Requirements for radar navigation aids for operational safety of autonomous navigation of facilities of the Arctic oil and gas complex

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Abstract. An analysis of the requirements for radar systems for autonomous sea vessels operating in the Arctic regions shows that to ensure the safety of transport and oil and gas facilities, it is necessary to evolution to radar systems with characteristics that significantly exceed the existing classification requirements. The application of ultra-wideband and ultra-short-pulse radars, including those based on the principles of microwave photonics, which will provide a radio-imaging mode and decimetre levels of accuracy when measuring coordinates, as well as observation of small objects, ice conditions and detection of oil spills, is proposed. The use of such radar facilities to ensure high-precision navigation will make it possible to start solving the problem of creating autonomous vessels, provided that the safety of logistics operations in the oil and gas complex is ensured.

1. Introduction
Currently, the development of the Arctic shelf is becoming more and more active, where the volumes of mineral extraction will significantly increase in the foreseeable future. With the growth of oil and gas production, the intensity of maritime transport and technological operations in the waters of the Northern Sea Route increases, which leads to an increase in requirements for ensuring their efficiency and safety. These requirements determine such priorities of scientific and technical development of the maritime transport system as [1]:
• development of innovative shipbuilding, including the development of automated "smart" vessels, the integration of the latest technologies in the construction of vessels, the use of robotics;
• development of port infrastructure, optimization of interaction of ports with other links of the logistics chain;
• improving safety of navigation, reducing the risk of disasters associated with the human factor, introduction of systems for accident free operation of vessels and transport infrastructure unmanned systems.

One of the most important areas of research and development within the framework of these areas is development of navigation means and systems of conditions information. This is due to such problems [2] of ensuring the logistics of sea transportation and technological operations in the Arctic region as:
- difficult weather and climatic conditions of navigation, sharply limiting the possibilities of visual observation means;
the relative shallowness of the Arctic seas, the lack of knowledge even of the reference fairways of the Northern Sea Route, the lack of a sufficient volume of high-precision three-dimensional maps of depths and bottom relief;

• shallow water and significant seasonal variability of the depths and bottom reliefs of the estuarine waters of the northern rivers in the areas of the key ports of the Northern Sea Route;

• limited capabilities of the system of meteorological control, forecast and real-time notification of changes in the weather situation;

• limited capabilities of the ice conditions information system and insufficient efficiency of its functioning;

• the complete absence of domestic space radar facilities for remote monitoring and monitoring of the ice conditions;

• significant influence of geomagnetic disturbances of the auroral zone, leading to a significant deterioration in the characteristics of radio communication and navigation equipment, including satellite radio navigation systems.

Currently, the information support of navigation is solved by a whole set of different systems, including the means of space radio navigation systems, optical surveillance means and radar means. One of the main trends in the development of vessel's radar facilities is the search for solutions to significantly increase their information content, including both increasing the accuracy and resolution of radars, and transition to detailed visualization of the environment on display devices.

Creation of a new generation of highly informative navigation systems should ensure an increase in navigation safety and create prerequisites for the transition to a new generation of surface vehicles, including robotic and autonomous ones.

2. Trends in the development of the concept of autonomously operated vessels

In recent years, the direction of autonomous vehicles has been intensively developing. Autonomous aircraft, passenger and cargo vehicles with autopilot, and unmanned and robotic surface vessels are becoming increasingly widespread. In a number of works [3-11], various approaches to the principles of construction and information tools of autonomous and robotic systems are considered. At the same time, a high quality of information support becomes an absolutely necessary requirement for ensuring the technical efficiency and safety of their operation.

In August, 2020 for the first time, the Russian Maritime Register of Shipping presented a regulation on the classification of marine autonomous and remotely navigated surface vessels (MANS) [12]. According to this provision, the information basis of the MANS should be a situational awareness system (SAS), which should receive and process information about environmental conditions and the state of the MANS for making decisions on the management of the vessel and its systems:

• when driving in the open sea;

• passage of narrownesses, straits;

• anchoring/release from an anchor and being at anchorages;

• entering/exiting the port;

• mooring operations, movement in port waters and

• carrying out cargo operations.

At the same time, the SAS should combine all available information sources located on and off the vessel, using operational and chronological data, in particular, radar, video, acoustic information around the vessel, collected and processed in real time.

According to the requirements of the Register, the data sources for SAS must be at least two vessel radar stations (radars) with an automatic radar course navigation system (ARCNS) and the function of detecting small-sized surface targets (4 radars are recommended: 2 X-band and 2 S-band), duplicated vessel equipment of the automatic identification system (AIS), at least three different systems for determining the location of the vessel (with the function of satellite time synchronization). The requirement is also formulated for the availability of back-up gyroscopic compasses, echo sounders, lags showing absolute and relative speed, an inertial navigation system, infrared and television cameras.
for organizing a circular viewing system that can be operated in difficult meteorological conditions and in different conditions of daily illumination, non-electronic inclinometer, anemometers, visibility sensors, equipment for detecting objects at a close distance to the vessel's side, used for high-precision mooring, systems for receiving and registering external sound signals, systems for receiving navigation, meteorological and navigation safety information on the route based on NAVTEX, NAVDAT, VHF (including tidal changes and the environmental situation in the port).

Optical means, including various cameras and laser locators, are characterized by sufficiently high accuracy and informative content, but at the same time they have a relatively short range and are strongly limited by meteorological factors, which is especially critical in the Arctic conditions.

