An Automatic Analytical Procedure for Searching Corresponding Feature Points in a Cadastral Map

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SUMMARY

In some recent papers Beinat and Crosilla (2003a, 2003b) have illustrated a new direct procedure, based on Procrustes analysis techniques, for the least squares adjustment of digital cadastral map features. The method has been successfully applied to simultaneously fit a series of fiducial point networks (polygons), each one connecting at least three points measured in the field by professional surveyors, strictly preserving their geometrical shape and linking the whole polygon set to a limited number of fixed points. The proposed procedure considers the various partially or totally overlapping measured polygons as unitary component parts of the general network of fiducial cadastral points to be adjusted. Direct and independent similarity transformation models are applied to each polygon – i.e., the so called Procrustes adjustment model – so to minimise a measure of discrepancy among the various polygons.

As well as for the fiducial point network, the same technique can also correctly perform the conformal mosaicking of the new surveyed cadastral parcels with those ones obtained by digitisation of the original map, satisfying further possible geometrical constraints of the map entities like alignments, orthogonality and so on.

To achieve the conformal parcel mosaicking in the absence of any topological or structural information, a specific procedure is needed to automatically identify the point-to-point correspondences between the various geometric entities to be connected.

Several methods to detect possible correspondences between two sets of equal number of unlabeled points have been developed and investigated. Among these, we report the Umeyama's method (1988) developed to compute the permutation that maximises the agreement between two weighted graphs by way of a singular value decomposition of the relative adjacency matrix product. Another original direct solution, based on pure geometric rules, has been implemented and successively described.

For the more general problem of detecting a geometric entity entirely contained within a more complex configuration, e.g. a measured parcel belonging to a cadastral map, a "kernel growing" geometric approach has been developed. The method explained in the paper is based on the analysis and segmentation of the adjacency matrices relative to the specific parcel and to the entire map vertex coordinates, and on the computation and validation of transformation parameters performed by Procrustes analysis techniques.

In addition to the cadastral cartographic purposes, the procedure seems suitable for a wider range of possible applications, spacing from the Geographic Information Systems to the industrial and civil engineering design.

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1. INTRODUCTION

The definition of new sound revision procedures of the cadastral mapping is needed in general, since many years, by public administrations, users and professional technicians of many Countries. In Italy, the cadastral administration – properly "Agenzia del Territorio" – since the beginning of the nineties, imposed specific norms to correctly implement the new data bases of the cadastral map and to define the rules for its management.
These procedures are based on the following steps:

- the use of the metrological information furnished by the professional technicians relating to their new field surveys;
- the realisation of a fiducial point network providing a reference for the various field surveys;
- the storage of the acquired geometrical data onto a digital support by using a standardised software tool, named Pregeo.

According to these specifications, the digital archives have reached, for some Italian areas, a consistency such that, from the experimental point of view, it becomes significant to perform an automatic updating of the cartographic database. Nevertheless, there are still many problems that interfere with the realisation of a sound updating procedure able to manage, in a valid manner, the amount of measurements already acquired.

First of all it is necessary to consider the poor reliability of the fiducial point network that generates low quality data for cartographic applications – i.e. field surveys executed with high accurate procedures and adequate instruments, might result affected by a significant error of positioning.

In this context, the Italian Cadastre Administration has introduced an updating procedure of the fiducial point networks based on the use of the direct and indirect distance measurements between the fiducial points. The method imply the choice of an origin, of a point to which to orient the cadastral survey, and the computation of some rigid transformation parameters (translation and rotation) to apply to the surveyed geometrical entities when compared with the corresponding ones of the original map.

In our opinion this procedure is not the optimal one for the reason that:

- the homogenisation effect due to the coordinate correction acts locally and it does not rigorously propagates to the contiguous parts of the network;
- the frequent variation of the fiducial point coordinates deforms, in anisotropic way, the shape of the cadastral parcels taken into account.

