THE USABILITY OF VECTORIZATION AND A NEW POINT MATCHING PROCEDURE AS FIRST STEP IN CONFLATING RASTER AND VECTOR MAPS

Maria Antonia Brovelli, Giorgio Zamboni

Politecnico di Milano – Polo Regionale di Como, Via Valleggio 11 – 22100 Como
+390313327517, fax +390313327519, e-mail maria.brovelli@polimi.it
+390313327528, fax +390313327519, e-mail giorgio.zamboni@polimi.it

KEY WORDS: cartography, GIS, integration, algorithm, vector, raster

ABSTRACT:

The growing fields of GIS application (local administration, tourism, archaeology, geology, ...) has increased the interest in studying the information sharing from different geographic databases, also known as "GIS data interoperability". This is a huge problem, involving several aspects. Among them, we decided to concentrate an a geometric conflation of different maps since maps coming from different sources often show significant geometric differences. In order to solve, or at least mitigate this problem, a number of different approaches were proposed in the past years. Particularly referring to the specific case of vector maps, almost at the same scale, recently the authors presented a possible solution based on the automatic detection of homologous points on different maps and a further transformation based on multiresolution spline functions. To extend the proposed approach also to the case of raster maps, the possibility of using the point matching approach on vectorized maps obtained from raster ones was investigated. In order to avoid duplicating the effort of developing software and, at the same time, of taking advantage of existing free code, the first attempt, here presented, focuses on the application of our method on vectorized maps obtained by using the software Ras2Vec.

1. INTRODUCTION

The cartographic map integration is an unsolved problem due to the existence of different in reference frames in measuring techniques, in conventions on the information representation, etc., with the final result of a geometrical incompatibility of different maps.
Moreover, though recent maps data are in vector format, nowadays a strong circulation and usage of raster maps still exists. The reason is that the fastest way to recover the vast paper cartographic patrimony is to make a "digital scanning" of the paper sheets in order to use them subsequently into a CAD software or into Geographic Information Systems.
The vectorization of the maps is hardly ever done because it is a time consuming task of high economic cost.
Moreover the vector format is not indispensable for all the basic maps (cadastral maps, technical maps) that are used as background on which we build and overlap cartographic layers defining the real informative contents.
The vectorization is finally not necessary when it is not required to modify the maps or to directly investigate their geometrical attributes (length, area, ...).
Another reason that leads to the use of a raster cartographic map in its raster format is the wish of preserving the "expressivity" of the original graphic representation: in a lot of historical maps (used for example in town planning, landscape and morphological studies of the territory) colour tones, simbology and, in general, graphic representation that are not repeatable in a simple way with the geometrical primitive typically used in the most diffuse CAD and GIS are reproduced.
To propose a possible solution to the integration of raster and vector maps, we start by considering the simple case concerning maps almost with the same scale.
As the authors have already developed a method to conflate vector maps at similar scale, the attempt is to use the same approach in the raster case. Therefore, in the following, the method for vector maps conflation is presented and the problems of its extension to the raster case are analysed. Particularly a specific vectorization software (it was choose as available with GPS licence) was used in order to perform the point matching with the vector map to be used in the conflation. The numerical results were compared with those achieved in the case of conflation between vector maps and a critical analysis of them is presented in the conclusion.

2. THE SOLUTION FOR VECTOR DATA INTEGRATION

Map conflation was first addressed in the mid-1980s in a project to consolidate the digital vector maps of two different organizations (Saalfeld, 1988). The problem was split into two parts: detecting homologous elements between the two maps, and transforming one map into the other (Gillman, 1985; Gabay and Doytsher, 1994). Point elements within one map were selected as the group of features whose counterpart points on the other map enable the conflation process (Rosen and Saalfeld, 1985). Since then, many conflation algorithms have been developed and improved.
A possible solution for the automatic integration of vector maps for the specific case of map with similar geometric resolution and information model has still been designed and implemented in a software developed at the Laboratorio di Geomatica – Politecnico di Milano – Polo Regionale di Como (Brovelli and Zamboni, 2004).
Independently from the kind of transformation used, the estimate of its parameters becomes better (more accurate) as the number of control points increases. Usually they are manually chosen interactively: they are displayed on the screen and the user clicks on a location in one map and then the same corresponding location in the second map.
To alleviate the time-consuming manual search of these correspondence and avoid the possible human errors, the first step of our approach is the design of an automatic process to

