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EXPANDING THE FUNCTIONALITY OF AN APPLIED GEOGRAPHIC INFORMATION SYSTEM FOR MODELING SEARCH CORRELATION-EXTREME NAVIGATION SYSTEMS

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Abstract. This paper further develops the concept of an applied geographic information system (AGIS) for modeling search correlation-extreme navigation systems (CENSs) intended to control moving objects. The possibility of using parallel, distributed, and cloud computing for modeling CENSs is investigated. In modern conditions, it is necessary to diagnose the operation of CENSs under stress exposure on their shooting systems. The stress exposure parameters are modeled by accessing specialized databases containing the characteristics of terrain objects in different electromagnetic radiation wavelength ranges. As a rule, such characteristics are unavailable in geographic information systems (GISs) and cloud environments. It is demonstrated that CENSs should be diagnosed by modeling the shooting system using cloud GISs. The issues of parallel computing for pattern recognition tasks are considered. The peculiarities of the parallel structure of CENS search algorithms are revealed. When implementing these algorithms in parallel computing systems, proper consideration of the peculiarities allows utilizing their advantages to the highest degree.

Keywords: cloud computing, cloud service, parallel computing, computing systems, pattern recognition, cloud geographic information system, search correlation-extreme navigation system.

INTRODUCTION

Onboard search correlation-extreme navigation systems (CENSs) for various-purpose unmanned vehicles (marine, aerospace, and ground) determine the parameters of their motion by checking hypotheses about the values of these parameters: CENSs match the current terrain sector image received by the onboard shooting system in the next autonomous navigation session in a given area with fragments of a reference image of this area. The reference images are prepared in advance and are stored in the memory of the onboard computer. When searching for a reference image fragment close by content to the terrain sector image (in the sense of a closeness function in the onboard algorithm), a regular shift grid of the frame of the appropriate size and orientation is used to select the next reference image fragment. The hypotheses that the sought parameters have values equal to those at the grid nodes are checked. The hypothesis for which the closeness function achieves maximum is accepted. Global (exhaustive) and local (gradient) optimization schemes are applied. According to the authors' publications [1, 2], autonomous navigation in modern conditions requires developing more general methods for checking hypotheses about the values of the motion parameters of unmanned vehicles than those described above. In this paper, such methods will be called overview and comparative methods. For the technical systems implementing these methods, we will retain the above name and designation established historically.

The topicality of the accelerated development of CENSs at the present stage was justified in [1, 2]. As was shown therein, a promising R&D line is the creation of an applied geographic information system (AGIS) for modeling CENSs. This system should be equipped with the means of assembling computer models of a wide range of CENS variants and draft technologies to adjust their operating sessions in specified areas from off-the-shelf software components for conducting computational experiments in order to assess the effectiveness and stability against stress exposures.

The authors proposed a mathematical model [1] to justify the composition of such software components as well as their functionality and spatial data requirements. In Section 1 below, this mathematical model is applied to identify (and describe in terms of related problem domains) some analogs of software components and spatial data of AGIS CENSs. Under appropriate access to such components and data, the implementation costs of AGIS CENSs can be minimized. Also, the general parallel structure of CENS search algorithms is given a compact description. This description can be used when implementing AGIS CENSs based on parallel computing systems.

Sections 2 and 3 are devoted to the possibility and options for accessing analogs of AGIS CENSs components in related problem domains.

Many images in different electromagnetic radiation (EMR) wavelength ranges are used in the development of models and layouts of search CENSs and their adjustment for operation. Image processing on computing systems involves large amounts of data; much processor time is spent on simulating CENSs [1–3]. The performance of computing systems should be improved using parallel computing in modern cloud environments (cloud GISs), the so-called distributed GISs with decentralized control in the parallel execution of simulation tasks [4, 5].

Cloud environments permanently store large amounts of data (remote sensing images of the earth), e.g., a hypercube of information that will be temporarily cached on the user's side. The user also gets quick access to the data, while saving time and resources. The matter concerns distributed GISs belonging to one or several organizations dealing with CENSs. Software tools, the structures of storage devices and the interface of AGIS CENSs, and all the methods (pattern recognition, scene analysis, clustering, and training of neural networks) can be implemented using network services with fast search of necessary information [3, 6, 7].