From these considerations it follows that it is necessary to apply new analytical techniques to globally adjust all the direct and indirect distance measurements between the fiducial points, constraining the network to a little number of control points defined, for instance, by GPS, so to improve the precision of the fiducial point network and to transform the point coordinates into a unique and common reference system.

The second cadastral map updating problem consists of the optimal aggregation of new geometrical entities, surveyed with high precision techniques, with the ones digitised from the original paper map.

For the solution of both problems, Beinat and Crosilla (2003a, 2003b) have recently proposed an analytical method based on the Generalised Procrustes analysis techniques. This procedure can advantageously be applied for the rigorous adjustment of the fiducial point networks and for the simultaneous update of the fiducial point networks and of the cadastral parcels.

The leading idea of the process is to consider all the geometric elements of a cadastral survey like an unique collection of measurements, not decomposable, for which a proper similarity transformation is admitted. The different surveys are in this way independently rotated, translated and scaled, according to the analytical formulation of the Procrustes analysis, so to satisfy their reciprocally optimal fit, like small pieces of a mosaic.

If the various surveys specifically refer to the cadastral parcels, this procedure makes it possible to obtain the cartographic mosaic of the parcels through the following phases:

- initial decomposition of all the considered parcels;
- insertion of the new ones, usually more reliable and precise, in place of the existing entities;
- adjustment of the old and the new parcels with the satisfaction of specific geometrical constraints.

If the cadastral measurements are given by the fiducial polygons and by the cadastral parcels, the proposed procedure, considered the strict correlation existing between the two different entities, can be applied to simultaneously execute the adjustment of the fiducial point network and the optimal insertion of the surveyed parcels into the digital cadastral map. In this way, the dual initial problem is faced in a global manner and solved with a unique analytical tool.

Some experimental results of the Procrustes analysis techniques, limited for the moment only to the case of the adjustment of the fiducial polygons, have furnished results of significant interest. The results confirm that the proposed algorithm is able to overcome the majority of the systematic errors characterising the measurements stored in the cadastral database, obtaining more accurate results with respect to the ones from a conventional adjustment procedure (Beinat, Clerici & Crosilla, 2002).

The next goal of the procedure is the extension of the Procrustes method for the optimal mosaicking of the cadastral parcels. This phase, due to the particular format of most of the existing digital data and to assure their backward compatibility, is not so immediate and leads to new problems that will be in detail analysed in the following, and for which a valid solution will be suggested.

2. THE POINT SETS CORRESPONDENCE

In the Procrustes analysis, every similarity transformation parameter is computed in such a way to minimise the discrepancies between the corresponding point sets; the correspondence knowledge among the vertices of two figures is therefore a necessary condition for the correct use of such a tool.

In the cadastral field, correspondent points are the vertices that represent, for different surveys of the same parcel, the images of the same real points. Therefore, for a correct application of the procedure, it is necessary to know the topological structure that makes possible to relate the points of one survey with those of another one. In the case of the fiducial polygons, such a knowledge is based on the univocal and rigorous name coding of the fiducial point, and the correspondence is deduced by a simple comparison of the alphanumeric code content. For the cadastral parcels, these conditions are completely different. In this case there are not rigorous specifications about the name of a single vertex; the same point of a parcel can assume a wide range of names, according to the choice of the technician who has executed the survey. The specific problem of the cadastral parcels is therefore the identification of the corresponding points. The following example will explain the case (Figure 1).

Let us suppose that two different technicians (A and B) have executed, at different times, the survey of the same unchanged parcel, and have referenced it to a common fiducial polygon. The available data are the co-ordinates of the describing vertices referred to two different datums (origin and orientation), whose values are reported in Table 1.

The rising question is the following: which are the right pairs of corresponding points?

A man made solution is the graphical comparison of two pictures of the point configurations. These are rotated in such a way to put one upon the other, as shown in Figure 1. The correspondent point identification is immediate.

