Maritime Safety Monitoring On The Northern Sea Route

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***Abstract*—GIS-oriented systems are often used for maritime safety monitoring and situation assessment. Such systems allow to analyze, visualize receiving information and what is more to support organizational decision-making processes in various dangerous situations. This paper presents an approach to maritime safety monitoring in the Arctic seas on the base of special system – intelligent GIS. Ontology, expert subsystem and some other artificial intelligence technologies are proposed as basic ones for the system implementation. The application of the technique is illustrated via case study of situational route planning for a vessel navigating along the Northern Sea Route.**

I. INTRODUCTION

Over the last decade, there has been an increasing interest in the use of the Northern Sea Route for marine transportation. The route along the arctic coast of Russia does not only offer alternative to the Suez Canal (due to the huge reduction in distance from Western Europe to East Asia) or Panama Canal, it can also be used for supporting oil and gas industry in the Arctic.

However, the opportunities afforded by Arctic navigation can be greatly lessened by some specific aspects. The region above the Arctic Circle is characterized by extreme climate with short summers and long polar nights, extensive snow and ice cover and large areas of permafrost. Some regions of the Arctic Ocean remain ice-covered for much of the year, and nearly all parts of the Arctic experience long periods with some form of ice on the surface. Average summer temperatures range from about −10 to +10 C, winter temperatures can drop below −40 C over large parts of the Arctic. Average amount of storms in Arctic Ocean can reach 22 with duration up to 9 days. For example, some parts of the Northern Sea Route are covered with ice more than 7 months a year. The thickness of ice can reach 2 meters, the thickness of ice hummock – 6-8 meters.

Trans-Arctic navigation is also complicated by the general lack of the marine infrastructure throughout the Arctic Ocean. Comparison of the Arctic and mid-latitude routes shows that existing Atlantic and Pacific routes have rich historical experience of navigation, detailed and constantly updated navigation nautical charts, and a large number of navigational aids (buoys, lighthouses, lanterns, etc.). The situation in the Arctic is different. Although Russian Federation has an extensive system of fixed and floating aids to navigation, the possibilities of the system are not sufficient for safe marine navigation in the region.

At present, many of government and commercial organizations use a large number of marine traffic monitoring systems, decision support systems and navigation systems to solve the common safety tasks of marine navigation. However, such systems are not always able to solve specific problems related to the safe navigation in the Arctic.

This paper describes an approach to situation awareness, which allows supporting the safe navigation in the Arctic. The proposed approach is based on GIS technology, intelligent analysis tools and special-purpose mathematical models (including forecasting). Authors argue the use of AI technologies allows flexibly adapting to the conditions of the Arctic and solving wide range of specific tasks.

The outline of the paper is as follows. The next section discusses the related works. This is followed by the intelligent GIS overview and intelligent GIS architecture description in Section III. Section IV presents the basic approach for vessel route planning. In Section V we introduce an ontology-based approach to situation awareness for vessel route planning in the Arctic. Section VI describes a case study of situation awareness for vessel route planning along the Northern Sea Route. Conclusions are presented in the final section of this paper.

II. RELATED WORKS

In papers [1], [2] authors discuss various aspects of safe navigation in the Arctic. The main attention was given to changing ice situation and challenges for ships navigating in the Arctic waters.

In paper [3] authors focus on the concept of situation and ontology-based situation awareness. Authors define a situation in terms of so-called “infons” and suggest using rule-based inference for situation assessment.

In paper [4] is given an example of safe navigation system based on GIS technology. Main attention is given to the issues of navigation monitoring in vessel’s location area and system’s functioning in real-time mode. It is necessary to note that this paper is dedicated to the problem of shipborne system development. Integration of solution suggested in [4] with added intelligent navigation system is presented as one of the new lines of research.

Paper [5] describes capabilities of modern GIS for "intelligent decision making" in information systems associated with safety of maritime activities. Authors pay close attention to perspectives of cooperation of different organizations that possess important information about various fields of maritime activities. Also, aspects related to training personnel to operate monitoring and safe navigation systems are considered in this work.

