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Alignment Process of Large-Scale Master Plans in a GIS Environment

Abstract

Large-scale master plans in current use by municipalities and government authorities, serve as the basis for urban management and appropriate engineering land development. Due the poor geometric accuracy level of the master plans, geometric contradictions appear following their digitization and conversion from a graphic product into the layers of a GIS database. These contradictions, particularly in the overlapping areas of the master plans, weaken the reliability and correctness of these plans and present many doubts for the user.

This paper presents a process for aligning the master plan maps so as to eliminate these contradictions and improve the accuracy of each plan. The process bringing the maps to geometric unification is composed of several successive stages, primarily the identification of systematic and random errors on the one hand, and separation between handling of corresponding lines and handling of single lines on the other hand. Identification and implementation of the geometric conditions embedded in the master plan maps and use of the rubber sheeting mechanism facilitate the implementation of the alignment process.

Introduction

Large-scale master plans (like other engineering maps) in current use by municipalities, are intended to direct land development in the region and regulate its use. Since such plans are usually prepared by architects (on the background of cadastral block maps of the area) with the emphasis on planning paramount in the plan preparation process, the geometrical and topological aspects of the plans are of secondary importance only. As customary in Israel, the master plans may cover other plans in full or in part, thus the link between the various plans describing the same area is a many-to-many relationship. Transformation of the various graphical master plan paper maps of the same area to a digital format and their presentation in a GIS system reveals topological and geometrical discrepancies. In the case before us, such misalignment stems from several reasons:

- Inherent inaccuracies in the master plan maps.
- Different accuracy levels of the plans as a function of scale, graphic quality of the drawing (such as thickness of the line describing the circumference of the plan), etc.
- Different updating levels of the master plan maps stemming from the different dates on which the plans were prepared.
- Errors as a result of the digitizing process of the master plans.

In order to reduce as much as possible the discrepancies between the various plans, it is necessary to align the various maps. The mutual alignment process of maps covering the same area to improve their internal accuracy and eliminate existing geometrical contradictions is known as conflation. This subject was first addressed in the mid-1980's in the U.S. in a project that dealt with merging the maps of the USGS (United States Geological Survey) and the Bureau of the Census (Saalfeld, 1988). Within the conflation framework, we can identify two principal consecutive parts of the aligning process of overlapping maps (Gabay and Doytsher, 1994):

Identifying correspondence between the maps:
Finding the "*corresponding entities*", and identifying the "*single entities*" – where the corresponding entities are those appearing in more than a single map (the same geographic entity may appear in a somewhat different geometric location and different topological structure in each map) while the single entities appear in one map only and do not appear in the others. Discovering the correspondence between the maps can take place on several levels of implementation: correspondence between the points, lines or polygons. Various solutions can be found in literature such as in (Rosen and Saalfeld, 1985) and (Filin and Doytsher, 2000).

Bringing the maps to geometrical uni

Bringing the maps into a single geometrical scheme while changing the geometrical characteristics of the various entities appearing in the maps (both the corresponding and the single entities) so as to achieve uniform and identical representation on all the original maps. When transforming the maps, it is necessary to take into account the prevailing geometrical conditions of large-scale plans, such as straight lines, parallel lines and perpendicular lines, in order to improve the graphic appearance of the maps in the uniform version. In view of the inaccuracies embedded in maps in general, and in master plans in particular, especially in view of the non-uniformity of the inaccuracies within the boundaries of each and every map – the ordinary transformations (such as affine, conformal and others) from one map to another among the various maps cannot provide a proper solution for the problem. Rubber-sheeting transformations have been accepted in recent years as being able to provide a solution to the mutual adjustment of maps. Various approaches to rubber sheeting are found in professional literature with the proposed solutions usually characterized each time as specific solutions for separate problems (Doytsher and Gelbman, 1995) and (Doytsher and Hall, 1997).