Currently, these tasks are performed using the well-known classical approaches on computers that are linked to server databases within one or several organizations. Each group of tasks is performed in dedicated applications, and it is possible to use different approaches when decomposing the tasks. The methods and means to implement parallelism depend on the level where they should be provided. The capabilities and means to implement parallel computing depend on the level of commands, data flows, and tasks.

The authors outlined the further development of search CENSs towards new design principles for onboard algorithms, their intellectualization and self-organization, the application of new types of shooting systems and their combination, and the implementation of parallel CENS algorithms, including the capabilities of cloud technologies.

The accelerated development of CENSs has become topical due to the emergence of parallel computing-oriented processors and the development of software tools for training neural networks on big data in cloud computing environments [1, 2].

In view of these conditions, R&D works have been expanded using a computational complex that provides all the necessary means for, first, assembling models of a wide range of CENSs and draft technologies to adjust their operation in specified areas from off-the-shelf software components via a special interface to databases and, second, conducting experiments.

The functionality to model search CENSs and draft technologies for their adjustment can be implemented in a general-purpose GIS using universal tools for handling geospatial information. In Sections 2 and 3, this functionality is expanded based on the analysis of cloud technologies and parallel computing. Also, we investigate the capabilities of cloud technologies and parallel computing, the peculiarities of their application when modeling advanced CENSs, and their possible implementation based on data processing means and technologies.

A computing system supporting parallel calculations achieves maximum efficiency at the level ensuring system parallelism with the decomposition of tasks that can be performed simultaneously [1, 2]. The approaches to calculations in modern computing systems are analyzed, and the data necessary for choosing a computing system for complex tasks are obtained. We decompose one of the main tasks of AGIS CENSs: modeling CENS operation and determining the peculiarities of the parallel structure of the corresponding algorithms.

This study expands the functionality of the existing general-purpose GISs to model search CENSs effectively. To achieve this goal, we further develop the mathematical model of search CENSs. Based on this model, we decompose the tasks of AGIS CENSs, including those of modeling stress exposures on their imaging systems. We analyze general-purpose cloud technologies and existing cloud GISs designed for processing geospatial information in terms of their application to the tasks mentioned above. The results presented below can be used when implementing AGIS CENSs.

1. THE PARALLEL STRUCTURE OF CENS MODELING ALGORITHMS. SOME ANALOGS OF SOFTWARE COMPONENTS OF AGIS CENSS IN RELATED PROBLEM DOMAINS

The starting points are as follows.

• The maximum efficiency of the computing system selected for implementing AGIS CENSs can be achieved if its characteristics are chosen considering the peculiarities of the initial data and computer algorithms to simulate CENS adjustment processes for autonomous orientation using overview and comparative methods and the operation processes of the adjusted CENS under various disturbances, including stress factors. Such processes are simulated by means of contemporary computing systems at the limit of their performance. Besides the available memory and the speed of processors and exchange devices between them, the key role is played by their specialization and the possibility of parallelizing the subtasks of general tasks during simulation [4]. The central general task in AGIS CENSs is to simulate the operation of CENSs adjusted for autonomous orientation. The peculiarities of the parallel structure of algorithms to perform this general task are considered below. The peculiarities of simulating CENS adjustment processes and image synthesis processes for different shooting systems used in CENS will be addressed in subsequent publications of the authors.

• In order to determine the specialization of computing system processors and organize their parallel operation for the central general task of AGIS CENSs, it is necessary to decompose this task into subtasks and to distinguish those that must be performed sequentially (the output of a previous subtask is the input for the subsequent one) and those that can be performed in parallel.