find homologous points between different maps (know as feature matching), to reduce the instability of the estimated coefficients of the transformation. In this way the choice of the observations became an automatic step.
At present the main efforts to automatically or semi-automatically detect matched features are focused on road vector datasets (Cobb et al., 1998; Walter and Fritsch, 1999; Chen et al., 2004). Various GIS and computer vision researchers have shown that the intersection points on the road networks provide an accurate set of control point pairs especially in case of imagery and map conflation (Flavie et al., 2000; Chen et al., 2003).
In order to increase the detected pairs, we want to exploit also other cartographic information, such buildings, hydrography, etc.).
Our idea is to reproduce as much as possible what the operator manually does when she/he tries to superimpose two maps: they visually search for the same geographic features represented on the two different cartographic supports.
During the visual analysis, the operator compares the shape of the features on the maps. We have modelled this operation in three steps: an analysis of the coordinates of the points that geographically describe these objects, an analysis of "directional" compatibility of the segments issuing from the points and finally a semantic analysis.
Before any detection operation, a raw fitting has to be done, as the two maps could have slightly different scale or different orientation. This first fit consists of an affinity transformation on the map to be transformed, done by applying a least square estimate on at least five manually selected points. Subsequently, for each point on the reference map we are able to select a set of candidate homologous points (within a surrounding area with extension proportional to the precision of the affinity transformation) on the other map: the choice of the effective homologous point is based on geometrical controls (points distance), the compatibility of the azimuth angles of the segments spreading from the vertices of the geometrical entities (within a certain tolerance angle) and the "semantic" compatibility (the attribute of features are matched with a relationship attribute table defined by the user).
Using the new homologous points we start an iterative process where, at each step, the affinity parameters and the corresponding set of homologous couples are determined. The whole procedure is repeated until the number of the detected points becomes stable.
Once homologous pairs have been detected a warping transformation follows to optimally conflate the different maps.
There are several types of transformations. Polynomial transformations between two coordinate systems are typically applied in case one or both coordinate systems exhibit a lack of homogeneity in orientation and scale. Depending on the degree of variability in the distortions, approximations are carried out using second, third, or higher degree polynomials. The second method commonly used applies a variable transformation within different parts of the unadjusted data. A possible solution is based on the triangulated data structures method suggested by Gillman (1985) and Saalfeld (1987) and a piecewise linear homeomorphic transformation, known also as rubber sheeting, suggested by White and Griffin (1985), Saalfeld (1985), Gabay, Gelbman and Doytsher (1995). This approach, again based on homologous points of the two maps, is today the most popular (Lupien and Moreland, 1987; Doytsher and Hall, 1997; Cobb et al., 1998; Doytsher, 2000).
The main disadvantage of the rubber sheeting transformation is that it holds the control points fixed, that is the control points in the two maps match exactly, therefore they are treated as completely known with no error. This kind of approach is purely deterministic and doesn't consider the fact that any coordinate in a geographic database has a measurement-representation error.
For this reason, the second step was the definition of a multiresolution interpolation method with a linear combination of least squares estimated spline functions appropriately scaled and localized on the plane (bi-dimensional space) in order to estimate the deformation field (Brovelli and Zamboni, 2004). In this way the spatial resolution (and consequently the precision) follows the distribution of the spatial observations in order to make the most of the information on the local deformations contained into the homologous points.

