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THE INTELLECTUALISATION OF ELECTRONIC SURVEYING INSTRUMENTS IN SPATIAL MANAGEMENT SYSTEMS AS A FOUNDATION FOR INTEGRATING ARTIFICIAL INTELLIGENCE INTO THE GEOINFORMATION ENVIRONMENT

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Abstract. *The article is devoted to the formation of applied foundations for the intellectualization of electronic geodetic instruments through their integration with artificial intelligence (AI) technologies. The study focuses on the transition from traditional measuring devices to adaptive geodetic systems. Such complexes maintain* *metrological stability in a changing environment. The methodology is based on a technical-analytical approach and structural modeling of intelligent devices. A comparative assessment of functional operating modes was carried out. An analysis of time series of geodetic observations was performed. Practices of artificial intelligence application in geoinformation systems were generalized. The information base consisted of the technical parameters of total stations and GNSS receivers. The characteristics of laser scanners and sensor monitoring platforms were used. Data from digital urban infrastructure management systems were applied.*

The results confirm the effectiveness of computer vision algorithms. It was established that intelligent geodetic complexes form a new approach to the organization of spatial control of infrastructure and territories. The systems operate not only in the mode of coordinate fixation, but also in the format of continuous analysis of object conditions. Integrated machine learning algorithms assess displacement dynamics, signal stability, vibration load levels, and the nature of changes in spatial parameters in real time. Particular attention is paid to the integration of total station surveying, GNSS, LiDAR, photogrammetry, and unmanned platforms within a unified digital environment. The effectiveness of intelligent geodetic sensors in monitoring systems for bridges, dams, tunnels, transport hubs, and high-rise structures was separately confirmed. The practical value lies in the development of a concept for a new generation of geodetic complexes. New instruments combine precise measurements with predictive analytics. Software automatically supports management decision-making. The scientific novelty is determined by a comprehensive approach to the integration of artificial intelligence. Instrumental tools are combined with analytical models. Infrastructural aspects of technology implementation in geodetic practice are taken into account.

Keywords: *artificial intelligence, geodetic instruments, spatial management, laser scanning, infrastructure monitoring, digital twins.*

Introduction

Spatial data used in municipal and infrastructure planning processes are transforming the requirements for geodetic equipment. A measuring device is no longer perceived as a separate technical means of fixing coordinates. It is expected to work stably in a dynamic environment, quickly analyse results, automatically control accuracy and be able to interact with digital management platforms. These requirements are particularly evident in domains where decision-making depends on response time, such as construction, transport, monitoring of structures and urban infrastructure. Conventional processing algorithms no longer consistently cope with large volumes of measurements and complex field conditions.

Existing electronic total stations, GNSS receivers, laser scanners and related complexes are mostly focused on performing measurements according to predefined operating modes. However, the challenge lies elsewhere: the field environment changes faster than the user has time to adjust the settings manually. As a result, guidance errors, signal interference, loss of time for repeated cycles, as well as delays during desk verification occur. These factors indicate the necessity of integrating AI solutions into intelligent geodetic instruments.

Analysis of recent research and publications

In the study by M. A. Kukhar [2], it is demonstrated that the digital combination of several measurement sources increases the efficiency of updating territorial information. However, the aspects of adapting such solutions directly to field devices were ignored. Ye. V. Dorozhko and I. O. Udovenko [1] traced the evolution of electronic geodetic systems from standard automation to intelligent control of observation processes. They emphasised the growing role of algorithmic quality control. Nevertheless, the issue of technical implementation of autonomous functions in serial equipment remains incompletely resolved. S. H. Nesterenko and co-authors [3] systematised modern approaches to geodetic monitoring of structures and territories. While the importance of regular observations for the safety of objects is indisputable, predictive risk based on time-series data remains controversial. A. Hamzić [5] provided a general review demonstrating that automated recognition and classification of data using AI significantly expand the capabilities of geodesy and geoinformatics. However, insufficient attention has been paid to the integration of such models directly into geodetic operations. R. Pierdicca and M. Paolanti [13] analysed GeoAI approaches to the interpretation of complex geomatic data. Neural networks demonstrate high performance in working with heterogeneous observation arrays. Nevertheless, the issues of energy and computational optimisation of such models remain unsolved.