The decomposition can be performed using the mathematical models proposed in [2, 3]. As in these papers, we consider search CENSs in which the shooting system captures a scene image S on a terrain section, and the onboard algorithm refines the planned coordinates $d=(X,Y)$ of the carrier at the shooting instant. Let M be the set of all possible images S coming from the shooting system to the input of the onboard algorithm of the CENS at the shooting instant. Then the search CENS adjusted for autonomous orientation can be treated as a calculator of the values of a function $\hat{f}(S): M \to \hat{D}$ fixed during the adjustment process for any "value" of the "variable" $S \in M$ coming from the shooting system. In other words, upon receiving an image S, the CENS will calculate and output the value of the function $\hat{f}(S)=\hat{d} \in \hat{D}$ (its response). The finite set $\hat{D}$ combines all variants of the computer's responses to the question about the carrier's location at the instant of receiving the image S. In [1, 2], a general analytical expression was derived for generalized step functions defined on hierarchical partitions of the set M into disjoint classes, in which a different prior image transformation can be applied for each partition level. In this paper, we consider $r = 2$ levels of hierarchical partitioning into classes and subclasses. This number is sufficient for decomposing the general task and revealing the peculiarities of parallelism. In addition, with a high degree of confidence, this variant will attract major interest in the practical use of CENSs.

In this case, we have

$$M=\bigcup_{i=1}^{l} K_i, \text{ where } K_m \cap K_n = \varnothing \ \ \forall m, n \in [1, l], \ m \neq n,$$

$$K_i=\bigcup_{j=1}^{l_i} K_{ij}, \text{ where } K_{im} \cap K_{in} = \varnothing$$

$$\forall i = 1, \ldots, l \text{ and } m, n \in [1, l_i], \ m \neq n.$$

Then the function $\hat{f}(S)$ can be written in the generalized vector form

$$\hat{f}(S)=\left\langle \boldsymbol{\chi}(S), \left(\left\langle \boldsymbol{\chi}_1(S), \hat{\mathbf{d}}_1 \right\rangle, \left\langle \boldsymbol{\chi}_2(S), \hat{\mathbf{d}}_2 \right\rangle, \ldots, \left\langle \boldsymbol{\chi}_l(S), \hat{\mathbf{d}}_l \right\rangle\right)\right\rangle \quad (1)$$

with the following notations: angular brackets indicate the inner product of two vectors; $\boldsymbol{\chi}(S)$ = ($\chi_1(S)$, $\chi_2(S)$,..., $\chi_l(S)$); $\chi_i(S)$ is the characteristic function of class K_i, $i=1,\ldots,l$; $\chi_i(S) = (\chi_{i1}(S),\ \chi_{i2}(S),\ \ldots,\ \chi_{il_i}(S))$; $\langle \chi_i(S), \hat{\mathbf{d}}_i \rangle = \sum_{j=1}^{l_i} \chi_{ij}(S)\hat{d}_{ij}$; $\chi_{ij}(S)$ is the characteristic function of class K_{ij}, $i=1,\ldots,l$, $j=1,\ldots,l_i$; finally, $\hat{\mathbf{d}}_i = (\hat{d}_{i1},\ \hat{d}_{i2},\ldots,\ \hat{d}_{il_i})$.

At the first and second partition levels, the input image S possibly undergoes preliminary transformations $\pi(S)$ and $\pi_i(S)$ of respectively. The algorithms for calculating the values of the vector functions $\chi(\pi(S))$ and $\chi_i(\pi_i(S))$ determine the class of the image S. Therefore, by the fundamental theorem on representing any recognition algorithm through the sequential execution of a recognizing operator and a decision rule, we obtain [8]

$$\chi(S) = \mathbf{C}\,(\mathbf{B}(\pi(S))),$$

where $\mathbf{B}(\pi(S)) = (b_1(\pi(S)),\ b_2(\pi(S)),\ldots,\ b_l(\pi(S)))$; $b_i(\pi(S))$ is a numerical measure of the closeness of the image to the class $K_i \in M$; $\mathbf{C}\,(b_1(\pi(S)),\ b_2(\pi(S)),\ \ldots,\ b_l(\pi(S))) = (c_1,\ c_2,\ldots,\ c_l)$, where $c_i \in \{0, 1\}$, $i=1,\ldots,l$; $\boldsymbol{\chi}_i(S) = \mathbf{C}_i\,(\mathbf{B}_i\,(\pi(S)))$, $\mathbf{B}_i$, and $\mathbf{C}_i$ are described by analogy.

