HIGH-EFFICIENCY BUILDING SURVEYS BY DYNAMIC AND STATIC DIGITAL IMAGES ORIENTED WITH “MIXED MODELS”

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ABSTRACT:
Throughout this paper, a method to efficiently survey buildings by digital images, dynamically and statically acquired, is presented by investigating methodological and analytical aspects and by suggesting an integrated surveying procedure, in order to well exploit the synergy among different imaging sensors.
At first, it is earlier evaluated and then discarded (for described operative reasons) the idea to use exclusively digital images of a Mobile Mapping System to photogrammetrically survey buildings, exploiting them instead to survey 3D-control points only. In this way, classical topographic measures on the facades are no more required. The original “pseudo-dynamic” model allowing this photogrammetric technique of control point positioning, also with a simplified low cost system, is briefly shown.
Afterwards, the digital rectification of static CCD images is investigated, taking into account the effect of coordinate errors in control points measured by MMS. This problem can be suitably overcome thanks to an original mixed model algorithm considering also the prediction of control point coordinate simultaneously to parameter estimation of homographic image transformations.
At the end, the testing of this integrated survey method to some historical buildings is presented, as well as the operative problems and limitations occurred. In any case and considering image scales involved, the CCD images so rectified on façades planes have a decimeter accuracy, more than satisfactory for a lot of applications as surveys of aggregate buildings or urban blocks.

1. INTRODUCTION

This paper presents a method to efficiently survey buildings by means of the integration of digital images acquired either in dynamic or in static way. The central concept is to well 3D or 2D-orient images on control point coordinates photogrammetrically too obtained before thanks to the application of “mixed (estimation and prediction) analytical models” (Dermanis, 1990).
Consequently, two main acquisition phases characterize this surveying method: in the first, a low-cost Mobile Mapping System (MMS) is employed to acquire dynamic images of the buildings: these images permit an efficient photogrammetric survey of 3D-points, later usable as control points.
Afterwards, by using a higher resolution CCD camera, (classical) static shots are instead achieved; in these other images, same buildings (but in better geometric/resolution conditions) and just before measured control points are portrayed so allowing digital rectification.
The analytical and operative steps making possible this integrated survey and the obtainable results will be explained in next chapters. In any case, the field of application has been thought for decimetre accuracy surveys of aggregate edifice and not for more precise/detailed architectonic goals: the realization of façade raster textures of building volume for profitable VRML purposes is a emblematic example in such a sense.
This integrated survey has been in reality tested for digital 2D-façades rectification of some historical buildings in Serravalle - Vittorio Veneto (Italy). All paper figures are relating to this case, also those in the analytical chapters, so that to better clarify general methodological topics.

2. MMS TECHNOLOGY AND BUILDING SURVEY

In these lasts years, the photogrammetric survey technology by means of MMS, that is terrestrial vehicles equipped with GPS, INS, CCD on other integrated sensors, has had an increasing development and interesting applications, mainly to 3D-survey geometry and pavement characteristics of roadways.
This advanced technique, involving completely different measuring sensors (satellite, inertial, odometer, imaging, etc), is obviously characterized by lots of analytical, methodological, and technological sub-aspects. Obviously, this paper can only briefly hint to some of them, forwarding the interested reader to references for deeper investigations: a good starting point of the enormous available literature is surely given from the proceedings of the International Workshops held on this technology (Ohio State University, 1995; Li and Murai, 1999; El-Sheimy, 2001).
Anyway, the fundamental innovation introduced by (terrestrial) MMS is the direct orientation of the imaging sensors thanks to its navigation sensors, likewise for analogous aerial systems before improved. In this way, to survey whatever kind of object, a “one time only” moving acquisition of data is sufficient, by simply passing through the interest area with a vehicle.
Furthermore, bearing in mind the elevated level of technological instrumentations and analytical models involved in acquiring and processing MMS data, a high efficiency 3D-survey in terms of correctness, accuracy, reliability, completeness, and productivity can be realistically expected.

