INTEGRATED TECHNIQUES FOR LOW-COST SURVEYING OF URBAN AREAS

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ABSTRACT:

This paper deals with the purpose of a methodology integrating different surveying techniques to efficiently produce a large-scale digital mapping of urban areas.
At first, a comparison among methods for reuse/updating of existing maps, aerial modern techniques and terrestrial ones is carried out, highlighting the pros/cons characterizing each one and in the attempt to find the "best technique" as well a suitable integration/synergism among them.
The integration herewith adopted considers the availability of a 3D-vector numerical mapping and the photogrammetric exploiting of images acquired either (dynamically) by a low-cost MMS or (statically) by a non-metric high-resolution CCD. MMS allows the survey of 3D-control points for the successive processing of the CCD images.
Afterwards for such techniques, the global work strategy and the different analytical model applied are explained. The main features of the algorithm for MMS data processing are: a direct/indirect orientation model, the stochastic prediction of point coordinates, and a pseudo-dynamic solution approach. Moreover, the analytical model of photogrammetric use of CCD images takes into account the inauspicious errors due to MMS survey by means of suitable techniques for stochastic prediction of unknowns.
At the paper end, the promising results obtained from an application on real data of this integrated method are shown and evaluated.

1. INTRODUCTION

The realization of a precise, accurate, detailed, up-to-date, consistent, and complete cartographic database is the well-know goal for surveying disciplines. Nevertheless, a well explanation of the GIS employment for such cartography is required, since what is necessary and sufficient for an application, it could be needless or insufficient instead for other ones.
In this sense, the mapping "nominal scale" is a generally significant parameter to suitably define technical specifications for the characteristics just mentioned above. But, in spite of this, for the same scale, the GIS application could push towards vector data formats rather than raster ones, or towards data reachable by photogrammetry instead of topography, and so on.

In this paper, to fix anyway the concepts, we consider the production of a vector 3D large-scale mapping as our cartographic target, i.e. maps for urban areas at scale from 1:2.000 up to 1:500. These numerical data constitute the geometrical base of a GIS for planning, management, and technological purposes. Moreover, we suppose to be also interested, starting from this mapping, to perform virtual city reconstructions for VRML 3D-navigations. In other word, we consider having to also acquire and geo-reference digital images as well as raster texture of the building façades.

As last consideration, the aim of this paper is NOT a boastful conviction to know each aspect of cartography to resolve everything by a wonder-touch! It is only a attempt to consider in widespread way such a complex problem, proposing some ideas based on the personal limited knowledge in this field.

2. COMPARISON OF SURVEYING TECHNIQUES

In next paragraphs, a comparison of advantages/disadvantages among advanced surveying techniques is done. The main characteristics are listed in following tables, with some obvious generalizations: in the first row, common features of the technique are reported, while specific ones for each sub-technique are later enrolled.
Off course, the "perfect technique" can't exist and, as consequence, the "best technique" is a clever integration among all of them, so that to better exploit/augment advantages and to skill overcome/reduce disadvantages.

2.1 Reuse and updating of existing maps

The "recycle" of any kind of (already) existing map is an unconventional technique to produce digital cartography; nonetheless, often such a low-cost possibility is not even taken into account. In fact, also when territory variations are not so dramatic, a completely "ex-novo" map is generally realised, since it is easier (but more expensive) to make, instead of to locally update it only where variations happened.

On the other hand, for a convenient reuse of 2D/3D coordinates information, the real accuracy of the existing maps has to be carefully evaluated. In particular for conventional maps storing 2D-coordinate in their cartographic signs, reliable procedures for (more or less automatic) vector digitising and multi-sheet geo-referencing are mandatory.

Starting instead from numerical but out-of-date mappings, a geodetic datum transformation could be required; however, nowadays, this is no more a problem from the computational point of view, since software tools can efficiently perform it, either in vector or in raster format. The important accuracy aspects here involved outcome the topics of this paper.

The final step, i.e. the updating of an existing map, is then performed by suitably introducing the occurred variations, these lasts surveyed by means of the aerial and/or terrestrial techniques described below.