Then the function $\hat{f}(S)$ (1) of the CENS computer takes the form

$$\hat{f}(S) = \Big\langle \mathbf{C}\big(\mathbf{B}(\pi(S))\big), \Big(\big\langle \mathbf{C}_1\big(\mathbf{B}_1(\pi_1(S))\big), \hat{\mathbf{d}}_1 \big\rangle, \big\langle \mathbf{C}_2\big(\mathbf{B}_2(\pi_2(S))\big), \hat{\mathbf{d}}_2 \big\rangle, \ldots, \big\langle \mathbf{C}_l\big(\mathbf{B}_l(\pi_l(S))\big), \hat{\mathbf{d}}_l \big\rangle\Big)\Big\rangle. \quad (2)$$

According to (2), the general task includes the subtasks of calculating the "values" of the preliminary transformations involved (hereinafter called the subtasks of type π). The results of performing a subtask of type π are the initial data for the corresponding subtask of calculating the vector of numerical measures of closeness to the partition classes $M = \bigcup_{i=1}^{l} K_i$ (hereinafter called the subtask of type *B*). The results of performing a subtask of type *B* are the initial data for the corresponding subtask of type *C*, which determines the class of the image by analyzing the vector of closeness measures. After deciding that the image belongs to some class of the first partition level, the procedure is repeated for the partition of this class with performing the subtasks of types π, *B*, and *C*. The process is completed by extracting from the computer's memory the value $\hat{d}_{ij}$ (the partition class selected by the decision rule of the second partition level). The subtasks of type *C* are performed only after the corresponding subtask of type *B*, which can be performed only after the subtask of type π. The vector "coordinates" in this process can be computed in parallel; the inner products, only sequentially as soon as the operand values are available. This is the peculiarity of parallelism when modeling CENS operation. According to the classification given in [5], the corresponding computing system has parallelism at the level of threads. In this case, the acceleration of program execution due to parallelizing its instructions on the set of computers is limited by the time required for executing its sequential instructions.

Note that this mathematical model allows implementing AGIS CENSs with the maximum use of off-the-shelf computer components from the problem domains intended for performing the tasks of types π and $\chi(S) = \mathbf{C}(\mathbf{B}(\pi(S)))$ and collecting and generalizing initial data to adjust CENSs for autonomous orientation by overview and comparative methods in a given area.

Based on the mathematical model, we also identify components of AGIS CENSs that have analogs in related problem domains. The cost of implementing AGIS CENSs can be minimized under the required options of access to such components. The connections between the elements of the mathematical model and the software components from related problem domains implementing them are presented in the table below.

The next sections of the paper are devoted to analyzing the capabilities and forms of access to analogs of AGIS CENSs components in related problem domains.

2. ACCESS TO CLOUD TECHNOLOGIES AND CLOUD GISS: THE EXISTING CAPABILITIES AND PROSPECTS

To analyze off-the-shelf components (programs and databases) in the implementation of algorithms for modeling search CENSs, we overviewed cloud technologies and cloud GISs based on scientific research that can be used in GIS applications for modeling search CENSs. Cloud technologies were investigated to identify the existing applications that can serve to model search GISs, particularly the shooting systems of CENSs. No such applications were found.

The mathematical models of AGIS CENSs components (see the table) can be implemented as independent tasks using parallel and distributed computing.

The initial information about orientation conditions in an autonomous navigation area of an unmanned vehicle by the overview and comparative method in the form of relational data (a representative set of N "samples") is in storages that can be accessed in an organized way. For distributed GISs, the access is already organized; for cloud GISs, it is necessary to develop appropriate access applications.

The initial information about orientation conditions in an autonomous navigation area of an unmanned vehicle by the overview and comparative method in the form of a computer model of the shooting system includes the following models:

– computer models of the terrain in the areas of autonomous navigation sessions,

– simulation models of the shooting system,

– computer models of stress exposures on the terrain and the images of its sections for different shooting systems.

