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Maritime Situation Monitoring for Safe Navigation on Northern Sea Route

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ABSTRACT: Considering growing intensity of navigation on Northern Sea Route and of continuous exploration and development of Arctic shelf, problems of maritime situation monitoring in Arctic become particularly important. Firstly, complex operational informational support of activities in Arctic is needed. Secondly, constant access to actual and valid information about hydro-meteorological, navigational and ice situations is required.
Solution of stated problems entails integration, processing and analysis of large amounts of heterogeneous data. Consequently, development of unified system for situation monitoring and intellectual support is essential.
Such system allows to execute operational monitoring of dangerous situations of different sort (natural or anthropogenic) that influence safety of objects in Arctic region, and to perform intellectual analysis of such situations and prompt provision of suitable recommendations.

1 INTRODUCTION

In the last decade, interest in major Arctic waterway – Northern Sea Route (NSR) is constantly increasing. Mostly, it is due to discovery and development of new promising oil and gas fields on Arctic shoreline and on shelf and, as a consequence, due to constantly growing demand for transportation of various cargoes. According to different sources Russian Arctic region contains from 15% to 25% of world's energy resources. Despite the evident profit of using NSR, practically all its sections are characterized with harsh weather conditions, complex hydro-meteorological, ice and navigational situations, underdeveloped shore infrastructure, far reach from main industrial centers.

It stands to mention that, at present time, considerable amount of various maritime situation monitoring systems of local and global scale are functioning. Main purpose of such systems is aggregation of information from primary sources – sensors (AIS, satellite AIS, radars, reports from vessels and etc.) and its representation on digital map. Users of such systems are able to acquire information in real time scale about vessel's location, its current route and its route history for a given period of time. Popular examples of such systems are MarineTraffic [1], ShipFinder [2], which are open web-services. Moreover, data could be acquired form closed systems, with the consent of owners, such as vessel monitoring system "Victoria" [3] and others.

However, at present stage of maritime monitoring system development, it is not enough for user to only have access to information about location of his and nearby vessels. Year after year, requirements for "intellectual abilities" of maritime monitoring systems have been growing. It is necessary to possess accurate and prompt information about hydro-meteorological dangers (strong wind, thick fog, and rough sea), navigational dangers (shelves, reefs, and drifting ice), ice situation in vessel's navigation area.

To increase the quality of representation and processing of information about maritime situation geoinformation system (GIS) technology is usually used. Modern GIS provide new, convenient and fast approach to analysis of various problems and to solving complex tasks. GIS capabilities allow to predict evolution of events and occurrences of outside world, with their processing and identification of major factors and causes, and also to predict possible consequences, to plan activities and to provide decision making support.

However, in traditional GIS approach, the user usually is bound to process large amount of data, entering the system, about situation development himself, relying on his intuition and experience, and resorting to relatively simple primary means of data analysis. At that, the rate of data flow that information system operator receives has a tendency only to increase. It is due to growing software capabilities and engagement of additional information sources. All this leads to inevitable demand for new method of GIS intellectualization in order to increase GIS capabilities.

For the benefit of monitoring and analysis of maritime situation and safe navigation support in Arctic region, it is necessarily to develop specialised system of situation monitoring and intelligent decision making support. As a basis of such system intelligent geographical information system [4–6] is to be used, which is designed to effectively solve tasks of determination of vessels' locations and nature of maritime objects' activities, of automated control of complex situation development and interpretation of results of situation analysis.

In this paper we present an approach to development and creation of situation monitoring system and intelligent decision making support. Principles and technologies of situation awareness estimation are also covered. Main factor of this approach is application of intelligent GIS, that allows to solve tasks, related to automatized control over development of complex situations, interpretation of analysis results and intelligent identification of location and nature of activities of maritime objects.

2 RELATED WORKS

Currently, different countries, members of Arctic block, have concluded large number of scientific researches, have created a lot of concepts and have carried out considerable amount of projects [7-8] focused on development of Arctic region. It is noteworthy that due to unique specificity of the region, application of maritime monitoring systems, existing at the moment, without preliminary specific adaptation is near-impossible.