G. Mai, Y. Xie, X. Jia et al. [8] proposed a vision of the next generation of geospatial artificial intelligence with the transition to self-learning analytical platforms. However, the practical compatibility of these solutions with existing geodetic equipment requires additional development. B. Soja, M. Kaselimi, M. Asgarimehr and their colleagues [15] defined the role of AI in modern geodesy at the level of international initiatives, emphasising the prospects of global data processing services. Nevertheless, the issues of local use of such technologies in infrastructure monitoring remain insufficiently detailed.

G. Zhang, H. Cheng and H. Yang [16] presented the results of the application of robotic technologies for large-scale geodetic data collection. Although autonomous platforms show high efficiency, the complex interaction of robotics and intelligent geodetic instruments remains complete. Overall, these findings indicate the relevance of further research into the integration of AI into electronic geodetic instruments with spatial management.

Purpose

The purpose of the article is to substantiate the applied principles of combining AI technologies with the operation of electronic geodetic instruments to increase the accuracy of spatial measurements and automate the processing of geodetic data.

Materials and research methods

The study is based on the technical characteristics of modern electronic total stations, GNSS receivers, laser scanners and mobile geodetic platforms. In addition, analytical data on the functioning of digital spatial management systems were incorporated. The research utilised datasets including coordinate observations, time series of deformation measurements, positioning accuracy parameters, signal stability indicators, as well as the results of sensor monitoring of infrastructure objects. The methodological basis of the study was formed by several approaches. First, a comparative analysis of technical solutions was conducted, alongside structural modelling of intelligent device functions and scenario-based evaluation of operating modes. Secondly, a systemic approach was applied to integrate geodetic data into digital management environments. Finally, an analytical generalisation of AI use practices was undertaken, including automatic object recognition, equipment self-diagnosis, and prediction of spatial changes.

Results

Geodetic operations have always depended on unstable support factors. The first production stage of modernisation is associated with computer vision systems. An intelligent total station no longer searches for a target only by a contrast spot or a reflected beam. It analyses the geometry of the scene, the contour of the prism, the nature of the landmark movement, angular changes in position, even the probability of temporary overlap of the target by transport or personnel. This provides stable auto-tracking where classical modes lost guidance. The second stage of modernisation relates to self-calibration and error prediction. The classical device operates based on fixed factory parameters, which change over time due to wear, temperature deformations, and impacts during transportation. The intelligent system forms its own behavioural model and tracks small deviations before they become a metrological problem [10, p. 168]. To evaluate dynamic parameter drift, the following function is introduced:

$$D_k = \sqrt{\frac{1}{m}\sum_{j=1}^{m}(p_{j,k} - \hat{p}_j)^2} + \eta\left|\frac{dp}{dt}\right| + \rho T_v. \quad (1)$$

where:

D_k – technical drift index at time k;

$p_{j,k}$ – current parameter of the *j-th* node;

$\hat{p}_j$ – reference value;

m – number of controlled parameters;

$|\frac{dp}{dt}|$ – parameter change rate;

T_v – vibration load;

η, ρ – sensitivity coefficients.

When the index exceeds the stability threshold, the device initiates a service scenario. After that, a repeated verification cycle blocks the high-precision mode. This is not merely a user interface enhancement, but a contextual interaction system. It recognises whether the operator is performing axis removal, deformation observation or executive shooting, after which it rebuilds the action scenario, control messages and data entry structure. This significantly reduces the likelihood of human error [9, p. 200]. To assess the applied effectiveness of the modernisation, it is advisable to compare the change in technical performance of work after AI integration (Table 1).