In paper [6] development of intelligent GIS for maritime situation monitoring is studied in detail. Also, this work focuses on issues of integration, harmonization and fusion of data, obtained from various sources (sensors). In the paper ontology approach is offered as basic one for IGIS architecture.

In paper [7] authors discuss how intelligent GIS may be used for scenario-based geospatial processes description of dangerous situations in different subject domains.

III. Intelligent GIS

Geographic information system (GIS) provides a powerful tool for analyzing dangerous situations in different subject domains [6], [8].

Usually GIS allows to solve the following problems: manage, analyze, visualize and produce geospatial data.

However, great number of problems cannot be resolved with traditional approaches realized in common GIS.

Technological advances in Artificial Intelligence (AI) are providing new tools with potential application in spatial data analysis. These technologies not only promise to add accuracy and speed to the decision making and geospatial process prediction, but also to provide a GIS with more user-friendly and intellectual interface.

The main methods and technologies that can be used in GIS intellectualization are

- intellectual data processing;
- intellectual data mining;
- expert system;
- machine learning;
- neural networks.

Utilizing methods and technologies of AI can greatly improve the efficiency of GIS and let us talk about so-called intelligent GIS (IGIS). In this paper, IGIS is considered as a GIS that includes integrated tools and/or systems of artificial intelligence. IGIS is basically an information system designed to interact with spatially referenced data.

Through the use of GIS technology can be solved various complex problems such as

- monitoring of different situations (sea, air, ground and space situations) in near-real time;
- intelligent decision support and situation assessment using modern methods and artificial intelligent techniques;
- spatial processes trend prediction;
- complex geospatial processes modelling including visual creation and execution of scenarios.

Usually IGIS includes following basic components [6], [9]:

- an inference machine and expert system;
- a knowledge-based system (ontology);
- a visual environment for developing classes and objects of a subjects domain;
- a visual environment for developing models of objects;
- a system for scenario implementation in real-time using special visual development environment;
- recommendations for decision makers during the scenario planning, situation analysis.

Consider the general structure IGIS for maritime safety monitoring. Such monitoring system incorporates six basic components: information sources subsystem, expert system, ontology, modelling subsystem, math function library and GIS interface.

Fig. 1 illustrates IGIS architecture. The central part of the IGIS is a 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, which can be used for real-time situation assessment.

The information sources interface performs the communication between sensors (acoustic, radar, location) and IGIS for maritime safety monitoring. Also we consider the following information system as information sources:

- vessel traffic monitoring systems;
- remote sensing and Earth system;
- hydroacoustic monitoring system of ice situation;
- hydrometeorological and ice situation data base.

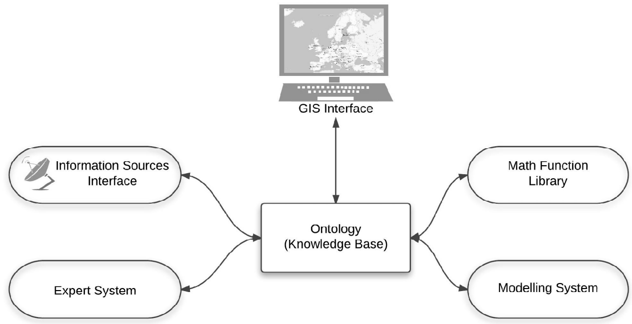

Fig. 1. Intelligent GIS architecture

GIS Interface provides a set of interfaces for interaction with other IGIS components at technology level.

GIS Interface is used for:

- displaying many forms of incoming data in real time mode;
- visualizing results of spatial processes analysis, prediction and modeling;
- choosing combination of algorithms for modeling.

Math Function Library is an important part of IGIS. The library includes set of special mathematical functions and models that can be used by any IGIS subsystem. The set of functions supports extension and variability.

For example, for modeling 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, terrorist and etc.);
- vessel navigation on given route;
- search in location of rescue operation and etc.

Expert system is a rule-based system that uses human expert knowledge to assist decision-makers in developing response to dangerous situation risks.