The first two models have already been implemented in distributed GISs and cloud GISs, in contrast to computer models of stress exposures on shooting systems.

Analogs of AGIS CENSs components in related problem domains

Mathematical models of AGIS CENSs components	Analogs in related problem domains
The initial information about orientation conditions in an autonomous navigation area of an unmanned vehicle by the overview and comparative method in the form of a table containing a representative set of N "samples" $\left(S_j, d_j\right)$ of the function $f(S): M \to D$ that describes these conditions: $$I_0\left\{ f\left(S\right): M \to D\right\} = \left(S_j,\, d_j\right),\ d_j \in D,\ j = 1,..., N,$$ where D denotes the set of admissible values of the parameter being refined in an autonomous navigation session.	Storages of images of different territories from various moving objects that were obtained using shooting systems similar to those adopted in CENSs.
The initial information about orientation conditions in an autonomous navigation area of an unmanned vehicle by the overview and comparative method in the form of a computer model of the shooting system operating in this area: $$I_0\left\{ f\left(S\right): M \to D\right\} = \hat{f}^{-1}\left(d, p\right),\ d \in D,\ p \in P,$$ where $p \in P$ are the disturbing parameters considered in the shooting system model (one generalized parameter p with the domain P of admissible values). The simulation model of the shooting system should approximate the function $f^{-1}\left(d\right)$, $d \in D$ (the inverse of $f(S): M \to D$).	Computer models of shooting systems operating in the areas of autonomous navigation sessions. They have the following components: • computer models of the terrain in such areas; • simulation models of shooting systems that form the images of sections in such areas using a terrain model of the areas similar to real shooting systems; • computer models of stress exposures on the terrain and the images of its sections for different shooting systems.
The onboard computer of CENS: a parametric family of single-valued functions $\left\{\hat{f}\left(\alpha\right)(S)\right\}_{\alpha \in A}$, where $\hat{f}(\alpha)(S): M \to \hat{D}$ is a particular function from this family. When CENS is adjusted for autonomous navigation by the overview and comparative method in a given area, the choice of this function is uniquely determined by the value of the generalized parameter $\alpha \in A$. The approximating functions from the parametric family of step functions include components of types π and B; see above.	They have the following components: • type π, all known types of digital image processing operations (filtering, boundary selection, scene description in the areas caught in the frame, segmentation, etc.); • type B, components of all known types of recognition operators within families of pattern recognition algorithms (potential functions, separating surfaces, voting, etc.).

According to the third row of the table, the model of onboard computers includes components of types π and B, where π corresponds to known types of digital image processing operations (filtering, boundary selection, scene description for the areas caught in the frame, segmentation, etc.) and B to known types of recognition operators within the families of pattern recognition algorithms (potential functions, separating surfaces, voting, etc.). Their implementability in cloud GISs is still under study. The main databases, their structure, and content for possible use in modeling search CENSs were also considered. As was established, terrain images obtained in different EMR wavelength ranges are mostly standardized and are stored in different known formats; their use via cloud services will cause no difficulty. However, the problem lies in the processing of significant amounts of information contained primarily in space images.

As was discovered, cloud environments have no specialized databases with reflecting and absorbing characteristics of terrain. Such characteristics are necessary to form initial navigation reference data in given EMR wavelength ranges and to diagnose CENS operation under stress, when the necessary parameters of stress exposures are obtained considering the parameters of terrain objects.

Currently, there exist the following types of services using cloud computing: *Software as a Service* (SaaS), *Infrastructure as a Service* (IaaS), and *Platform as a Service* (PaaS).

Simple integration solutions involve conventional software tools that define software architecture [5, 9]. Such engineering solutions as containerization, microservice cloud architecture, multi-cloud solutions, and hybrid cloud environments are being intensively developed nowadays. They are directly related to the development of AGIS CENSs, where multiple tasks need to be performed in parallel using cloud technologies for decentralized computing.

