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STATE-OF-THE-ART AND DEVELOPMENT TRENDS OF GEOGRAPHIC INFORMATION SYSTEMS

A. I. Alchinov*, I. N. Gorokhovsky**, and E. V. Akif'eva***

*,***Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia
**Research Center of Topographic and Navigational Support, Central Research Institute No. 27, Moscow, Russia

*✉ alchinov46@mail.ru, **✉ gin_box@mail.ru, ***✉ lenatalka1@mail.ru

Abstract. When managing complex organizational and technical systems, decision support remains relevant due to the growing role and capabilities of geographic information systems (GISs). This survey is devoted to GISs. We analyze the level of their representation in the world and Russian environment, the peculiarities of their development, and the main related results obtained at the Trapeznikov Institute of Control Sciences, the Russian Academy of Sciences. We highlight the technologies and functionality of GISs that are in high demand in the field of management. A GIS is interpreted as a mechanism to process and support managerial decisions. The main foreign and Russian GISs are reviewed, including their main characteristics, applications, and development trends as well. We describe geoinformation technologies and algorithms implemented in full-fledged GISs and also those providing platforms for creating various-purpose GISs.

Keywords: geographic information system, remote sensing of the Earth, data storage, cloud service, knowledge base, modeling, visualization, aerial photography, Internet of Things, cartographic research method, artificial intelligence, machine learning.

INTRODUCTION

Modern geographic information systems (GISs) contain information about objects of interest in the form of spatial data, which are processed by GIS tools to obtain the data necessary for making effective managerial decisions. R&D works on converting traditional paper maps into digital form were pioneered in Canada, later followed by the USA, USSR, and other countries. Digital information processing methods for the cartographic and mathematical modeling of processes and phenomena, as well as their representation on thematic maps, were developed in parallel.

Geographic information systems provide knowledge about natural phenomena and socio-economic processes through databases and geographical knowledge in the form of computer models. GISs collect, store, transform, and display information, as well as provide necessary support to analyze geographic information and make managerial decisions for the objects and processes under study.

This paper reviews the state-of-the-art and global development trends of GISs and the peculiarities of the related research in Russia, indicating the most important results obtained at the Trapeznikov Institute of Control Sciences, the Russian Academy of Sciences (ICS RAS, also referred to as the Institute), during the emergence and evolution of geoinformation technologies. GIS technologies led to a new branch of digital cartography, i.e., the creation of maps in real time and their use for making managerial decisions in different spheres of human activity.

In modern conditions, GIS technologies are evolving rapidly. GIS capabilities are associated with the use of various animation modules that produce unexpected effects during display. Nowadays, shifting a map image across the screen, changing maps in the form of frames, and managing separate map elements are new forms of handling cartographic information, including the visual effects of abstract representation of GIS content in 3D scenes.

This survey is intended to reveal the development trends of GISs and promising directions for their improvement. For this purpose, we analyze foreign GISs, indicate the peculiarities of Russian GISs, and determine the trends of their further development.

In addition, the existing technological design schemes of GISs are described, including their practical implementation. Note that this survey covers only the full-fledged GISs used in Russia.

The initial hypothesis of this paper is that the recent advances in parallel computing, cloud technologies, and big data processing methods are closely related to the development of new-generation GISs. Therefore, these R&D directions should be considered together.

The scientific contribution of this paper lies in determining the development trends of general-purpose GISs and expanding the range of tasks by using new opportunities provided by contemporary information technologies.

1. GEOINFORMATION SYSTEMS: THE STAGES OF DEVELOPMENT, BASIC CONCEPTS, AND FUNCTIONS

To date, several stages can be distinguished in the development of GIS technologies.

During the initial stage, the new capabilities of cartography with electronic computing means were investigated. In the field of cartography, an important role was played by studies on establishing spatial relations between objects with the representation of their quantitative characteristics and attributive data. The main results of GIS works were published in [1–3]. Charles Dana Tomlin, the author of [1], is the pioneer of map algebra, dictionaries, and the concept of combining cartographic data to form new maps during their geospatial analysis.

The first system of this class is the Canada Geographic Information System (CGIS). It marked the beginning of geoinformatics. This GIS successfully implemented the conceptual and technological developments of Roger F. Tomlinson, an English-Canadian scientist known for his work in the field of electronic computational methods and methods for the storage, compilation, and evaluation of mapped data.

The core functionality of one of the first GISs was intended for *Canada Land Inventory* (the production of land statistics and land management based on these data).

This GIS provided several fundamentally new operations as follows:

- Geodata were entered by scanning.
- Cartographic information had layer representation. This solution to divide cartographic information into layers laid the foundation for the separation of geospatial information about the location of objects and descriptive information about these objects [2, 3].
- Several algorithms (Sutherland–Hodgman, Weiler–Atherton, Holwerda, triangulation, linear-node, and some other algorithms for the intersection, union, and difference of polygons) were used to develop the first programs for the construction of overlays with cartometric operations, i.e., the calculation of areas and other characteristics of polygons [1]. All these programs are, to some extent, implemented by primitives in GISs, which create a new map layer by two or more images of equal size [2, 3].

Depending on the spatial neighborhood of information analysis in GISs, there are four classes of operations: local, focal, global, and zonal. Local operations are executed for individual pixels of a raster map whereas focal operations for adjacent pixels. Global operations are executed for the entire layer. Finally, zonal operations are executed for cell domains that have the same values. The operators for map elements can be combined to execute a separate procedure. It is possible to combine them into a script when solving more complex tasks. The operators listed above and the GRID module (ArcInfo GIS) form important components of spatial analysis in GISs.

Map algebra allows implementing Spatial Analyst tools, operators and functions for the geographic analysis of raster data in simple and complex map algebra expressions. It is currently integrated into Python with the ability to use the entire Python’s functionality (including the ArcPy module) as well as numerous extensions (modules, classes, functions, and their properties). For example, an object with name *outRas* is created using a tool or operator specified to the right of the equality sign [4, 5]:

```
from arcpy.sa import *
outRas = Slope("indem").
```

This expression calculates the slope for each cell in the *indem* dataset and creates the *Raster* object to save the results.