3. PROBLEMS OF INTEGRATION OF RASTER AND VECTOR MAPS

In order to integrate and to use together raster and vector data into a GIS, we can theoretically apply the same solutions previously described with a suitable adaptation of the algorithms for the homologous points search and for the deformation field multiresolution interpolation to transform the map.
As regards the homologous point selection we need to develop an analysis image process allowing us to extract from the raster data the information necessary to the algorithm in order to carry out the relevant points detection: the vertices of the objects represented (building, fences, streets, …) and the directions of the segments outgoing from them.
Differently from the vector maps where the vertices and the segments match directly with the geometrical primitives that describe the cartographic entity represented, into raster maps this information must be produced starting from a simple pixel matrix. It is important to notice that while in vector maps these information are directly usable unambiguously, in raster maps a unique extraction process doesn't exist; therefore different results can be obtained on the basis of the rasterization approach used.
Finally it is essential to point out how the use of raster data doesn't allow us the application of "semantic" controls that are useful in high density urbanized area where the high concentration of points can lead the algorithm to choose wrong associations.
A solution for this last problem can be the design of an image interpretation tool. However we think that such an approach is justified if the final goal is the vectorization of raster data; our goal instead is the extraction of auxiliary information for the transformation of data that preserve the raster nature.
Moreover, as regards the deformation field application (and the consequent deformation of the map) it is necessary to deal with the problem known as "image resampling".
The deformation of a raster image is defined by a transformation rule that allows us to compute the target coordinates of a point starting from its original coordinates. Since the pixel coordinates of a raster image belong to a discreet set, it is not guaranteed that each pixel of the transformed image is the transformation of a single pixel of the source image; for this reason it is necessary to interpolate the value of the target pixel starting from suitable pixels of the source image.
Because of the representation proposed for the deformation field (combination of bilinear splines), the inverse function to compute the values of the pixels of the source image starting from the pixel coordinates of the transformed image is not directly defined.

The following experiments look after the first of the two problems related to the heterogeneous data integration: the automatic homologous point detection.

4. THE USE OF A VECTORIZATION ALGORITHM TO DETECT HOMOLOGOUS POINTS

A first test was the automatic vectorization of a portion of an urban raster map published by the cartographic office of the corresponding Region (in Italy these are called technical maps) and the direct use of the algorithm for automatic homologous pairs detection between the vectorized and the cadastral map (also in vector format) of the same area, used as a reference.
The results of the detection were compared with those obtained by applying the algorithm on the manually vectorized technical map and the vector cadastral map.
The area chosen for the experiment was the town of Modena, which is in the Central-Northern part of Italy. The scale of the two maps are respectively 1:1000 for the cadastral and 1:5000 for the technical one. The main characteristics of the portion of the maps taken into account are the following:

Map	Scale	Extension	Typology
Cadastral map	1:1000	1 Km x 1 Km	vector (manual process)
Technical map	1:5000	1 Km x 1 Km	raster
Technical map	1:5000	1 Km x 1 Km	vector (manual process)
Technical map	1:5000	1 Km x 1 Km	vector (automatic process)

Table 1: Map used in the experiment

Therefore the aim of the experiment was to identify cases that turned out to be critical for the detection algorithm (i.e. the points that are wrongly automatically classified as homologous), analysing the geometrical configuration of the vectorized map in the area where such errors occur.
For this reason we didn’t focus on the vectorization algorithm and, at first, we searched for a software with GPL license available in the internet and producing a data output format compatible with our software (DXF format).
Unfortunately the choice with these limitations is reduced at two packages: Ras2Vec (D. Libenzi, 1989) and AutoTrace (M. Weber, 1998). Some tests on our data suggest to use the former as, visually, it seems more suitable to processing cartographic maps.
Ras2Vec is a program that convert uncompressed 1-bit (black and white) raster images into vector format. Input data must be in BMP or TIFF format. Available outputs are in DXF, EMF, HPGL and TXT formats. Two different vectorization methods are implemented: double line and centreline. Between them we chosen the second one where central pixels within a raster line, after a thinning pre-processing, are tracked.
In the following figures a portion of the technical map (Figure 1), the corresponding cadastral map (Figure 2) both in the vector format, the technical map in raster format (Figure 3) and the result of the automatic vectorization process (Figure 4) are presented.