At present time, cloud computing is used in different spheres. However, the application of cloud computing to manage the information support of CENSs technologies was not described in the literature [10, 11]. This conclusion follows from the analysis of numerous publications. The explanation is software peculiarities: complexity, high price, and the skill level of those engaged in processing large amounts of data with specified requirements. Databases on different territories are needed for the information support of the CENS technology. They require the performance of large, complex, and expensive works as well as flawless operation of the means of using these databases.

CENS modeling tasks cannot be fully implemented using cloud technologies due to the existing technical and regulatory constraints:

- large amounts of data that are difficult to transmit over networks [12–15];
- limiting requirements for the use of aerospace survey materials, UAVs, or maps and plans of given scale and content.

In recent years, cloud technologies have been widely used to provide Russian government services. Note the National Digital Economy Project and its contribution to market growth and IT development.

The use of cloud technologies is subject to the following constraints: stability and recoverability, security standards, special standards, and compliance with state regulations.

Existing data are mostly unstructured, some are organized using metadata, with a crucial component to unify any data. Virtualization, parallel processing, distributed file systems, and databases used in computers significantly increase the efficiency of big data processing.

The Internet is a distributed computing network that requires powerful computers and, moreover, connection optimizers over WAN channels to improve big data processing. The components of this service need to be distributed among several nodes with the management of a hypervisor that supports the optimal utilization of the IT infrastructure. The structure and interoperable standardized environments of big data are essential for application access. These data are mostly in the form of conventional relational databases. The distribution of applications for parallel computing is the core of any big data solution.

According to the analysis of the available databases, the reflecting and absorbing characteristics are absent for many terrain objects. They are heterogeneous, not systematized, have different formats, and cannot be used to model search CENSs without preliminary processing. The external management of databases is difficult to optimize by software automation. Therefore, automatic data supply, copying, and scaling as well as database access security are problematical. Furthermore, such cloud environments are necessary for specialized organizations that have not yet formed databases of the reflecting and absorbing characteristics of terrain objects in different EMR wavelength ranges. This task requires many years of work.

All these considerations necessitate the use of distributed GISs, e.g., cloud GISs. Such a solution provides access to many types of information that can significantly increase the capabilities of GIS technologies to create new types of thematic GISs. Different

GISs can form their own databases, available to other users as a cloud service. Note the following aspect concerning cloud GISs: by now, GIS capabilities have almost not changed, and only the possibility of virtual work with GISs has been implemented.

The next section describes cloud technologies with parallel computing in CENS modeling tasks.

3. DISTRIBUTED AND CLOUD COMPUTING IN APPLIED GISS FOR MODELING CENSS

Distributed computing to perform tasks in applied GISs for modeling CENSs can be implemented on separate computers united in a parallel computing system. Such calculations can be in one organization or several specialized organizations. The entire package of tasks performed by an applied GIS can be arranged on one computer in a general-purpose GIS in the case of no time constraints. This approach involves a distributed database in the form of a set of relations constituting a single dataset. It can be accessed when performing any task from the set of tasks with simultaneous assignment of tasks to other computers, servers, and cloud services. Also, note parallel databases with a dedicated management system for parallelization of CENS modeling tasks.

The tasks performed in applied GISs in computing systems are represented as separate applications with different task decomposition methods (algorithms, hypotheses, etc.; see below). Nowadays, IT experts use mainly GIS technologies, e.g., in thematic cartography. On the one hand, cloud technologies contribute to IT development; on the other hand, not every platform can be used to process large amounts of data, including complex and bulky software.

Cloud services can represent data repositories for GIS technologies used to model CENS. These are aerospace images of different scales, as well as images obtained from UAVs in different EMR wavelength ranges. Images of appropriate resolution are used for high-accuracy navigation. Image processing requires applications, which are now being developed by some companies. For example, Esri considers cloud technologies one of the directions to develop the ArcGIS platform. A cloud variant of ArcGIS Server 10 is embedded in Amazon’s cloud infrastructure. Note that the software is not installed in the cloud environment: the corresponding functions remain in-house. This is a new technology for cameral and field surveying, where a cloud GIS provides the necessary access to data and tools.