Table 1. Change in operational parameters of geodetic works after the introduction of intelligent modules [3, 16]

No	Type of geodetic work	Critical parameter for modernization	Intelligent correction mechanism	Parameter status after modernization	Production side effect
1	Deploying construction axes	Unstable axis guidance	Prism auto tracking	High positioning repeatability	Less re-inspections
2	GNSS surveying in the city	Multi-beam signal	ML multipath filtering	Reduction of coordinate noise	Shorter downtime
3	Executive surveying of facades	Loss of small details	Intelligent focus and segmentation	Clear object contours	Less manual editing
4	Monitoring of structures	Slow detection of displacement trends	Online time series analysis	Early detection of deformations	Preventive actions
5	Geodetic networks	Hidden calibration drift	Node self-diagnosis	Accuracy stability	Longer service cycle

No	Type of geodetic work	Critical parameter for modernization	Intelligent correction mechanism	Parameter status after modernization	Production side effect
6	Quarry work	Dusty environment and vibrations	Measurement mode adaptation	Stable measurement process	Less downtime
7	Cadastral work	Operator omissions of details	Contextual hints	Completeness of logs and attributes	Faster processing

The first application domain relates to the intelligent classification of LiDAR and laser scanning point clouds. After a field pass, the system receives millions of spatial points with different densities, reflectivity, and noise impurities. The neural network module not only groups point into classes, but also evaluates the shape of the object, vertical profile, regularity of contours, and material structure of the surface [6, p. 32]. This enables the differentiation of buildings from vegetation, small structural elements from noise artefacts, and road surfaces from open terrain (Figure 1).

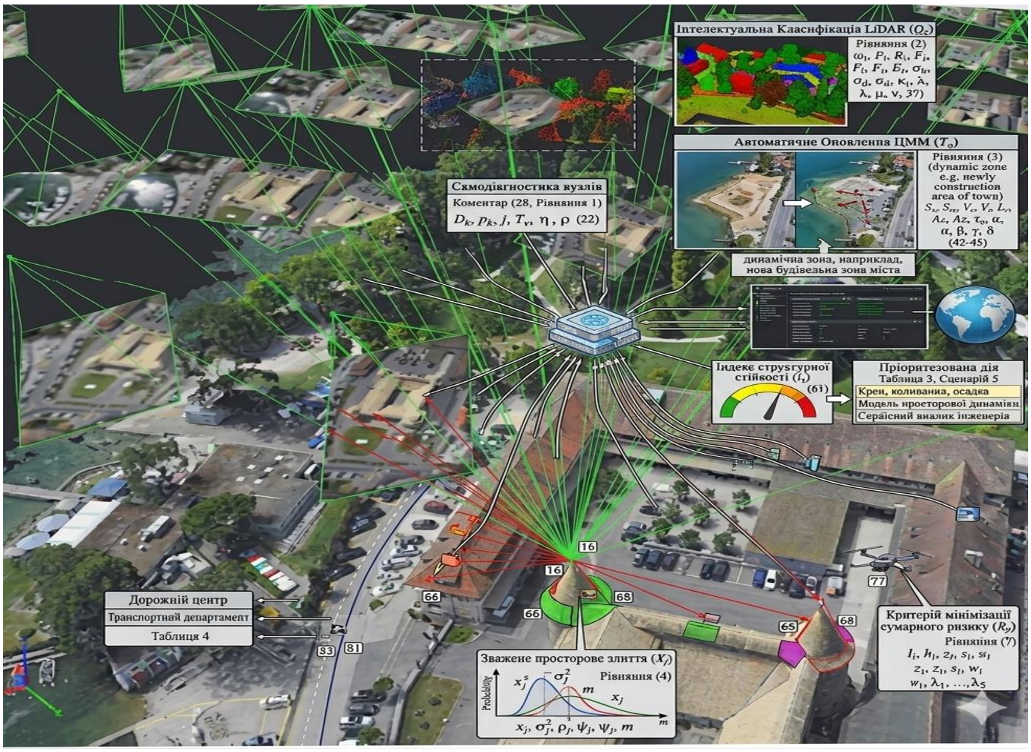

Figure 1. Integrated model of multi-position aerial photography of the territory with UAV, predictive deformation analysis and intelligent LiDAR classification (built by the authors in the SolidWorks environment)

To assess the quality of automatic classification, an integral model of the form is proposed:

$$Q_c = \frac{\sum_{i=1}^{n} \omega_i \left(\frac{P_i R_i F_i}{1 + E_i} \right)}{1 + \lambda \sigma_h + \mu \sigma_d + \nu \kappa_t}. \tag{2}$$

where:

Q_c – overall classification quality;

ω_i – object class weight;

P_i – class assignment accuracy;

R_i – detection completeness;

F_i – geometric shape consistency;

E_i – false positive rate;

σ_h – height variance;

σ_d – point density variance;

κ_t – data temporal noise;

λ, μ, ν – stabilisation coefficients.