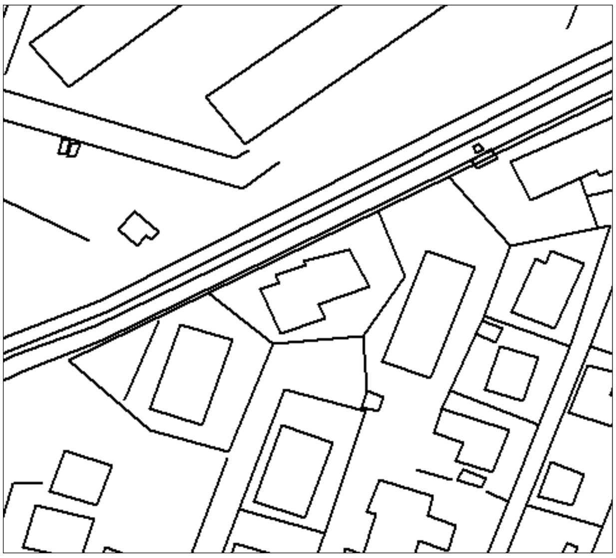


Figure 1: The manually vectorized technical map (detail)

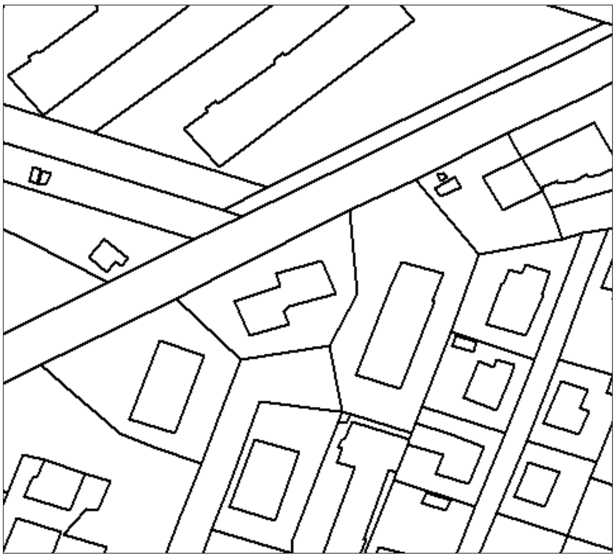


Figure 2: The vector cadastral map (detail)

The analysis of the two maps in Figure 1 and 2 shows how the different representation of the same information (as an example give a look to the buildings) in maps with different scale and with different contents (respectively technical and cadastral maps) can complicate the homologous points detection also in case both maps are in vector format. Obviously the map model (raster or vector) is only one factor in this kind of problem: the cartographic generalisation and the different map content, due to the different map production aim, greatly affect the possibility to detect homologous pairs. Our starting point is that maps are at scale not so different and with about the same features. Obviously, the farther we go from these hypotheses, the more the algorithm is expected to fail.

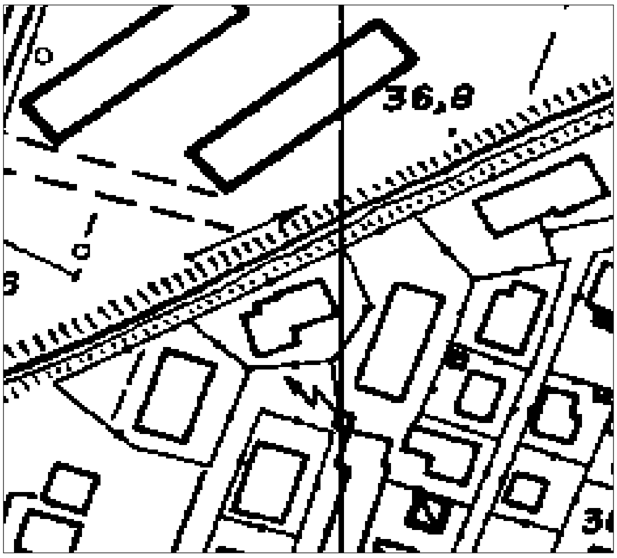


Figure 3: The raster technical map raster (detail)