The initial stage was also remarkable for the appearance of new electronic computers, digital plotters, graphic displays, and other peripheral devices of higher performance. In addition, formal spatial analysis methods and database management software were simultaneously developed. Since GISs were used in different industries, their fundamental capabilities were examined in the adjacent areas of knowledge and technology, which led to the development of automated navigation systems, vehicle traffic control systems, etc.

A large set of various software tools was formed as desktop GISs. GIS applications expanded through integration with various databases, including non-spatial databases. Network applications supporting individual datasets on separate computers also appeared. All these achievements underlaid the creation of distributed geographic data [6, 7].

The next stage is characterized by the design and development of large-scale geoinformation projects for solving governmental tasks. For example, in the USA, a GIS with Dual Independent Map Encoding (DIME), a special cartographic data format, was created for population census. This format included the rectangular coordinates of intersections with streets divided into separate domains of map fields. Citizen addresses were converted to coordinates represented by a graphical street segment (the POLYVRT program). Government funding for the development and use of DIME files increased the number of research works in the field of GIS applications. The issues of map-supported navigation in urban transport management were investigated. With the GIS used for the population census in the USA, the atlases of major US cities and simplified electronic maps were created for retailers and transportation companies.

Dating back to the early 1980s, the third development stage is characterized by the active use of GISs and their applications. With the advances in computing means, software products and their applications became available to many users [6].

During this stage, various software tools were created and desktop GISs were further developed. The scope of GISs was extended due to integration with non-spatial databases and the emergence of network applications supporting individual datasets on individual computers. The concept of distributed databases of geospatial, graphical, and attributive data was introduced as well.

The availability and openness of software tools made it possible to use and modify the existing GISs. The need for different geographic data increased significantly. It was the beginning of a global geographic information infrastructure, which continues to develop, especially now in China.

Presently, the geoinformation industry implements GIS technologies for the analysis of geographic information to support managerial decisions. Numerous modern (foreign and Russian) GISs differ in some features, such as territorial coverage, the level of management, subject area, and functionality.

The last feature—functionality—is the main one. For instance, full-fledged GISs provide operations on the visualization of selected objects and input and editing of raster data. They simultaneously support topological relations between objects and the construction of buffer zones, as well as work with different types of terrain objects, providing two-way communication with the database and objects on the map. Full-fledged GISs also solve various tasks using different map projections, including the creation of new symbols and printing of the results.

Events, processes, and phenomena investigated by GISs can be scale-independent, spatiotemporal, and integrated.

Consider full-fledged GISs, which comprehensively implement geoinformation technologies [8–10].

Currently, over twenty foreign and domestic full-fledged GISs are used in Russia. They possess common properties as follows:

– implementation on a platform with a single operating system;

– support of exchange formats for interaction with other information systems;

– support of raster images of most known formats: TIFF, JPEG, GIF, BMP, WMF, and PCX;

– processing of attributive information of all major databases using the ODBC and BDE drivers.

To compare GISs, it is necessary to analyze the technologies of data storage and handling implemented by different design schemes. The implementation features of foreign and Russian GIS platforms were considered in [11–13].

The first design scheme is represented by one or more programs combined into a software system. An internal data format is used to store the results. At the initial stage, each GIS developer implemented individual data storage formats; as a rule, they were closed.

The second design scheme is based on the client-server technology. It has a program for the end user and a server program that maintains a spatial database. These technologies have already started to use programs for data conversion. For example, we mention converters from Panorama GIS to NEVA GIS, from Mapinfo GIS to Panorama GIS, etc.

The third design scheme is a client-server system that uses database management systems with SQL servers (Microsoft SQL Server, Oracle, MySQL, PostgreSQL, etc.) to store spatial data. This stage is characterized by the most complete and good relations with foreign software developers.

The fourth design scheme involves SQL server extensions or Oracle Locator as a spatial data warehouse.

The fifth design scheme is cloud GISs, which provide data access from any computer connected to the Internet and organize joint work with spatial data. The SaaS (software as a service) principle is employed, so it can be used on any device connected to the Internet. The infrastructure allows expanding the circle of users simultaneously working with the created map. If necessary, data from different formats are converted to a supported format [14, 15]. The fifth (modern) stage of GIS technologies is characterized by insufficient relations with foreign software developers.

At the same time, the emergence of new spatial data handling schemes does not mean their appropriateness for solving any tasks. Many applied tasks for GISs can be effectively solved using any design scheme. The choice of a suitable scheme is determined by the particular task to be solved. When working with heterogeneous and distributed spatial data, the fourth and fifth design schemes of GISs are preferable.

Nowadays, GISs provide work with databases that are constantly supplemented and updated. Any map can be represented in the 3D form with the view possibility. Available databases allow determining the location of objects, building routes for vehicles, analyzing land plots, and obtaining their quantitative and spatial characteristics. All data are constantly updated using raster and vector sources. The information is formed layer-by-layer with the geographical reference of each object [2]. All these possibilities have become a reality with the joint use of cartographic tools and recent information technologies. Different design schemes of GISs involve basic software tools for data linking and editing and displaying spatial and attributive information. To solve special tasks, GIS technologies use applications for mapping, analysis of linear, areal, and high-altitude terrain objects, text and statistical information, data conversion, including raster-to-vector conversion, as well as some auxiliary programs for data pre-processing.

2. STATE-OF-THE-ART AND DEVELOPMENT TRENDS OF FOREIGN GEOINFORMATION TECHNOLOGIES. SPATIAL DATA EXCHANGE STANDARDS

In Russia, GISs on the ArcGIS platform (ESRI) and a family of products on the GeoMedia platform (Intergraph) and the MapInfo Professional platform (Pitney Bowes MapInfo) are most widespread [15]. Other software products on different platforms of domestic and foreign developers are also used.

Discussing software products on different platforms, we will proceed from the following considerations that describe GIS capabilities quite accurately:

- Map making is the main function of GISs.
- GIS technologies involve cartographic and mathematical modeling methods to analyze and display the results in a dynamic mode.
- Cartographic projections and coordinate systems used in cartography are the basis for localizing the coordinates and attributive information of objects in databases.
- Thematic maps are the primary source of geospatial information for GISs.
- The spatial data exchange standards implemented in GISs predetermine the capabilities of different geographic information systems.