In 2009 Norwegian government initiated a project called i-Nord [7], aimed at Arctic Ocean monitoring and based on Norwegian Government's High North Strategy. Main objective of this project is creation of integrated information system, that allows to solve issues of safety, ecology, monitoring of oceanic processes and events, climatic changes, fast response to emergency circumstances, control of industrial businesses' activities, such as oil and gas production, fishing and etc. Fully functioning version of the system is intended to appear in 2017. However, the main focus of this project is Barents Sea.

On 16th of March 2012 the Defence Advanced Research Projects Agency (DARPA) of the US Department of Defence has announced an open competitive tender for R&D of autonomous distributed unmanned (robotic) system for integrated monitoring and surveillance in Arctic [8]. The objective of this project is to provide information to clients about current situation in Arctic region: on the surface (above-water, land), underwater (under ice and on the bottom) and air situation.

As can be seen, for support of safe navigation, for reconstruction and development of transport infrastructure of Arctic region it is essential to develop a global maritime monitoring system for whole Arctic that will allow not only to perform surveillance along the NSR but to coordinate and support decisions of operators, responsible for ship-traffic control. Such global system will allow to monitor ecological, terrorist, natural and other threats and alert about them in time.

3 MARITIME SITUATION AWARENESS

Estimation and detection of dangerous situations is one of the key problems of maritime activities monitoring and decision support. The term maritime situation denotes a combination of some parameters, directly or indirectly defining observable system's state in given point of time. Maritime situation awareness represents analysis of certain characteristics for obtaining conclusion about current state of system and its possible state in near future [9]. The term situation management, in turn, denotes purposeful influence on system aiming at changing the situation to our benefit. Stated influence can be accomplished by executing certain actions, oriented on changing system's properties, characterized by detected features.

Maritime situation awareness suggests:

- detection of factors (features) that influence development of dangerous situations in maritime activities location;
- visualized mathematical (computer) modelling of current situation in real-time mode;
- prediction of further development of dangerous situations and their analysis;
- generation and execution of decisions regarding further actions concerning arising dangerous situations.

The basis for estimation and detection of dangerous situations is situation awareness model proposed by M. Endsley [10]. Under situation awareness is understood "perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [10].

The situation awareness model includes three levels [10]:

– Level 1 (Perception of the elements in the environment) – perception of the current situation, its properties and dynamic development of elements, related to observed situation, in environment.
– Level 2 (Comprehension of the current situation) – synthesis of the disconnected elements of the situation received on the Level 1, comprehension and processing of information, integration of various heterogeneous data and determination of its significance for particular situation.
– Level 3 (Projection of future status) – available prognosis of future actions and future situation development based on knowledge of situation status and its elements development, for taking decisions on future actions betimes.

And reasoning thus the problem of integrating heterogeneous information into an ultimate picture of the environment at the semantic level of human comprehension and projection remains open.

For effective usage of situation awareness, integrated approach on ontologies and IGIS-technologies is applied. Ontology model is a symbolic description of the subject domain in form of concepts and relations between them. In [11] the description of the ontology-based situation awareness approach based on situation theory is discussed. The piece of information according to this theory is called infon. Infons are written as:

$$<< R, a_1, ..., a_n, 0/1 >>,$$

where R – n-place relation; $a_1,...,a_n$ – objects peculiar to R; $0/1$ – polarity of infon. The value 1 means that, in the situation s, objects $a_1,...,a_n$ stand in the relation R. The value 0 means that, in the situation s, objects $a_1,...,a_n$ do not stand in the relation R.

Infons of subject domain consist of objects, their properties and relations existing in the given subject domain. Relation between situations and infons write as:

$$s \models \sigma,$$

means, that infon σ is made by the situation s. The official terminology is that s support σ.

In addition, for current situation monitoring, operational forecasting, well-timed decision-making in dangerous situation and recommendation for their prevention, IGIS-technologies described in [6, 12] should be used.

Objects for situation planning of vessel routes are ships (cargo vessels, tankers and etc.), ice-covered regions, weather conditions, and such areas as oil spill area, closed for navigation area and others. Vessels make voyage from a starting point to a final point. On all waterways there can be various dangerous situations influencing vessel safety. In this paper we consider three dangerous situations: influence of the ice situation, weather conditions and oil spill situation on the vessel route.