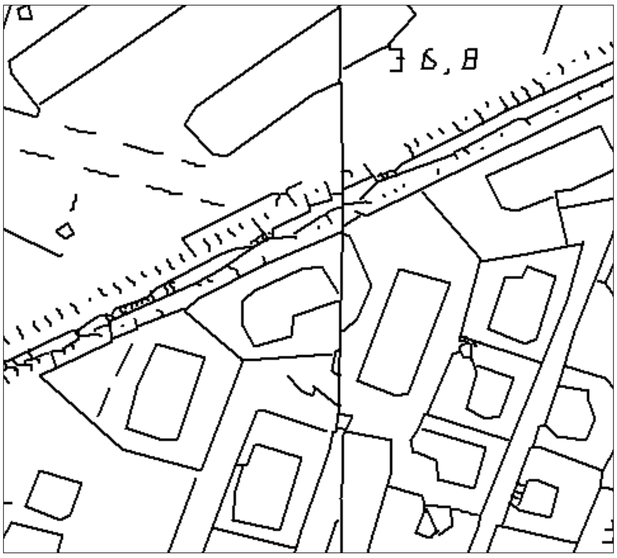


Figure 4: The automatically vectorized technical map (detail)

Moreover the analysis of the map in Figure 3 and the comparison between the automatic vectorized technical map (Figure 4) and the manually vectorized map (Figure 1) puts clearly in evidence the limitations of the used vectorization algorithm: the main limit is the excessive smoothing of the corners that define the geometry of the entities; the result produces an alteration both in the position of the vertices and in the angles of the outgoing segments. But unfortunately these two information are exactly the data we need for the correct work of our detection algorithm.
The second limitation of the automatic vectorization is the impossibility to distinguish the real geometric entities from the other completion symbols (e.g., the symbolic representation of the electrical rooms, the texts, the lines of the reference grid, …) that act as “noises” in the detection process.

5. NUMERICAL RESULTS

To analyse the results of the algorithm for the automatic detection of homologous points between vector and raster data, we decided to use, as reference, the ones obtained (with satisfactory performances) from previous tests performed only on vector data.
The same area was investigated: manually vectorized technical and cadastral maps (from now named simply vector maps) were taken into account. The algorithm was executed by setting a tolerance angle of 15° (geometric check) and considering the semantic associations shown in Table 2.

Cadastral map	Technical map
RIVER	HYDROGRAPHY
BUILDING	RESIDENTIAL BUILDING
BUILDING	BUILDING
PARCEL	STREET
PARCEL	FENCE

Table 2: Layers association used by the semantic control

The automatic detection was manually checked: doubt cases were assumed as “uncertain” homologous pairs. The manual classification gives the results presented in Table 3 and 4.

			Manual check		
Cadastral map	Technical map	Points	Correct points	Wrong points	Uncertain points
RIVER	HYDROGRAPHY	38	0	8	30
BUILDING	RESIDENTIAL BUILDING	1878	1796	14	68
BUILDING	BUILDING	462	457	5	0
PARCEL	STREET	83	75	5	3
PARCEL	FENCE	559	523	1	35
	Total:	3020	2851	33	136

Table 3: Performances of the homologous point search algorithm between vector-vector maps (absolute values)

The procedure, but without semantic associations, was performed on the corresponding automatically vectorized and vector maps and the results, manually checked, are shown in Table 5.

Cadastral map	Technical map	Points	Manual check		
			Correct points %	Wrong points %	Uncertain points %
RIVER	HYDROGRAPHY	38	0	21,1	78,9
BUILDING	RESIDENTIAL BUILDING	1878	95,6	0,7	3,6
BUILDING	BUILDING	462	98,9	1,1	0
PARCEL	STREET	83	90,4	6,0	3,6
PARCEL	FENCE	559	93,6	0,2	6,3
	Total:	3020	94,4	1,1	4,5

Table 4: Performances of the homologous point search algorithm between vector-vector maps (percentages)

Homologus points	Correct points	Uncertain points	Wrong points
2148	1439	265	444

(a)

Homologus points	Correct points (%)	Uncertain points (%)	Wrong points (%)
2148	67	12,3	20,7

(b)

Table 5: Performances of the homologous points detection algorithm between automatic vectorized-vector maps (a - absolute values; b – percentages)

They substantially confirm what we were expecting: the high uncertainty in the position of the vertices defining the vectorized geometric features forces the algorithm (based on an adaptive search) to enlarge the searching region for homologous candidates for a fixed point on the vector map. This increases the probability to detect an erroneous or at least uncertain homologous point.