If the indicator decreases, the system transfers the fragment to the manual examination mode or re-training of the model. The second direction concerns the automatic updating of topographic plans and digital terrain models. In this case, AI analyses not only new measurements, but also the difference between several temporal states of the territory. If a new building contour appears, the slope of the site changes, a network node is dismantled, or a soil excavation occurs, the system records the event and forms a package of changes [7]:

$$T_u = \frac{\alpha S_n + \beta S_m + \gamma V_e + \delta L_r}{A_z \cdot (1 + \tau_a)}. \tag{3}$$

where:

T_u – territory renewal index;

S_n – area of new objects;

S_m – area of modified contours;

V_e – volume of earthworks;

L_r – length of reconstructed linear elements;

A_z – area of control zone;

τ_a – coefficient of archival aging;

$\alpha, \beta, \gamma, \delta$ – weighting coefficients.

Higher values indicate a greater need for repeated scanning, enabling allocation of resources. For operational management, it is advisable to compare the update parameters by territory type (Table 2).

Table 2. Parameters for automatic updating of digital territory plans [4, 13]

No	Territory type	Primary data source	Dominant type of change	Office workload	Recheck Priority
1	Central urban area	UAV + GNSS	Reconstruction of buildings	High	High
2	Residential area	Orthophoto	Additional buildings and small structures	Medium	Medium
3	Industrial cluster	LiDAR	New sites and technical areas	High	High
4	Suburb	Satellite imagery	Expansion of use limits	Medium	Medium
5	Logistics hub	Mobile scanning	Transport changes	High	High
6	Recreational area	Satellite + UAV	Change in land cover	Low	Low

The third direction concerns the construction of a single coordinate base from total station, GNSS, photogrammetry and UAV. Each source has its own error structure. If the combination is performed roughly, the system only accumulates contradictions [11, p. 102]. For weighted spatial data fusion, the following indicator is introduced:

$$X_f = \frac{\sum_{j=1}^{m}\left(\frac{x_j}{\sigma_j^2}\cdot\rho_j\cdot\psi_j\right)}{\sum_{j=1}^{m}\left(\frac{1}{\sigma_j^2}\cdot\rho_j\cdot\psi_j\right)}. \tag{4}$$

where:

X_f – summary coordinate value;

x_j – coordinate from the *jth* source;

σ_j^2 – source variance;

ρ_j – reliability coefficient;

ψ_j – time relevance coefficient;

m – number of sources.

Traditional engineering control had a cyclical nature. The facility was inspected according to a schedule, local measurements were carried out, a report was prepared, and the object was revisited after a certain period [1, p. 122]. An intelligent geodetic system operates differently. An intelligent geodetic system works differently. GNSS modules, robotic total stations, inclinometers, laser scanners, accelerometers, temperature sensors, and technical vision cameras are installed on the structure. The data is fed into a single analytical loop, where AI algorithms detect deviations, analyse trends, and rank risks [12, p. 166]. This, in fact, changes the very principle of management, from reactive to preventive. For an integral assessment of technical stability, a multifactor index is introduced:

$$I_s = \frac{\sum_{i=1}^{n} \omega_i \left(\frac{L_i^{cr} - L_i}{\sigma_i + \varepsilon} \right) \cdot \rho_i}{1 + \alpha t_e + \beta v_d + \gamma c_f + \delta m_r}. \tag{5}$$

where:

I_s – structural stability index;

L_i^{cr} – maximum permissible value of the control parameter;

L_i – current value of the parameter;

σ_i – dispersion of observations;

ρ_i – sensor reliability coefficient;

t_e – service life of the structure;

v_d – dynamic load;

c_f – material fatigue coefficient;

m_r – repair delay;

$\omega_i, \alpha, \beta, \gamma, \delta$ – weighting coefficients.

If the index value drops to the threshold limit, the system automatically generates an alarm signal, a load limit mode or an emergency diagnostics plan. Such solutions are primarily implemented at facilities where the consequences of failure are large-scale. Such facilities are bridge crossings, transport overpasses, dams, tunnel complexes, reservoir structures, tall buildings and large retaining structures [14, p. 332]. They require continuous monitoring, not point-by-point monitoring (Figure 2).