The subject of discovering correspondence between maps – the first part within the framework of the conflation problem – has been dealt with extensively in the late 1980's and 1990's (Harvey and Vauglin, 1996; Doytsher and Shmutter, 1989; and, Walter and Fritsch, 1999). This paper deals with the second part of the adjustment, the process of bringing overlapping plans to geometric uniformity and relates to master plan maps, as noted above. The objective of this adjustment process in respect to the master plan maps is to obtain digital data of the master plans within the GIS framework, as well as master plans produced from the GIS, which will better correspond to each other with greater reliability and accuracy than the original plans themselves. The proposed solution is based on the following successive stages:

Initial global transformation

In order to eliminate the existing systematic errors between the maps, the initial global transformation is based on affine transformation between each pair of overlapping maps. Based on the corresponding points between each map pair, the six parameters of the affine transformation are calculated separately for each map, the parameters that are used for transforming the contents of each map to the new location. In view of the multivalent relations between all overlapping maps in a given area, each map may participate concurrently in several map pairs, and the global transformation process can be executed in two parallel manners. For a large number of maps an iterative global transformation according to a particular order of map pairs is preferred, whereas for a smaller number of maps the transformation can be executed simultaneously for all the maps participating in the initial global transformation.

Averaging the corresponding boundaries

Averaging of the common boundaries relies on analyzing the geometrical and topological accuracies and properties of the various master plan maps. The evaluation of the errors of point location in the various maps facilitates determination of weighting and subsequently determination of uniform locations for all the corresponding lines.

Geometric conditions

Master plan maps, just as other large-scale engineering maps, are characterized by internal geometric conditions (primarily straight lines) embedded in the information of each map. Since the geometric conditions are not given in an explicit manner, this stage of the solution involves identification of the corresponding lines that may be defined as straight lines. The process is carried out separately at the level of each feature (polyline) between two nodes on each map, on the level of the continuity of the conditions beyond the individual feature on each map, as well as on the level of corresponding lines between overlapping maps of the same area. These geometric conditions are practically constraints enabling the corrections of locations of different features in the various maps.

Handling of single lines

The last stage deals with single lines whose location is to be corrected based on corrections of the corresponding lines in their near vicinity. To this end the plans are divided into transformation regions – closed polygons assembled from corresponding lines. Location corrections for single lines that fall within the boundaries of the transformation polygons are calculated based on an interpolation of the corrections of the blocking polygon, while the corrections of single lines outside of the transformation polygons are calculated based on a local extrapolation. The corrections take into account the differences between the various maps while identifying the systematic component on the one hand and the random component on the other hand.

The following sections of the paper describe the solution stages and the current state of this research.

Initial Global Transformation

The master plans, in the form of paper maps, are transferred to the GIS databases following a digitization process (or a scanning and vectorization process) and are brought, through mathematical transformation, into the state plane coordinate system. Since each master plan is digitized and transformed separately, we obtain in addition to all other errors imbedded in each master plan map, also the relative distortions between the various maps. At the stage of identifying the correspondence between the various maps (as stated, by an external process preceding the framework of this paper) a correspondence list of points is obtained – a separate correspondence list between every pair of overlapping plans, lists that are utilized to perform the initial global transformation for the purpose of increasing the proximity between the various maps and eliminating the existing systematic errors: changes in scale, translations and rotations. A variety of different existing mathematical transformations can be applied for the extraction of systematic errors, such as polynomial, affine, orthogonal, etc. According to analysis of the geometric properties of the master plans and based on previous research, linear affine transformation has been chosen for extracting the systematic errors (Shmutter and Doytsher, 1992).

For the series of maps i, j, k between which there is partial or full overlapping, a list (from an external process) of point correspondence between maps (1) is given – with point correspondence possible between more than two maps:

$$match_{i,j} = \begin{bmatrix} x_1^1 & y_1^1 \\ x_2^1 & y_2^1 \\ \vdots & \vdots \\ x_N^1 & y_N^1 \end{bmatrix}_i \Leftrightarrow \begin{bmatrix} x_1^1 & y_1^1 \\ x_2^1 & y_2^1 \\ \vdots & \vdots \\ x_N^1 & y_N^1 \end{bmatrix}_j \quad match_{i,k} = \begin{bmatrix} x_1^2 & y_1^2 \\ x_2^2 & y_2^2 \\ \vdots & \vdots \\ x_M^2 & y_M^2 \end{bmatrix}_i \Leftrightarrow \begin{bmatrix} x_1^2 & y_1^2 \\ x_2^2 & y_2^2 \\ \vdots & \vdots \\ x_M^2 & y_M^2 \end{bmatrix}_k$$
$$match_{j,k} = \begin{bmatrix} x_1^3 & y_1^3 \\ x_2^3 & y_2^3 \\ \vdots & \vdots \\ x_R^3 & y_R^3 \end{bmatrix}_j \Leftrightarrow \begin{bmatrix} x_1^3 & y_1^3 \\ x_2^3 & y_2^3 \\ \vdots & \vdots \\ x_R^3 & y_R^3 \end{bmatrix}_k \qquad (1)$$

Since the mutual link is usually between more than two maps of the given area, as mentioned previously, two approaches to performing the global transformation were examined: simultaneous full transformation of all maps; or, transformation of only two maps at a time by an iterative process. Since there is no difference between the final results of both approaches, and in view of the simplicity of the iterative solution and the unlimited number of maps that can be handled (Shmutter and Doytsher, 1992), the iterative approach for executing the global transformation is described in the following paragraphs (the simultaneous approach can be implemented in a very similar manner).

The matching between each set of overlapping maps is carried out by a weighted least squares adjustment method. The weighting is determined as a function of the scale of each map and its graphic quality (as global parameters) and the number of polylines entering each node (as a graphic/topological local parameter). In the matching, six parameters are calculated for each of the two maps participating in the matching, and each map is transformed to its corrected place according to these parameters.

$$\begin{aligned} \overline{x}_1^{ij} &= a_1^i + b_1^i \cdot x_1^i + c_1^i \cdot y_1^i \\ \overline{y}_1^{ij} &= a_2^i + b_2^i \cdot x_1^i + c_2^i \cdot y_1^i \end{aligned} \tag{2}$$

Due to the fact that there are a number of overlapping map pairs, it is important to determine the order of performing the transformations, from the first pair of maps to the last pair. Examination of the influencing factors lead to a definition of four parameters for determining the transformation order: number of corresponding points between the maps, size of the common overlap area for both maps, scales and the graphic quality of the master plan map (the last two parameters express the joint accuracy of the map pair). The function that produces satisfactory results and in whose descending order the transformations between the map pairs are carried out is:

$$\begin{aligned} O_{ij} &= \left(\frac{A_{com} - A_{\min}}{A_{\max} - A_{\min}}\right) \cdot g_1 + \left(\frac{N_{com} - N_{\min}}{N_{\max} - N_{\min}}\right) \cdot g_2 + \left(\frac{f_{com}}{f_{\max}}\right) \cdot g_3 \\ f_{com} &= \left(\frac{1}{s_i \cdot w_i}\right)^2 + \left(\frac{1}{s_j \cdot w_j}\right)^2 \qquad f_{\max} = \max(f_{com}) \end{aligned} \tag{3}$$

where A expresses the overlapping area (minimum, maximum, and common to the map pair), N the number of corresponding common points, f expresses the accuracy of the two maps, s and w express the scale and graphic quality of the maps, and ã the relative weights.

Averaging the Corresponding Boundaries

At the end of the preceding stage of the initial global transformation, positional corrections are made on all master plans with the result that the maps "approach" each other. Due to the reduced geometric differences between the master plans, re-activation of the stage for finding correspondence between the maps leads to identification of new corresponding points, thus strengthening the links between the maps. The result of the matching process is a list of point pairs linking a real point on the first map to a real point in the second map, or alternatively, a real point on one map to a pseudo point on the other map. In Figure 1, the polyline points are marked on the first map by circles, and those on the second map by triangles, while the pseudo turning points (both in respect to the turning points and/or nodes of the first map, as well as in respect to the points and/or nodes of the second map) are marked by squares.