Being entered, information is recorded in databases with attributes (semantics); the obtained data are displayed on the screen or printed, e.g., on a plotter. Devices for input, logical-mathematical processing, and output of cartographic information form a computer-aided cartographic system (CCS), the basis of any GIS for creating and analyzing thematic maps to support managerial decisions.

The complete automation of all map creation processes with meeting the necessary requirements has not been achieved so far: it is difficult to mathematically formalize the creative process of interpreting objects and phenomena for their mapping [16].

The evolution of CCSs and GISs was associated with 3D terrain modeling and multimedia technologies for the joint processing of maps and snapshots. The next stage in their development was due to new client-server and cloud technologies.

Among many formats used in different development stages of GISs, in modern conditions, it is reasonable to apply the international standards of the Open Geospatial Consortium (OGC). All OGC standards (currently, about 30) are open. They were designed within the HTTP web service paradigm for message-based communication. Subsequently, the paradigm was extended using a common approach to the SOAP protocol and bindings to WSDL (an XML-based descriptive language for web services). Significant progress was made in defining the web services of Representational State Transfer (REST API), which provides access for server software to client applications via specific URLs, e.g., OGC SensorThings API [13].

An explanation is needed here: web service is a way of communication between two electronic devices over a network, whereas an HTTP service provides an interface to the user via HTML, PHP, and JavaScript technologies. In addition, a web service with full accessibility of geodata is implemented in many general-purpose GISs.

Currently, the majority of foreign and key Russian developers support the main OGC standards for geospatial data exchange: OpenGIS Web Map Service (WMS) Implementation Specification, representing a standard for exchanging geo-referenced raster images built on data from one or more spatial databases via the HTTP protocol [7]. Nowadays, these standards are basic for creating a unified geospatial information exchange environment not only in Europe but also on a global scale. The full support of OGC standards was a key requirement for choosing GIS software before the sanctions restrictions.

Table 1 summarizes the main implementation platforms of full-fledged GISs. Platforms 1–5 predetermined the development of geoinformation technologies. Platform 6 is a cross-platform GIS solution that supports various operating systems (Linux, Mac OSX, Windows, and Android). QGIS allows creating multilayered maps using different projections as well as viewing, editing, and analyzing raster or vector data.

SuperMap GIS (China, platform 7 in the table) is one of the most advanced GISs. Besides the capabilities of a full-fledged GIS, it integrates artificial intelligence (AI) technologies. Chinese company Huawei standardized applications and optimized technological solutions to make significant progress in the development of the Internet of Things (IoT) to implement AI in GISs [12].

The following types of GISs are distinguished depending on the complexity of their tasks, their software and hardware, and their telecommunication capabilities:

- Network GISs operate on an enterprise scale and provide shared access to GIS data. Relational DBMSs Oracle, IBM DB2/Informix, and MS SQL Server are used as a database server. Geospatial data are placed in a relational database by a spatial data server, e.g., ESRI ArcSDE (SDE—Spatial Database Engine) and ArcGIS 9.2, which is integrated into ArcSDE [15].
- Personal GISs operate on a single computer without involving network technologies. They are represented by mass-service GISs and desktop GISs.
- Desktop GISs are an element of a corporate GIS for solving particular applied tasks.

3. DEVELOPMENT OF GEOGRAPHIC INFORMATION SYSTEMS IN RUSSIA: SOME PECULIARITIES

Currently, there is an increasing demand for spatial data services. The USA, some European countries, and recently China have taken the lead in the development of geoinformation technologies.

In this context, we note the following. Russian experts in GIS technologies understood that data with objects and events georeferenced to territorial maps are needed for effective work. Also, data processing required spatial analysis methods. In the initial development stage of GISs, there was insufficient geospatial information due to little work in this field.

Foreign experience in using GISs in the field of information technologies became available to Russian experts in the early 2000s. GIS tools began to be applied in different sectors of the national economy (geological exploration, energy, oil and gas production, manufacturing, as well as land management), often with the involvement of foreign GIS suppliers. This was due to insufficient information about GIS capabilities, the quality of existing cartographic materials, their availability, and the lack of a unified database for activities in different sectors of the national economy [17].

Over time, there was a gradual transition to the use of open data. The volume of available information grew, and new methods were developed for collecting, analyzing, and visualizing such data.

Table 1

The most advanced platforms for implementing full-fledged GISs

No.	Platform	Developer	First release date	URL
1	ArcGIS	ESRI, Inc. (Environmental Systems Research Institute, USA. Founded in 1969)	December 27, 1999	https://www.esri.com
2	GeoMedia	Hexagon Geospatial (a Swedish multinational company representing a division of Intergraph, USA)	1996	https://hexagon.com/products/geomedia
3	MapINFO	Exactly (formerly Pitney Bowes Software and MapInfo Corporation, USA)	1986	http://www.pbinsight.com/welcome/mapinfo/
4	AutoCAD	Autodesk, USA	December 1982	https://www.autodesk.com
5	WinGIS	Progis, Austria	1993	https://testprogis.jimdo.com
6	PostGIS + QGIS + MapServer + OpenLayers	PostGIS (Canada) QGIS (USA) MapServer (USA) OpenLayers (USA)	2001 2002 1994 June 26, 2006	https://postgis.net/ https://www.qgis.org/ https://www.mapserver.org/ https://openlayers.org/
7	SuperMap GIS	SuperMap Software (China)	1994–1996	https://www.supermap.com

The development peculiarities of GISs in Russia were conditioned by the following problems:

– There were no up-to-date requirements for the information needed to solve related tasks.

– The means of collecting, processing, updating, storing, and transmitting information did not fully meet the tasks to be solved.

– There was no real technology to update data.

– There were no Russian standards of cartographic information and no semantic data about terrain objects and other objects; there were no unified formats for exchanging digital cartographic data.

Under these conditions, foreign platforms for creating GIS technologies, differing by their functionality, appeared at some enterprises and organizations in Russia. With the advent of workstations, the popularity of GISs increased; this dates back to the early 2000s. At that time, however, GIS was not applied as a technology for developing geoinformation projects. For some time, various cartometric and cartographic operations with small volumes of data were performed using GISs. GIS technologies began to be applied within complex IT projects only in large companies. The advantages of working with GIS technologies were first appreciated by cartographic experts. Note that an important role in the popularization of GISs in Russia was played by foreign companies with GIS technologies [17, 18].