Throughout this chapter is evaluated the idea to use digital images of a MMS to photogrammetrically survey buildings façades and any other interested architectonic entity.
Although it looks extremely promising, since removing some measure steps it appropriately increases the automation level of the surveying, on the other hand it unavoidably spawns new operative problems.
The new-fangled incoming restrictions, as difficulty to cover a complete surrounding path, buildings too near/distant from a road, fixed shot geometry respect building and/or among successive images, are easily understandable. Nevertheless to make better clear them, supposing to have to survey a certain edifice, following figures report digital images potentially

exploitable for such end (on left) and as they will result after rectification (on right at the same 1: 400 scale), leaving out any consideration about how to accomplish it.

Figure 1: Original and rectified MMS image (complete façade).

This figure shows the rectification of a MMS 640x480 image selected, from all the sequence, as the best in full depiction of a certain edifice. The digital camera is mounted on a car roof with an azimuth of 45° right-side trajectory: for such end, the house is rather far from MMS and foreshorten. Thus, pixels represent the façade in rectangular way and with very large elements (low definition, low mean image scale). The corresponding rectified image is therefore eloquently unable for building surveying.

Figure 2: Original and rectified MMS image (partial façade).

In this figure, among the MMS sequence, the most detailed dynamic image for the same edifice has been used instead: the façade is now closest from MMS and better portrayed, but it is only partially visible. Furthermore, in the resultant incompletely rectified image, also a radial image deformation appears in right side. This is due to the high objective distortion of MMS digital images: off course, it could be suitably correct, but it requires reliable software routines.

Figure 3: Original and rectified CCD image (complete façade).

At the end, this third figure shows again the same house, before and after rectification, as traditionally surveyed with a 1.526x1.024 image statically acquired by a CCD: the best accuracy and completeness is manifest.
In Figure 4, to better appreciate the gain in definition of the rectified output by changing original image, little parts of the same area coming from such three cases are extracted and reported in the same previous order. The really required definition of the rectification depends from the specific application, but the radiometric quality assured with this example, nowadays a quite standard CCD resolution, seems to be not renouncing.

Figure 4: Part of three previous rectified images (1:150 scale).

Summarizing, for their general better resolution and for easier and more flexible shot geometry, static "ad hoc building" CCD images are preferable to dynamic MMS images ones. Although MMS cameras could be pointed orthogonally with respect to direction motion, the gain in definition is treated vertically with façade incompleteness and in horizontally, working at standard image acquisition frequency, even with loss of building façades.

Last but not least, another reason strongly pushes towards the employment of static images: nowadays for most architectural goals, the raster ortho-rectification is a numerical output absolutely favorite to a vector representation (this last can be ever easily obtained from the previous one). As well known, to obtain such an image rectification, one has to know:

- The surface reconstruction of the portrayed building façade, i.e. the Digital Elevation Model (DEM) for complex geometry requiring differential rectification (orthophoto) or just the plane displacement for simplest case (global rectification). In any case, geometrical information on building façades has to be known and these have to be measured by photogrammetric or topographic techniques.
- The image external orientation, explicit for orthophoto case and implicitly contained in homographic transformation parameters for rectification: such an orientation can be directly measured by MMS sensors or indirectly by means of 3D control points.

It can be view as, independently from the dynamic or static way to acquire images, we need either precise measures on façade points or good façade images to be rectified. This means that 3D-survey by MMS of points appearing on two images is not sufficient for architectonical surveying purposes! In fact, MMS digital images should be used two times: not only to discretely survey 3D-points but also to continuously represent the surface and for this last goal such images are not optimal. The proposal to "directly rectify MMS images of buildings" is then quite idealistic!

For all these motivations, as definitive paper work idea, a simplified (low-cost) MMS is used to photogrammetrically obtain control point 3D positioning on which to 2D-rectify image façades statically acquired.
As very important consequence, classical topographic measures on façades (e.g. by global station) are no more required and, not involving any surveyor field measure, this method can be entitled as "high-efficient".
Summarizing, this method to measure control points is much more efficient to survey kilometers of street fronts wherever:

- stacks of buildings continuously appears in MMS images (not very useless images without objects);
- edifice façades are contiguous, as well as it often happens in historical urban centers.