Russian GIS products, both multipurpose and distributed, have been developing following the global trends in geoinformatics, i.e., client-server applications and support for Oracle Spatial [16].

The main Russian GISs are as follows: Panorama (Panorama Design Bureau), Talka-GIS (Trapeznikov Institute of Control Sciences, Russian Academy of Sciences), GeoGraf (Mining Exploration Center, the Institute of Geography, Russian Academy of Sciences), PARK (The All-Russian Geological Research Institute (VSEGEI), Moscow Branch), Sinteks ABRIS (TRISOFT LLC), and InGeo (Integro, Center for System Studies, Ufa) [17].

Panorama, the most famous GIS in Russia, also employs cloud technologies on the Panorama @ GeoCloud GIS station with a control system for selecting computing power and time of use. Developed by an Israeli company, this service provides remote work with software products, databases, and the best software solutions in GIS technologies. Currently, this station creates digital maps, processes remote sensing data, performs various measurements, and builds 3D terrain models from cloud databases created, however, by an Israeli company. This fact may be unsuitable for Russian users.

The current interest in cloud technologies does not reduce the interest in conventional GISs. It is possible to talk about distributed GISs as a service (cloud GISs), an additional platform to expand engineering solutions and optimize production costs simultaneously [14]. Hardware and software means provided and distributed through networks is an important line to develop new-generation GISs. Therefore, GIS tools for modeling CENS still remain more attractive. Data retrieval (visualization and loading if necessary) and data transformation according to the established requirements occur when accessing the appropriate services; these functions are implemented in GIS. Cloud service support is possible in terms of providing images, the spectral brightness coefficients of terrain objects in different EMR wavelength ranges. These services are departmental.

As a rule, GIS applications are implemented in one operating system. Simultaneous access to multi-task applications is possible; in this case, task calculations in applications have to be parallelized. When implementing several applications in GIS, it is necessary to speak about multithreading. In particular, this applies to the creation of disturbances for the operation of CENSs (stress exposures on the shooting system), random or purposeful [1, 2]. Assessing the performance of the shooting system of CENSs subjected to stress exposures is complex and multi-cyclic; it requires considerable processor time.

ArcGIS Pro is a multithreaded application. It offers over 70 surveying tools supporting parallel computing. As a rule, when working with ArcGIS Pro, it is possible to process geodetic data in the background mode and create maps and work with other scenes simultaneously [19]. However, no enterprises in Russia currently use this software product with vendor's technical support.

In GIS Panorama (ver. 12, Russia), multithreaded file processing is implemented. As a result, the performance of data processing is increased almost linearly (by the number of processor cores) based on MAPAPI interface functions adapted to multithreading [19].

Digital photogrammetric station (DPS) PHOTOMOD (Russia) can be used as a local DPS with a distributed network environment [20]. DPS is the main tool for creating high-quality images for AGIS CENSs.

Also, let us mention the Talka technology and the digital photogrammetric station developed at Trapeznikov Institute of Control Sciences (Russian Academy of Sciences) [21]. At present, it does not support cloud computing: the technology is conventional, being implemented on the institute's server. Most of the world's leading websites are currently inaccessible for Russian software products. Cloud services are also unavailable, and there are no Russian cloud services in GIS technologies.

Over the past 50 years, computing has been based on five major platforms: mainframes (powerful computing systems), minicomputers, personal computers, servers, and mobile devices. Now a sixth type, the cloud platform, is emerging. Therefore, GIS developers consider cloud services and parallel computing an important line for developing their own platforms, including AGIS CENSs.

When choosing an appropriate platform for multiple information tasks, one should keep in mind that the gain in computational efficiency depends on the task algorithm and the number of consecutive calculations [8, 22]. For some tasks, increasing the number of processors in a computing system not necessarily leads to higher efficiency.

In this case, Amdahl's law concerns not the components of a single task but the set of tasks implemented in applied GISs to design search CENSs with given properties for efficient navigation.