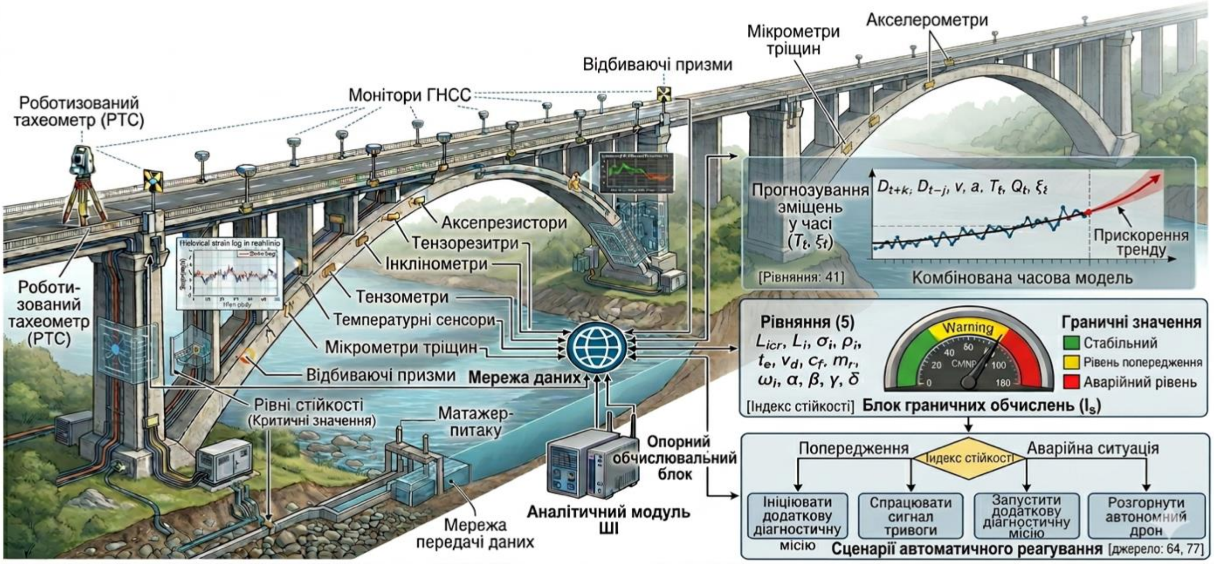

Figure 2. Intelligent system for monitoring and predicting bridge deformations based on TIM (Information Modelling Technology) and AI (built by the authors in the SolidWorks environment)

To form a technical structure for the application, it is advisable to compare proposals for different types of infrastructure objects (Table 3).

Table 3. Comprehensive proposals for the implementation of intelligent geodetic systems at infrastructure facilities (developed by the authors)

No	Object type	Sensor configuration	Controlled parameters	AI Analytical Module	Automatic system action	Expected operational result

1	Road bridge	GNSS, total station, accelerometer	Deflection, vibration, thermal joint	Deformation Trend Forecast	Lane restriction	Reduction of accident risk
2	Dam	GNSS, inclinometer, piezometer	Body displacement, filtration, tilt	Mass Stability Model	Dispatcher warning	Increase in hydraulic safety
3	Tunnel	Laser scanner, total station	Settlement, contour convergence	Geometric Profile Control	Unscheduled inspection plan	Operational stability
4	Overpass	GNSS, camera, crack sensors	Support displacement, slab defects	Defect Recognition	Temporary weight restriction	Reduction of overloads
5	High-rise building	GNSS, inclinometer, IMU	Tilt, oscillation, draft	Spatial Dynamics Model	Engineer service call	Building stability control
6	Underground collector	Linear sensors, scanner	Subsidence, section displacement	Anomaly Detector	Emergency crew dispatch	Reduction of breakthroughs
7	Quarry wall	UAV, GNSS, LiDAR	Crack opening, displacements	Geomechanical Forecast	Danger zone closure	Personnel protection