3. CONTROL POINT 3D-SURVEY BY CCD DYNAMIC IMAGES

As mentioned before, the essential innovation of MMS technology survey is the (instantaneous) direct orientation of (moving) imaging sensor thanks to optimal integration of kinematic GPS and INS measures (see International Workshop proceedings for involved topics).
Using notation where:

- $\mathbf{r}_i^j$ position vector of *i*-th point with respect to a *j*-th reference frame,
- $\mathbf{R}_j^k$ matrix of rotation from *j*-th reference frame to *k*-th reference frame,

in MMS approach, the instantaneous $\mathbf{r}_{ccd}^{map}$ position and $\mathbf{R}_{ccd}^{map}$ rotation are therefore known for each imaging sensor in use.

Nevertheless, the author research in MMS field has been devoted to envelop a simplified system without inertial sensors and with only one imaging sensor. It can anyway fulfil the survey since the INS contribution to the relative positioning/attitude is replaced by considering the analytical point coplanarity condition between successive images. Sending to Visintini (2001, 2002a) for analytical details on such "pseudo-dynamic" model, here an outline is reported to expose the basic ideas.
To obtain the instantaneous orientation parameters of each digital acquired image, a Kalman filter model has been applied considering $\mathbf{r}_{ccd}^{map}$ and angles of $\mathbf{R}_{ccd}^{map}$ as "state vector" and suitably obtaining the transition matrix for the "state equations". Now considering two successive images, the second one is oriented with respect to the previous by exploiting three kinds of linearized orientation observations (if available):

1. Digital image coordinates of each visible homologous point submitted to the coplanarity condition.
2. Digital image and 3D-coordinates $\mathbf{r}_{known\,point}^{map}$ of every visible map point submitted to the collinearity condition.
3. CCD-frame coordinates obtained by kinematic GPS measures and taking into account known eccentricity $\mathbf{a}_{ccd}^{gps}$ and rotation $\mathbf{R}_{ccd}^{gps}$ between CCD and GPS frames.

In the second kind of photogrammetric observation, the potential availability of a 3D-vector numerical mapping is then exploited: in this sense, the approach should be defined as an "indirect orientation" but, since it considers also direct GPS orientation parameters, it can be better called as well as an "integrated orientation".
From the photogrammetric point of view, 3D map points (submitted to collinearity condition) "only" conveniently fix the datum of the "optical model", this last built with MMS images thanks to coplanarity condition (where map point are not involved instead). Thus, by using a lot of homologous (whatever) points, the MMS optical model has a strong geometrical internal (relative) auto-consistency In this way, for points near to MMS, their 3D-accuracy is very higher with respect to the map one: in fact, the MMS image scale is one or more times higher in magnitude with respect to aerial images generating the map.
Concerning instead absolute accuracy, a fine benefit is assured from the "mixed model" resolution (Dermanis, 1990) allowing either orientation estimation or prediction of 3D-coordinates starting from stochastic values stored in map (see for details Visintini, 2001). In such a way, also for external orientation, the high image scale is well exploited, enforcing the optical model onto more precise 3D point positions, and besides keeping into account GPS information constraint.

Concluding, the MMS "control points sowing" can be easily realize as soon as well visible natural points have been chosen on images/façades. In fact, having in whatsoever way computed vector $\mathbf{r}_{ccd}^{map}$ and matrix $\mathbf{R}_{ccd}^{map}$, by space resection from two different CCD-frames, the East, North, Height (E,N,H) position $\mathbf{r}_i^{map}$ of *i*-th point is obtained as:

$$\mathbf{r}_i^{map} = \mathbf{r}_{ccd}^{map} + S_i \mathbf{R}_{ccd}^{map} \mathbf{r}_i^{pix} \quad (1)$$

where:

- $\mathbf{r}_i^{pix}$ pixel coordinates observed on one image,
- S_i scale factor in the same image: really, within photogrammetric re sections it is implicitly computed only.

