UDC 625.721 : 004.94 **DOI: 10.30977/BUL.2219-5548.2025.110.0.147**

EXPERIENCE IN SOFTWARE IMPLEMENTATION OF RASTER SUBSTRATE TRANSFORMATION IN GIS FOR UTILITY NETWORKS

Musiienko I. V.
Kharkiv National Automobile and Highway University

Abstract. *This article is part of a broader study devoted to the computer implementation of the "Flexible Bracelet Method" for road alignment design. The paper addresses the problem of raster substrate transformation, which plays a crucial role in the transition from the internal coordinate system of the program to the real-world coordinate framework. Several approaches to coordinate transformation were tested, including affine and projective transformations. After comparative analysis, the similarity transformation was chosen as the most efficient option, since it preserves object geometry while allowing scaling, rotation, and translation. The developed algorithm includes reference point input, calibration, scale and angle computation, raster offset determination, forward and inverse transformation, and accuracy verification. The implementation was tested on engineering raster maps in the context of BIM/GIS integration. The results provide a reliable mechanism for georeferencing raster data, extending the functionality of the "Flexible Bracelet" software and supporting further research in automated road alignment optimization.*

Key words: *road tracing, flexible bracelet, coordinate transformation, similarity transformation, georeferencing, BIM/GIS.*

Introduction

The idea of using a raster base (substrate) was widespread even before the era of computer technologies. Maps and plans served as such bases, from which individual points as well as contours of situational or relief objects were transferred to a new plan or map using needles or other instruments.

The introduction of computer technologies has made this process more convenient and accurate. However, the problem of software implementation of raster substrate transformation, although solved in commercial software packages, has been insufficiently addressed in academic literature. The experience of solving this problem is presented in the present article.

The problem of software implementation of raster substrate transformation is a part of the general implementation of the "flexible bracelet method" in road design.

Analysis of publications

The problem of raster data georeferencing has traditionally been addressed within Geographic Information Systems (GIS). Widely used tools such as QGIS Georeferencer and ArcGIS

Pro provide functionality for raster transformation using affine and projective transformations based on ground control points [1–3]. Additionally, libraries such as GDAL and toolkits like MathWorks offer algorithms for geometric transformations and image registration, which serve as the mathematical foundation for software solutions in this field [4].

With the advancement of design technologies, the integration of Building Information Modeling (BIM) and GIS has become particularly important, requiring the unification of coordinate systems. Azari (2025) provides a comprehensive review of existing georeferencing methods for BIM models, with special attention to data format incompatibility [5]. Zhu and Wu (2021) propose a unified approach to georeferencing IFC-based models, thus facilitating the development of digital twins and improving BIM/GIS interoperability [6]. In turn, Diakité (2020) develops an automatic framework for transforming local BIM coordinates into geographic ones, significantly accelerating the integration process [7].

The use of BIM/GIS integration is especially critical in the field of utility mapping. Sharafat et al. (2021) introduce an integrated framework for underground utilities, linking ground-penetrating radar and UAV data with digital models [8]. Slongo et al. (2022) present the GEOBIMM4FM system, designed for underground infrastructure management through IFC-based BIM and GIS databases [9]. The study of Esekhaigbe et al. (2020) highlights the advantages of moving from 2D drawings to 3D BIM for utility asset management, improving both reliability and safety [10].

Recent developments also include algorithmic solutions for aligning local and global coordinate systems. For instance, Kim (2025) proposes an automatic algorithm for matching BIM local coordinate systems with GIS reference maps, reducing positional inaccuracies [11].

Research objectives

The computer implementation of the flexible bracelet method involves the following steps.

First stage. Modeling of the flexible bracelet itself, its geometry, and manipulation methods [12-13].

Second stage. Adding the function of substrate uploading to the program. At this stage, it became possible to implement the principle of alignment using a "flexible ruler," although the specification of geometric constraints was not yet available [13].

Third stage. Solving the problem of obtaining the coordinates of the centers of the bracelet's segments in the internal coordinate system.

Fourth stage. Developing an algorithm for simulating the physical model of the flexible bracelet.