Survey executed by the technician A						
Vertex id.	*101*	*102*	*103*	*104*	*201*	*202*
Coordinate X	73,22	95,97	82,94	120,87	125,36	186,84
Coordinate Y	80,87	100,22	115,39	147,97	19,99	72,12

Survey executed by the technician B						
Vertex id.	*101*	*102*	*201*	*202*	*301*	*302*
Coordinate X	151,76	73,53	90,25	188,04	177,59	158,03
Coordinate Y	113,49	96,77	18,53	39,44	88,34	84,16

Table 1: Cadastral surveys of the same parcel executed by two different technicians.

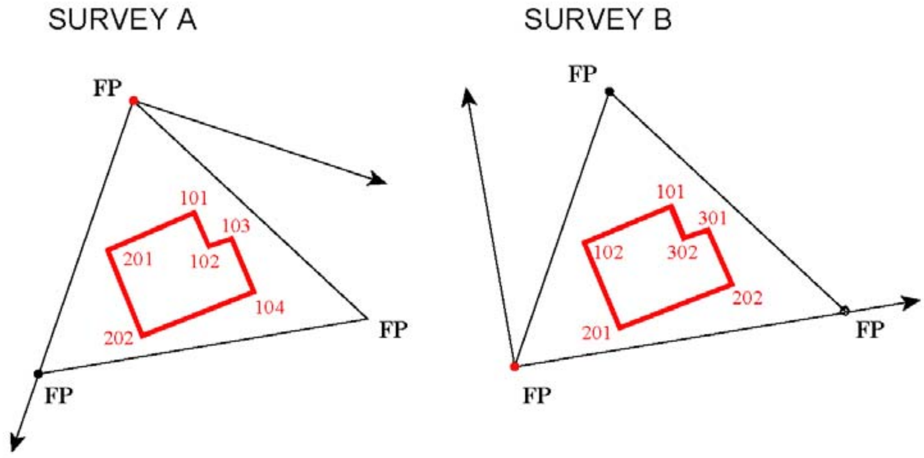

Figure 1: Graphical comparison of two cadastral surveys

Corresponding vertices	
Survey A	Survey B
101	*101*
102	*302*
103	*301*
104	*202*
201	*102*
202	*201*

Table 2: Corresponding vertices of the two cadastral surveys

This graphical solution is difficult to obtain by an automatic process, since it requires structural information, i.e. the joining lines between the various couples of points. It is therefore necessary to identify an analytical procedure able to define, with the only knowledge of the vertex co-ordinates, the point correspondence for two or more configurations of the same geometrical entity. The correspondence knowledge represents the solution of the topological connection problem for the various surveyed figures and makes it possible, to apply the Procrustes analysis tool. Referring to the cartographic applications, to our knowledge, there are not useful bibliographical references showing any solution to the mentioned question. The problem of correspondence identification between two or more sets of points has nevertheless interested many researchers in the field of the computer graphics.

One fundamental contribution to the problem solution was that offered by Ulmann (1979), who recognised the importance of using the stiffness of the existing constraints between two vertices with the aim of identifying the correspondence among point sets. Later, many authors, being inspired by Ullman's work, developed algorithms, using the weighed proximity matrix as a function of the computed distance lengths among the points. In particular, Scott and Longuett-Higgins (1991) have determined the correspondence by the spectral decomposition of the proximity matrix relative to point configurations under study. Shapiro and Brady (1992) reached the objective through the comparison of the modal structures deduced from each proximity matrix referred, this time, to a single configuration. Finally Umeyama (1988) came up with the definition of correspondence using the spectral decomposition of the adjacency matrices relative to weighed graphs of equal measure. The same author has later reconsidered (1993) these ideas, applying them for the solution of the matching problems among complex objects.