Let us consider these typical situations that are common for navigation on the Northern Sea Route. Among those are dangerous ice conditions (*IceDangerVessel*). Status of the ice cover affects vessels velocity and increases travel time on planned route. Besides, vessel's velocity is reduced due to the danger of damage to the hull inflicted by ice. Mathematically, this information can be presented by the following relation tuples **near**(*Ice*, *Vessel*), **clash**(*Ice*, *Vessel*) and **threat**(*Ice*, *Vessel*). Given infons relations can be written as follows:

$$IceDangerVessel \models << location, Ice, L_{Ice}, 1 >>,$$
$$IceDangerVessel \models << velocity, Ice, V_{Ice}, 1 >>,$$
$$IceDangerVessel \models << location, Vessel, L_{Vessel}, 1 >>$$
$$IceDangerVessel \models << velocity, Vessel, V_{Vessel}, 1 >>,$$
$$IceDangerVessel \models << near, Ice, Vessel, 1 >>,$$
$$IceDangerVessel \models << clush, Ice, Vessel, 1 >>,$$
$$IceDangerVessel \models << wait, Ice, Vessel, 1 >>,$$
$$IceDangerVessel \models << isSafety, Ice, Vessel, 0 >>,$$
$$IceDangerVessel \models << threat, Ice, Vessel, 1 >>.$$

Here L_{Ice} – ice location. L_{Vessel} – vessel location, V_{Ice} – ice velocity, V_{Vessel} – vessel velocity.

Another representation of infons for *IceDangerVessel* situation is shown in Fig. 1.

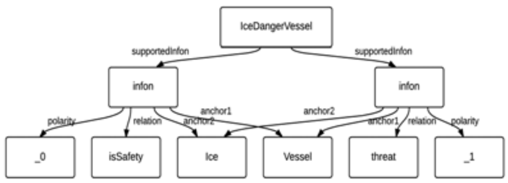

Figure 1. Two infons for IceDangerVessel situation

Another situation that occurs during the vessel route planning in the Arctic region is various meteorological conditions affecting the navigation (*WeatherDangerVessel*). This situation is similar to the *IceDangerVessel* situation. Infons for this situation can be written as follows:

$$WeatherDangerVessel \models$$
$$= << isWind, Weather, Vessel, 1 >>,$$
$$WeatherDangerVessel \models$$
$$= << isHeavy, Weather, Vessel, 1 >>,$$
$$WeatherDangerVessel \models$$
$$= << isFog, Weather, Vessel, 1 >>,$$
$$WeatherDangerVessel \models$$
$$= << wait, Weather, Vessel, 1 >>,$$
$$WeatherDangerVessel \models$$
$$= << isSafety, Weather, Vessel, 0 >>,$$
$$WeatherDangerVessel \models$$
$$= << isDanger, Weather, Vessel, 1 >>.$$

Figure 2 shows two infons for *WeatherDangerVessel* situation.

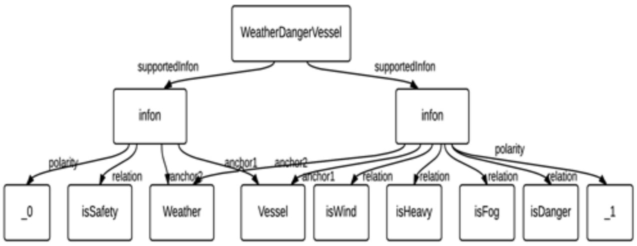

Figure 2. Two infons for WeatherDangerVessel situation

Finally, the oil spill situation and closing of area for navigation on the planned route is possible (*OilSpillArea*). In this case, it is necessary to make changes in the planned route with consideration of by-passing closed area, meteorological and ice conditions. The additional infon for this situation is the following (Fig. 3):

$$OilSpillArea \models$$
$$= \ll near, Vessel, OilSpillArea, 1 \gg,$$
$$OilSpillArea \models$$
$$= \ll changeRoute, Vessel, OilSpillArea, 1 \gg,$$
$$OilSpillArea \models$$
$$= \ll isSafety, Vessel, OilSpillArea, 0 \gg.$$