Fifth stage. Solving the problem of optimally fitting the flexible bracelet into a corridor simulating situational or relief constraints. This operation was defined as the "beginning of optimization."

Further implementation of the flexible bracelet method requires a transition from the internal coordinate system to the coordinate system of the raster substrate. This transition cannot be carried out without specifying the coordinates of a certain number of points.

This article describes the computer implementation of transforming raster substrates in GIS engineering networks, using the "Flexible Bracelet" program as an example.

Implementation of raster substrate transformation in GIS for utility networks

Coordinate transformation algorithm between systems includes:

– step 1 – calibration process initialization;
– step 2 – reference point input;
– step 3 – transformation parameters calculation;
– step 4 – raster offset calculation;
– step 5 – forward coordinate transformation (GK → GDI+);
– step 6 – inverse coordinate transformation (GDI+ → GK);
– step 7 – transformation accuracy verification.

Step 1 – calibration process initialization: when the "Setting Coordinates" button is pressed, the program enters reference point setting mode; the user is prompted to sequentially indicate three corner points of the kilometer grid in the following order (Fig. 1):

– Bottom-Right point (BR);
– Bottom-Left point (BL);
– Top-Left point (TL).

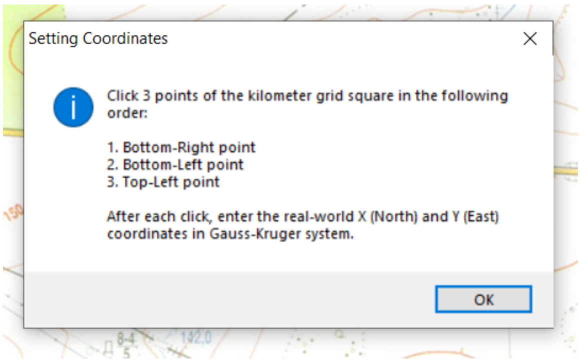

Fig. 1. Window with instructions on point selection order

Step 2 – reference point input: for each selected point, the user enters corresponding coordinates in the Gauss-Kruger system (Fig. 2):

– X – northern coordinate (North);
– Y – eastern coordinate (East).

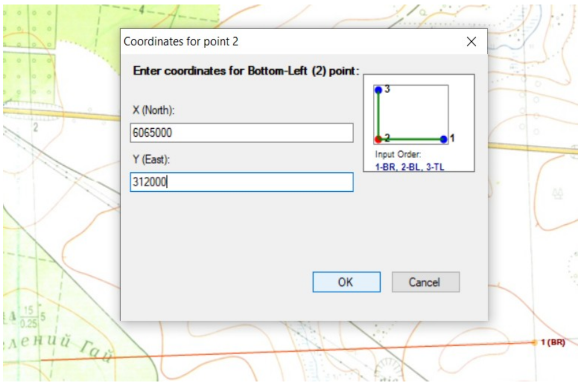

Fig. 2. Window with instructions on point selection order

Step 3 – transformation parameters calculation: after entering three reference points, the coordinate system calibration is performed:

– determining the basis vector between points P_1 (BR) and P_2 (BL) in pixel coordinates;
– calculating basis length in pixel coordinates:

$$L_{internal} = \sqrt{B_x^2 + B_y^2}, \quad (1)$$

where B_x, B_y – are coordinates.

– determining the basis directional angle in GDI+ system:

$$\Theta_{basis} = arctan\left(\frac{B_y}{B_x}\right), \qquad (2)$$

– calculating real basis length in meters;

– determining scale (pixels per meter):

$$S = \frac{L_{internal}}{L_{real}}, \qquad (3)$$

where L_{real} – is a real length (1000 m).

Step 4 – raster offset calculation:

– determining expected position of third point P_3 assuming perfect square formation:

$$\vec{V}_{P_2 \to P_3} = \left(-B_y, B_x\right), \qquad (4)$$

where the vector is rotated 90° counter-clockwise relative to the basis;

– calculating expected P_3 coordinates;

– computing raster offset (Fig. 3):

$$\vec{R}_{offset} = \left(-\Delta_X, -\Delta_Y\right), \qquad (5)$$

where Δ_X, Δ_Y – are difference between actual and expected coordinates.