The following algorithms and hypotheses are directly related to the final result of the navigation system [23] and are used when implementing CENS models:

– the types of Earth's physical fields (optical, thermal, radio-thermal, radar, etc.),

– possible image search and processing algorithms in onboard computers,

– weather conditions at the time of navigation,

– possible carrier's location errors,

– possible sizes of navigation sections,

– linear sampling intervals of the original map,

– navigation system altitude,

– pattern recognition algorithms,

– scene analysis algorithms,

– algorithms for determining navigation references,

– clustering algorithms,

– training algorithms for neural networks,

– possible values of the CENS decision function for accurate navigation and navigation with a given error,

– stress algorithms for the shooting system of CENSs with different means of stress exposure in EMR wavelength ranges with specified conditions (accuracy, the capabilities of such means, etc.).

The map of stress exposures on the shooting system of CENSs is built in accordance with the adopted algorithms and hypotheses for modeling CENSs. This map determines the conditions of accurate (specified) navigation and navigation with a given error. All the algorithms and hypotheses mentioned above are dynamic: they can be changed within the specified ranges.

Distributed GISs installed in several relevant-profile enterprises may provide some cloud services. These can be data prepared in advance, e.g., maps with navigation properties of a given area based on images in different EMR wavelength ranges. In particular, such maps may have reference points obtained using the SURF method. This method searches for reference points in images using the Hessian matrix and then creates their descriptors invariant to the image scale and rotation.

Thus, the general-purpose GIS platform should be extended and implemented in the form of AGIS CENSs. The same applied GIS serves to implement the mapping models of stress exposures on the shooting system using the reflection and absorption coefficients of terrain objects [19].

Finally, note serverless cloud environments in which a database adjusts itself to the load [24]. The result of event processing is independent of the server memory state. These elastic calculations may be of interest in modeling CENSs and need further research.

Serverless computing has emerged due to the transition from servers to virtualization and containerization: more resources are provided for tasks rather than platform and infrastructure maintenance [12]. Essentially, this approach is an implementation of multithreaded and parallel computing in cloud serverless environments. Serverless computing is not yet used in Russian enterprises; see the publications [16–18, 25]. Probably, serverless cloud environments need not be used in cloud GISs, particularly in applied GISs for modeling CENSs. All necessary information should be concentrated on the servers of distributed GISs of several profile organizations. This issue is debatable.

CONCLUSIONS

Cloud technologies, parallel computing, and their state-of-the-art and use in cloud GIS have been analyzed. The main conclusions are as follows.

• The dependence of Russian organizations on foreign technologies has been very strong over the last few years. Many foreign IT vendors have recently left Russia and have limited supply and support of licenses, including data storage systems, servers, and information protection systems. There is an obvious need for a comprehensive approach to building domestic infrastructure, from architecture to data backup and protection.

• When introducing cloud technologies in a cloud AGIS CENSs, it is necessary to find novel architecture and software solutions and alternatives among Russian suppliers and developers. At the same time, it is necessary to solve the problem of product compatibility.

• In cloud environments, the execution of tasks that were performed autonomously in GISs should be planned using parallel computing in AGIS CENSs with specified properties considering the entire EMR wavelength range in transparency windows, including disturbances in the form of stress exposures on the sensors of navigation systems to ensure effective navigation under interference.

• The peculiarities of the parallel structure of CENS search algorithms are revealed. When implementing these algorithms in parallel computing systems, proper consideration of the peculiarities allows utilizing their advantages to the highest degree. A computing system for modeling CENSs should provide parallelism at the level of command and data flows when implementing the models of search CENSs using cloud technologies and parallel computing**.**

• The components of AGIS CENSs with analogs in related problem domains have been identified. Under appropriate access to such components and data, the implementation costs of AGIS CENSs can be minimized. Access can be organized in a network of distributed GISs with the required level of information protection.

• It is possible to implement AGIS CENSs using classical technologies based on the existing image analysis and processing systems, cloud GISs, and general-purpose cloud technologies. At present, classical image processing technologies remain the most attractive. In this case, source materials must be used in strict compliance with the corresponding regulations; the materials used and created must be protected. General-purpose cloud technologies will still occupy an insignificant place in the tasks of modeling CENSs: the creation of new applications will require time and funding.

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