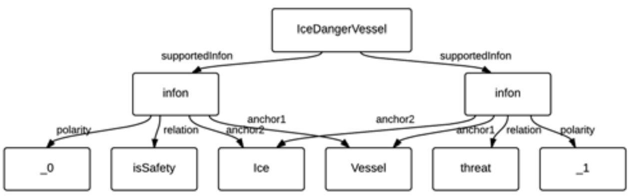

Figure 3. Two infons for OilSpillArea situation

For each of above-mentioned infons we can define rules which allow to describe the set of IGIS-actions in case of changes in the current situation. For this it is necessary to define classes for each of the three parts of the rule. Also we suppose that the following classes are already defined in the ontology: *IceThreatenVessel*, *WeatherThreatenVessel* and *OilSpillThreatenVessel*.

4 IGIS FOR ESTIMATION OF MARITIME ACTIVITIES' SAFETY

The term intelligent GIS is defined here as GIS that includes integrated tools and/or systems of artificial intelligence (AI) [5].

Figure 1 illustrates IGIS architecture. The central part of the IGIS is knowledge base including ontology. Ontology presents the 'framework' for representation concepts and relations between them in subject domain. Another part of knowledge base is storage of subject domain real object instances.

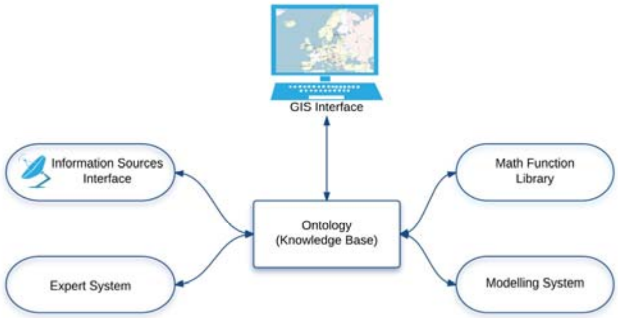

Figure 4. Intelligent GIS architecture

Various active and passive sensors (AIS, radar) as well as information systems of global and local level can act as sources of information for maritime navigation system. While obtaining data from different sources the following problems may arise. Firstly, duplicated information: obtained information from different sources about same objects. However, similar data about same object is not necessarily a disadvantage since it increases credibility of data and consequently increases quality of specific decisions. One of the means for solving duplication problem and increasing quality of data obtained from various sources is application of concept of integration, harmonization and fusion of data which is described in [6].

Second problem is the issue of discrepancy between concepts in different systems. To format initial data to one standard we have developed a unified information interoperability model on basis of ontology database. Information interoperability model includes three ontology levels: domain ontology, geographical ontology and upper ontology.

GIS-interface is a program component for visual representation of geo-spatial data in various digital formats and of objects stored in knowledge base (Fig. 5). It combines different sources of geo-spatial data and program components that execute data processing using traditional methods.

GIS-interface allows:

- to update and display data in real-time mode along with processed results, predicted and modelled data;
- to display all infrastructure of observed area of maritime activities;
- to set combinations of algorithms for execution of all stages of dangerous situation modelling (verification, interpolation, prediction);

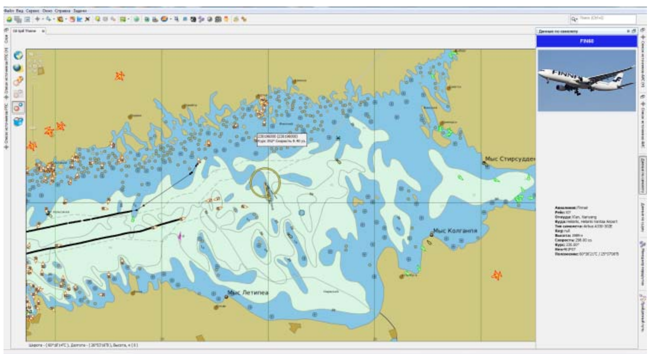

Figure 5. GIS Interface

Library of mathematical functions is one of the important parts of intelligent GIS. Set of functions has to be open for access by any subsystem of IGIS, support changeability and expansion.