The second application circuit concerns the prediction of settlements, rolls and displacements from time series of observations. A simple comparison of two dates is no longer sufficient. If the rate of change increases, even a small absolute displacement can be critical. It is these facts that human (engineer) analysis often reveals quite late [5, p. 138]. To predict the behaviour of a structure, it is advisable to use a combined time model:

$$D_{t+k} = a_0 + \sum_{j=1}^{p} a_j D_{t-j} + b_1 \dot{D}_t + b_2 \ddot{D}_t + c_1 T_t + c_2 Q_t + \xi_t. \qquad (6)$$

where:

D_{t+k} – predicted displacement at time $t+k$;

D_{t-j} – previous observations;

$\dot{D}_t$ – rate of change;

$\ddot{D}_t$ – acceleration of the process;

T_t – temperature factor;

Q_t – transport or operational load;

ξ_t – random component;

a_j, b_1, b_2, c_1, c_2 – model parameters.

If the model detects an acceleration of the negative trend, the system transfers the object to the enhanced control mode. To select a safe trajectory of the robotic complex, a criterion for minimizing the total risk is formed:

$$R_p = \min \sum\nolimits_{i=1}^{m} (\lambda_1 l_i + \lambda_2 h_i + \lambda_3 z_i + \lambda_4 s_i + \lambda_5 w_i). \qquad (7)$$

where:

R_p – optimal risk route;

l_i – length of the path segment;

h_i – elevation difference;

z_i – obstacle level;

s_i – surface instability;

w_i – environmental impact;

$\lambda_1 ... \lambda_5$ – weighting factors.

City management also gains new opportunities. If sensors of bridges, roads, collectors and high-rise buildings are integrated into the Smart City platform, the data is transferred to the mode of operational dispatching use. Road flows can be redirected, repair services can be sent to specific addresses, and the load can be distributed according to the actual condition of the structures (Table 4).

Table 4. Proposals for integrating geodetic sensors into municipal operational management centres (developed by the authors)

No	City Management Circuit	Geodetic data source	Control indicator	Algorithmic response	Communication channel	Practical result
1	Road Centre	Bridge and overpass sensors	Deflection and overload	Traffic flow redistribution	Dispatch panel	Reduction of congestion and risks
2	Communal Unit	Linear collector sensors	Sheave and subsidence	Repair request generation	City ERP services	Rapid elimination of accidents
3	Construction Supervision	GNSS of high-rise structures	Roll and draft	Automatic facility audit	Inspector's office	Strengthening control
4	Civil Protection	Dams and fortifications	Slope and filtration	High-alert mode	Response centre	Increasing safety
5	Transport Department	Tunnels and stations	Structure deformations	Unscheduled inspection	Operational network	Continuity of transportation
6	Geotechnical Monitoring	Quarries, slopes, embankments	Slide risk	Closing of dangerous area	Notification system	Protection of workers
7	City Analytical Centre	All integrated sources	Composite risk index	Resource prioritization	City Data Hub	Rational management

The practical foundations for the implementation of artificial intelligence in the geoinformation environment should be formed through the integration of sensor-based geodetic systems, digital management platforms, and analytical modules for spatial data processing. First of all, it is necessary to integrate total stations, GNSS receivers, laser scanners, and unmanned platforms into a unified coordinate database with automatic synchronization of temporal and spatial parameters. This approach will ensure continuous updating of topographic models, cadastral layers, and digital twins of territories.

The second direction is related to the implementation of intelligent data quality control modules. Computer vision algorithms should automatically detect measurement anomalies, signal stability losses, displacement of control points, and deformation processes of infrastructure facilities. This reduces the amount of manual verification and increases the efficiency of spatial analysis. Such solutions demonstrate particularly high effectiveness in urban monitoring systems for bridges, tunnels, and transport hubs. The third practical foundation concerns the creation of municipal geoinformation centers equipped with predictive analytics functions. Intelligent geodetic systems should automatically generate risk signals, response scenarios, and priorities for repair operations. As a result, spatial data are transformed from archived information into an operational management resource. This increases the speed of response to deformation processes, optimizes the use of urban resources, and strengthens the safety of critical infrastructure.

Discussion.