Moreover the impossibility of using semantic associations stresses this problem especially in the urban areas, where the high concentration of geometric features and therefore homologous candidates is present.

To compare point-to-point the results of the homologous detection between vector to vector map and vector to vectorized map, only the 1432 points common to both the sets were analysed.

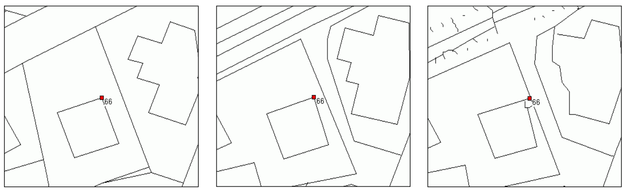
The discrepancies in the classification are presented in Table 6.

Vector-Vector map / Vector-Vectorized map	Correct points	Uncertain points	Wrong points	Total points	(%)
Correct points	1047	23	0	1070	74,7
Uncertain points	150	11	7	168	11,7
Wrong points	171	17	6	194	13,5
Total points	1368	51	13	1432	100
(%)	95,5	3,6	0,9	100	

Table 6: Comparison of homologous points between vector-vector maps and vector-vectorized maps

The first consideration is that the majority of points which in the comparison between cadastral and vectorized regional map are evaluated as erroneous or uncertain (the 89% of the uncertain and 88% of the erroneous points) are correctly classified in the case of the comparison between cadastral and vector technical map; this confirms that wrong or uncertain associations do not derive from an intrinsic incompatibility between the data but from the deformation due to the vectorization process.

As an example, Figure 5 shows the homologous of point 66 of the cadastral map (Figure 5.a), correctly detected in the vector map (Figure 5.b) and wrongly associated in the vectorized map (Figure 5.c) because of a false geometry generated by the vectorization.

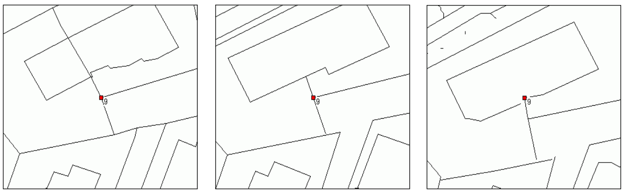


(a) (b) (c)

Figure 5: Point 66 in the cadastral map (a), the corresponding correct point in the vector technical map (b) and the wrong point in the vectorized map (c)

The visual analysis of the results moreover confirms that the impossibility of applying the semantic control is a second source of errors: as an example, Figure 6 shows the homologous of the point 9 of the cadastral map (Figure 6.a), correctly detected on the vector map (Figure 6.b) and wrongly associated on the vectorized map (Figure 6.c), where the semantic check was not applied.

The second phase of the experiment was the analysis of the "complementary" homologous points, that is the points of the cadastral map with an homologous point in the vector technical map but not in the vectorized map and, vice versa, the points with an homologous point in the vectorized map but not in the vector one.



(a) (b) (c)

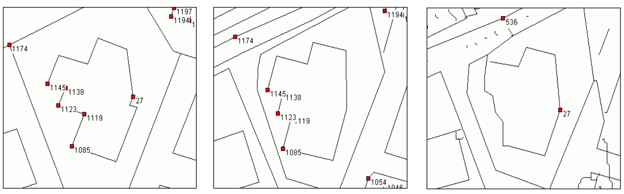
Figure 6: Point 9 in the cadastral map (a), the corresponding correct point in the vector technical map (b) and the wrong point in the vectorized map (c)

The results of the classification are summarized in the Table 7, in which we present the classification of the points that are detected in the vector map and not detected in the vectorized one (first column) and the classification of the points detected in the vectorized map and not detected in the vector one (second column).