Cartographic source	Advantages	Disadvantages
PREVIOUS MAPS	Economic	No update No façades Low accuracy
1. CONVENTIONAL	Availability	2D or 2,5D Out-of-date Digitising & geo-referencing
2. VECTOR DIGITAL	3D “Only to update”	Datum transformation
3. RASTER DIGITAL (ORTHO-PROJECTION)	Big qualitative information	2D Vectorizing Datum transform.

Table 1. Features of map production by reuse of existing maps.

2.2 Imaging and laser-scanning aerial surveys

Nowadays, the diffusion of commercial high-resolution satellite (e.g. Fraser, 2000) opens a new era for the imaging “aerial” survey. However, considering here the realization of large-scale mappings only, such a methodology is still insufficient (up to now!) for accuracy and detail.

Discussing now on classical aerial photogrammetry, the “master way” to product digital mapping even now, its pros/cons can be assumed as familiar for the person who reads. For this reason, here we give only notice about some fascinating recent developments in this field, as well as the use of:

- Techniques for automatic aerial triangulation;
- Navigation sensors (GPS and INS) for direct image external orientation;
- Digital imaging aerial sensors.

A complete collection of these and other related topics can be found in Heipke (editor, 2001).

Cartographic source	Advantages	Disadvantages
AERIAL SURVEYS	Efficiency	“High cost” No wall perimeter No façades
1. HIGH-RESOLUTION SATELLITE IMAGERY	Daily survey No control points	Low accuracy Low detail High cost
2. AERIAL PHOTOGRAMMETRY	High efficiency Homogeneity	High cost No daily survey
3. AERIAL LASER-SCANNING	High automation Fast production	No interpretation Noised results

Table 2. Features of map production by aerial surveys.

Closing the aerial surveys, the recent “topographic” technology of laser scanning (e.g. Baltsavias, 1999) looks very promising for the production of detailed DTM of urban areas. However, for the moment, it is not immediate to convert it in a reliable and structured vector (wire-frame) model because of noise in the generated DTM and impossibility to classify the objects, unless a digital image has been also acquired during the flight.

2.3 Imaging and topographic terrestrial surveys

In some way, terrestrial surveys have opposite good/bad characteristics with respect of aerial ones, and in particular, the same complementary performances can be state for photogrammetric techniques. In any case, it must be highlight how terrestrial surveys have not been developed to extensively map territorial areas (apart topographic surveys for old cadastral maps), but rather single or grouped man-made objects (buildings, roads, infrastructures, plants and so on) at a very large scale.

Besides, it should be redundant to recall now the features of close-range photogrammetry, very well known for the reader. Anyway, as done for aerial purposes, here we report again some interesting advances only, as the use of:

- Euclidean coordinates (e.g. Förstner, 2000);
- Images vanishing point (e.g. Van den Heuvel, 1998);
- Object space geometric constrains (e.g. McGlone, 1995).

Cartographic source	Advantages	Disadvantages
TERRESTRIAL SURVEYS	On-demand measures	“No roofs” Lower efficiency
1. TERRESTRIAL PHOTOGRAMMETRY	High detail	Control points survey
2. MOBILE MAPPING SYSTEMS (MMS)	High efficiency	High cost Only next to roads
3. (TERRESTRIAL) TOPOGRAPHY	Very high detail Low cost	Inadequate efficiency
4. TERRESTRIAL LASER-SCANNING	High automation Fast production	No interpretation Noised results

Table 3. Features of map production by terrestrial surveys.

In these lasts years, the use of terrestrial MMS (vehicles with GPS, INS CCD integrated sensors, e.g. El-Sheimy, 1996) has had an increasing development and interesting applications, mainly to survey geometry and pavement characteristics of roadways. The innovative use of a MMS for the cartographic production is extremely exciting, but it is not so easy to carry out. Their “tout-court” application to measure man-made objects is quite impossible, due to these restrictions:

- GPS signal outages happen very usually in urban environments and MMS position only computed by INS accelerometers could be not so accurate for a precise map.
- Only for very few objects, to cover a road circular path around them for a complete survey is possible.
- Objects too near or too distant from a road cannot be surveyed with a constant detail and accuracy.
- The shot geometry among successive CCD images is very difficult to optimise in a dynamic survey. Therefore, many objects would be partially portrayed only, so that this surveying procedure would give out incomplete results.

