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Determination of the limits of municipal formations in the inhomogeneous geoinformation space

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Abstract. The article discusses the technical design of the boundaries of municipalities in the inhomogeneous geospace. The scientific hypothesis of the work is that the use of technical approximation in the design of municipal boundaries will allow them to be scientifically established locally and increase the level of automation. It is noted that the existing methods of technical design of the boundaries of municipal formations do not allow taking into account the heterogeneity of geospatial data, and the functionality of the software for the preparation of land management documentation has a low level of automation of geometric design. The consequences of this are significant labor costs and the influence of the subjective factor on the design decisions. Nowadays, there is no single approach to perform technical (geometric) design of the boundaries of municipalities in Russia. At the same time, the establishment of the Institute of local self-government in Russia requires reliable and relevant data on the state of the territory and the boundaries of municipalities. To solve this problem, a methodology has been developed, which includes principles, additional requirements, theoretical basis of technical design of municipal boundaries, algorithm and software module for geometric design.

1 Introduction

The formation of the institute of local self-government and the management of the development of territories is impossible without complete, reliable and relevant data on their state, including without the established boundaries of municipalities, since this is interconnected with the organizational, financial and competence basics of local self-government [1].

In Russia, the constituent entities of the Federation in 2016 started implementing the Comprehensive Action Plan for entering into the Unified State Register of Real Estate (USRRE) information about the borders between the subjects of the Russian Federation and the boundaries of municipalities [2]. And by 2021, the share of the boundaries of municipalities in the USRRE should be 100% [3].

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For January-February 2018, information about the boundaries of 144 municipal formations was entered into the USRRE. As a result, the amount of information about such borders in the USRRE increased by 3% compared with the beginning of the current year. As of March 1, 2018, the USRRE contains information on 11,430 of 22,327 borders of municipal formations (51.2%) [4].

All this underlines the relevance and practical importance of the research topic.

The analysis of foreign experience [5–8], the legislative framework and regulatory and technical documentation in Russia in the aspect of establishing the boundaries of municipal formations [9–14] revealed the following.

Land management work to establish the boundaries of municipalities (MC) includes two stages: the approval and description of the location and (or) the establishment on the ground of the boundaries of the object of land management.

At the first stage, prepare a map-scheme of the borders of the MC and the corresponding package of documents and hold public hearings. After consideration by the Legislative Assembly of the subject of the Federation approve the map-scheme and the cartographic (coordinate) description of the borders of the MC in the form of the law of the subject of the Federation. The map-scheme is made on topographic maps of scales 1: 100 000 - 1: 10 000.

At the second stage, the description of the location and (or) the establishment of the borders of the MC on the ground in the form of a map (plan) of the land management object is performed.

The map (plan) of a land management object consists of two parts: textual and graphic [13]. The graphic part (plan of borders) is recommended to be presented on materials and data of cartographic works of scale 1: 100 000 and larger. In preparing this part, information from the USRRE and the following materials are used: geodetic, cartographic, topographic data, Earth remote sensing data, land surveying, urban planning and other data, i.e., initial data that are heterogeneous both in appearance and accuracy. Therefore, at this stage there arises the task of refining the coordinate description of the boundaries of the MC with allowance for the heterogeneity of geospatial data.

The process of refining the coordinate description of MC boundaries is called technical design, where three methods are used: analytical; graphic and combined. In practice, the most widely spread first and third methods. Here two types of tasks are solved: the area of the territory must be equal to the given value; the area of the territory must be greater than the minimum allowable value. In this case, formulas of analytical geometry and planimetry are used (well-known formulas for calculating the area of a triangle, a rectangle, and a trapezium). These formulas are combined with the solution of the reverse geodesic task. Therefore, this process is also called geometric design [14].

The experience of establishing boundaries in the Novosibirsk region showed [15 - 17] that the existing analytical apparatus of geometric design does not allow to take into account the heterogeneity of geospatial data.

It should also be noted that now there is no single approach to the implementation of the technical design of the boundaries of the MC.

A number of software packages are presented on the Russian land management software market: ACT, ARGO, ARM-KIN (cadastral engineer workstation), Land Case 8.1, ProGeo, Polygon program complex, modules in the Credo-Dialogue program complexes, GIS Map geographic information system, Cadastral office land information system, etc. [18–23]. The functionality of these complexes is focused on automating the design of text and graphic parts of a land management document and interacting with law registration authorities. In the program complexes there is no special mode for geometric design of the boundaries of the MC and the possibility of taking into account the heterogeneity of geospatial data is not provided. But the graphic editor of the software allows you to perform the clarification of the boundaries of the MC in a combined way in an interactive mode. The consequence of this are considerable labor costs in the preparation of the plan for the boundaries of the MC and the influence of the subjective factor on the design decisions.