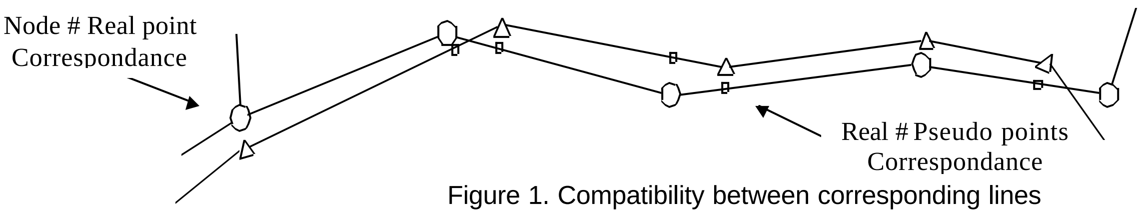

Figure 1. Compatibility between corresponding lines

Adjustment of joint boundaries is carried out by weighted averaging of the corresponding points – with the averaging at each point carried out for each master plan in which the point exists. The weight of every point in each master plan is determined according to the relevant parameters in similar to the description in the preceding section. For each point (participating in n master plans) the accuracy is calculated in the X and Y directions as well as accuracy of its radial location (4).

$$M_{\overline{x},\overline{y}} = \sqrt{\frac{\sum_1^n p v_{\overline{x},\overline{y}}^2}{\sum_1^n p \cdot (n-1)}} \qquad M_R = \sqrt{M_{\overline{x}}^2 + M_{\overline{y}}^2} \tag{4}$$

Moreover, an evaluation is made of the accuracy of the single point for which there is no correspondence (when k is the number of appearances of the corresponding points in all master plans and u is the number of corresponding points) according to:

$$M_{0,\bar{x}} = \sqrt{\frac{\sum_{1}^{k} pv_{\bar{x}}^2}{(k-u)}} \qquad M_{x,q,i} = \frac{M_{0,\bar{x}}}{\sqrt{p_q^i}} \qquad M_{R,q,i} = \sqrt{M_{x,q,i}^2 + M_{y,q,i}^2} \tag{5}$$

Geometric Conditions

The geometric conditions in the master plan maps are not given explicitly but are rather inherent in the information of each map. The geometry of the straight lines dictates the positional corrections of the various features in the maps as constraints in the adjusting and processing stages of the master plan maps. The straight lines are treated in several stages: locating the conditions of the straight lines in each map separately, connecting the conditions from various maps, and finally activating the conditions and straightening the lines.

Locating the conditions of straight lines separately for each map

Locating the straight lines on each map is carried out in two steps – locating straight segments on the polyline in the feature (arc) between two nodes (according to an initial examination) and subsequently locating the conditions around the nodes (in relation to different polylines) and connecting all separate straight segments into continuous straight lines. The first step of examining each polyline separately is performed by checking the turn angles along the polyline as demonstrated in Figure 2. To determine the accuracy of the turn angle ä$_i$ between three consecutive points, it was assumed that accuracy of the location in both axes directions (X and Y) equals $m_x = m_y = m$, and amounts to half the thickness of the drawn line (according to scale), with tolerance T taken with a probability of 99%. It should be noted that this constitutes an initial examination, with the complete examination to take place after the actual straightening of the line.

$$m_d = m \cdot \sqrt{2} \cdot \sqrt{\left(\frac{1}{d_{i-1,i}}\right)^2 + \left(\frac{1}{d_{i,i+1}}\right)^2} \qquad T = 2.5 \cdot m_d \tag{6}$$

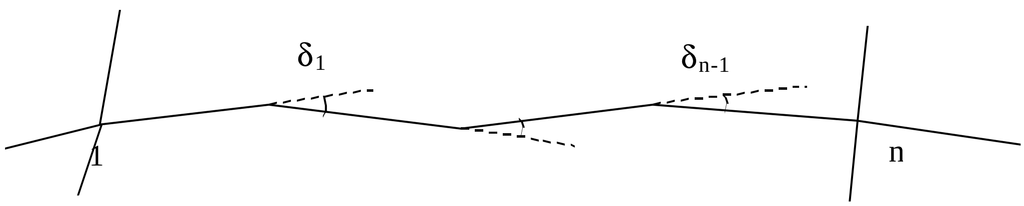

Figure 2. Locating the conditions of the straight lines within the polylines

The second step in locating the straight lines – that of finding the separate straight segments (on both sides of the nodes on the map) and linking these into continuous straight lines is carried out in a manner similar to the previous step, but the examination relates here to the separate polylines connected to each other at the nodes ("node conditions"). The concatenation of the node conditions with the line conditions is carried out in an iterative manner since a straight line can extend over a relatively large number (more than two) of polylines. See the schematic description in Figure 3.