More recently many authors have tried to model the structural deformations of point sets. In this regard, Amit and Kong (1996) have used the graph theory to model the deformations of 2-D shapes contained in some medical images. Finally, other authors have formalised the concept of correspondence by using the links of a rigid body: in this regard we mention the work done by Morgera and Cheong (1995). Cross and Hancock (1988) proposed instead, for the correspondence problem solution, a statistical methodology based on the theorem of Bayes. Afterwards Luo and Hancock (2002) have associated to this methodology a procrustean criterion for the solution of an alignment problem between configurations with a different number of vertices.

For the problem of the cadastral parcel updating, the geometrical configurations requiring the definition of a correspondence function are, first the figures of the same cadastral entity surveyed at different epochs, and second the new field surveys and what already reported in the map. Since the set of the same vertices, presents in two or more configurations, has the same shape, apart for some geometrical distortions and measurement errors, the correspondence search is, in any case, associated with the shape recognition, so to guarantee a congruence to the problem solution. Therefore, to apply the procrustean updating procedure also to the cadastral surveys, it is necessary to identify analytical tools able to characterise the topological links of the geometrical entities by defining a correspondence function for their vertices.

This requires some changing of the procedures reported in the literature with respect to the specific context here treated. From the other side, it is necessary to investigate new processes to face the particular situations originated from the correspondence problem solution in the cadastral field. In this regard, three different cases can be considered:

- the comparison of two geometrical entities,
- the inclusion of one entity into another one,
- the intersection of two entities.

3. CORRESPONDENCE PROBLEM SOLUTION

Two cadastral entities are defined “comparable“ if they remain unchanged for two different surveys (e.g. the same parcel). In this case every vertex of the geometrical configuration find its full correspondence in the other.

Two cadastral entities satisfy a relationship of “inclusion“ if:

- the two configurations have a different number of vertices;

- all the vertices of the configuration with a less number of points (enclosed configuration) find a correspondence within the configuration with a greater number of points (including configuration).

In other words, there exists a relationship of inclusion if the comparison between the enclosed figure and a sub-configuration of the enclosing figure is satisfied.

Two cadastral surveys satisfy a relationship of “intersection“ if the correspondence set of points for both configurations is a subset of the global vertices. In other terms, an intersection is admitted if and only if there exists a relationship of comparison for two sub configurations.

Since for the three above described situations a relationship of comparison between different configurations is considered, the first thing to do now is the definition of a recognition process able to identify a relationship of comparison.

3.1 The Case of Two Comparable Configurations

In this case, the proposed procedure is similar to the method developed by Umeyama (1988) to determine the permutation matrix that optimise the shape matching of two geometrical configurations. Starting from the vertex coordinates characterising the geometrical configurations X and Y, the proposed procedure allows the correspondence solution by the knowledge of the mutual distances among the points.

Let $\mathbf{X} = \{x_1, x_2, \dots, x_n\}$ be an arbitrary configuration of n vertices. To this configuration, a matrix $\mathbf{A}_X$ of dimension n×n can be associated. Its elements (a_{ij}) are defined as $a_{ij} = |x_i - x_j|$, i.e. the Euclidean distance between the vertices x_i and x_j. Matrix A_X is called “(weighed) adjacency matrix“ characterised by the following properties:

- It is a symmetrical matrix;
- all its diagonal elements are null.

The spectral decomposition of A_X can be written as $\mathbf{A}_X = U_X D_X U_X^T$, where U_X is the orthonormal eigenvector matrix, and D_X is the diagonal matrix of the eigenvalues. In a similar manner, starting from the matrix configuration Y, it is possible to determine the eigenvector matrix U_Y. From the knowledge of U_X and U_Y, considering their elements in absolute value, it is possible to compute the proximity matrix Z, defined as $Z = |U_X||U_Y|^T$.