For example, for modelling spatial processes associated with dangerous situation development in maritime activities location following functions from library can be applied:

- mathematical model of different dangerous situations (e.g. oil spill, seizure of vessel by pirates and etc.);
- vessel navigation on given route;
- search in location of rescue operation and etc.

To increase the quality of specific decisions made by user it is necessary to include prognostic models in mathematical functions library, i.e. such models, that allow to obtain estimation of dangerous situation development in future instances of time, based on data obtained to the current point of time.

It should be noted that any function from mathematical functions library can be used in creating production rules for expert system.

The term expert system (ES) denotes a system that utilizes expert knowledge (knowledge form specialists) to provide qualified solution to tasks in given field of study [6].

Such systems are able to present knowledge, to clarify (examine) their processes-reasonings and are intended for fields of study where a person can reach professional level only after years of special education and training.

Expert knowledge is represented in form of condition-action rules and is saved in IGIS knowledge database. Let us note that any of mathematical functions given in library can be used in creating rules for IGIS expert system.

Expert system allows to execute integrated assessment of maritime activities' safety and suggest further actions to user in case of dangerous situation arising. For example, if system's user views successive triggering of rules: "Dangerous closing-in of vessels 1 and 2" and "Vessel 2 has left channel", evident is situation: "Vessel 2 has violated regime of navigation".

IGIS modelling system is intended for computer modelling of various spatial processes and also for visual generation of corresponding scenarios of processes development based on expert systems technology and represented as ontology database. Visual representation of the modelling allows the user to effectively estimate occurring process.

Modelling system allows us to solve the following tasks:

- Building models of complex spatial processes based on their description in form of visual scenarios that are represented as two-dimensional digraph (block-scheme) where nodes are separate scenario tasks and decision making points in which scenario branches on various execution routes depending on satisfaction of specified conditions (Fig. 6). Scenario tasks can be executed both sequentially and in parallel, depending on block-scheme. For merging parallel branches special nodes "connectors" are used. Scenario tasks consist of individual atomic actions and are as well represented as block-schemes connecting atomic actions. Task's actions can also be executed both sequentially and in parallel, depending on task's block-scheme.
- Construction, debugging and testing of scenarios by field of study specialists mostly with use of visual drag-and-drop of icons, corresponding to tasks, solutions and actions, to the scenario and task scheme form and connecting them in accordance with scenario logic.
- Scenario execution of complex spatial processes in optional time scale against digital map background, represented as moving simulated point objects with changing form, size, location, colour, transparency and etc. extended objects along with messages on natural professional language.
- Interaction of number of complex processes, modelled on one as well as on several machines in network.
- Manual object and process control option, modelling process in general (start/stop, time scale change, maps and etc.), scenario replay from control point, time jumps and etc.

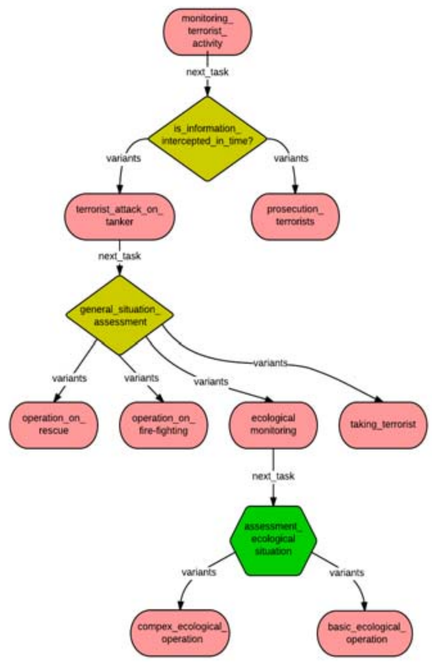

Figure 6. Example of terrorist situation assessment

5 CASE STUDY

As an explanation, consider the following situations that demonstrate maritime dangerous situation assessment using the proposed IGIS-technologies.