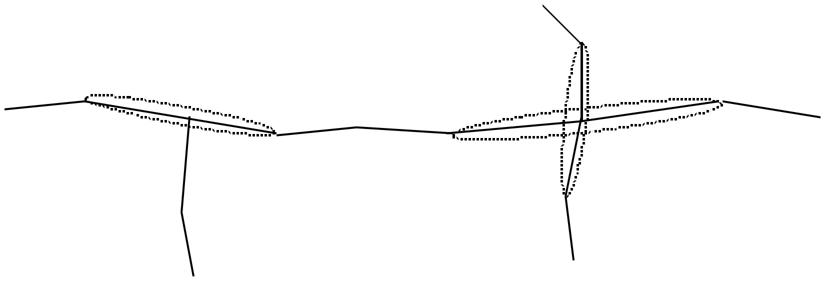

Figure 3. Locating the node conditions

Based on the resulting cumulative conditions of the first two steps (for each polyline separately and the concatenation of polylines), the straight line is applied as the solution of the adjustment problem for finding the two coefficients of the line, with each point that participated in the smoothing assigned a weight (a reciprocal value to its MSE square), while distinguishing between a point participating in several maps and a single point whose pair is a pseudo point. Following the adjustment, the residuals are checked against the MSE of each point separately (as found to be suitable with 95% probability).

$$v=\begin{bmatrix} v_{x1} \\ v_{y1} \\ v_{x2} \\ v_{y2} \\ \vdots \\ v_{xn} \\ v_{yn} \end{bmatrix} \quad \Rightarrow \quad \begin{matrix} \sqrt{v_{x1}^2+v_{y1}^2} \le 2\cdot M_{R1} \\ \sqrt{v_{x2}^2+v_{y2}^2} \le 2\cdot M_{R2} \\ \vdots \\ \sqrt{v_{xn}^2+v_{yn}^2} \le 2\cdot M_{Rn} \end{matrix} \tag{7}$$

Joining conditions from different maps

In view of the requirement to attain a unified description of the data from all overlapping master plan maps, it is necessary to unify the various conditions of each separate plan. Located at the first stage are all groups of conditions that are geometrically mutually close to one another. Following that, the groups of conditions are separated into two sets of groups, the first where the conditions are contained within each other, and the second set of groups of conditions that partly overlap one another. In a group where one condition of the group is included completely within another condition of the group, since it is of no geometric significance, it is deleted from the list of conditions (there is no significance whatsoever in defining part of a long straight line as an additional straight line).

For groups with partly overlapping conditions, concatenation of the various conditions is carried out according to the running distance of all points (from an arbitrary edge) participating in all conditions of the group. Thus a concatenated condition is obtained, a condition that replaces all the separate conditions. As to the concatenated condition, smoothing is performed over the string of points and the differences in location are examined both before and after the smoothing. The concatenated condition is saved for the adjustment process only if all radial differences fall within a 95% location tolerance (and the separate conditions that defined the concatenated condition are cancelled), otherwise the original conditions of each straight line are saved separately.

Activating the conditions and smoothing the lines

Implementing the various conditions (whether concatenated or original) by a least squares adjustment and smoothing the straight lines is to be iterative, since some of the points are common to some of the conditions and thus may be affected and corrected according to several conditions. Since the number of these points is relatively small, the operation of this iterative process is relatively fast.

Handling of Single Lines

Shifting corresponding lines in each map to a new position due to the averaging and smoothing of these lines as needed, requires positional corrections of single lines within in each and every map. Analysis of such shifting shows non-homogenous and discontinuous local distortions along the corresponding lines. Based on this local nature of the distortions, it is only natural to try to divide the map into less non-homogenous area units – transformation polygons – based on the corresponding lines. For each such transformation polygon that defines a relatively limited area, the local transformation is aimed at the correction of the location of the single lines in the near vicinity of the transformation polygon.