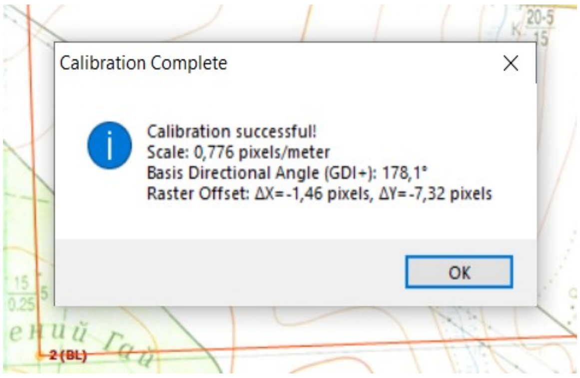

Fig. 3. Window with calibration results

Step 5 – forward coordinate transformation (GK → GDI+) – to transform a point from Gauss-Kruger system to pixel coordinates:

– calculating relative offsets;

– transformation to intermediate system:

$$X_{temp} = \Delta Y_{GK}, \qquad Y_{temp} = -\Delta X_{GK}, \qquad (6)$$

where $\Delta Y_{GK}, \Delta X_{GK}$ – are relative offsets;

– rotation by angle $-\Theta_{basis}$:

$$\begin{bmatrix} X_{rot} \\ Y_{rot} \end{bmatrix} = \begin{bmatrix} \cos(-\Theta) & -\sin(-\Theta) \\ \sin(-\Theta) & -\cos(-\Theta) \end{bmatrix} \begin{bmatrix} X_{temp} \\ Y_{temp} \end{bmatrix}, \qquad (7)$$

– scaling and offsetting.

Step 6 – inverse coordinate transformation (GDI+ → GK): the reverse sequence of operations is performed with appropriate inversions.

Step 7 – transformation accuracy verification; for each reference point, the following is calculated (Fig. 4):

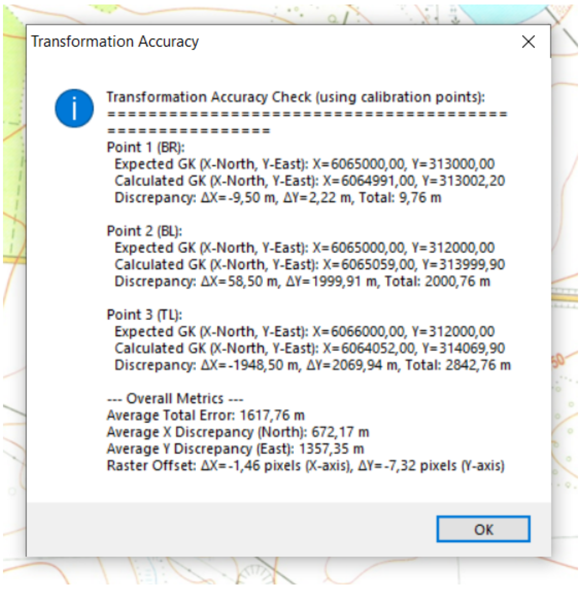

Fig. 4. "Check Accuracy" window with verification results

– expected GK coordinates;

– calculated GK coordinates;

– discrepancies: $\Delta X_{error}, \Delta Y_{error}$;

– total error (Fig. 5):

$$\Delta_{total} = \sqrt{\Delta X_{error}^2 + \Delta Y_{error}^2}. \qquad (8)$$

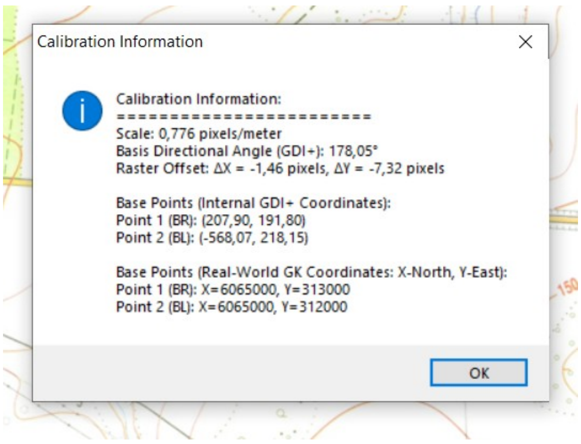

Fig. 5. "Debug Transform" window with detailed calibration information

Coordinate transformation algorithm flowchart shown in the figure 6.