Then, for cartographic goals, MMS technology has to be used together with other survey methods, as afterwards explained.

“Terrestrial topographic techniques” means nowadays surveys by global stations without reflective prism, large use of GPS systems for detail survey and/or for geodetic datum fixing, powerful software for measure adjustment and for cartographic representation. All these remarkable facilities have improved the survey efficiency but, as well as any kind of terrestrial measurements, also this method seems to be restricted for locally update a map and not for realize it starting from zero.

As ultimate technique, a hint on terrestrial laser-scanning applications (e.g. Runne, Niemeier and Kern, 2001) has to be done. This technology has similar pros/cons of the aerial one, however so obtained DTMs have better accuracy now, not only for closer measures but also for easier knowledge of laser external orientation. The problem of partial DTMs joining arises now: it can be solved by Computer Vision approaches where the problem is known as "global registration" (e.g. Bergevin et al., 1996) or by "procrustes analysis" as recently developed by our research group (Beinat and Crosilla, 2001).

3. INTEGRATION OF SURVEYING TECHNIQUES

In order to find an optimal integration among the previously explained surveying techniques, in this paper we have taken more into account these three general preference criteria:

- Exploiting of each easy available information;
- Low-cost instrumentations techniques;
- On-demand (everyday) opportunity of data acquisition.

Therefore, following Section 2 considerations and these above choices, with the term "optimal surveys" we mean a process correctly integrating the reuse of existing maps (2.1) and the employment of photogrammetric terrestrial techniques (2.3).

Within the first topic, the availability of a 3D-vector numerical mapping is assumed, and a satisfactory updating level characterizes it; the not so many variations can be thus efficiently surveyed by terrestrial techniques. Otherwise, for new urbanized areas and for never surveyed regions, an aerial photogrammetric survey is the best solution too.

Regarding instead the terrestrial photogrammetry processes, the idea is to well exploit images acquired either (dynamically) by a low-cost MMS or (statically) by a non-metric CCD.

For the MMS survey, the main problem that is the images external orientation has been solved in an alternative indirect way, considering that we do not use (still) expensive INS sensor. In such a sense as for aerial triangulation, the images have been exploited also for orientation and not for 3D-point survey only. However, this approach, usual in traditional photogrammetry, has also some disadvantages, as:

- requirement of hundreds of control points along the route;
- influence of such point precision on orientation accuracy;
- not optimal estimation by classic (static) analytical models.

A model to overcome these cons has been proposed (Visintini, 2001b), which main features are (in the same previous order):

- direct (by GPS only) and indirect orientation (by 3D digital mapping points as control points, so that topographic survey is not required);
- stochastic prediction of control point coordinates, to well orient the images also with low accuracy for such points;
- pseudo-dynamic approach, to estimate the orientation parameters by numerically efficient computations.

Summarizing, the steps for this MMS/CCD survey are:

1. Identification of "new" objects to be insert for updating the digital map. For such end, techniques matching maps with high-resolution satellite imagery can be advantageously applied, but if and only if these images are cheap enough.
2. Planning and fulfilment of the terrestrial survey, evaluating 3D-mapping points distribution and splitting up in two hierarchical surveying levels:
   a. Simplified MMS dynamic technique to measure much more possible 3D-control points;
   b. Classical static shots to acquire images, in better geometric/resolution conditions, depicting the objects to survey and the before 3D-control points.
3. Photogrammetric processing of the dynamic MMS digital images, by specific analytical models (next paragraphs 4.1 and 4.2) and by using 3D-map points.
4. Photogrammetric processing of the static CCD digital images, by specific analytical models (next paragraphs 4.3 and 4.4) and by using 3D MMS surveyed points.

A MMS without inertial sensors, as the system we consider to use, can fulfil in the same way the survey since the INS contribution to the relative positioning/attitude is replaced by considering the analytical condition of points coplanarity between successive images.