One of the possible strategies for defining transformation polygons proposed by (Deretsky and Rodny, 1993), relies on defining a topological structure of all polylines whose edge points are corresponding points, and assembling the polygons themselves in a structured process based on the topological connectivity between the various polylines (Doytsher and Shmutter, 1990). The principles of the algorithm as described in Figure 4, are primarily to move within the topological network of the polylines and from a random node point (Node

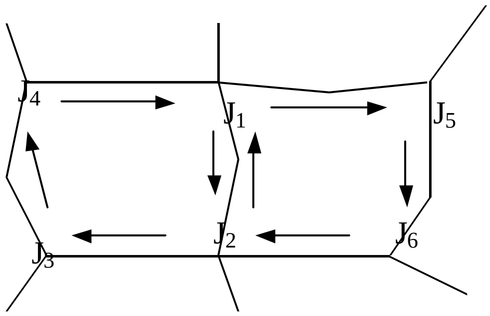

Figure 4. Assembling the polygons

J_1 – as a departure point), arbitrarily select one of the directions emerging from the node (direction toward J_2) and from here on move from one node to another in a clockwise direction (to continue from node J_2 to node J_3, and so on) and continue in this order until returning to the departure point. The procedure of assembling of polygons is continued until passing through all nodes in all possible directions.

For each transformation polygon that has been assembled and contains within it single lines, in part or in full, on one or more map, local transformation needs to be calculated to correct the location of the single lines. Since a transformation polygon composed of corresponding lines does not define or delimit regular shifts, the possible transformation is that of rubber sheeting. Different rubber sheeting methods exist, each providing a solution of a specific problem. Among these methods, we have chosen to apply the method described in (Doytsher, 2000) which deals with a similar case, that of cadastral blocks. It should be stressed that the rubber sheeting transformation is to be applied only to transformation polygons that contain single lines. Thus, for example, Figure 5 presents two transformation polygons, the first polygon (I) without single lines and the second polygon (II) containing two single lines a,b and thus the transformation will be applied to it only.

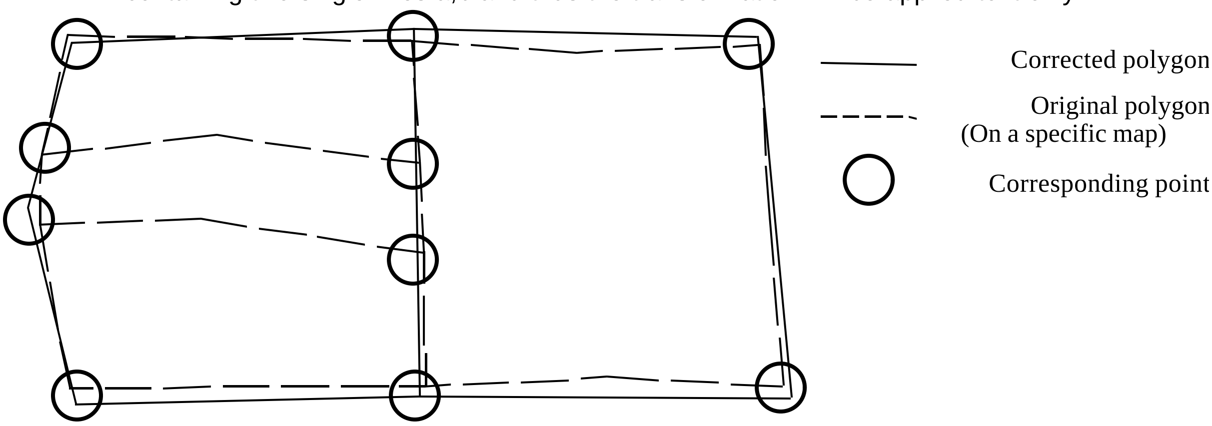

Figure 5. Defining transformation polygons

The proposed method for rubber sheeting transformation assumes a linear change of the corrections along the sides and linear change perpendicular to the polygon sides. According to the shape of the polygon perimeter a skeleton line is built, dividing the polygon into