Such system "knows" how to obtain knowledge from a human expert and code it into form that the IGIS may apply to similar problems. Expert's knowledge is described in the form of producing rules and saved in IGIS knowledge base. It is necessary to mention that any of the mathematical functions from Math Function Library can be used in rules.

IGIS Modeling system provides a powerful tool for computer modeling of various geospatial processes. The important part of modeling system is an interactive visual environment for scenario development.

IV. VESSEL ROUTE PLANNING PROBLEM STATEMENT AND ASSUMPTIONS

The problem of vessel route planning can be considered as the choice of safe navigation points. The procedure can be divided into the following steps:

Step 1: Choice of the all possible safe navigation points in the region.

The first step is usually assisted with properly updated navigation nautical charts and suppose that the sea region in interest has to be 'covered' with so-called "possible route points". Each point has coordinate (latitude, longitude) and may be used as a node for some route, two points are chosen as start and end points. Then the vessel route can be defined as a path in directed or undirected geospatial graph where points are nodes connected with arcs. (Fig. 2). In Fig. 2 points, which cannot be used as route nodes, are marked with black fill.

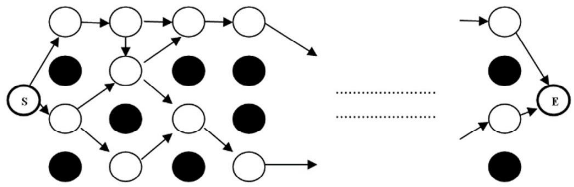

Fig. 2. Vessel route and geospatial graph (safe navigation points)

In practice, nodes positioning and binding can be performed with geographical information system (GIS) and digital navigation chart.

Step 2: Choice of the possible safe navigation points in the region with regard to weather and ice information.

Safe marine navigation in the Arctic depends on accurate and timely weather and ice information to help to minimize the risk of accidents in this challenging environment.

Some of the possible vessel route points can be navigation dangerous ones because of weather or ice situation in the region. For example, according to navigation map a point can be used for vessel route planning, but due to wind and wave forecasts, the using of the point as a route node is not reasonable. In Fig. 3 these points are marked with gray fill.

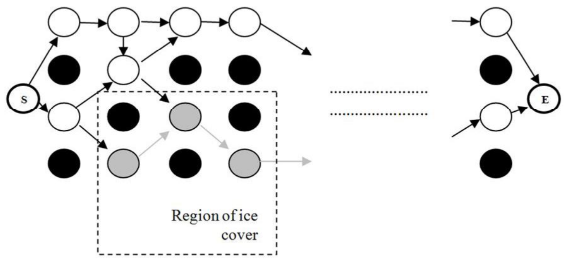

Fig. 3. Vessel route and geospatial graph (with regard to weather and ice information)

Step 3: Choice of the optimized route.

The vessel owner or captain often has the problem of determining the optimized vessel route (based on different criteria). It is clear that the mentioned above graph may be considered as weighted, so each arc has its own positive weight.

The cost of route's arcs may have a following meaning:

- distance between nodes (the simplest case);
- the fuel cost;
- the cost of the passage through some route parts; etc.

Further, the problem may be reduced to the shortest path problem (or the linear programming problem) and the optimized vessel route can be found in polynomial time.

It readily seen that all of the three steps are easy in theory but difficult in practice. The first problem is in the choice of the safe navigation points for our future route. In the mid-latitudes and the low-latitudes the ships often go on standard and proven routes; route planning can be performed simply by the selection of one of the well-known routes. For some parts of the Northern Sea Route, there exists no standard routes; planning of the route also depends on current ice, weather situation. Moreover, many high-risk areas in the Arctic are inadequately surveyed and charted that means that some charts available to mariners may not be current or reliable.

The other problem consists in the necessity of correcting the planned route when our vessel is already on the route. The necessity can be explained by fast changing ice and weather situation in the Arctic Ocean, need to use icebreakers for the parts of the route, etc.

Authors suppose that in order to handle the problems the new techniques have to be used. One of the most perspective approaches to solving the problem is to use GIS-technologies with artificial intelligence and situational planning methods.