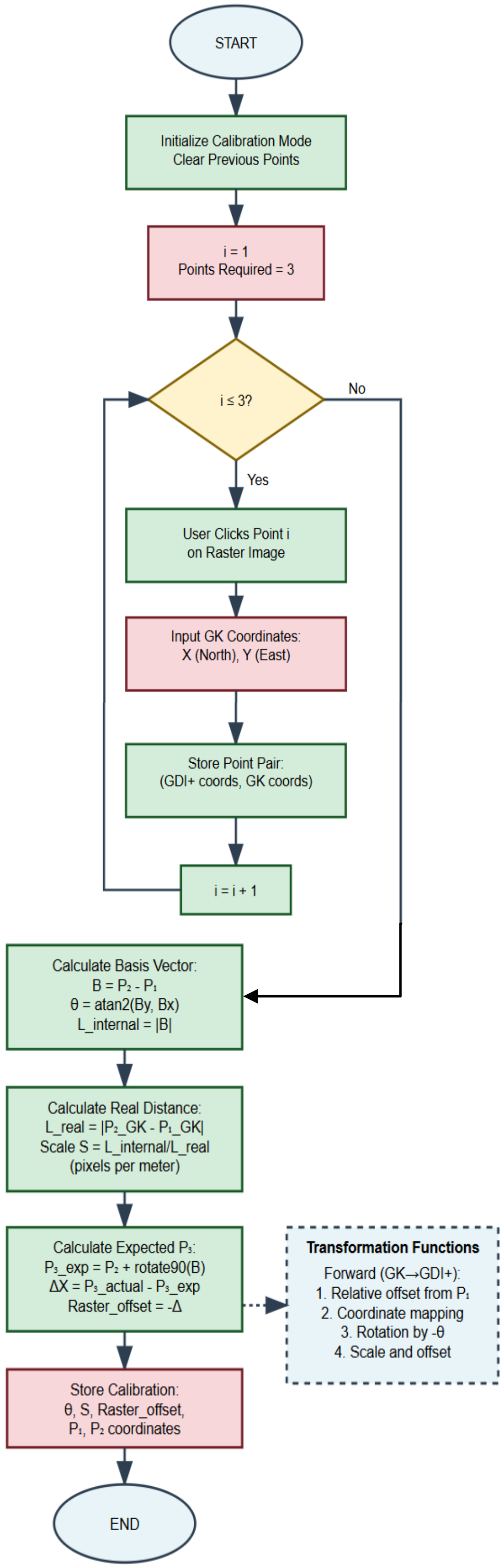

Fig. 6. Coordinate transformation algorithm flowchart

Analysis of coordinate transformation in the "Flexible bracelet method" application: similarity transformation

The coordinate transformation mechanism implemented in the "Flexible bracelet method" application, specifically within the *CoordinateTransformer* class, belongs to the category of a Similarity Transformation (also known as Equiform Transformation). This type of geometric transformation preserves the shape of objects (angles between lines and ratios of lengths) but allows for changes in their size, orientation, and position.

Mathematically, a similarity transformation can be expressed as a composition of three fundamental operations:

– uniform scaling: changes the size of an object without distorting its proportions;

– rotation: changes the orientation of an object around a given point;

– translation: moves an object to a new position without altering its size or orientation.