Applying to the matrix Z the so-called Hungarian method (Papadimitriou et al, 1982) limited to the first iteration, it is possible to obtain a permutation matrix, called “correspondence matrix“, that represents the problem solution. Now, to ascertain the correctness of the comparison problem, it is necessary to verify that the configurations taken into account have the same shape, apart for possible random errors. This can be evaluated by a simple check of the shape index, by applying Procrustes analysis to the studied configurations, and by fixing a proper tolerance threshold, defined as “shape parameter“.

Further developments of the problem solution are under testing and will be the argument of next papers.

This procedure for the recognition of comparable geometrical configurations allows the solution of all the correspondence problems for the cadastral entities; nevertheless the field of application of this procedure is, for definition, limited: in fact, it is possible to find a solution just in the case of sets of vertices composed by the same number of elements.

The next step is to reformulate this procedure in such a way to extend its application also for those configurations having a different number of vertices; in particular the recognition process will be readapted to the “inclusion“ case.

3.2 The Case of One Included Configuration

3.2.1 Solution by a combinatorial analysis method

The research of correspondence of one configuration enclosed into another can be done by applying a combinatorial analysis method.

Let *A* and *B* be two configurations with a number of vertices equal to a and b respectively. Let us assume that a>b; furthermore let *A* be the codomain and let *B* be the domain of the correspondence function. To apply a recognition process of the comparable configurations and define the correspondence function, it is necessary, for what stated above, to consider sub-configurations of *A* having the number of vertices equal to b. Now, the question is, which one of the possible sub-configurations must be taken into account? The easiest answer is to investigate all the possible sub-configurations of **A** having b vertices, since each one is a potential image of the enclosed configuration *B*.

Once a first sub-configuration is chosen, it is evaluated if there exist a rate of comparison with respect to *B*; if this happens, the chosen sub-configuration is considered image of the domain, while the discrepancy between the configurations becomes the new shape parameter. Now, let us execute these steps also for the second sub-configuration; if also in this case the comparison might be real, for the dynamic value of the threshold, this new set of vertices is considered a potential image. The same reasoning is repeated for all the remaining individuated sub-configurations, till their exhaustion. The resulting image at the end of the procedure corresponds to the inclusion problem solution.

The described procedure requires $c = a!/(a-b)!b!$ steps. If the number of vertices of the larger configuration is limited, and the difference of the number of points between the two configurations is small, this process is very valuable. On the contrary, the method results very expensive for many reasons.

The fundamental aspect of the process based on the combinatorial analysis method is that it takes into account all the possible sub-configurations. It becomes necessary to define a geometrical criterion so to reduce the number of the sub-configurations to analyse. This is based on the fact that in the cadastral survey the various configurations have a fixed dimension and the scale factor is therefore known, apart for some random error components due to the field measurements.

3.2.2 Solution by a correspondence kernel

The above mentioned method, even if rigorous and robust, has the disadvantage of being computationally time-consuming. For example, the problem of inclusion described in Figure 2, in which we search for the correspondences of parcel (A) into the whole cadastral map (B), can need to analyse several hundreds of thousands possible combinations.