V. SITUATION AWARENESS AND ONTOLOGY FOR MARITIME SAFETY MONITORING

Situation planning of vessel route is based on in-deep understanding of situations and their development, allowing to make more reasonable decisions, and also to predict dangerous situations at sea and to take action in time to prevent them.

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The basis for situation vessel route planning 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 [2] 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, 8] 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. 4.

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:

$$WeatherDangerVessel \models \ll isWind, Weather, Vessel, 1 \gg,$$
$$WeatherDangerVessel \models \ll isHeavy, Weather, Vessel, 1 \gg,$$
$$WeatherDangerVessel \models \ll isFog, Weather, Vessel, 1 \gg,$$
$$WeatherDangerVessel \models \ll wait, Weather, Vessel, 1 \gg,$$
$$WeatherDangerVessel \models \ll isSafety, Weather, Vessel, 0 \gg,$$
$$WeatherDangerVessel \models \ll isDanger, Weather, Vessel, 1 \gg.$$

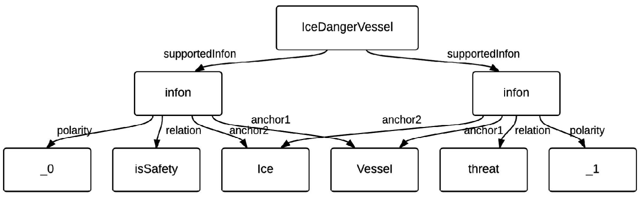

Fig. 4. Two infons for *IceDangerVessel* situation

Fig. 5 shows two infons for *WeatherDangerVessel* situation.

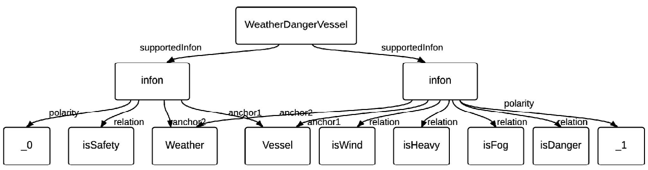

Fig. 5. Two infons for *WeatherDangerVessel* situation

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. 6):

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

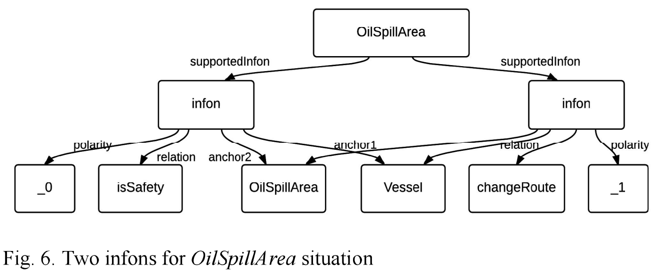

Fig. 6. Two infons for *OilSpillArea* situation

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.

VI. Case study

In this section, the results of the application of the proposed approach are given. IGIS has been used to define the areas at risk and vessel route corrections.

IGIS provides powerful tools for vessel traffic monitoring, route planning, weather conditions, and ice situation analysis in given sea region. IGIS Expert system is used for control of navigation safety and decision-maker support in case of dangerous situations on the Northern Sea Route.

Main scenario: A cargo vessel V goes along pre-planned route on the part of Northern Sea Route (Kara Sea) (Fig. 5). 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. 7).

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. 8).

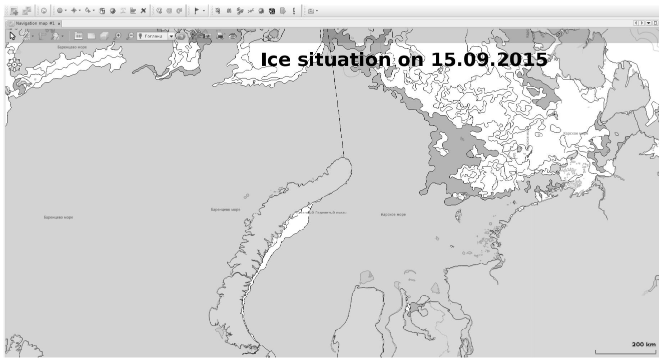

Fig. 7. Ice situation in the Kara Sea

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 [7].