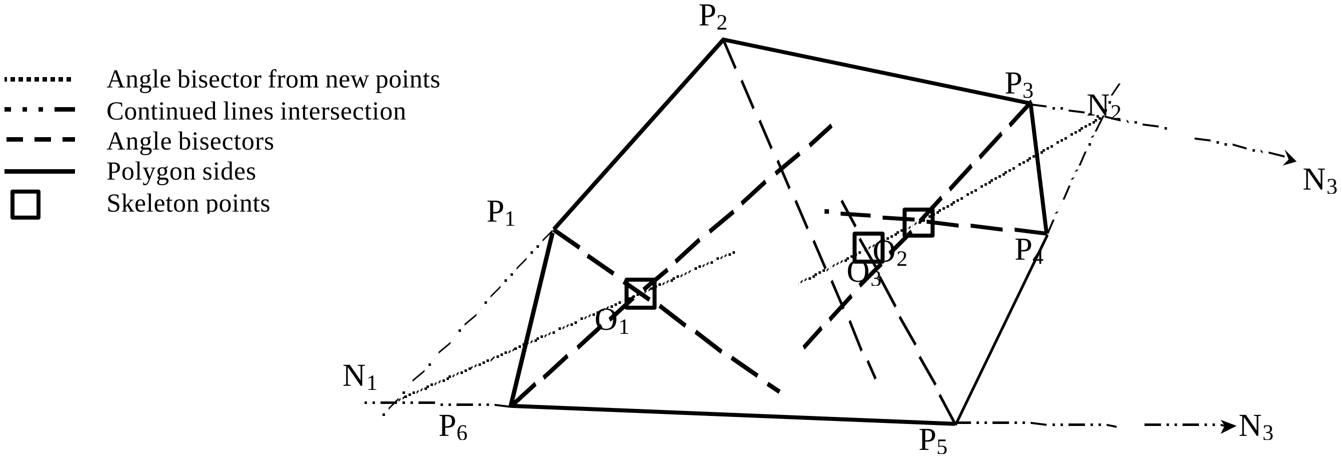

Figure 6. Constructing the skeleton line

several areas of influence, as the number of the polygon's sides. Within the areas of influence, the corrections are reduced in a linear manner, from values equal to the corrections in the two points of the side, to zero on the skeleton line. The principal stages of the algorithm for building the skeleton line and the division into areas of influence are: calculation of the bisectors of angles of the transformation polygon; classification in ascending order of the distance of the intersection points of the angle bisectors from the polygon sides; graded neutralizing of the polygon vertices; and, connecting the polygon sides with the intersection points of the angle bisectors to create areas of influence. Figure 6 depicts an example of building the skeleton line and Figure 7 the division into areas of influence. Full details of the algorithm can be seen in (Doytsher, 2000).

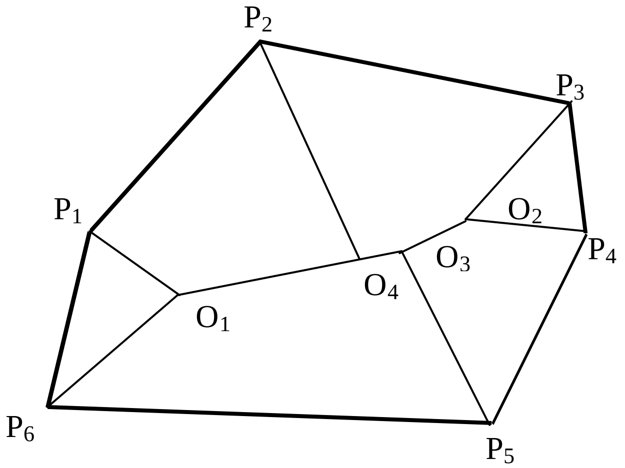

Figure 7. Division into areas of influence

In this example, the polygon is divided into six areas of influence, equal to the number of sides, obtaining areas of influence in different geometric shapes, triangles, quadrilaterals and trapezoids, with some having even more complex shapes. Correction of locations of the single points or single lines that fall into each area of influence are calculated based on interpolation from the existing values in the four points defining the area – the corrections at the two points along the perimeter and zeros at the two points along the skeleton. The interpolation is bi-linear (8), with value c expressing the corrections on the X or Y axes. Calculation of the relative location of the single point within the area of influence is carried out in an iterative manner.