Off-course, points visible on more than two MMS images can be surveyed in different geometric configurations or by multiple resections, having later to choose the more reliable solution.
Relating to correctness and accuracy so reachable, just analysing relationship (1), one can see how, for obtained $\mathbf{r}_{ccd}^{map}$ and $\mathbf{R}_{ccd}^{map}$ precisions, it strongly depends from $\mathbf{r}_i^{pix}$ and S_i exactnesses. These lasts are correlated among them and depend from relative orientation between images (the shot base must be not too much short) and, obviously, from image scale. Once more, this is dramatically variable (generally and unfortunately) due to considerable obliquity between MMS images and building façades (45° in this case!).
Summarizing a general criterion, also in case of multiple image sensors (e.g. stereoscopic couple as in many existing MMS), to well survey a point, it is geometrically advantageous to use two or three consecutive images where it appears close and sideway much more as possible (see Figure 5).

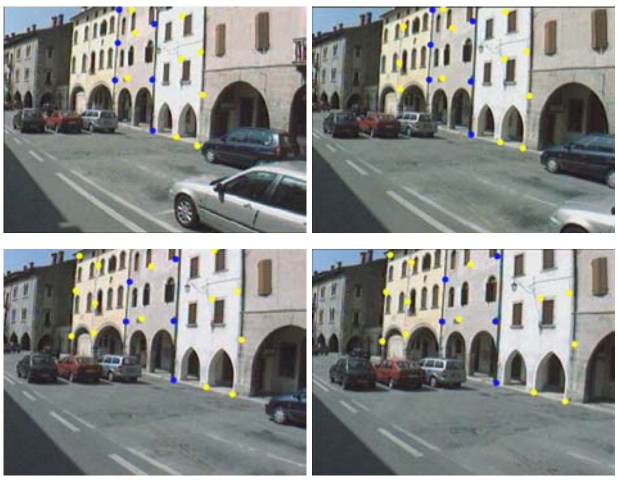


Figure 5: 3D-survey of control points by means of four consecutive MMS images.

The displacement on buildings of control points should later satisfy a homogeneous distribution on the static CCD images and/or on the façades. Without loss of generality, we suppose one image sufficient to survey one façade and contiguous façade planes differing among them for very small planimetric angle only. Unfortunately, some points in the higher part of building could be not well (low image scale) or not measurable at all (not portrayed) by MMS dynamic images.

Likewise for control points topographically measured, the point amount can be reduced by choosing points exactly in the boundary (vertical) area between two contiguous façades so that to twice use them (as a pseudo-strip with minimal overlapping). In truth, this extremely simple idea has a usefully effect on the accuracy of rectification, as it will be shown in next chapter.
In Figure 5, the survey of three adjacent houses is considered: single control points are then marked in yellow colour, while double ones are plotted in blue (see Figure 6 to look for same points on the static images). As can be seen, the geometry changes among the points: some low points are visible even four times, while other points located on second floor appear two times only. Off course, choosing other images, point reappearance could improve but, on the other hand, pixel scale and geometry resection could make worse.

4. BUILDING FAÇADE 2D-SURVEY BY CCD STATIC IMAGES

Once a satisfactory cluster of 3D-control points has been surveyed by (1), the image digital rectification can be achieved. For such end as explained before, high-resolution images are statically acquired by a CCD (even if no-metric) and submitted to an homographic transformation to create a geo-referenced raster texture of the building façades. With this widely applied analytical approach, there is no difference among metric and no-metric cameras, apart optical distortion involved and not considered by the homographic model.
Sharing the survey for each façade, it is necessary a coordinate roto-translation from mapping reference to those defined by each front plane. In this way, starting from all these E,N,H 3D-coordinates, sub-groups of X,Y 2D-coordinates arises for each façade, while corresponding Z values are the distances from the plane due to actual architectonical prominences/indentations and/or to inaccuracy in MMS survey.
For adjacent façades, having used same control points for both, they will be suitably used twice to define the least squares façade planes. Moreover, X-coordinates origin has to be unique for all them, so assuring continuous horizontal abscissas.
The homographic transformation equations for digital image rectification (here written from X,Y-plane to j,i-pixel plane) are:

$$j = \frac{a_1X + b_1Y + c_1}{uX + vY + 1} \qquad i = \frac{a_2X + b_2Y + c_2}{uX + vY + 1} \qquad (2)$$

where:

- $a_1, b_1, c_1, a_2, b_2, c_2, u, v$ unknown transformation parameters, to estimate by control point X,Y-coordinates.