For the automatic detection of the homologous points, acting relative orientation of a "second" image with respect to a "first" image (already externally oriented), an original pseudo-dynamic matching algorithm has been proposed also (Visintini, 2001a).

Other interface tools to help the user in acquisition of image points could be developed as, for instance, the projection of vector map objects in the MMS raster images to assist the extraction of map coordinates. Such image projection is always possible since, by roughly knowing the MMS path, we have information on external orientation also for not oriented images!

4. ANALYTICAL MODELS APPLIED

To well understand the surveying models here explained, we recall that, although using only one CCD on the MMS, thanks to images sequentially acquired during the motion, anyway the control points 3D-positioning is geometrically achievable.

4.1 Dynamic orientation of sequential MMS images

To obtain the external orientation parameters of the CCD image acquired at (t+1) time:

$$\mathbf{x}_{t+1} = [E_{t+1} \quad N_{t+1} \quad H_{t+1} \quad \omega_{t+1} \quad \varphi_{t+1} \quad \kappa_{t+1}]^T$$

a Kalman filter model has been applied (Visintini, 2001b). In fact, since the MMS motion has a "regular trajectory (in local sense) with an irregular course (in global sense)", a transition matrix $\mathbf{\Phi}_t$ describing the evolution of $\mathbf{x}_t$ can be suitably obtained, starting again from 3D-map data. The linearized form of the state equation is then:

$$\boldsymbol{\delta}\mathbf{x}_{t+1} = \mathbf{\Phi}_t \boldsymbol{\delta}\mathbf{x}_t + \boldsymbol{\mu}_{t+1} \qquad \boldsymbol{\mu}_{t+1} \sim N(0, \mathbf{\Theta}_{t+1}) \qquad (1)$$

The following three kinds of linearized orientation observations (if available) are consequently exploited:

1. Digital image coordinates of each visible homologous point submitted to the coplanarity condition **h**:

$$\mathbf{h}\{\bar{\mathbf{x}}_{t+1}, \mathbf{l}_1\} + \mathbf{C}_1 \boldsymbol{\delta}\mathbf{x}_{t+1} + \mathbf{D}_1 \mathbf{v}_1 = 0 \qquad (2)$$

2. Digital image and 3D-coordinates of each visible mapping point submitted to the collinearity condition $\mathbf{y}_2$:

$$\mathbf{g}\{\bar{\mathbf{x}}_{t+1}, \mathbf{X}\} + \mathbf{C}_2 \boldsymbol{\delta}\mathbf{x}_{t+1} + \mathbf{E}_2 \mathbf{s} + \mathbf{v}_2 \qquad (3)$$

3. CCD-frame coordinates $\mathbf{m}$ obtained by kinematic GPS measures and taking into account known eccentricity $\mathbf{a}_{\mathrm{ccd}}^{\mathrm{gps}}$ and rotation $\mathbf{R}_{\mathrm{ccd}}^{\mathrm{gps}}$ between CCD and GPS frames:

$$\mathbf{r}_{\mathrm{gps}}^{\mathrm{map}} \cong \mathbf{m}\{\bar{\mathbf{x}}_{t+1}\} + \mathbf{C_3}\boldsymbol{\delta}\mathbf{x}_{t+1} + \mathbf{v_3} \tag{4}$$

where:

- $\mathbf{h}\{\bar{\mathbf{x}}_{t+1}, \mathbf{l_1}\}, \mathbf{g}\{\bar{\mathbf{x}}_{t+1}, \mathbf{X}\}, \mathbf{m}\{\bar{\mathbf{x}}_{t+1}\}$ equations values computed with approximated value $\bar{\mathbf{x}}_{t+1}$;
- $\mathbf{C_1}, \mathbf{D_1}, \mathbf{C_2}, \mathbf{E_2}, \mathbf{C_3}$ partial derivatives matrices of the equations respect to the unknowns;
- $\mathbf{s}$ predicted coordinate increments of 3D-map points, starting from stochastic values $\mathbf{X}$ of the digital map.