Not only the authenticity and reliability of the adopted design decisions, but also the effectiveness of management decisions on the territory of the municipality depends on the quality and efficiency of technical, including geometric design. Therefore, there is a need to develop a methodology for technical design of the boundaries of the MC, where the development of design solutions takes into account the heterogeneity of geospatial data.

To do this, it is necessary to develop a theoretical basis for technical design, an algorithm and a software module for geometric design.

The scientific hypothesis of the work is that the use of technical approximation in the geometric design of the borders of MC will allow them to be scientifically established on the ground and increase the level of automation.

2 Theoretical basis

Suppose that in the area of designing the boundaries of municipal formation B there is a heterogeneous geospace $GS = \bigcup ID_S$ – a subset as a union of initial geospatial data (*IDs*) on the boundaries of land plots (LP) of heterogeneous in appearance and accuracy; land management facilities (LMF); real estate objects (REO); territorial zones (TZ); natural or artificial contours (NAC). Also, in the composition of the initial heterogeneous geospace, we introduce the approved MC boundaries, displayed on large-scale plans – Go and the proposals of the heads of municipal administrations on the part of the MC boundaries – $\hat{g}_i$.

Based on the general formulation of the dynamic programming problem [24], we will present the process of the technical design of MC boundaries as follows.

Let the state of the boundaries at step *i* be characterized by a vector $G_i \in G$ that depends on the previous state G_{i-1} and control (displacement vector *i* of the characteristic point of the boundary in two-dimensional space) $U_i \in U$, taking into account the heterogeneity of the original geospatial data ID_S. Variable parameters U_i (Δx_i, Δy_i) satisfy the constraint $f_i(U_i) \le b_i$, for all U_i the following inequality must be satisfied: $-b_j \le U_i \le +b_j$, where Δx_i, Δy_i – are the increments of the coordinates *i* of the characteristic point of the boundary. And in this sense, the set U_i is a subset of the permissible controls or impacts on the border, taking into account the heterogeneity of the initial geospatial data ID_S.

Then the state of the boundary can be written as the following equation:

$$G_i = \varphi_i(G_{i-1}, ID_S, U_i) \tag{1}$$

To determine the set of control actions *U* on the state of the *G* boundary of the MC boundary in the process of technical design, a number of principles have been developed:

– relevance;
– unambiguity;
– comparability;
– coherence;
– continuity;
– from general to specific [25].

Let us assign a control efficiency function Z: $G \cdot ID_S \cdot U \to T$ on the Cartesian product $G \cdot U \cdot ID_S$:

$$z_i = \min f_i(G_{i-1}, ID_S, U_i) \tag{2}$$

Then the task of technical design of the MC boundaries is reduced to the choice of such a set of controls U_1, U_2, …, U_N that alter the boundaries from the initial condition G_H to the final condition – specify G_K, at which the objective function Z takes the lowest value:

$$Z = \sum f_i\left(G_{i-1}, ID_S, U_i\right) \rightarrow \min \tag{3}$$

In this case, the effective displacement i of the characteristic point in two-dimensional space is performed when the remaining characteristic points of this boundary are fixed, that is $N \backslash \{i\}$, with $N = (1, 2, \ldots, N)$, $i = (1 \vee 2 \vee \ldots \vee N)$.

Let us take as the main condition the observance of the land balance at the level of the municipal district, then the expression (3) can be written as a function of the difference in the area of the territory of the borders of MC on the map-scheme G_P with the current state of the contour G_i of the borders of MC, obtained in the process of technical design:

$$d_S|(G_P, G_i)| \leq \varepsilon, \tag{4}$$

where ε is 0.1 of the accuracy of the representation of the area in the land management document (map (plan)).

Consequently, the technical (geometric) design of MC boundaries can be represented as an approximation with constraints U, where the land balance (the main condition) and the heterogeneity of the initial geospatial data IDS are taken into account.

Approximation methods and their classification are defined in [26]. Conventionally, all methods of approximation are divided into two types:

- a rigorous theory of mathematical approximation;
- technical approximation.

It is noted that the use of technical approximation allows one to solve a large volume of problems efficiently with a limited amount of time.