The GIS Association, established in 1995, significantly contributed to the development of GIS technologies. Experts from universities, research, project, and design centers, as well as other organizations engaged in the development and application of information technologies on the territory of the former USSR, met at conferences, seminars, and other events and adopted the idea of creating a Russian spatial data infrastructure. The idea was supported in 2004 by the Government of the Russian Federation, and the corresponding project was included in the Federal Target Program “Electronic Russia (2002–2010).” The Concept of creating and developing a spatial data infrastructure as an element of the national information resource was elaborated to provide a transition to fully digital technologies for collecting and using spatial data. A hierarchical distributed system was created in Russia to collect, process, store, and provide basic spatial data and metadata [19]. This system included subsystems of the federal authorities and local self-government and provided remote access to digital spatial databases and metadata [20].

Large regional GISs began to be created and developed in Russia. Instrumental and informational GISs were created simultaneously.

The use of GISs became an integral part of the professional activities of many Russian organizations. The ability to form multifaceted queries, access to external databases and maintenance of internal databases, and integration with other information systems led to the development of geoinformation technologies in many sectors of the economy.

GIS technologies gave rise to the creation and use of maps in real or near-real time. Aerial photography, direct observations, and geodetic measurements, including satellite systems, statistical data, the results of censuses and referendums, and cadastral information, were used as input data for operational mapping.

The advanced capabilities and unexpected effects of cartographic animations led to their fast implementation in many GISs. Panning effects, perspective changes, scaling of image parts, as well as flying over the mapped territories with different velocities became common procedures in GISs [12–14].

These processes were facilitated by the results of scientific works in the field of cartography, which were carried out in parallel with the development of GIS technologies. Russian GIS developers started using procedural programming, the object-oriented approach (data and terrain objects), and global automation trends for analysis and software design in different programming languages. Additional versions of Russian GISs were created in foreign languages, e.g., NEVA GIS in Spanish, Panorama GIS in English, and GeoGraph GIS in several languages.

The main types of geoinformation analysis are as follows:

- work with spatial and attributive databases, surface modeling, buffer zone construction, overlay operations, network analysis, data aggregation, zoning, and specialized analysis;
- changing the database structure, data input, updating, editing, generation of derived information based on spatial analysis results, modeling, spatial and attributive queries, search for objects by a given condition, formation and editing of data, analysis and automatic correction of spatial data topology, and positioning of spatial objects in a given coordinate system.

We mention the national economy’s sectors that use Russian GISs as a tool for management and decision-making: administrative and territorial governance, telecommunications, oil and gas, transportation and road maintenance, engineering communications, agriculture and forestry, architecture and construction, mining, security agencies, public authorities, healthcare, banking, urban planning, and land cadastre. When making well-grounded decisions, organizations in various industries are becoming increasingly dependent on geographic information. Specialized GISs are used in Russia. As a rule, they consist of separate modules. The basic module implements the main GIS functions: software support of input-output devices, data export and import, etc.

Nearly all full-fledged GISs have homogeneous capabilities to work with attributive information. Most systems support work with all major DBMSs through the ODBC and BDE drivers (Windows OS) [21].

In the preponderance of cases, the capabilities of modern full-fledged GISs can be expanded. The main expansion method is programming in high-level languages (MS Visual Basic, MS Visual C++, Borland Delphi, and Borland C++ Builder) with the connection of DLL and OCX libraries (ActiveX) [13].

The key Russian GISs with modern achievements in the field of geoinformation technologies are combined in Table 2.

In addition to these GISs, many specialized GISs were developed in Russia to solve narrower (industry-specific) tasks [16].

According to their functional capabilities analysis, GISs are isolated and sectorally oriented and have no common exchange formats. Some GISs contain tools for developing GIS applications for solving private tasks. Many state GISs are currently exposed to critical risks of failure due to possible termination of their IT infrastructure maintenance. In Russia, there are about 4,000 federal- and regional-level GISs with foreign software or hardware components. Most of them do not meet the modern requirements of digital technological sovereignty. Over 60% of Russian GISs involve VMWare and Microsoft Hyper-V, virtualization tools of foreign suppliers [22]. Virtualization has now become the main trend of Russian information technologies, and this problem will be solved shortly.

Due to various foreign GISs widespread in Russia, when developing Russian GISs, it was necessary to ensure the possibility of using the previously created spatial data by the existing GISs in their exchange formats. Different converters were also developed when needed.

The complete list of raster images supported by GeoGraph GIS includes the following formats: GeoGraph raster file (.seg), Windows Bitmap (.bmp), Aldus Tiff (.tif), Cals (.xal), Macintosh Pict (.pet), Zsoft PCX (.pcx), Truevision TARGA (.tga), WordPerfect (.wpg), Windows Metafile (.wmf), Multi-page PCX (.dcx), PostScript (.eps), and JPEG (.jpeg).

In addition to the formats listed above, GeoGraph GIS supports a wide range of raster image formats: BMP, TIFF, PCX, TARGA, DCX, EPS, WPG, JPEG, PICT, and others. These formats can be used and scaled simultaneously with vector maps.