To attain best rectification accuracy, further to use an adequate number (more than four) of control points, it is quite essential to keep into account their inauspicious errors due to MMS survey: now centimetre accuracy, as assured by topographic measures, is generally not reachable. This is the analytical key-point of the method proposed in the paper; for such end the linearization of (2) is done as follows:

- gathering together a strip of n contiguous images, where m_1 control points are common (double) in two images, while m_2 are control points in only image;
- considering as unknown either 8n transformation parameters or $2(m_1 + m_2)$ X,Y-coordinates;

In this way, a linear mixed system is obtained as follow:

$$\mathbf{b} = \mathbf{Ax} + \mathbf{Gs} + \mathbf{v} \qquad \mathbf{v} \sim N(0, \mathbf{C}) \;\; \mathbf{s} \sim N(0, \mathbf{C_{ss}}) \quad (3)$$

where:

- **b** [$2(m_1 + m_2)$ x 1] vector of point pixel coordinates, whose constant accuracy fills covariance matrix **C**;
- **x** [8n x 1] vector of images transformation parameters;
- **s** [$2(m_1 + m_2)$ x 1] vector of predicted X,Y-coordinate increments of 2D-points, starting from stochastic values measured by MMS with (1), whose accuracies suitably fill covariance matrix $\mathbf{C_{ss}}$;
- **A**, **G** respectively [$2(2m_1 + m_2)$ x 8n] and [$2(2m_1 + m_2)$ x $2(m_1 + m_2)$] partial derivatives matrices of (2) with respect to **x** and **s** unknowns; their elementary blocks are:

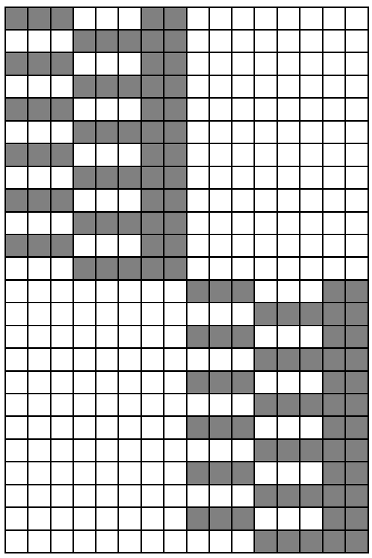
$$\mathbf{A}_{2x8} = \begin{bmatrix} X & Y & 1 & 0 & 0 & 0 & -jX & -jY \\ 0 & 0 & 0 & X & Y & 1 & -iX & -iY \end{bmatrix}$$

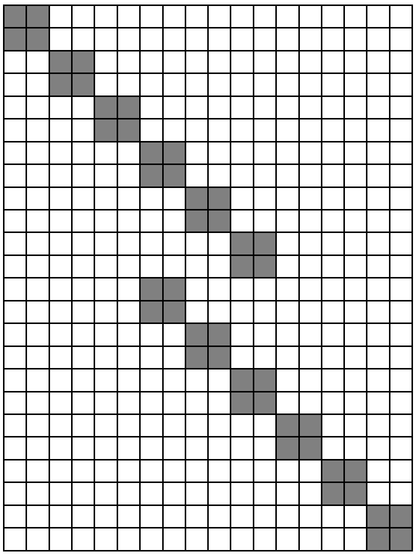
$$\mathbf{G}_{2x2} = \begin{bmatrix} (a_1 - ju) & (b_1 - jv) \\ (a_2 - iu) & (b_2 - iv) \end{bmatrix}$$

From definition of matrix **G**, let note as homographic parameters values are already required before solution: for such end, in a first step by neglecting **s**, the classical rectification model is applied.

The m_1 common control points, tying together images and so assuring analytical correlation in system (3), are very well predicted, since they have to simultaneously satisfy homographic conditions for two images.
Writing for shortage of space as working example a situation (not optimal for reliability!) with n = 2 contiguous images, m_1 = 3 common points in the centre and m_2 = 3 + 3 single points aside, the [24 x (16+18)] resulting system is given from following so filled **A** and **G** matrix:

A =



G =


It is now clearest how in matrix **G**, 7th÷18th rows link the images in a unique solution or, conversely, 7th÷12th columns submit the common points to two homographic constraints.

