric workflow applied for the survey and 3-D reconstruction of the Milan Dome main spire. To cope effectively with the high-rising character of the building, a RC model helicopter equipped with a digital camera Nikon D200 was adopted. The final 3-D model will result from the integration of photogrammetric data with different scale TLS surveys.

The current UAV platform is not provided by navigation/positioning sensors, than it cannot be used in autonomous way. The main consequence of this drawback is the irregular shape of the resulting image block, as can be seen in figure 10. To guarantee enough coverage on the object for a complete surface reconstruction, a highly redundant number of images was captured.

Image orientation is achieved through an automatic procedure based on a Structure and Motion strategy extended to work also with block having a general shape and not only with sequences. The algorithm is based on CV methods integrated to photogrammetric bundle adjustment to compute final orientation. Also with the forthcoming availability of a second UAV with autonomous navigation capability and with direct orientation recording, this procedure will remain important to increase precision and reliability of the final result.

Object reconstruction is currently at a initial stage. Indeed, some experiments with a commercial low-cost photogrammetric software have been tried. Results are encouraging, even though the method should be improved by using more efficient and reliable *dense matching* techniques (multiphoto with geometric constraints - Baltsavias, 1991). Alternative solutions have to be found either in commercial and existing packages (Remondino & Menna, 2008), and in software implemented internally at SITE research group.

The workflow presented along the paper and discussed in this subsection 5.1 will enable to obtain the 3-D surface reconstruction of the whole Cathedral's spire and its basement on the roof of the church. This result is relevant, because it will offer a durable digital documentation of the current as-built state. In 1996 the most advanced photogrammetric technology was applied to get the reconstruction of a single statue (Kludas *et al.*, 1996). What can be obtained with relative ease today is not comparable to that results, considering the cheaper cost of SW and HD, and the reduced time for data processing.

5.2 Open issues

To complete and improve the workflow described above is needed a lot of work, some to get the alignment with the state of the art, some to develop technical aspects typical of this specific application.

The real challenge is represented by two innovative aspects.

The first one concern the automation of data acquisition by means of autonomous and intelligent UAVs, which are capable to define its flight-plan and to follow it so that a full coverage of the object is achieved.

The second main open issue is the automatic object modelling and understanding. On the other hand, a correct data acquisition (platform, sensor, block design and data capture) and a fast and robust orientation procedure (included sensors and integrated systems calibration) allow to have good images to extract information. However, at the current state of the art of photogrammetry information is derived manually, with a still stronger human contribute. Exception is given by surface modelling, even though also dense matching algorithm don not give any semantic interpretation. Disregarding consideration about data quality, the full photogrammetric process gives more or less the same finding that a TLS could, if applicable. The real frontier of Photogrammetry is given by the development of cognitive systems that are capable to understand the semantic meaning of a geometric shape of an object, and then to guide its reconstruction and modelling.

AKNOWLEDGEMENTS

The authors would like to thank the Milan Cathedral "architect", Ing. Benigno Mörlin Visconti Castiglione. Aknowledgements also go to Prof. Carlo Monti (Politecnico di Milano, BEST/SITE Dept.) for supporting and coordinating this project.

REFERENCES

Baltsavias, E.P., 1991. *Geometrically Constrained Multiphoto Matching*. Mitteilungen No. 49, Institute of Geodesy and Photogrammetry, ETH, Zurich.

Barazzetti, L., and M. Scaioni, 2009. Automatic orientation of image sequences for 3-D object reconstruction: first results of a method integrating photogrammetric and computer vision algorithms. *IAPRSSIS*, 37(5/W1): 8 pp.

Bendea, H.F., Chiabrando, F., Tonolo, F.G., and D. Marenchino, 2007. Mapping of archaeological areas using a low-cost UAV the Augusta Bagiennorum Test site. In Proc. Of XXI Int. CIPA Symp, Athens, Greece, on CDROM.

Bento, M. D. F., 2008. Unmanned Aerial Vehicles: an Overview. *InsideGNSS* (Jan/Feb 2008): 54-61.