The means of satellite radio navigation in high latitudes are characterized by insufficiently stable operation under the influence of ionospheric interference and instability of elevation observed due to small angles of satellite grouping, which in some cases does not provide acceptable accuracy of location determination. Thus, the radar becomes the key information sensor for autonomous vessels in the conditions of difficult meteorological and climatic conditions of the Arctic region.

3. About the implementation options for radar systems

Radar systems that are sources of information for SAS MANS must meet the relevant requirements of the Register set out in the Rules for the Equipment of Marine Vessels, and their characteristics are not inferior to the requirements for the means of the vessel traffic control system (VTS) of the highest category.

According to the classification regulation [12], the vessel's location determination systems must provide with a probability of 95% absolute accuracy of location determination:

- when navigating in the open sea: 100 m;
- performing an automatic collision avoidance maneuver and navigation on approaches to ports and coastal waters: 10 m;
- maneuvering in the port: 1 m;
- automatic mooring: 0.1 m.

Accordingly, the instrumental accuracy of information sensors should be at least an order of magnitude higher than the specified values. From the point of view of the requirements for the radar means of the situational awareness system, this makes it necessary to create a system for lighting the situation based on radar means that provide a sufficient level of spatial resolution, up to the implementation of the radio vision mode.

A typical example of the task of high-precision navigation and the need to obtain a highly detailed radar image is the wiring of the Christophe de Margerie LNG tanker by the icebreaker “50 years of Victory” along the sea channel in the port of Sabetta (Figure 1).

![Figure 1. Image of the sea channel wiring](image-url)
The extremely high requirements for mutual positioning and the need to obtain highly detailed radar images are due to the fact that the approach channel in the port of Sabetta is comparable in its transverse dimensions to the length of the vessel being conducted and is surrounded by shallow water (Figure 2).

Even in conditions of low-intensity existing traffic, the passage of LNG tankers to the berth is provided by means of high-class pilotage. Taking into account the commensurability of the dimensions of the approach channel and the serviced vessel, an extremely high quality of positioning by location, heading angle and speed vector is required. The estimated accuracy of positioning the bow and stern reference marks of the vessel should be units of decimeters. Similar requirements should be applied to the means of information support of navigation for autonomous vessels.

Currently, there are several technical solutions that can significantly improve the accuracy and resolution of radars, and the information content of radar images obtained from them with a quality that provides the required radio vision function. These solutions include the use of millimeter-wave radars, radars operating in the reverse aperture synthesis mode, multi-position and multi-band radar systems, including systems based on radiophotonics [13-15], as well as radars with complex and ultra-wide-band signals [16], including ultrashort pulse ones.

Variants with multi-position systems can be implemented in conditions of sufficient development of the coastal infrastructure and at relatively short distances from their installation sites to the observation zone. Millimeter-range radars have a significantly limited range in conditions of intense precipitation, typical for most regions of the North and the Arctic. Thus, the most versatile radar sensor for coastal, offshore objects and equipment of autonomous vessels are radar stations with ultra-wide-band signals, including ultra-short-pulse ones.

Currently, a sufficient scientific, technical and technological reserve has been created, which allows us to create radar navigation tools that, on the one hand, meet the requirements of the Register, and on the other hand, provide a fundamentally new quality of radar information. These funds will ensure the solution of such tasks as:

- local navigation system for safe navigation of vessels, helicopter flight;
- landing of helicopters on offshore drilling platforms and ground airfields;
- mooring of vessels to drilling platforms and berths of terminals;
• monitoring and dispatching of vessel traffic in ports and the area of responsibility of terminals, including monitoring the position of vessels at anchorage;
• high-precision operational assessment of the ice conditions and the weather in the radar's area of responsibility;
• tasks for the protection of offshore drilling platforms and territories of onshore terminals;
• information support of means of protection against potential terrorist threats.

The solution of these tasks requires a number of new capabilities from the radar, such as:
• high accuracy of measuring the distance to an arbitrary point object (about 0.5 m);
• high resolution in range (1-2 m, that is, about 10 times higher than modern radars);
• small blind spot (1-5 m);
• confident detection of small-sized targets near objects with a significant scattering surface and against the background of reflections from the underlying surface;
• the ability to observe sedentary marine objects and air objects with a chaotic trajectory of movement (small-sized unmanned aerial vehicles (UAVs));
• recognition and classification of object types;
• high detail of the radar map and its good match with topographic and marine maps;
• the possibility of high-precision determination of the orientation of vessels and watercraft.

None of the domestic and foreign radars presented in the list of the Russian Maritime Register of Shipping has even close to the required qualities.

The basis for creating a radar capable of solving this range of tasks can be made up of domestic reserves in the field of ultra-short-pulse and ultra-wide-band radar, as well as radiophotonics [17]. Figures 3 and 4 show experimental radar images obtained during testing of experimental products of such X-band radar equipment.

Figure 3. Photo and radar image of a large and small radar target.
4. Conclusions
The development of autonomous transport technologies creates new requirements for vessel information sensors. Ensuring high-precision navigation during the operation of vessels and stationary objects of the oil and gas complex requires the creation of a new generation of radar facilities. The proposed approaches to the creation of such means based on ultra-wideband and ultra-short-pulse signals and radiophotonics technology will significantly increase the information content of radar means, up to the transition to the radio vision mode provided for by the classification requirements. The introduction of such tools on promising models of autonomous vessels and offshore facilities of the oil and gas complex will significantly increase the safety of their operation.

Acknowledgment: The authors acknowledge the support from HR.dr UTFORSK Project (project number UTF-2017-four-year/10044) between University of Stavanger and Gubkin Russian State University of Oil and Gas.

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