The integration of electronic geodetic instruments with artificial intelligence algorithms is transforming the principles of the measurement process. Modern devices are no longer limited to fixing coordinates. They constantly analyse environmental parameters. Systems automatically check the stability of observations. Operating modes are adjusted without operator participation. These functions minimise the influence of the human factor. Consequently, the number of repeated measurements is significantly reduced, while the reliability of the obtained data increases under adverse field conditions.

The integration of total station with GNSS technologies forms a new model of spatial monitoring. Laser scanning and photogrammetry complement this architecture. Unmanned systems provide operational information collection. Separate spatial data sets are combined into a single geoinformation environment. Data from different sources are coordinated according to common coordinate parameters. Such an organisation accelerates the updating of topographic plans. Changes in development are recorded with high accuracy. The instruments ensure stable tracking of deformations in engineering structures. The speed of formation of digital twins of infrastructure is increasing. The obtained results support the validity of management decisions. The implementation of the considered technologies enhances the efficiency of geodetic control.

The intellectualization of electronic geodetic instruments in spatial management systems has the greatest applied effect in the field of critical infrastructure security and urban operational management. This concerns continuous monitoring of bridges, dams, tunnels, high-rise buildings and transport hubs. Such monitoring makes it possible to detect hazardous trends even before visible defects appear. As a result, the risk of accidents is reduced, the distribution of repair resources is improved, and technical control shirts from reactive to predictive management.

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ІНТЕЛЕКТУАЛІЗАЦІЯ ЕЛЕКТРОННИХ ГЕОДЕЗИЧНИХ ПРИЛАДІВ У СИСТЕМАХ ПРОСТОРОВОГО УПРАВЛІННЯ ЯК ОСНОВА ВПРОВАДЖЕННЯ ШТУЧНОГО ІНТЕЛЕКТУ В ГЕОІНФОРМАЦІЙНЕ СЕРЕДОВИЩЕ

Стаття присвячена формуванню прикладних засад інтелектуалізації електронних геодезичних приладів через їхню інтеграцію з технологіями штучного інтелекту (ШІ). Дослідження присвячено переходу від традиційних вимірювальних приладів до адаптивних геодезичних систем. Такі комплекси зберігають метрологічну стабільність у мінливому середовищі. Методологія базується на техніко-аналітичному підході та структурному моделюванні інтелектуальних пристроїв. Проведено порівняльну оцінку функціональних режимів роботи. Виконано аналіз часових рядів геодезичних спостережень. Узагальнено практики застосування штучного інтелекту в геоінформаційних системах. Інформаційну основу склали технічні параметри тахеометрів і GNSS-приймачів. Використано характеристики лазерних сканерів та сенсорних платформ моніторингу. Застосовано дані цифрових систем управління міською інфраструктурою. Результати підтверджують ефективність алгоритмів комп'ютерного зору. Програмні модулі автоматично розпізнають віхи та призми у польових умовах. Системи ідентифікують контрольні марки та просторові орієнтири без ручного налаштування. Цей підхід скорочує час на наведення приладів. Кількість повторних спостережень значно зменшується. Вбудовані діагностичні інструменти фіксують температурний дрейф на ранніх етапах. Алгоритми виявляють вібраційні впливи та нестабільність живлення. Система контролює відхилення калібрування в реальному часі. Це запобігає переходу похибок у критичний стан. Інтеграція тахеометрії з GNSS та LiDAR покращує точність даних. Використання фотограмметрії та безпілотних платформ прискорює оновлення топографічних планів. Цифрові моделі *місцевості та кадастрові бази формуються оперативніше. Геодезичні сенсе’ори ефективно працюють у мережах безперервного контролю. Їх застосовують для моніторингу мостів і дамб. Системи відстежують стан тунелів та висотних споруд. Практична цінність полягає у розробці концепції геодезичних комплексів нового покоління. Нові прилади поєднують точні вимірювання з прогнозною аналітикою. Програмне забезпечення автоматично підтримує прийняття управлінських рішень. Наукова новизна визначається комплексним підходом до інтеграції штучного інтелекту. Поєднано інструментальні засоби з аналітичними моделями. Враховано інфраструктурні аспекти впровадження технологій у геодезичну практику.*

Ключові слова: *штучний інтелект, геодезичні прилади, просторове управління, лазерне сканування, моніторинг інфраструктури, цифрові двійники.*