In the context of the provided *CoordinateTransformer* code, these components are manifested as follows:

– scaling (uniform): the key scaling factor is the *pixelsPerMeter* variable; it is calculated in the *Calibrate* method as the ratio of the measured length of the basis line (between *basisPoint1Internal* and *basisPoint2Internal*) in GDI+ pixels to the actual real-world length of the same basis line, derived from the user-provided Gauss-Kruger coordinates (*basisPoint1Real* and *basisPoint2Real*); this ensures that all dimensions in the GDI+ drawing space are proportionally scaled to their real-world metric counterparts, preserving their intrinsic shape and ratios;

– rotation: the difference in orientation between the real-world coordinate system (Gauss-Kruger: X-North, Y-East) and the internal GDI+ system (X-right, Y-down) is accounted for by *basisAngleRad*; this angle is calculated from the vector from *basisPoint1Internal* to *basisPoint2Internal*; within the *RealToInternal* and *InternalToReal* methods, operations involve: swapping of axes (GK X ↔ GDI+ Y), inverting one of the axes (GK Y-up → GDI+ Y-down), application of the calculated *basisAngleRad* for rotation; collectively, these steps effectively perform the rotation (and, in a sense, a reflection due to axis inversion) necessary to fully align the orientation of the coordinate systems;

– translation: several translation components are involved in the transformation process: initial points (*realPoint* or *internalPoint*) are first translated relative to *basisPoint1Real* or *basisPoint1Internal*, respectively; this is a standard part of transformation, where operations are applied relative to an origin; an additional and significant translation is applied via *rasterOffset*, this value is calculated from *DeltaX* and *DeltaY*, which represent the discrepancies between the expected and actual GDI+ position of the third calibration point (*point3Internal*); the *rasterOffset* mechanism effectively shifts the entire raster background to optimally align with all three provided control points, thereby improving the visual fit of the similarity transformation to the input data.

It is crucial to distinguish a similarity transformation from a more general Affine Transformation. An affine transformation, in addition to scaling, rotation, and translation, can also include shearing, which distorts angles and changes length ratios. In this case, as *CoordinateTransformer* does not incorporate components that would cause shearing or non-uniform scaling along axes, angles are preserved, and line segments are scaled uniformly. These are defining properties of a similarity transformation.

Conclusions

The conducted research is a part of the overall work on the implementation of the "Flexible Bracelet Method" for road alignment design. This article focused on the problem of software implementation of raster substrate transformation, which represents a necessary stage in the transition from the internal coordinate system to the coordinate system of the raster image.

Several approaches to coordinate transformation were tested, including affine and projective transformations. However, in practice, the most feasible solution was the use of similarity transformation, which preserves the shape of objects while allowing changes in scale, position, and orientation.

A step-by-step calibration algorithm was developed and implemented, including reference point input, scale calculation, rotation angle determination, raster offset computation, and transformation accuracy verification. Special attention was given to integration with utility networks and the application of the developed algorithms in the context of BIM/GIS technologies.

Thus, the presented material complements the previous stages of implementing the Flexible Bracelet Method (modeling, segment input, physical model simulation, and the beginning of optimization) and provides a foundation for further research related to integrating road alignment with digital cartographic and engineering data.

References

1. QGIS. Georeferencer – QGIS Documentation. Official documentation. URL: https://docs.qgis.org/latest/en/docs/user_manual/ managing_data_source/georeferencer.html (Last accessed: 31.08.2025).
2. Esri. Georeferencing tools – ArcGIS Pro Documentation. Official documentation. URL: https://pro.arcgis.com/en/pro-app/latest/help/data/imagery/georeferencing-tools.htm (Last accessed: 31.08.2025).
3. GDAL. Geotransform Tutorial. Official documentation. URL: https://gdal.org/en/stable/ tutorials/ geotransforms_tut.html (Last accessed: 31.08.2025).
4. MathWorks. Geometric Transformation and Image Registration. Official documentation. URL: https://www.mathworks.com/help/images/image-registration-and-geometric-transformation.html (Last accessed: 31.08.2025).
5. Azari, P. Georeferencing Building Information Models for BIM/GIS Integration: A Review of Methods and Tools. *ISPRS International Journal of Geo-Information*. 2025. №14. 180. (Review paper on georeferencing in BIM/GIS).
6. Zhu, J., Wu, P. A Common Approach to Geo-Referencing Building Models in Industry Foundation Classes for BIM/GIS Integration. *ISPRS International Journal of Geo-Information*. 2021. №10. 362.
7. Diakité, A. A. Automatic Framework for Transforming Local Coordinates of a BIM Model into Geographic Coordinates. 2020. (Paper on automatic geo-referencing of BIM).
8. Sharafat, A., Khan, M. S., Latif, K., Tanoli, W. A., Park, W., Seo, J. BIM-GIS-Based Integrated Framework for Underground Utility Management System for Earthwork Operations. *Applied Sciences*. 2021. № 11(12). 5721.
9. Slongo, C. et al. The IFC File Format as a Means of Integrating BIM and GIS for Facility Management of Underground Networks (GEO-BIMM4FM). *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*. 2022. V-4. P. 301–307.
10. Esekhaigbe, E., Kazan, E., Usmen, M. Integration of Digital Technologies into Underground Utility Asset Management. *Open Journal of Civil Engineering*. 2020. № 10. P. 403–428.
11. Kim, Y. S. Automatic Algorithm for Coordinate Transformation to Align LCS-based BIM to RCS-based GIS Maps. Sensors and Materials, 2025, Vol. 37, No. 6.
12. Musiienko I. V. The Implementation of Highways Tracing Physical Model – "flexible Bracelet". Procedia Engineering. Volume 134, 2016, Pages 365-370. 9th International Scientific Conference, Transbaltica 2015; Vilnius Gediminas Technical