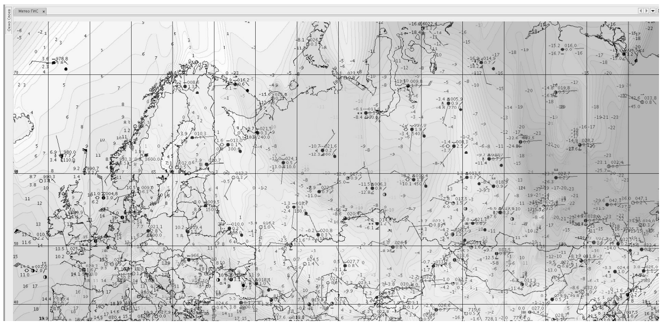

Fig. 8. Weather conditions along the Northern Sea Route

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 [7] 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.

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 MSRS (Fig. 9).

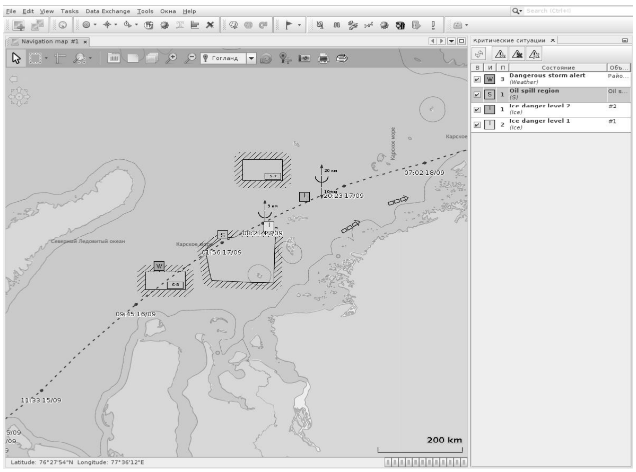

Fig. 9. Initial vessel route built with IGIS MSRS

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 $S_1 = \{s \mid s \models << near, Ice, Vessel, 1 >>\}$,

$S_2 = \{s \mid s \models << inDirectionOf, Ice, Vessel, 1 >>\}$,

$S_3 = \{s \mid s \models << clush, Ice, Vessel, 1 >>\}$.

Subsumption rule is the basis for description logic [3], which is the underlying logic for IGIS MSRS Modelling System.

The above-mentioned rules were saved in IGIS MSRS 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 MSRS.

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. 10). 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.

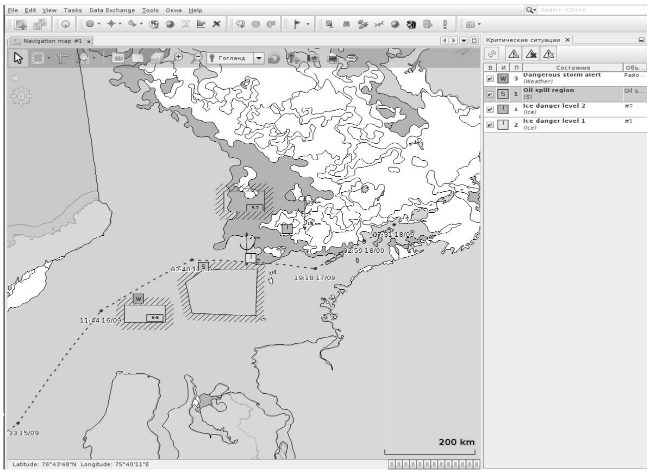

Fig. 10. Alternative vessel route built with IGIS MSRS

VII. Conclusion

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

Permanent monitoring of the different dangerous situations in the Arctic is also related to constantly changing navigation conditions typical for the region. There is a need to perform constant monitoring of current situations (weather conditions, ice situations) and their operational forecasting to provide safe navigation along the parts of the Northern Sea Route.

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