Gathering equations (2), (3) and (4) together, the following observation system can be written:

$$\mathbf{b}_{t+1} = \mathbf{C}\boldsymbol{\delta}\mathbf{x}_{t+1} + \mathbf{E}\mathbf{s} + \mathbf{D}\mathbf{v} \tag{5}$$

where:

$$\mathbf{b}_{t+1} = \begin{bmatrix} \mathbf{h}\{\bar{\mathbf{x}}_{t+1}, \mathbf{l_1}\} \\ \mathbf{y_2} - \mathbf{g}\{\bar{\mathbf{x}}_{t+1}, \mathbf{X}\} \\ \mathbf{r}_{\mathrm{map}}^{\mathrm{gps}} - \mathbf{m}\{\bar{\mathbf{x}}_{t+1}\} \end{bmatrix} \quad \mathbf{C} = \begin{bmatrix} -\mathbf{C_1} \\ \mathbf{C_2} \\ \mathbf{C_3} \end{bmatrix} \quad \mathbf{E} = \begin{bmatrix} 0 \\ \mathbf{E_2} \\ 0 \end{bmatrix}$$

$$\mathbf{D} = \begin{bmatrix} -\mathbf{D_1} & 0 \\ 0 & \mathbf{I} \end{bmatrix} \quad \mathbf{v} = \begin{bmatrix} \mathbf{v_1} \\ \mathbf{v_2} \\ \mathbf{v_3} \end{bmatrix} \sim N(0, \boldsymbol{\sigma}_{\mathrm{v}}^2 \mathbf{Q}_{\mathbf{v}})$$

Finally, the dynamic solution of observation (5) and state equations (1) gives out the prediction of orientation parameters:

$$\tilde{\mathbf{x}}_{t+1} = \boldsymbol{\Phi}_t \tilde{\mathbf{x}}_t + \mathbf{K}_{t+1}\mathbf{b}_{t+1} \tag{6}$$

where:

$$\mathbf{Q}_{\delta\hat{\mathbf{x}}_{t+1}} = \boldsymbol{\Theta}_{t+1} + \boldsymbol{\Phi}_t \mathbf{Q}_{\mathbf{x}_t} \boldsymbol{\Phi}_t^{\mathrm{T}} = \mathbf{Q}_{\hat{\mathbf{x}}_{t+1}}$$

$$\mathbf{Q}_{\mathbf{b}_{t+1}} = \mathbf{D}\mathbf{Q}_{\mathbf{v}}\mathbf{D}^{\mathrm{T}} + \mathbf{E}\mathbf{Q}_{\mathbf{XX}}\mathbf{E}^{\mathrm{T}} + \mathbf{C}\mathbf{Q}_{\delta\hat{\mathbf{x}}_{t+1}}\mathbf{C}^{\mathrm{T}}$$

$$\mathbf{K}_{t+1} = \mathbf{Q}_{\delta\hat{\mathbf{x}}_{t+1}}\mathbf{C}^{\mathrm{T}}\mathbf{Q}_{\mathbf{b}_{t+1}}^{-1} \quad \text{Kalman gain matrix}$$

4.2 Control point survey by MMS images

As mentioned, the MMS is used as well as a "control points sower" for succeeding photogrammetric orientations: such positions are therefore no measured by topographic techniques. Once all the acquired images have been oriented by model (6), the position vector $\mathbf{r}_{\mathrm{ccd}}^{\mathrm{map}}$ and the rotation matrix $\mathbf{R}_{\mathrm{ccd}}^{\mathrm{map}}$ are fulfilled for each epoch t. By means of reverse projection (space resection) from, at least, two different CCD-frames, the position $\mathbf{r}_{\mathrm{i}}^{\mathrm{map}}$ of i-th control point is given by the geometrical model:

$$\mathbf{r}_{\mathrm{i}}^{\mathrm{map}} = \mathbf{r}_{\mathrm{ccd}}^{\mathrm{map}} + \mathrm{S_i}\mathbf{R}_{\mathrm{ccd}}^{\mathrm{map}}\mathbf{r}_{\mathrm{i}}^{\mathrm{pix}} \tag{7}$$

where the pixel coordinates $\mathbf{r}_{\mathrm{i}}^{\mathrm{pix}}$ are observed on the image, while in truth the image scale values $\mathrm{S_i}$ are implicitly computed only within photogrammetric resection computations.