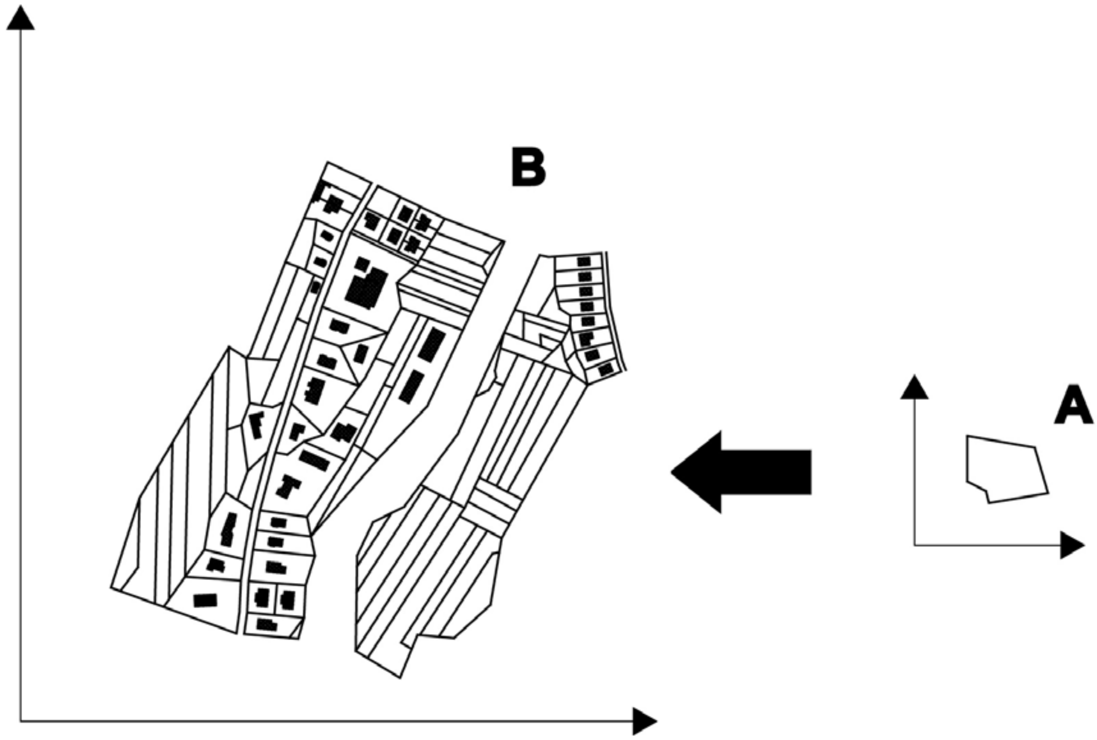

Figure 2: The problem of inclusion, that is to find the correspondences between a configuration **A** fully contained into a more general configuration *B*.

Because a merely combinatorial approach is unacceptable, we have to investigate new strategies in order to increase the efficiency of the method without distorting its nature. The goal is to reduce significantly the amount of possible solutions to check for. To achieve this, the analysis of the possible bottlenecks of the procedure is needed.

The first evidence is that, considering the entire - i.e. all the points at the same time - included configuration for the correspondence search, does not represent the best condition from a combinatorial point of view. The second concern about the combinatorial search approach, as already pointed out, is that it considers all the configuration subsets of possible matching in systematic way: the basic assumption is that, if a subset contains the same number of points of the included configuration, then it represents a potential correspondence. The choice is only based on the number of points, despite their reciprocal position.

To overcome these limitations a new procedure for the inclusion case, named “by a correspondence kernel”, has been developed. It has the same advantages of the combinatorial approach, together with an evident increase of performance and a reduced computation time.

To overcome the first evidenced limitation, the procedure identifies, in the included configuration, that specific subset of points satisfying the following properties:

- It minimises the number of its possible images within the including configuration;
- It minimises the ambiguities and the search mistakes in the correspondence search process.

This particular subset, defined by some combinatorial process and geometric rules, is defined "correspondence kernel".

Referring to the second drawback, a suitable help to the solution is based on the knowledge of the reciprocal scale factor between the two configurations. It is then possible to implement a set of appropriate filters, by which, given a predefined configuration – in our case the correspondence kernel – it is possible to draw the selection of the possible matching images contained within the including configuration.

The procedure, by combining both methods – the use of the correspondence kernel instead of the entire included configuration, and the selection of the possible matching configuration – can individuate in a more efficient way a compatible solution.

Of course, the first achieved result can be partial or not univocal. At this stage, the inclusion problem is solved just for the points of the correspondence kernel; moreover, even if the included configuration has a unique image into the including configuration, this could not be valid for its various sub-configurations.

Now, let we suppose that n possible images of the correspondence kernel have been individuated. For the complete and unique solution, we act in the following mode.