UniversityVilnius; Lithuania; 7–8 May 2016. P. 366–371.

13. Musiienko I. V. The fundamental principles of implementing software for highway tracing using the flexible bracelet method. *Bulletin of KhNAHU.* 2025. № 108. P. 257–262.

Musiienko Igor, Ph.D., Associate Professor of the Department of Road Design, Geodesy and Land Management,
saprad14@gmail.com,
tel. +38 050-753-08-85
Kharkiv National Automobile and Highway University, 61002, Yaroslav Mudryi St., 25, Kharkiv, Ukraine

Досвід програмної реалізації трансформації растрових підкладок у ГІС інженерних мереж

Анотація. Проблема. *У сучасному дорожньому проєктуванні дедалі більшого значення набуває впровадження цифрових методів, які поєднують автоматизацію інженерних розрахунків із використанням картографічних та геоінформаційних даних. Одним із перспективних підходів є метод «гнучкого браслета», що дає змогу моделювати трасу автомобільної дороги з огляду на геометричні та ситуаційні обмеження. Важливим етапом його реалізації є перехід від внутрішньої системи координат програмного середовища до системи координат растрової підоснови.* ***Мета.*** *Метою дослідження є розроблення та апробація алгоритму трансформації растрових підоснов для забезпечення коректної геоприв'язки в програмному комплексі «Гнучкий браслет».* ***Методика.*** *У роботі розглянуто та протестовано кілька підходів: афінне, проєктивне та подібне перетворення. Для реалізації було розроблено покроковий алгоритм: введення опорних точок, калібрування, визначення масштабу та кута повороту, обчислення зсуву растра, пряме й обернене перетворення координат, перевірка точності.* ***Результати.*** *Порівняльний аналіз показав, що подібне перетворення є найефективнішим, оскільки забезпечує збереження форми об'єктів у процесі масштабування, повороту й перенесення. Реалізований алгоритм успішно протестовано на інженерних растрових підосновах, що підтвердило його придатність для інтеграції з BIM/GIS-технологіями.* ***Наукова новизна.*** *Удосконалено методику цифрової реалізації методу «гнучкого браслета» за допомогою розроблення універсального алгоритму трансформації координат, який зважає на особливості дорожнього проєктування та потреби інтеграції з просторовими показниками.* ***Практична значущість.*** *Запропоноване рішення розширює функціональні можливості програмного комплексу «Гнучкий браслет», створює основу для подальшої оптимізації процесів трасування автомобільних доріг та може бути використане під час поєднання з цифровими картографічними та інженерними базами даних.*

Ключові слова: *трасування автомобільних доріг, гнучкий браслет, трансформація координат, перетворення подібності, геоприв'язка, BIM/GIS.*

Мусієнко Ігор Володимирович, канд. техн. наук, доц. кафедри проєктування доріг, геодезії та землеустрою,
saprad14@gmail.com,
тел. +38 050-753-08-85
Харківський національний автомобільно-дорожній університет, 61002, Україна, м. Харків, вул. Ярослава Мудрого, 25