In conclusion, it must to be stressed how MMS CCD images have a large mean scale: from the analytical point of view, this means that the "optical model" has a strong geometrical auto-consistency. As very useful consequence of these constraints on the point invariants quantities, a good relative (internal) precision of the orientation and resection process is assured.
Moreover, regarding instead absolute accuracy, the prediction model (3) applied onto stochastic map coordinates warrants the best results, conditions being equal.

4.3 3D-Map survey by CCD images onto control points

Once the control point 3D-positions have been computed with respect to a (unique) mapping frame by MMS applying model (7), the final mapping survey can be carried out by classical terrestrial photogrammetric approach.
In this way, the high-resolution CCD images acquired by best positions can be well oriented and used for the detailed survey.

To use no-metric cameras and to correctly manage the accuracy of control point again, we recollect an analytical "mixed model" developed some years ago (Crosilla, Manzino and Visintini, 1996) and based on well-known DLT (Direct Linear Transformation) photogrammetric approach. The linearized DLT (12-parameters) equations can be written as:

$$\mathbf{b} = \mathbf{A_1}\mathbf{x_1} + \mathbf{A_2}\mathbf{x_2} + \mathbf{A_3}\mathbf{x_3} + \mathbf{G}\mathbf{s} + \mathbf{v} \tag{8}$$

$$\mathbf{v} \sim N(0, \mathbf{C}) \qquad \mathbf{s} \sim N(0, \mathbf{C_{ss}})$$

where:

- $\mathbf{x_1}, \mathbf{x_2}, \mathbf{x_3}$ respectively DLT image parameters, surveyed point coordinates, and tie points coordinates;
- $\mathbf{s}$ predicted coordinate increments of 3D-points, starting from stochastic values obtained by MMS;
- $\mathbf{A_1}, \mathbf{A_2}, \mathbf{A_3}, \mathbf{G}$ partial derivatives matrices of the DLT equations respect to the unknowns.

Making use of a unique unknown vector $\mathbf{x} = [\mathbf{x_1} \quad \mathbf{x_2} \quad \mathbf{x_3}]^{\mathrm{T}}$ to be estimated, the "mixed model" solution (Dermanis, 1990) achieves simultaneously following estimation and prediction:

$$\hat{\mathbf{x}} = [\mathbf{A}^{\mathrm{T}}\mathbf{M}^{-1}\mathbf{A}]^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{M}^{-1}\mathbf{b} \tag{9}$$

$$\tilde{\mathbf{s}} = \mathbf{C_{ss}}\mathbf{G}^{\mathrm{T}}\mathbf{M}^{-1}\mathbf{H}\mathbf{b}$$

where:

$$\mathbf{A} = [\mathbf{A_1} \quad \mathbf{A_2} \quad \mathbf{A_3}] \qquad \mathbf{M} = \mathbf{G}\mathbf{C_{ss}}\mathbf{G}^{\mathrm{T}} + \mathbf{C}$$

$$\mathbf{N} = \mathbf{A}^{\mathrm{T}}\mathbf{M}^{-1}\mathbf{A} \qquad \mathbf{H} = \mathbf{I} - \mathbf{A}\mathbf{N}^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{M}^{-1}$$

The same positive considerations done in the previous paragraph about geometrical consistency and prediction worth can be repeated now, with an augmented significance. Therefore, we can state that, by means of the "cascade application" of the predictive models (5) and (8), the best reachable survey results could be obtained.
Finally, in this way, the 3D-survey of the objects for update the digital mapping (vector $\mathbf{x_2}$ in form (8)) has been accomplished.