Situation 1. In the Barents Sea at crash of the tanker there was an oil spill up to 5000 tons within 3 days. Figure 7 shows the scenario of oil spill taking into account navigation conditions around a dangerous situation, hydrographic and hydro-meteorological situation. Also the assessment and the analysis of an ice situation is done.

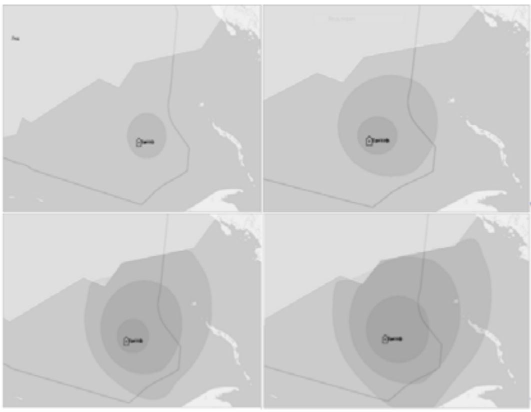

Figure 7. Oil spill modelling

The mathematical model on the basis of which the scenario was developed considers coastline, ice situation in given area, water flows and weather conditions. Figures 8–9 show modelling of the ecological search and rescue operation using IGIS.

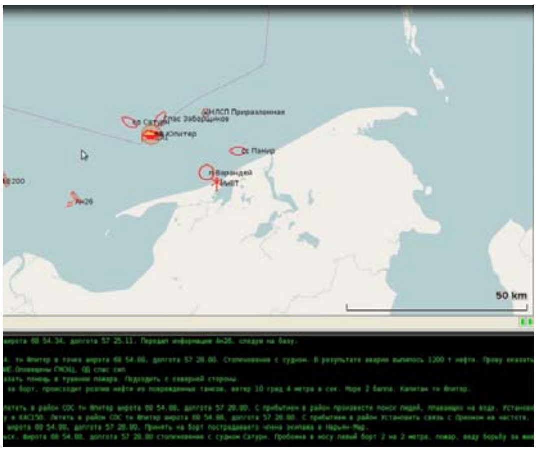

Figure 8. Modelling of search and rescue operation

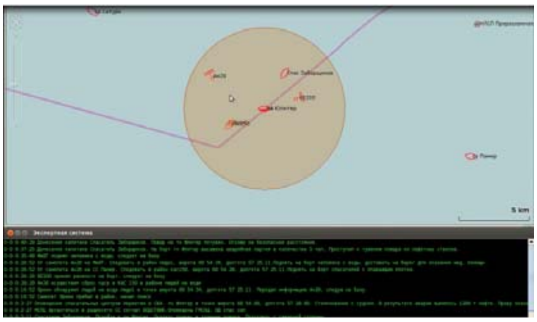

Figure 9. Modelling of search and rescue operation

Modelling of search and rescue operations allow to carry out the analysis of the estimated action plan, to estimate efficiency of rescue forces' actions, to consider various weather conditions and features of the area.

Situation 2. A cargo vessel V goes along pre-planned route on the part of Northern Sea Route (Kara Sea) (Fig. 10). The east part of the Kara Sea is ice-covered; an icebreaker is opening a safe passage through the ice field of Malygina Strait (Fig. 11).

It's also known that some parts of the Kara Sea along the pre-planned route are dangerous due to weather conditions (storm alert, WMO sea state code: from 5 to 7) (Fig. 11).

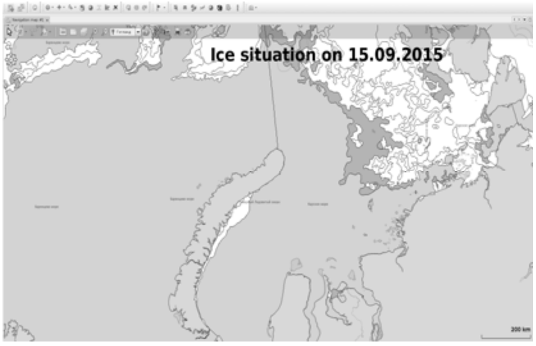

Figure 10. Ice situation in the Kara Sea

The ice and weather conditions maps are used to objects construction which involving in further calculations. Such objects may include weather dangerous regions, ice dangerous regions, closed regions and others. Then dangerous regions are transformed into multipoint polygons. These polygons are instances of ontology class [13].