Table 2

Modern Russian GISs

GIS	Developer	URL
GeoGraph GIS	Mining Exploration Center, the Institute of Geography RAS, Moscow	–
Karta – 2011 GIS	Panorama Design Bureau, Moscow	https://gisinfo.ru/item/79.htm
InGeo GIS	Integro, Center for System Studies, Ufa	http://www.geoinfograd.ru/ingeo.htm
REKOD GIS	REKOD PJSC, Moscow	–
Zulu GIS	Politerm LLC, St. Petersburg	https://www.politerm.com/products/geo/zulugis
GEOCAD GIS	GEOCAD plus LLC, Novosibirsk	https://geocad.ru
IndorGIS GIS (an instrumental GIS)	IndorSOFT LLC, Tomsk	https://www.sigirgroup.ru/sapr/indorgis.html
GeoMixer GIS (an information GIS)	SCANEX Engineering and Technology Center LLC, Moscow	https://www.scanex.ru/software/web/geomixer
Credo –Credo-Dialogue GIS (an instrumental GIS)	Credo-Dialogue JV, Minsk, Belarus	https://credo-dialogue.ru
CenterProgramSystem GIS (specialized GISs)	CenterProgramSystem LLC, Belgorod	URL:https://1cps.ru
Axioma GIS (a universal GIS for Windows, Linux, and macOS)	ESTI LLC, Moscow	URL:https://axioma-gis.ru
CSI-MAP	KSI-Technology LLC, St. Petersburg	–
Sinteks ABRIS	NTF Trisoft LLC, Troitsk	–
ObjectLand	Radom-T JSC, Taganrog	https://objectland.ru/

With IDAPI (Borland Database Engine), this GIS operates independently of the data source format. An access driver (ODBC) is used for each data source. Attributive data in other formats (MS Access, MS Excel, FoxPro, Oracle, InterBase, and MS SQL Server) can be connected to GeoGraph GIS through BDE drivers with its preliminary configuration. Due to the multi-format core and wide import possibilities, GeoGraph GIS integrates data from almost any formats and different GISs. The system can connect to local attributive data (Paradox, dBASE) and all modern DBMSs (Oracle, MSSQL, etc.).

Other Russian GISs support different formats and have different general functionality, but they are no less effective for solving narrow industry-specific tasks. In this context, we emphasize an important aspect related to spatial databases. Some Russian GISs, e.g., InGeo (Integro), were developed with an orientation on the TCP/IP protocol. In general, TCP protocols can block and transmit data. Nowadays, all data transmissions on the Internet use the American stack of TCP/IP network protocols. The Internet cannot be "broken" for a particular country, so user data must be encrypted for security; this process must be permanent. At the same time, Russia is working on the creation of a sovereign Internet for UAVs based on analogs of TCP/IP network protocols. Note that by the Chinese government's decision, Huawei is already developing a novel Internet protocol (New IP) to replace the American TCP/IP protocol [20].

When addressing the complex issue of technological independence from foreign companies, the following circumstances should be considered as well. For space communication channels, TCP/IP is unproductive, so other technological solutions are needed. For example, telecommunication protocols available only to one and several organizations can be used in corporate local (internal) networks isolated from the Internet.

These protocols can be transferred from the intranet to the Internet only under the cross-compatibility of equipment and software with the support of TCP/IP technologies. Therefore, replacing TCP/IP with a new protocol in the Internet is now inexpedient: users of all countries apply TCP/IP (network equipment, communication channels, the network stack of the operating system, libraries, and software). Equipment can be replaced; however, things are more complicated for operating systems and software. Indeed, it is necessary to create an intermediate layer with TCP/IP emulation or rewrite software on a new network stack. Therefore, the dependence on foreign technologies will probably continue in the near future. More research is needed here.

Currently, InGeo GIS is a set of programs. The main data server was developed by Integro. It communicates via a local network or the Internet.

Geodetic coordinate systems and map projections are not supported. It is impossible to get information about the coordinate system used in InGeo. This GIS neither recalculates data between different coordinate systems nor combines spatial data in different coordinate systems and/or projections in one project.

Due to no operation mechanism for coordinate systems, a separate spatial data bank has to be created for each territory. Moreover, the system admits working with only one spatial data bank at once.

InGeo is a well-adapted GIS for municipal administration, where all spatial data are created and processed in the same coordinate system. This system is difficult to use as a universal GIS; for many tasks, it becomes even inapplicable.

When working with raster images, InGeo has no support for building a pyramid of different-scale images to accelerate the display of general territory plans. There is only a mechanism of partitioning into fragments (tiles) to accelerate image viewing on large scales. The raster fragments are stored as standard BMP or PCX files, but the coordinate reference information is stored separately inside the DBMS.

This GIS provides no toolkit for exporting raster images to other formats with coordinate reference.

Due to the absence of tools to work with different coordinate systems, InGeo cannot be normally integrated with other GISs. The main OGC standards (WMS, WFS, and GML) are not fully supported. The available modules for web application development implement a particular protocol differing from OGC standards.

When storing data in Borland Paradox (a file DBMS), there are problems with the maximum database size. The system becomes inoperable upon reaching about 1.5 million spatial objects (a digital topographic plan scaled 1:2000 for a city with approximately 100 thousand people). All spatial analysis tasks are not solved due to the impossibility of building a correct topological data model.

The functionality of almost all GISs is largely identical: database (register) management, or interface management, or information output. The hardware and programs used for real-time GIS maintenance are subject to critical risks, especially hardware-software solutions from Oracle, IBM, and Microsoft, currently unavailable in Russia. These solutions are deeply integrated into the information technology infrastructure, and their replacement will require significant time and financial costs.

In such conditions, it is required to develop new organizational, technical, and hardware-software solutions within the import substitution framework. Some Russian products have already been developed to implement the basic GIS functionality. In the future, it is necessary to respond quickly to possible failures, finalize GIS functionality, and extend the component base for possible fast replacement, which requires the expansion of production capacities.

4. GEOINFORMATION SYSTEMS OF ICS RAS: DESCRIPTION AND ALGORITHMS

At ICS RAS, R&D works on geoinformation systems with information technologies for solving special tasks began in the mid-1990s. Methods were implemented for creating and displaying 3D terrain models in real time. *Polety* (Flights) was the first program in Russia to build aircraft flight routes at specified altitudes considering terrain relief and high-altitude objects using real space images of large volumes. Note that the flight time was optimized by the shortest path criterion. The Institute's studies on automatic terrain modeling based on computational geometry led to important scientific results as follows [23]:

1. The recognizability of terrain relief forms by the picture of contour lines without using the elevation matrix-based relief model was proved. This result refuted the established position that the picture of contour lines is not enough for the machine processing of terrain relief information without the altitude matrix. In addition, as was demonstrated, a given accuracy of the terrain relief representation by contour lines can be ensured by setting an appropriate density of points on isolines.

2. The classical marking problem was solved for extended objects while ensuring a uniform density of marks.

3. The full automation of the original relief design (application of contour line signatures and hachures) using information about contour lines only (without the height matrix-based relief model) was proved feasible.