4.4 2D-Map survey by CCD images onto control points

As last surveying output, the geo-referenced raster texture of the man-made objects, mainly building façades, is required. For such end, it is necessary a coordinate transformation from mapping reference to those defined by each front plane, once the different (vertical) planes have been chosen. A list of X,Y 2D-coordinates of control points become available for each façade, while corresponding Z values are the distances from the plane due to actual architectonical prominences/indentations and/or to inaccuracy in the MMS-survey again.

As well-known, from the analytical point of view, this widely used procedure of pixel resampling applies a (plane) homographic (8-parameters) transformation from a central projection (photo) to an orthogonal one (prospect). With this analytical approach, there is no difference between metric and no-metric cameras, apart every image distortion introduced and not considered by the homographic transformation.

In order to guarantee best rectification accuracy yet, further to use an adequate number of control points, well distributed on the image and façade, it is necessary keep into account their inauspicious errors for MMS survey, as proposed in 4.3.
Considering now the homographic transformation equation, it linearization conducts at the form, analogous to (8):

$$\mathbf{b}=\mathbf{A}\mathbf{x}+\mathbf{G}\mathbf{s}+\mathbf{v} \qquad \mathbf{v}\sim N(0,\mathbf{C}) \;\; \mathbf{s}\sim N(0,\mathbf{C}_{\mathbf{ss}}) \quad (10)$$

where:

- **x** image transformation parameters;
- **s** predicted coordinate increments of 2D-points, starting from stochastic values gained by MMS;
- **A**, **G** partial derivatives matrices of the homologous transformation equations respect to the unknowns;

The simultaneous estimation and prediction solution is given again from (9), but with the above meaning of the terms.

An application of the integrated method for façades image rectification can be found in Visintini (2002), with an architectonic survey example for seismic vulnerability analysis.

5. APPLICATION OF THE METHOD

This paragraph summarizes the results obtained by applying the integrated method on really acquired MMS&CCD data.
Figure 4 shows the test area as it is reported in a 1:5.000 scale 3D-vector digital technical cartography (but characterized by a 1:2.000 better-quality accuracy); this map was produced some years ago by means a classical aerial photogrammetric survey using 1:8.000 scale images.
We supposed to have now to realize the 2D-raster façade survey of the (orange filled) building for VRML purposes, that is for decimetre accuracy, and not for more precise architectonic goals. For such a brick structure, the 3D-edge of plane roof is reported in the map, together with the edge of the surrounding sidewalks. These (green enumerated) points are used as stochastic control points for orientation of digital images dynamically acquired by a simplified MMS.
In fact, we performed a MMS survey by employing our low-cost system DyNO (Visintini, 2001b). The digital images had a 38 mm equivalent focal length and a 1.152x768 size; they were acquired 45° right side respect the motion, with 5 m mean step.

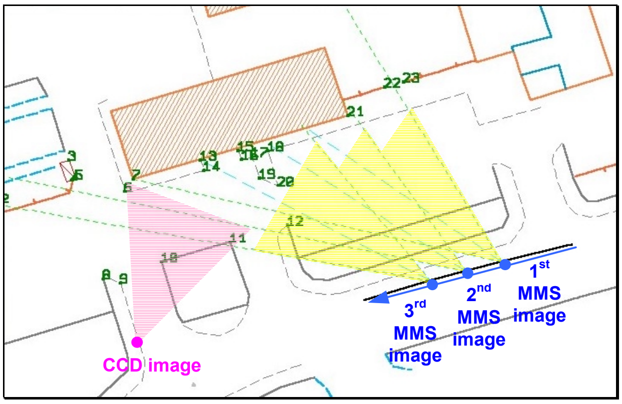

Figure 4. Digital technical map 1:5.000 (here plotted 1:1.000).

For MMS image orientation, further to kinematic GPS measures (by relation (4)), also homologous points (by relation (2)) and map points (by relation (3)) have been used.

Figure 5. 1^{st} MMS image.

Figure 6. 2^{nd} MMS image.