	Vector map	Vectorized map
Points	1588	717
Correct (%)	1483 (93,4)	362 (50,6)
Uncertain (%)	85 (5,3)	104 (14,5)
Wrong (%)	20 (1,3)	250 (34,9)

Table 7: Homologous points detected in the vector map and not in the vectorized one (column 1) and points detected in the vectorized map and not in the vector one (column 2)

As an example, Figure 7 shows some points of the cadastral map (Figure 7.a), the corresponding homologous points selected only on the vector technical map (Figure 7.b) and the corresponding homologous points selected only on the vectorized map (Figure 7.c).



(a) (b) (c)

Figure 7: Points of the cadastral map (a), the corresponding points on the vector technical map (b) and the points on the vectorized map (c)

The figures show how the "smoothing" of the building vertices introduced by the vectorization makes the angles of the segments outgoing from the vertices incompatible, resulting in a wrong associations with the corresponding points of the cadastral map.

Moreover the change of the angles can produce the inverse effect, as it is clear looking at the point 27: in this case the angle between the outgoing segments is initially incompatible (compare the cadastral map and the technical vector map) but the vectorization process changes it and the new configuration becomes compatible with the result of an association with a wrong homologous point on the vectorized map.
The statistics reported in Table 7 focus that 1483 points are not detected by the searching algorithm on the vectorized map (about half of potentially correct points); moreover the statistics show that the 50,6% of the points selected only on the vectorized map are wrong, confirming that these errors are the results of the geometrical alterations introduced by the vectorization process.
In order to have a second check of the unusability of the vectorization methodology adopted, the statistics of the classification of the homologous points were recomputed excluding all the pairs of points with geometric distance (computed after the affine transformation used by the algorithm to produce a first alignment of the maps) greater than the intrinsic error, the so called "drawing error", of the map at the smallest scale. In our case this threshold is equal to 1 m, as 1:5000 is the smallest scale. The new results are reported in Table 8.

Homologous points	Correct points	Uncertain points	Wrong points
591	455	68	68

(a)

Homologous points	Correct points (%)	Uncertain points (%)	Wrong points (%)
591	77	11,5	11,5

(b)

Table 8: Performances of the homologous points detection algorithm with distance less than 1m (a – absolute values; b – percentages)

The statistics show that the 72% of homologous points detected have a distance greater than the "drawing error"; this is the proof that the general positional inaccuracies of the features vertices in the maps do not allow us to use a searching area selective enough. Moreover, this characteristic yields a high probability to select wrong homologous pairs, as confirmed by the increase of the correct homologous points from 67% to 77% by using only points with distance smaller than the "drawing error".

6. THE NEED OF A NOVEL APPROACH

The results obtained confirm the necessity to design a vectorization approach finalised to the extraction of the two information essentials for a correct use of the homologous point detection algorithm: the position of the vertices of the geometrical entities and the angles of the segments outgoing from them.

Since the vectorization process is used only as an auxiliary tool in order to detect the homologous points (the final transformation is applied on the original raster map), it will not be necessary to focus on the global quality of the vectorized map but only on the accuracy of the information used by the algorithm, i.e. the position of the vertices of the geometrical features and the angles between the segments outgoing from them.

7. CONCLUSIONS

From the results obtained by the homologous points detection between vector and vectorized maps and from their comparison with those obtained using both vector maps, we can conclude that the vectorization algorithm proposed in Ras2Vec is not suitable to convert the raster map in an auxiliary vector map is order to efficiently use the automatic homologous points detection we implemented.
The main limitation is the inaccurate vectorization of the two essential pieces of information needed for the correct working of our detection algorithm: the position of the geometrical entities vertices of the and the angles between the segments outgoing from them.
Moreover, at the moment, Ras2Vec is the only GPL licensed software directly usable with our program, that we found. For this reason we conclude that it is necessary to design and implement a specific vectorization tool oriented to the accurate extraction of the previous mentioned geometrical properties of the map features.
The choice to develop a new tool instead of search for a commercial software with these characteristics, is justified by the will to extend the software till now produced and to carry out an unique workspace for automatic heterogeneous maps integration.