First, for each one of the n images, we solve all of the remaining correspondences. This is done by way of the Procrustes analysis, and by a point-to-point searching algorithm, based on statistical criterions, which estimates the correspondence probability as a function of the mutual Euclidean distances between the points supposed to be homologous.

After this operation, a collection of n possible images of the – entire – included configuration is obtaines among which we have to chose the most probable one.

To this aim, a shape test based on Procrustes analysis, is performed for each one of the n possible solutions and the included one. Finally, the unique – best – solution can be individuated, and because all the point correspondences have already been defined, the inclusion problem is completely solved.

3.3 The Case of Intersecting Configurations

Among the possible problems related to the correspondence search in the cadastral mapping, the case of intersection is the most difficult to solve. Here, we meet all the difficulties found in the inclusion case. Not only we have no knowledge of the image of the domain, but we know neither the domain itself, that is an unknown subset of the included configuration.

While in the case of the inclusion we had a term of comparison, represented by the included configuration, here this is missing, and there is not any suitable geometric criterion able to indicate which points to neglect. The combinatory approach seems, at the present, the only helpful solution.

Let X be the configuration that contains the domain of the correspondence function, Y the configuration containing its image. We assume $x \leq y$, where x and y represent the number of points of X and Y, respectively. A solution under investigation aims to link a sequential point elimination in the X configuration to search for a possible inclusion condition.
In a following paper we will deal more in detail with this topic.

4. CONCLUSIONS

From the obtained results it is possible to state that the methods presented in this paper make it possible to automatically identify the corresponding geometrical configurations of two or more digital maps in vector form. The methods have the peculiarity not to require the *a priori* knowledge of the tie points, since they are able to identify the tie points by themselves on the base of specific tests applied to the vertex coordinates of the two configurations.

The proposed methods are advantageously applicable for the cadastral cartographic updating, when the point coordinate data base is not characterised by a specific rule of recognition of the parcel vertices. In this case the procedures allow the automatic identification, within the digitised original cadastral map, of the new surveyed parcels, inserted in the Italian digital archive by the program Pregeo. The proposed techniques find wide applications also in GIS where they can permit the matching of the cartographic databases in a completely automatic manner by the comparison of the various totally or just partially overlapping cartographic units.

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BIOGRAPHICAL NOTES

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Basically educated in Land Surveying, successively graduated at the Faculty of Mathematical, Physical and Natural Science of Trieste University in 1976. A.v.H. senior scientist at the Geodetic Institute of Stuttgart University in 1984 and 1985. He was Assistant Professor of Surveying at Trieste University (1979-1985) and Associate Professor of Photogrammetry at Udine University (1986-1994). Since 1994 he is Full Professor of Photogrammetry at the Faculty of Engineering of Udine University (Italy) and lecturer of Surveying, Digital Mapping and GIS at the same University. He is author of 118 papers, of which almost eighty on applied statistics in Surveying and Photogrammetry. His research activities were mainly devoted to network design and optimisation, analytical photogrammetry, digital mapping, geographical information systems and mobile mapping systems. His research interests are now focused on the application of Procrustes analysis for the datum transformation in Geodesy and Photogrammetry, for the optimal alignment of laser scanning models and for the conformal updating of digital mapping. He served for many years in the ISPRS; is currently official member of the Italian Societies of Photogrammetry and Surveying, and Statistics.

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Civil Engineer graduated at the University of Udine (1986) PhD in "Geodetic and Surveying Sciences" at the Polytechnic of Milan (2000). Currently member of the Surveying and Photogrammetry research team at the University of Udine. He contributed with more than 65 papers, ranging from high accuracy geodetic surveys, to GPS, Photogrammetry, and Geomatics. His main research topics are now centred on the georeferencing, update and integration of digital maps by way of Procrustes analysis techniques, and on the problems of alignment and segmentation of 3-D model datasets coming from aerial and terrestrial laserscanning surveys.

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