$$c_n = c_1 + (c_2 - c_1)\cdot u + (c_4 - c_1)\cdot v + (c_1 - c_2 + c_3 - c_4)\cdot u \cdot v \qquad (8)$$

The location corrections for the list of the single lines that are fully or partly outside the transformation polygon, are to be calculated by extrapolation in relation to the corresponding lines (Figure 8). The solution is based on the Constrained Delauney Triangulations (Ding and Densham, 1994) in the areas between the transformation polygons. Each triangle is transformed by affine transformation that relies on the three vertices of the triangle without the need for the least squares adjustment solution. The single lines that fall within the triangles are transformed directly by the parameters of those triangles, while the transformation of the single lines that fall outside the triangles is carried out by an extrapolation (reciprocal distance-dependent). Figure 8 depicts assembling the Delauney triangles and two types of single lines – lines that fall within the triangles and those that fall outside the areas of the triangles.

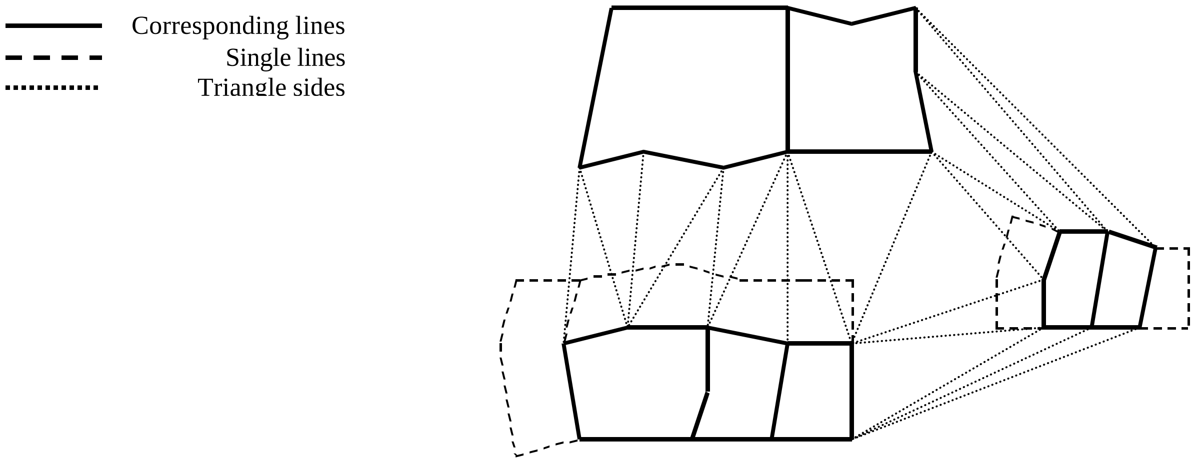

Figure 8. Extrapolation of single lines

Conclusive Remarks

The process presented in this paper substantially improves the location accuracy of master plan maps, reducing the geometric contradictions between the overlapping plans that existed in the original maps. Thus, for example, at the affine transformation stage, the average proximity between the master plans was an improvement of 1.3m. At the corresponding line averaging stage, in spite of the initial discrepancies, the final accuracies obtained in the alignment process are not beyond the level of the estimated location error for points on maps, expected from the digitization processes itself. Quality control of the process was maintained by comparing the final location of the lot boundaries with the cadastral block maps (and the cadastral parcel lines within the blocks) of the areas examined, maps that are of better accuracy than the master plan maps. Good correlation was found in the areas common to the plans and the cadastral blocks.

The research is currently at an advanced stage, and the ongoing stages are planned to include deeper analysis of the geometric and topological properties of the master plan maps, identifying additional geometric conditions such as perpendicularity and parallelism of lines, more accurate determination of weights, and improvement of the extrapolation of single lines that fall outside the areas covered by the corresponding lines.

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