Oil Spill Scenario: At about 00:00 am the tanker T collides with a cargo ship, the C, and spills oil from a damaged tank. The tanker T radios to report that the vessel has leaked about 4,000 tons of crude oil. The location of the collision and oil spill is known and marked on digital map. At the same time the vessel V is already going along the planned route on the part of Northern Sea Route where the dangerous ice covered areas are present.

IGIS has been used for quantifying oil spill size and trajectory [14] and for estimating the oil spill area. Model takes into consideration the following factors:

– coastline;
– ice situation in the area of interest;
– water flows;
– weather conditions.

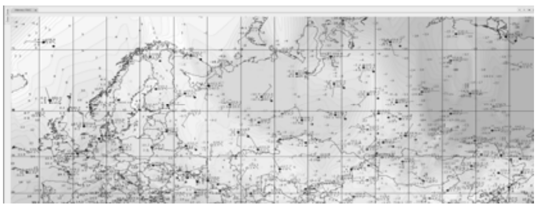

Figure 11. Weather conditions along the Northern Sea Route

In addition, IGIS knowledge base can store information from previous incidents and present it through additional expert system rules which can be used in future.

The current dangerous situations along the pre-planned route of the cargo vessel V are shown in the panel "Situation awareness" and on the digital map of IGIS (Fig. 12).

The rule for inferring this situation and supporting route change decision-making is as follows:

If
belongsTo(X, Vessels)
and belongTo(Y, OilSpillAreas)
and near (Y, X)
Then
threat(Y, X)

Then we define situation type for given situation. At any time vessel that by-passes closing of area for navigation (oil spill area) can meet ice and ice will be threat to vessel if vessel is near the ice and moving in the direction of ice. This condition can be represented in the form of mathematical expression as subsumption rule:

$$S_1 \cap S_2 \Rightarrow S_3,$$

where

$$S_1 = \{s \mid s \models \ll near, Ice, Vessel, 1 \gg\},$$
$$S_2 = \{s \mid s \models \ll inDirectionOf, Ice, Vessel, 1 \gg\},$$
$$S_3 = \{s \mid s \models \ll clush, Ice, Vessel, 1 \gg\}.$$

Subsumption rule is the basis for description logic [15], which is the underlying logic for IGIS Modelling System.

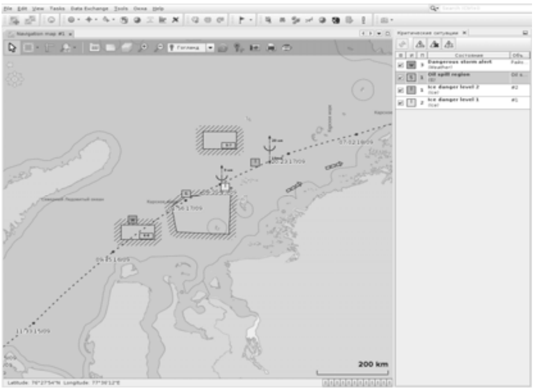

Figure 12. Initial vessel route built with IGIS

The above-mentioned rules were saved in IGIS knowledge base and used for situation awareness along the pre-planned vessel route. The results of the rules inferring are shown on the digital map of IGIS with special marks along the vessel route. The throughout descriptions of detected dangerous situations are presented in the panel “Situation awareness” of IGIS.

Alternative vessel route has been chosen for vessels instead of regularly used one to avoid oil spill area, storm dangerous waters and ice-covered regions of the Kara Sea (Fig. 13). The alternative vessel route was automatically constructed and shown on the digital map of IGIS MSRS. So IGIS supports intelligent decision making for maritime safety monitoring in the Arctic.