One of the widely used methods of technical approximation is the Kriging method [27], which is based on a mathematical model of a weight moving average. Therefore, when developing the geometric design algorithm, we relied on the mathematical model of this method.

Before considering the essence of the geometric design algorithm, we introduce a subset of the main objects of the heterogeneous geospace GS: $G_{GS} = LP \cup LMF \cup REO \cup TZ \cup G_O \cup NAC$.

So, the essence of the developed geometric design algorithm in a heterogeneous geospace is as follows.

For each i-th movable characteristic point of the contour of the boundaries MC (G), the specified coordinates $\tilde{x}_{i,k}$ and $\tilde{y}_{i,k}$ are determined by the formulas presented below:

$$\tilde{x}_{i,k} = X^T_{i,k-1} \cdot W^x_{i,k-1} \cdot \left(E^T \cdot W^x_{i,k-1}\right)^{-1};$$
$$\tilde{y}_{i,k} = Y^T_{i,k-1} \cdot W^y_{i,k-1} \cdot \left(E^T \cdot W^y_{i,k-1}\right)^{-1}, \tag{5}$$

where $X_{i,k-1}$ and $Y_{i,k-1}$ – the column vectors of the abscissa and ordinate of the variants of the location of the i-th characteristic point G, respectively, in the ((k –1)-th iteration; $W^x_{i,k-1}$ and $W^y_{i,k-1}$ – column vectors of weights of abscissas and ordinates of variants of the location of the *i*-th characteristic point *G*, respectively, in the (*k* – *1*) -th iteration; *E* – matrix-column scale factors of matrix elements $\Lambda^{x(y)}$.

After calculating the refined coordinates $\widetilde{x}_{i,k}$ and $\widetilde{y}_{i.k}$ characteristic points of the MC boundaries, the accuracy of approximation is checked by formulas (5), i.e. the main condition of geometric design:

$$d_{S,k-1} = |P_P - P_{k-1})| \leq \varepsilon, \tag{11}$$

where P_P – the approved area of the territory of the MC in the law of the subject of the Federation; P_{k-1} – area of the territory of the municipality in the (*k*–*1*)-th iteration.

If this condition is not met, then again for each *i*-th movable characteristic point of the contour *G*, the location options are set and calculated $\widetilde{x}_{i,k}$ and $\widetilde{y}_{i.k}$ by formulas (5). Otherwise, complete the process of clarifying the boundaries of MC.

3 Methods

Based on the theoretical basis of the technical and algorithm of geometric design of the borders of MO, a technique has been developed, the block diagram of which is shown in Figure 3.

The process of the technical design of the borders of the MC includes three stages: semantic (I); geometrical (II); design solution (III).

Semantic design is understood as meaningful, informative design based on the initial geospatial data of the main objects IDS.

Under the geometric design refers to the refinement of the area and location Gl of the borders of MC.

At the stage of semantic design, the project boundary G_O of the MC is created by displaying the cartographic description G_P on large-scale plans, taking into account the conditions of the first group of requirements.