REFERENCES

Brovelli M.A., Zamboni G., 2004. A step towards geographic interoperability: the automatic detection of maps homologous pairs, Proceedings of UDMS ’04, Chioggia, Italy, October 27-29, 2004, chapter 9 (9.I.2).

Brovelli M.A., Zamboni G., 2004. Adaptive transformation of cartographic bases by means of multi-resolution spline interpolation, *XXth Congress ISPRS* – Istanbul (Turkey) 12-23 July 2004

Chen, C.-C., Shahabi, C., Knoblock, C.A., 2004. Utilizing Road Network Data for Automatic Identification of Road Intersections from High Resolution Color Orthoimagery. In Proceedings of the Second Workshop on Spatio-Temporal Database Management (STDBM'04), collocated with VLDB, Toronto, Canada, August 30, 2004, pp. 17-24.

Chen, C.-C., Thakkar, S., Knoblok, C.A., Shahabi, C., Automatically Annotating and Integrating Spatial Datasets. In Proceedings of the 8th International Symposium on Spatial and Temporal Databases (SSTD'03), Santorini Island, Greece, July 24-27, 2003, pp. 469-488.

Cobb, M.A., Chung, M.J., Foley, H., Shaw, K., Miller, V., 1998. A rule based approach for the conflation of attributed vector data. *Geoinformatica*, 2(1), pp. 7-35.

Doytsher, Y., Gelbman, E., 1995. A rubber sheeting algorithm for cadastral maps. *Journal of Surveying Engineering – ASCE*, 121(4), pp.155-162.

Doytsher, Y., Hall, J.K., 1997. Gridded affine transformation and rubber sheeting algorithm with Fortran program for calibrating scanned hydrographic survey maps. *Computers & Geosciences*, 23(7), pp. 785-791.

Doytsher, Y., 2000. A rubber sheeting algorithm for non-rectangular maps. *Computer & Geosciences*, 26(9), pp. 1001-1010.

Flavie, M., Fortier, A., Ziou, D., Armenakis C., Wang, S., 2000. Automated updating of Road Information from Aerial Images. In Proceedings ASPRS 2000, Washington, DC.

Gabay, Y., Doytsher, Y., 1994. Automatic adjustment of line maps. Proceedings of the GIS/LIS'94 Annual Convention 1, pp. 333-341.

Gabay, Y., Doytsher, Y., 1995. Automatic feature correction in merging of line maps. Proceedings of the 1995 ACSM-ASPRS Annual Convention 2, pp. 404-410.

Gillman, D., 1985. Triangulations for rubber sheeting. In Proceedings of 7th International Symposium on Computer Assisted Cartography (AutoCarto 7), pp. 191-199.

Libenzi, D., 1989. Ras2Vec 1.2. http://xmailserver.org/davide.html (accessed 25 Jan. 2006).

Lupien, A., Moreland, W., 1987. A general approach to map conflation. In: Proceedings of 8th International Symposium on Computer Assisted Cartography (AutoCarto 8), pp. 630-639.

Rosen, B., Saalfeld, A., 1985. Match criteria for automatic alignment. In: Proceedings of the 7th International Symposium on Computer Assisted Cartography (AutoCarto 7), pp. 456-462.

Saalfeld, A., 1985. A fast rubber-sheeting transformation using simplicial coordinates. *The American Cartographer*, 12(2), pp. 169-173.

Saalfeld, A., 1987. Triangulated data structures for map merging and other applications in geographic information systems. In: Proceedings of the International Geographic Information Symposium, III, pp. 3-13.

Saalfeld, A., 1988. Conflation - automated map compilation. *International Journal of Geographical Information Systems*, 2(3), pp. 217-228.

Walter, V., Fritsch, D., 1999. Matching Spatial Data Sets: a Statistical Approach. *International Journal of Geographic Information Sciences*, 13(5), pp. 445-473.

Weber, M., 1998. AutoTrace – convert bitmap to vector graphics. http://autotrace.sourceforge.net/ (accessed 25 Jan. 2006).

White, M.S., Griffin, P., 1985. Piecewise linear rubber-sheet map transformations. *The American Cartographer*, 12(2), pp. 123-131.