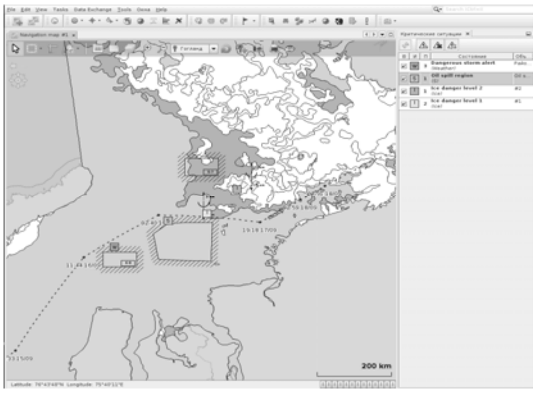

Figure 13. Alternative vessel route built with IGIS

6 MOBILE IGIS

On the base of stationary maritime situation monitoring system mobile version was created. The developed mobile IGIS is indented for mobile devices such as smartphones, laptops, tablets with Android operating system. To update the information model and download the function modules Internet access is required.

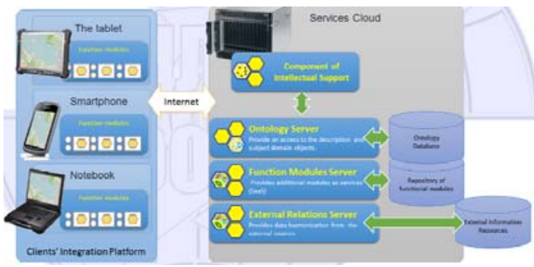

Figure 14. General structure of the mobile IGIS for vessels

The generalized structure of the mobile IGIS is shown on Figure 14. System includes the following elements:

- Cloud Services Platform – network of distributed servers that provides the set of necessary services;
- Client Integration Platform – application, that provides necessary interfaces for connecting modules that implement required features and that are installed on the mobile device.
- Function Modules Repository – storage of functional modules, capable to extend functionality of client’s integration platform.

By means of these structure components mobile IGIS supports a wide range of functions and services such as:

- displaying the nautical chart showing the location of user’s own ship and other maneuvering vessels;
- option of manual and automatic (AIS, radar) targets’ drawing, target movement calculation;
- ship’s routing between predetermined ports/points, accounting for the navigational area features and desired duration of movement/recreation;
- display and registration of weather data at a point/on the route, broadcast of storm warnings;
- calculation of manoeuvres aimed at storm escape; speed and course calculations;

- solving tasks of manoeuvring; positions' gaining and targets' passing;
- warning about dangerous manoeuvres; entry into the closed/restricted areas, areas with special conditions for navigation, shallow water areas;
- warning of manoeuvres on the route in advance (time and turning point, speed changes, etc.);
- retrieving data about locations of other vessels equipped with mobile IGIS.

Figure 15 shows a map where vessels' icons, routes (blue line) and additional information are plotted. The data on the map are updated in real time mode. By clicking on the vessel's icon additional information about the vessels, such as vessel's location (latitude and longitude), their lengths, widths, speeds, courses and names can be obtained. Various colours are used for displaying various vessels' types: green colour for cargo vessels, blue – for passenger vessels, orange – for high speed crafts, grey – for unspecified vessels.

It is necessary to notice that the system is rather simple and easy in use; the user needs no additional knowledge and skills to start working with the system. Furthermore, the system can work in autonomous mode that allows using the system without a permanent connection with the server during a certain period of time.

Figure 15. Vessels' routes

7 CONCLUSIONS

Marine transportation in the Arctic plays a critical role in the development of the region. The approach described in this paper considers the development and implementation of maritime situation monitoring system based on the IGIS concept and technology of maritime safety assurance in Arctic area. The approach has demonstrated a fusion of different science and technology: GIS, intelligent GIS and mathematical methods.

New technologies and methods of dangerous maritime situation assessment with application of IGIS tools, proposed in this paper, are designed to increase the security of maritime activities seeing that dangerous maritime situation progress modelling requires application of various mathematical methods and models.

Considering further research, we plan considerable expansion of services for solution of a larger class of tasks and problems connected with assessment of dangerous maritime situations, extensions of the knowledge base due to introduction of new rules and scenarios for new types of dangerous situations. We are also actively developing user services and instruments for mobile IGIS.

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