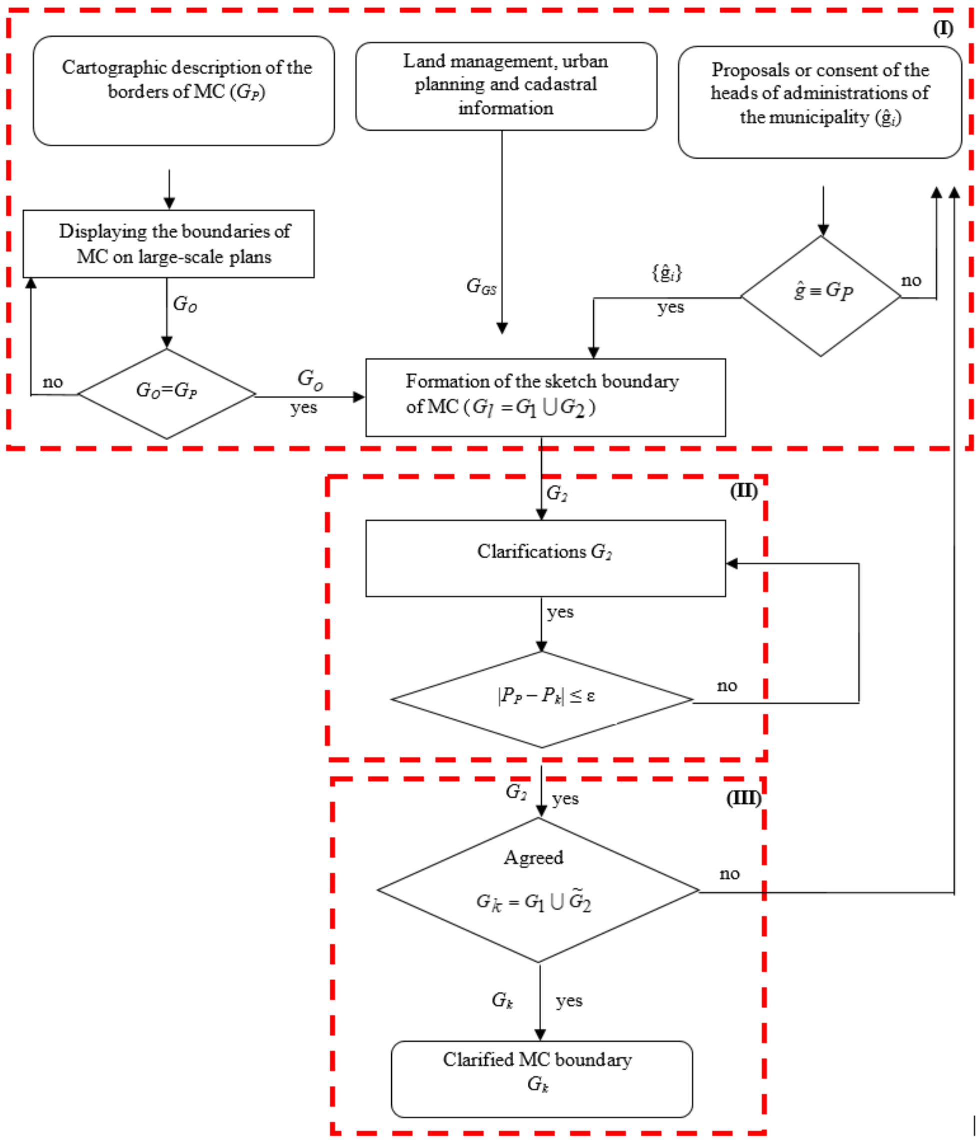

Fig. 1. Block diagram of the technical design boundaries of municipalities.

Perform the collection and systematization of heterogeneous on the accuracy of geospatial data ID_S and proposals from the heads of municipal administrations $\{\hat{g}_i\}$. Then the main objects are represented as a weighted digraph $G_{GS} = (V_{GS}, E_{GS}, M_{GS})$, where V_{GS} – the set of vertices (characteristic points of the borders); E_{GS} – many edges (borders); M_{GS} – set of estimates of the mean square error of the position of the vertices of the digraph.

The model of sketch boundaries MO – G_l – is the union of two subgraphs G_1 and G_2 obtained on the partition of two sets of edges R_1 and R_2, i.e. $G_l = G_1(V_1, R_1) \cup G_2(V_2, R_2)$, wherein $R_1 \cap R_2 = 0$ and $V_1 \cap V_2 \neq 0$, because $\exists r_j(v_i, v_j) \in R_2$, where $v_i \in V_1$ and $v_j \in V_2$. Therefore, this model is formed in two steps:

1) the subgraph G_l is formed taking into account the conditions of the second group of combined requirements, i.e. the subgraph G_l is combined with the corresponding vertices

and edges of the graph G_{GS} and includes vertices and edges $\hat{g}_i$ if their spatial position meets the conditions presented in the first and second group of combined requirements;

2) the subgraph G_2 is also formed in the area of designing B the boundaries of MC, but taking into account the conditions of the third group of combined requirements. At the same time, vertices V_2 and arcs R_2 tend to combine with artificial (natural) boundaries and not to allow broken contour boundaries. And also achieve the difference in the area of the sketch outline P_l with a design value P_P of not more than 30%.

All the above actions, as well as geometric design, are performed in the developed software module Design Municipality [28].

At the stage of geometric design, the location of the subgraph G_2 and the area G_l of the MC borders are refined in the following order:

1) for each i-th vertex of the subgraph G_2 in the transverse direction, specify m variants of its location;

2) the specified coordinates $\tilde{x}_{i,k}$ and $\tilde{y}_{i.k}$ are determined in the program module. And based on them, the contour of the refined subgraph $\tilde{G}_2$ and G_k the boundaries of the MC are formed in the k-th approximation;

3) the condition $|P_P - P_k| \leq \varepsilon$ is checked if the value $\geq\varepsilon$ then returns to item 1 of the geometric design. Otherwise, the technical design is completed, and the design decision is coordinated with the local authorities.