The "mixed model" solution of (3) achieves simultaneously following **x** estimation for and **s** prediction (Dermanis, 1990):

$$\hat{\mathbf{x}} = \left[\mathbf{A}^T\mathbf{M}^{-1}\mathbf{A}\right]^{-1}\mathbf{A}^T\mathbf{M}^{-1}\mathbf{b} \qquad \tilde{\mathbf{s}} = \mathbf{C}_{ss}\mathbf{G}^T\mathbf{M}^{-1}\mathbf{H}\mathbf{b} \qquad (4)$$

with:

$$\mathbf{M} = \mathbf{G}\mathbf{C}_{ss}\mathbf{G}^T + \mathbf{C} \qquad \mathbf{N} = \mathbf{A}^T\mathbf{M}^{-1}\mathbf{A} \qquad \mathbf{H} = \mathbf{I} - \mathbf{A}\mathbf{N}^{-1}\mathbf{A}^T\mathbf{M}^{-1}$$

This kind of rectification, here called as "mixed rectification", so allows to estimate homographic parameters and to predict more correct control point X,Y-coordinates. The same previous positive considerations done in chapter 3 about mean image scale, geometrical consistency and prediction worth can be repeated now, with an augmented significance.
In conclusion, by means of the "cascade application" of predictive models on dynamic and static images, best reachable survey results can be obtained.

5. APPLICATION FOR A BUILDING SURVEY

In the last part, the application of the proposed method for façade survey in the historical center of Serravalle - Vittorio Veneto (North/East Italy) is described and evaluated.
This area was chosen as "test-site" for the national research project "Simulation of Seismic Events and Damage Scenarios in Urban Areas" of Italian National Group for Defense from Earthquakes (GNDT-CNR, see http). Two lengthened blocks of three/four-floors historical buildings constitute the "test-site".

The MMS survey was realized by means of Geosoft Video Survey (GVS) system (see http). It acquires 640x480 images by means of four synchronized digital video cameras, one pointing forward the motion, other two ±45° turned (right and left) and one pointing behind. Among different sequences acquired, "45° right turned" (see Figure 5 and 6) were best images to survey a lot of 3D-control points in the most of façades. They were grabbed at 1 Hz frequency, so leading to a 5 m mean step, while simultaneously GPS pseudo-range measures, INS accelerations and rotation speed, and odometer data were acquired.
With such MMS was run four different streets of this historical quarter, so that to form a near-closed loop around such houses. Unluckily, sometimes the building distance from the traffic-lane is dramatically variable: as can be seen in Figure 6 in very few frames, the yellow color edifice very far and positioned behind a river even (on left), bypassing a road bridge it practically becomes the road edge (on right)!

Figure 6: MMS images not ideal for control point survey.

This is another classical situation confirming how much care has to be devoted in using MMS images for control point sowing, since image representation of everything is outside of road can quickly change during the motion.
Anyway, by applying analytical model mentioned in chapter 3 involving homologous points, map points of an available 3D-vector 1:2.000 digital map, and kinematic GPS measures, MMS images orientation has been fulfilled (without INS data).
As already told, the object pixel size value is essential to settle 3D-point accuracy: in our case, with this 640x480 (low) resolution, this so very variable distance MMS-buildings, and using data as a simplified MMS, the absolute 3D-precision ranges a lot, varying between 0,20÷0,60 m.
Afterwards, color images were acquired by a 1.536x1.024 Kodak DC265 no-metric CCD (as reported in Figure 7) to be rectified onto these control points (averagely nine for façade).

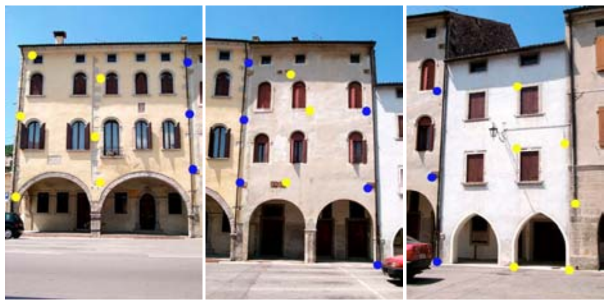


Figure 7: CCD static images of contiguous façades to be rectified by MMS surveyed control points.