4. An algorithm was developed to recognize local relief forms by a set of contour lines defined as broken lines. This algorithm determines the locations of given relief forms in a time $O(n\log n)$, where n denotes the total number of segments on all broken lines representing contour lines. In other words, it was established that the problems of recognizing relief forms by the picture of contour lines, as well as the problems of original relief design (application of contour line signatures and hachures), using the picture of contour lines in the form of broken lines as initial data have a quasi-linear complexity. The critical stage determining the lower bound of their complexity is the construction of Delaunay triangulation.

5. The general algorithm (see item 4) was adapted to particular relief forms; as a result, the quasi-linear complexity $O(n\log n)$ was proved for the problems of recognizing almost all relief forms affecting their final representation.

6. An algorithm was developed to recognize relief forms using contour lines only (without ground-level point objects). This algorithm has a quasi-linear complexity in the number of vertices and allows automating the editing and verification of terrain relief information. For example, it recognizes peaks and troughs, saddles, orographic lines, and discrepancies in the system of contour lines and elevations.

7. Algorithms were created to construct the terrain relief automatically based on mutually oriented images. A higher-reliability algorithm was created to recognize and display the terrain relief without using low-informative terrain sections.

Computational operations for the processing of large volumes of aerial photographs required considerable time, representing a significant obstacle toward achieving the given accuracy of 3D terrain models. For the fast processing of aerial photography data, a digital photogrammetric station (DPS Talka) was created. Talka carries out all necessary mathematical calculations and constructs with the subsequent visualization of the model [23].

The following fundamentally new solutions in the field of geoinformation technologies were developed at ICS RAS:

– algorithms for interpolating a 2D function over a set of values at known points based on a 2D modification of the Kalman filter;

– algorithms for approximating a sequence of points by an Imai- and Iri-type broken line for a triangulated line and by lines from arcs of circles using the least squares method;

– algorithms for solving systems of nonlinear block phototriangulation equations with minimizing the fourth and sixth degrees of the residuals;

– algorithms for constructing the Delaunay triangulation and the Voronoi diagram for a set of points and segments in a quasi-linear time in the number of vertices;

– algorithms for constructing the terrain relief automatically based on mutually oriented images;

– a method for identifying the corresponding points of two images using the Marr–Hildreth edge detection algorithm and rubber stretching transformations;

– methods for applying contour line signatures automatically on the original relief and assigning the positions of marks for extended linear objects.

The creation of original terrain reliefs, including smoothing of contour lines and applying contour line signatures and hachures, was fully automated in the developed software products. Note that the algorithms and programs for solving this problem can be used for the automatic generation of maps in navigation and control systems for moving objects [23].

The program provides a significant degree of automation for photogrammetric processing and mapping operations. Also, a special format was developed to store the regular spatial data structure; this format supports the unlimited data storage possibility due to the level storage concept. It provides fast access to the data of each level and the possibility to store data for a given area of arbitrary shape.

The Institute's employees developed methods for forming images of broken line parts lying inside or outside a polygonal domain and the boundaries of domains obtained by applying logical operations to two polygonal domains. These methods are based on finding the segments of a broken line lying in the neighborhood of the domain's boundary and form the desired images reliably.

The Institute's unique technology creates a multi-window stereo interface without specialized video controllers. It uses the video controller cloning mode and a software interface with primary and overlay surfaces for input images. The overlay surface covers only the stereoscopic part of the screen, which saves resources on window processing of other applications.

The solutions mentioned above were patented and fully implemented in Talka GIS, created at ICS RAS. They are not found in any known software product. Technologies were developed to work with satellite devices in order to control receiver measurements and create corresponding objects in the map. In the Real Time Kinematic modes and post-processing, the high accuracy of results is achieved, and the control of moving objects is improved accordingly.

The Institute's Talka-PPC GIS runs on pocket personal computers and is used to create and update maps and plans. It can work with bitmap images and vector maps and survey the terrain using geodetic equipment: GPS and GLONASS receivers, as well as total stations. This pocket GIS possesses all the capabilities of navigation and viewing and, moreover, advanced tools for editing and collecting data on the ground and transferring information to a data server. The well-developed tools of Talka-PPC's raster georeferencing editor allow changing the coordinates of georeferencing points, both visually and through their numerical values.

Talka-GIS, the system designed to work with bitmap images, vector maps, and satellite equipment, has the functionality of viewing, creating, and editing geoinformation materials, GPS navigation, geodetic measurements, and device control. This system supports professional geodetic equipment and navigation receivers. It allows managing satellite measurements of the receiver by mapping objects based on measurements or linking measurements to the existing objects. The processing results are accepted by the Talka-GIS tools, and the measured areas of the map objects acquire accurate coordinates.

Talka-PPC, Talka-GIS, and DPS Talka have a similar interface and provide fast information exchange for managing the corresponding software tools.

A hardware and software complex for SUEK3D GIS was developed at ICS RAS. This complex processes and displays 3D information for the technological support of the coal company's management processes. As part of this work, scientific research was carried out to improve methods and technologies for obtaining geospatial data using unmanned aerial vehicles (UAVs) [24].

SUEK3D GIS has the client–server architecture and is intended for digital 3D terrain modeling in real time. The system builds models of relief and strata using aerial photographs, geological well data, standard geodetic constructs, and ground photos of terrain objects. Based on these models, the program calculates the lengths and volumes of excavations as well as rock residues in real time. In addition, the software environment provides the ability to work with other software via API using functions, classes, methods, structures, and (sometimes) constants. Interactive terrain models are created considering the movements of mining equipment over the covered area by the predetermined trajectories and schedules. As part of the work, a large database was collected for the 3D models of the main types of mobile mining equipment used in open pit operations.

The Institute's employees developed NEVA GIS. This system creates various 3D terrain models: relief, relief with terrain objects, and halftone models based on aerial photographs. It is used in map printing, being the main tool for pre-publication editing of various atlases and maps.

In recent years, within the digitalization of agriculture, information and communication technologies, data analysis methods, and IoT technologies were studied at ICS RAS. Based on the results of these studies and the NEVA GIS platform, the following approaches and methods were developed [25–29]:

– new approaches to the ecological monitoring of water surface;

– methods for crop condition monitoring and the identification of pests, diseases, and irrigation status;

– methods for using virtual polygons to test group control scenarios for multicopter UAVs.