4 Results and discussion

It can be assumed that the following factors influence the number of approximations and the accuracy of geometric design of MC boundaries:

- the magnitude of evasion of the draft area from the project;
- rules for specifying the location of the vertex of the subgraph G_2;
- approach to the implementation of approximations: to perform approximations for each vertex separately or along all the vertices of the subgraph G_2.

To determine the degree of influence of the first factor, the computational experiment was carried out in the following order:

- formation of a sketch of the territory with a certain value of deviation from the project area dP (from 1 to 50% in 5% increments);
- formation of options for the location of vertices in the subgraph G_2;
- perform approximations.

After the iteration was completed, the deviation of the specified area from the design value (ds) was determined.

From the results of the study, it was found that there is a close correlation between ds and dP ($r = 0.95$). When $dP = 50\%$ that ds is increased by 0.5% of the project area.

To determine the nature of the second and third factors, a computational experiment was conducted on five models of MC territories.

The study looked at two iteration approaches:

- for each individual vertex of the subgraph G_2;
- on all tops of the subgraph G_2.

Variants of the location of the i-th vertex of the subgraph G_2 were assigned in the transverse direction to the contour of the MC's sketch boundaries in two ways, i.e. adhered to the following rules. In the first method, the designer placed the vertices of the subgraph G_2 between the boundaries of the main objects G_{GS}, and in the second, on the borders G_{GS}.

As a result of the study, it was revealed that the iteration approaches do not affect the accuracy of geometric design. The application of the first hike, in relation to the second, leads only to an increase in labor costs in proportion to the number of refined vertices in the subgraph G_2.

The rules for assigning the location of the vertices of a subgraph G_2 significantly affect the number of approximations. If in the zero approximation to set the location of the vertices of the subgraph G_2 on the borders of the main objects G_{GS}, then this leads to a significant reduction in the number of approximations. In the experiment, the number of approximations was 1-2.

Based on the studies performed, the following conclusions can be drawn:

- the influence of the deviation value of the area of the sketch outline of the MC boundary from the design one on the accuracy of geometric design is not significant. But when designing, we recommend to set the area of the outline sketch within 30% of the design value;
- the choice of options for the location of the vertices of the subgraph G_2 in the zero approximation should be carried out in the transverse direction of the contour G_l at the boundaries of the main objects G_{GS};
- clarification should be performed on all vertices of the subgraph G_2.

Taking into account the recommendations, the geometric design of the boundaries of seven municipalities of the Novosibirsk Region has been completed. Then they compared the labor costs with the combined method, where well-known formulas were used to calculate the area of a triangle and a four-sided square.

The length of the updated MC boundaries ranged from 1.1 km to 6.5 km. The number of peaks from 5 to 15 per kilometer. For each boundary of MC, specified vertices 1, 2, 3, 5, and 10 were specified.

As a result of the comparison revealed the following.

When the number of refined vertices in the MC boundary is less than or equal to three, the total design time using a combined method and using the Design Municipality program module was comparable. And it was found in the range from 5 to 10 minutes.

When the number of refined vertices from five to ten, an increase in the time to design the boundaries was observed when using the combined method. This was caused by a large amount of geospatial data, broken borders, as well as the search for a site to clarify the area and location of boundaries.

By urban districts: Iskitim, Ob, Novosibirsk - on average, it took 10-15 minutes (in a combined way) and 3-4 minutes (using a software module) to design one kilometer of the border.

When designing the borders of village councils: Berezovsky, Kamensky and Tolmachevsky and Krivodanovka settlement - on average, it took 5-7 minutes (in a combined way) and 2-3 minutes (using a software module) to design one kilometer of the border.

Consequently, the automation level of the software module is almost two times higher than in the combined method. And the method of geometric design of the boundaries of MC allows to exclude the influence of the subjective factor on the design decision.

5 Conclusion

Thus, we can conclude that the developed methodology, including a software module and an algorithm for geometric design, allows us to automate the process of technical design of the boundaries of municipalities. This takes into account the heterogeneity of geospatial data on the boundaries of land plots, land management facilities, real estate, territorial zones and municipalities. This allows you to increase the efficiency, accuracy of the description of the boundaries of the municipality and their relevance to the modern level of development of the territory, as well as minimize the costs of resolving territorial disputes, increase the efficiency of management decision-making.

Therefore, the scientific hypothesis of the work is proved, i.e. the use of technical approximation in the design of the boundaries of municipalities will allow scientifically-based installation on the ground and increase the level of automation.

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