The resulting image of the global rectification and automatic photo-mosaic by the mixed model (3) is reported in Figure 8.

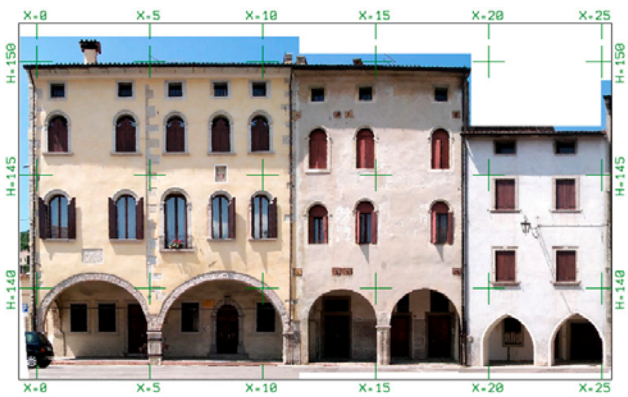


Figure 8: Previous CCD static images rectified (1:300 scale).

Figure 9 shows instead the rectification of the other subsequent buildings facing the way (via Casoni), while in Figure 10 both rectified areas are plotted together.

Figure 9: Other CCD static images rectified (1:300 scale).

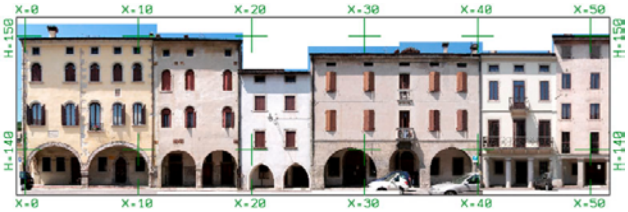


Figure 10: Joining of previous rectifications (1:600 scale).

To evaluate the rectification accuracy, several control points were in truth topographically 3D-surveyed by an electronic total station and these E,N,H values, once transformed on façade planes, were taken as reference X,Y-coordinates.
The mean errors of 2D-control points, that is the X,Y differences among MMS values and topographic ones, have a standard deviation of 0,29 m along X and 0,25 along Y. These mean values are substantially confirmed from the mean of residuals after "simple rectification" onto such points.
An interesting accuracy improvement is realized with "mixed rectification" (3) predicting better X,Y-coordinates according to homographic conditions: standard deviation values go down to 0,18 m and 0,16 m respectively for "single" control points.
The gain is much more noteworthy for "double" control points, where, as explained before, the X,Y prediction has to satisfy two images homographic transformations: standard deviation values decrease yet again to 0,10 m for X and 0,07 m for Y.

These results proof as, even with a few control points, the mixed (estimation/prediction) rectification has given a well support to the final accuracy by improving, dissimilarly to simple rectification, the coordinates of MMS surveyed points. Concluding, this method having decimeter accuracy can be applied for many cases of "no centimeter" surveys, such as for aggregate buildings or urban blocks and/o. VRML goals.
Remembering that MMS approach is advantageous for survey kilometres of roads, also accuracy values push towards surveys where the quantity is more important then quality.

CONCLUSIONS

The idea presented in this paper, that is an integrated method to efficiently survey buildings by dynamic and static images, is an attempt to maximize pro and minimize cons in using different photogrammetric sensors.
Dynamic MMS images of buildings are exploited to photogrammetrically survey control points only, while static CCD images, depicting same buildings and points, are employed instead for 2D-rectification thanks to a mixed homographic transformation model here shown.
A particular care has been devoted to achieve well final rectification accuracy, by suitably keeping into account the errors in control points due to MMS survey limitations. The employment of predictive/estimate models either on dynamic or static images is the analytical answer to such very important requirement.
Also thanks to the application of this proposed strategy work to a real case, potentials and limitations have been better explored and evaluated. For its high efficiency in terms of quantity of building quickly surveyable by simply passing through a road with a simplified MMS, this method is advantageous to extensively acquire kilometres of façades facing on roads. Nevertheless, considering high cost to develop an own MMS system, this approach requires for now the dynamic surveys by specialised MMS firms until the simplification of measuring multi-sensors will give available it for every potential user.

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