The Russian legislation in the field of geodesy and cartography, land management, and forestry was considered, and the possibility of its geospatial binding was studied when using Talka GIS and Karta 2011 GIS (Panorama GIS) [30]. Such results are not available in the open sources, including *ConsultantPlus*.

At different development stages, the solution of the control problem for moving objects was connected with studying the general principles for automatic synthesis of control parameters. For this purpose, control methods were analyzed for aircraft using correlation-extreme navigation systems (CENSs) for positioning and flight trajectory correction. The analysis covered new design principles for onboard algorithms, their possible intellectualization and self-organization, the modern types of shooting systems and their possible combinations, as well as the current level of parallel computing and special processors for implementing algorithms with the same parallel structure. As was established, the further development and mass adoption of autonomous navigation systems of this type as the only alternative to satellite navigation systems for aircraft control (in particular, UAVs) can be based on subject-oriented information technologies [16].

In modern conditions, GISs can be developed to model CENSs. ICS RAS proposed a concept of building a geoinformation system for modeling search CENSs to collect models for a wide range of CENSs and draft technologies for their adjustment for operation with the necessary computational experiments. A general mathematical model was constructed to determine the composition of the required software, storage structure, and interface features. While preserving the specifics of CENS algorithms, this model covers the known image matching algorithms and also includes a design scheme for novel CENS algorithms with the implementation of various intellectual methods in big data processing (pattern recognition and scene analysis, clustering, training of neural networks, and cloud computing).

Mathematical models were developed for the stress exposures on the shooting systems of a navigation system. They provide different operation conditions for CENSs as follows: a failure in aircraft positioning, aircraft positioning by false reference points, etc. The resulting information can be used to improve the control system of aircraft using terrain images in different wavelength ranges of electromagnetic radiation. Stress testing verifies the fulfillment of increased requirements for the reliability of CENSs and is the most important computational experiment with CENS models [31, 32].

Search CENSs solve their tasks by checking hypotheses about the values of motion parameters by matching the current terrain image from the onboard shooting system with fragments of the reference image stored in the CENS. Hypotheses about the equal values of the desired parameters are checked, and the hypothesis with the maximum value of their proximity function is accepted. Global search schemes, gradient-based, from the arsenal of optimization methods for numerical functions, as well as their combinations, are applied. In the first systems of this class, the correlation coefficient of the current and reference images was used as a proximity function, which explains the term “correlation-extreme navigation systems.” In a more general sense, this subject area covers any overview-comparative methods of autonomous navigation that do not necessarily involve image matching. Their distinctive feature consists in navigation by comparing the real survey results of the moving object’s space with a priori information about possible survey results. For the sake of brevity, in this paper, we will keep the name “CENS” for any such systems.

The accelerated development of CENSs became urgent due to the intensive progress of various-purpose unmanned vehicles. As a result, the potential of CENSs was more deeply disclosed compared to the existing solutions. If geodetic satellites (GLONASS, GPS) are put out of operation, satellite navigation control systems will become useless. Note that satellite signals are not stable enough in some Russian territories. This problem also exists in urban areas; moreover, due to flat high-altitude objects, it is possible to receive distorted signals [24, 33, 34].

In such conditions, this subject area can be developed by expanding R&D works using a subject-oriented computing complex. Such a complex will provide a designer with all the necessary tools for assembling CENS models and draft technologies for their adjustment from ready-made software modules via a special interface for software module warehouses and the ability to conduct computational experiments with them [34].

Mathematical models of CENSs and draft technologies for their adjustment will create an image of onboard control systems of aircraft equipped with correlation-extreme data processing means to solve their task under possible interference [16, 31, 35].

The subject-oriented complex will provide the user with access to all universal means of working with geospatial information, i.e., the general-purpose functionality based on expanding the functionality of Talka-GIS. The access was also verified using ArcInfo GIS, Mapinfo, Panorama GIS, and NEVA GIS [31, 35]. According to the analysis of the mathematical models mentioned above, such a subject-oriented complex for modeling search CENSs should have the structure of an applied GIS that will improve the dynamics of autonomous control systems through the principles of reconfigurable structures, neural networks, and AI for working with big data based on organized access networks.

5. DEVELOPMENT TRENDS AND PROSPECTS OF GISS: TECHNOLOGIES AND ALGORITHMS

One of the main development trends in GISs is the use of web services and cloud technologies with distributed computing resources to implement neural network technologies for big data processing. Web GISs have enhanced the capabilities for sharing methods, transferring research results, and visualizing, accessing, and processing data. As a result, they have evolved into a real-time interaction system.

Simulating the solution of certain tasks based on gradual learning using information from humans creates prerequisites for implementing AI within the IoT concept, which connects objects with each other. The IoT technology is represented as a set of devices with different spatially coordinated sensors connected to each other. They become intelligent and determinate in space [22, 36]. Therefore, geodetic networks can be organized in order to survey terrain objects using only the equipment for receiving signals from sensors (without geodetic tools).

Based on the IoT concept, it is possible to create neural networks for interaction between sensors and UAV data receivers [22]. Different sensors provide data about objects and processes in real time with the possibility of predicting their behavior and organizing an appropriate response to them. Since the information received in GISs has a coordinate reference and is stored in a database, it can be rapidly analyzed. Therefore, cloud computing and big data technologies should be used [37]. Classical servers, as well as data processing centers, have so far solved common tasks in known ways. The IoT leads to the appearance of new tasks, and their solutions are now being developed [38]. Note that the volume of information is increasing significantly. Sensors can measure temperature, weight, speed, pressure, humidity, illumination, and other parameters. They are installed on vehicles to measure the speed and determine the trajectory in real time, and they can be configured remotely or in situ [39, 40].

Data from IoT devices can be used to compile:

– heat maps showing faults and service failures;

– Wi-Fi-network congestion maps in certain places of a settlement;

– maps of traffic congestion and parking lots;

– illumination maps of a settlement, etc.