Figures 5÷7 illustrates three consecutively acquired images, each one partially portraying only the building to survey: the mean pixel dimension was 2,5 cm, but very variable due to geometric configuration of horizontal 45° shot angle with same direction of MMS trajectory and building façade. As well known, the object pixel size value is fundamental for the 3D-survey accuracy: with the previous entities, but especially taking into account the use of a simplified MMS, an absolute 3D-precision of 0,20÷0,40 m is expectable.
The yellow numbers indicate again the homologous/map points used for MMS image orientation (by relation (6)). Points enumerated from 101 to 110 are homologous points simply, that is building façade particulars (obviously not stored on map!).
As result of orientation process, such 3D-points become the 2D-control points for image rectification. Moreover, by applying relation (7), each other point visible into oriented MMS images can be 3D-surveyed, so that to be exploited as control point.

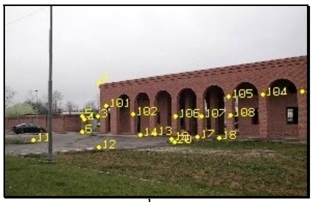

Figure 7. 3^{rd} MMS image.

Figure 8. CCD image to rectify.

Figure 8 depicts instead the 1.760x1.168 terrestrial image taken with a Kodak DC3400 from a suitable position assuring the maximum image scale and the façade wholeness: mean pixel dimension was now 1,6 cm. The blue façade 2D-control points are those 3D-surveyed by MMS and used as well as "stochastic constraint" with a mixed model for image rectification as explained in paragraph 4.4.
Such an estimation/prediction approach ("mixed" rectification, Table 10) has given a well support to the final accuracy with respect to the estimation one ("simple" rectification, Table 9), as can be seen by comparing residual mean values. The X,Y

residuals are the coordinate difference among 25 rectified points and measured ones (check points) by topographic total station. Furthermore, here we consider two situations: only 8 versus all 25 control points to evaluate the improvement in final accuracy.

	residuals with 8 points		residuals with 25 points	
	j [pixel]	i [pixel]	j [pixel]	i [pixel]
mean	-0,05	-0,24	0,06	-0,20
st.dev.	7,14	16,44	12,92	19,67
	X [m]	Y [m]	X [m]	Y [m]
mean	-0,001	-0,029	-0,001	0,000
st.dev.	0,262	0,305	0,249	0,308

Table 9. Residual mean values after “simple” rectification.

	residuals with 8 points		residuals with 25 points	
	j [pixel]	i [pixel]	j [pixel]	i [pixel]
mean	-0,06	-0,03	-0,89	-0,201
st.dev.	1,58	1,82	2,90	2,26
	X [m]	Y [m]	X [m]	Y [m]
mean	-0,117	-0,000	-0,049	0,028
st.dev.	0,095	0,093	0,104	0,093

Table 10. Residual mean values after “mixed” rectification.

As general considerations about this test, we can state that:

- by using the mixed approach, there is an accuracy increase, either in terms of pixel coordinates or in absolute ones;
- also with a minimum number of control points, the mixed approach gives out good results for image rectification.

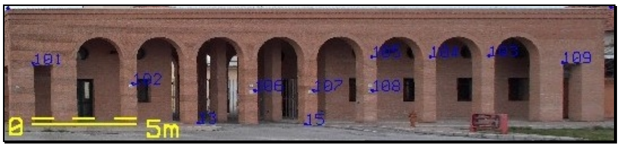

Figure 11: CCD rectified image (here plotted at 1:350 scale).

Figure 11 shows the obtained final rectified CCD image: the geometrical consistency of this final image proofs again the correctness of the global process proposed and followed.

6. CONCLUSIONS

Starting from the comparison among nowadays surveying methods (reuse/updating of existing maps, aerial and terrestrial techniques), an integrated procedure has been engaged.

Hypothesising the availability of a 3D-vector numerical mapping, images acquired by a low-cost MMS and by a non-metric CCD have been exploited for the updating. In particular, MMS allows the survey of all the 3D-control points for successively CCD image photogrammetric processing.

The analytical models adopted are characterized by interesting quality of generalization (direct/indirect orientation), robustness (stochastic prediction of point coordinates), and numerical efficiency (pseudo-dynamic approach).

Firsts promising obtained results here presented confirm these judgments, pushing nevertheless towards other necessary numerical tests and methodological investigation.

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