Colomina, I., Blázquez, M., Molina, P., Parés, M.E., and M. Wis, 2008. Towards a New Paradigm for High-Resolution Low-Cost Photogrammetry and Remote Sensing. *IAPRSSIS*, 37(B1): 1201-1206.

Dickscheid, T., Läbe, T., and W. Förstner, 2008. Benchmarking Automatic Bundle Adjustment Results. *IAPRSSIS*, 37(B3a): 7-12.

Eisenbeiss, H., 2004. A mini unmanned aerial vehicle (UAV): system overview and image acquisition. *IAPRSSIS*, 36(5/W1), on CD-ROM, 6 pp.

Eisenbeiss, H., 2008. The Autonomous Mini Helicopter: a Powerful Platform for Mobile Mapping. *IAPRSSIS*, 37(B1): 977-983.

Eos Systems, 2009. http://www.photomodeler.com. Last accessed on 31st January 2009.

Eugster, H., and S. Nebiker, 2008. UAV-Based Augmented Monitoring – Real-Time Georeferencing and Integration of Video Imagery with Virtual Globes. *IAPRSSIS*, 37(B1): 1229-1235.

Grenzdörffer, G.J., Engel, A., and B. Teichert, 2008. The Photogrammetric Potential of Low-Cost UAVs in Forestry and Agriculture. *IAPRSSIS*, 37(B1): 1207-1213.

Gruen, A., 1985. Adaptive least square correlation: a powerful image matching technique. *South African Journal of Photogrammetry, Remote Sensing and Cartography*, 14(3): 175-187.

Hartley, R., and A. Zisserman, 2004. *Multiple View Geometry in Computer Vision*. Cambridge University Press.

Kerle, N., Heuel, S., and N. Pfeifer, 2008. Real-time data collection and information generation using airborne sensors. In: Zlatanova, S., and J. Li (ed.s), *Geospatial Information for Emergency Response*. Taylor & Francis, London (UK), pp. 43-74.

Kludas, T., Pfeil, J.U., Scaioni, M., and G. Vassena, 1996. Automatic DEM Generation using Digital System InduSCAN: an Application to the Artworks of Milano Cathedral Finalized to Realize Physical Marble Copies. *IAPRS*, 31(B5/V), Vienna (Austria): 581-586.

Lowe, D.G., 2004. Distinctive image features from scale-invariant keypoints. *IJCV,* 60(2): 91-110.

Nebiker, S., Annen, A., Scherrer, M., and D. Oesch, 2008. A Light-weight Multispectral Sensor for Micro UAV - Opportunities for Very High Resolution Airborne Remote Sensing. *IAPRSSIS*, 37(B1): 1193-1200.

Remondino, F., and C. Ressl, 2006. Overview and experience in automated markerless image orientation. *IAPRSSIS*, 36(3): 248-254.

Remondino, F, and F. Menna, 2008. Image-based surface measurement for close-range heritage documentation. *IAPRSSIS*, 37(5/W1): 199-206.

Rousseeuw, P.J., and A.M. Leroy, 1987. *Robust Regression and Outliers Detection*. John Wiley, New York.

Scaioni, M., 2000. Robust estimation of relative orientation through the fundamental matrix. *IAPRSSIS*, 32(W8/2): 253-259.

Steffen, R., and W. Förstner, 2008. On Visual Real Time Mapping for Unmanned Aerial Vehicles. *IAPRSSIS*, 37(B3a): 57-62.

van Blyenburg, P., 1999. UAVs: an Overview. *Air & Space Europe*, I(5/6): 43-47.

Veneranda Fabbrica del Duomo di Milano, 2009. http://www.duomomilano.it. Last accessed on 31st January 2009.

Wang, J., Garratt, M., Lambert, A., Wang, J.J., Han, S., and D. Sinclair, 2008. Integration of GPS/INS/Vision Sensors to Navigate Unmanned Aerial Vehicles. *IAPRSSIS*, 37(B1): 963-969.

Zongjian, L., 2008. UAV for Mapping – Low Altitude Photogrammetric Survey. *IAPRSSIS*, 37(B1): 1183-1186.