Based on these maps, decisions can be made to provide differentiated services. The IoT in GISs allows estimating the utilization of many resources to balance supply and demand. Since the IoT includes a large volume of information representing ideal sets of spatially defined training data, the scalability of GISs is enhanced by the capabilities of artificial intelligence technologies. Thus, the development of IoT technologies is an important trend for the emergence of new applications in modern GISs.

Artificial intelligence allows finding new patterns in the use of data. These patterns serve to classify the large volumes of remotely sensed data and combine data from different sources. Some machine learning algorithms are already being applied to analyze geospatial information for the following purposes:

– classifying terrain objects;

– forecasting the numerical characteristics of phenomena and processes;

– grouping objects by their similarity based on descriptions;

– finding relations and dependencies between different terrain objects.

These algorithms are being developed and implemented in software solutions for the following purposes:

– jointly using GISs, Earth remote sensing devices, and GLONASS [33, 34, 41];

– utilizing the information resources of friendly countries [42];

– creating a unified telecommunication GIS and expanding its capabilities [38];

– using AI to analyze geospatial information and prepare managerial decisions [43, 44].

The most important problem, a development trend of cartography that has not yet been implemented to create thematic maps for GISs, is the full automation of the map creation process using AI. As has been mentioned, machine learning algorithms can be used for the automatic recognition and classification of terrain objects. The process of mapping these objects should also be done based on machine learning with many approaches implemented creatively by individual executors. Decisions are made considering the existing normative and technical rules and established requirements within given variations for the characteristics of objects displayed on the maps. Along with the reduction of time and costs for map creation, it is necessary to achieve the given accuracy and reliability of map creation or update processes.

Machine learning in the automatic processing and analysis of geospatial information in real time, as well as the creation of intelligent decision support systems in GISs, is a promising direction for GIS development.

The quality of geospatial data, their large volumes, and the existing heterogeneity of data representation cause difficulties when interpreting information [18, 45]. This factor restrains the current application of AI. According to the recent analysis of remote sensing data, there are problems and difficulties due to large volumes of data. Principal Component Analysis (PCA) is one of the most popular and well-known unsupervised feature reduction methods. With PCA being applied, the vast majority of information in an image can be retained simultaneously with a significant dimension reduction through cumulative eigenvalues [46].

The further development of machine learning technologies, methods, and algorithms for databases will make it possible to generate intelligent managerial decisions.

An important direction of GIS development is the creation of mobile geoinformation systems using mobile devices [47]. In the last few years, foreign and domestic researchers have obtained significant results in the form of separate software modules. Their functionality and the normative status of geoinformation support have not been formed yet. The software products developed recently are not the subject of this survey, but they are implemented on well-known full-fledged platforms.

CONCLUSIONS

Based on this survey of geographic information systems developed abroad and in Russia, particularly at ICS RAS, we draw the following major conclusions.

The creation of map algebra, which defines mathematical and algorithmic operations on raster data during their spatial analysis to obtain new raster datasets with the analysis results, underlaid a new direction in information and computer science, called geoinformation technologies. It became possible due to the R&D works of Canadian, Swedish, and American experts in cartography. The Canada Geographic Information System (CGIS) is considered to be the first software product implementing geoinformation technologies.

The USA, Canada, Sweden, and other countries developed GISs on different platforms with different functional capabilities. Based on them, Russian GISs appeared to solve different tasks using standard solutions, usually of higher quality. The need for independent technological solutions in Russian GISs was quickly realized. New GISs with unique technological solutions appear, but they are bound to imported hardware. New tasks are formed within the design schemes of Russian GISs, and their solution will provide independence from foreign software products in the field of GIS technologies. At present, some dependence on foreign technologies remains, but Russian GISs are now being developed on domestic platforms, which will ensure the technological sovereignty of Russian developers shortly.

Note also the important approaches to GIS development (new mathematical, technical, and algorithmic solutions) that were proposed at ICS RAS. They were implemented in GISs for generating managerial decisions and confirmed by many patents.

Modern GISs provide work with geospatial data to obtain necessary information for managerial decision support. Spatial databases allow determining the location of objects, routing vehicles, analyzing land plots, obtaining their qualitative characteristics, and solving many industry-specific tasks. Any GIS map can be represented in the 3D form to visualize the terrain for better analysis of events and natural phenomena and decision support. The permanent updating of data using raster and vector sources and attributive data increases the reliability and practical compliance of the results with the real conditions. All these functions have become available due to the joint use of cartography and information science tools developed recently.

The current development trends in GISs are as follows:

- creating communication and utilization methods for the GIS data obtained by remote sensing of the Earth and global navigation satellite systems;
- improving telecommunication and information resources of friendly as well as other countries;
- designing a unified telecommunication geographic information system on the territory of the Russian Federation and its regions;
- developing GISs using the IoT concept for intellectual management of different systems, territories, and activities in the national economy, emergencies, and the national defense.

Geoinformation systems have expanded the capabilities of method exchange, transfer of processing results, visualization, and access to data. They have accordingly evolved into real-time interaction systems. Simulating the solution of certain tasks based on gradual learning using human information creates prerequisites for implementing AI in the IoT.

As mentioned above, spatial databases can be used to determine the location of objects, route vehicles, analyze land plots, obtain their qualitative characteristics, and solve many industry-specific tasks. The analysis of scientific and technical results in the field of geoinformation technologies implies that, in order to improve information security in modern conditions, it is necessary to develop communication methods for spatial data reception, processing, and transmission using a Russian analog of the TCP/IP protocol on the Internet. The use of local internal networks isolated from the Internet seems realistic.

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Author information

Alchinov, Alexander Ivanovich. Dr. Sci. (Eng.), Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia
✉ alchinov46@mail.ru
ORCID iD: https://orcid.org/0000-0002-6553-376X

Gorokhovsky, Igor Nikolaevich. Cand. Sci. (Eng.), Research Center of Topographic and Navigational Support, Central Research Institute No. 27, Moscow, Russia
✉ gin_box@mail.ru

Akif’eva, Elena Viktorovna. Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia
✉ lenatalka1@mail.ru

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Translated into English by *Alexander Yu. Mazurov*,
Cand. Sci. (Phys.–Math.),
Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia
✉ alexander.mazurov08@gmail.com