Development and Implementation of the Robot Prototype with Inertial Navigation for Work in the Arctic

Alexey Lagunov, Alexey Orlov

Abstract*: Currently, there is a very rapid development of robotics. People use robots in many areas of their activities. Especially valuable is the use of robots in hazardous conditions for humans, in particular in studies in the Arctic. In this case, there is an acute problem of navigation. The use of global navigation satellite systems (GNSS) in the Arctic is difficult due to the small number of satellites and the influence of Aurora. Therefore, we chose the inertial type of navigation for the prototype of the robot. We used LSM330DL micromechanical sensors and Atmega8-16AU microcontroller to create a navigation system. We used wireless access point Ubiquiti Bullet M2HP Titanium to connect the robot with researchers. Tests of a prototype of a robot on a wheeled platform showed that the coordinate determination error does not exceed 6%. Tests of the navigation system were carried out up to -20°C. System components allow operation up to -40°C. The proposed navigation system can be used to create robots for work in the Arctic.

***Keywords*: robot, positioning, inertial navigation, mathematical model, Arctic.**

I. INTRODUCTION

Currently, Arctic becomes one of the most strategically important regions on the planet, and states make serious steps to protect their northern geopolitical interests, for example [1, 2, 3]. It occurs inevitably due to a quarter of the world's oil and gas reserves is admittedly located in the Arctic [4, 5]; due to the Northern Sea Route can significantly reduce the time of delivery of goods from east to west and back [6]; and so on. At the same time, Arctic region is sensitive to temperature changes, especially, over last decade, for example [7, 8, 9], including variety and uncertainty of local realizations in both statistical [10] and nonlinear [11] terms. These circumstances lead to specific scientific and engineering problems which are not typical for other regions even with similar low-temperature seasons.

For example, ships may encounter the following dangers in the Arctic [12]: an extremely flat terrain, a sea-level rise, a sea-ice reduction that facilitates more storm flooding and accelerating permafrost degradation. As a result, such hazards have particular impacts on conditions and safety of navigation, placements of floating platforms, communications cables and pipelines, and so on. Thus, it is a very important practical task to study the Arctic, creating and maintaining up-to-date accurate nautical charts that would take into account the migration routes of ice fields and icebergs. In particular, a part of the corresponding works need in the use of robots [13], first of all, it concerns places where the presence of a person is impossible, or there is a high danger to its life.

We can use global navigation satellite systems (GNSS) to solve the above problems, including the use of high-precision navigation methods [14]. But the following difficulties arise [15]:

1. The presence of Aurora in the polar regions.

Periodically on the Sun there are flashes, as a result of which the rarefied plasma (proteins and electrons of hydrogen and helium) attacks the screen of the earth's magnetic field, which causes a magnetic storm. At an altitude of 80-500 km, excited molecules and atoms of oxygen and nitrogen begin to glow. There is an Aurora borealis. K and Kp-index characterize the power of auroras, where 1 is all quiet, 9 is an electronic failure. Very often, the K-index in the Northern Hemisphere can reach values of 4-5 and above [16].

Aurora, which has the form of an auroral oval (Fig.1), occurs in layers that distort the signal from the GLONASS and GPS satellites [17]. Studies conducted by Chernousov [18] show that during auroras the GPS fails. For example, this happens to operate on GPS on sub-auroral and auroral stations, such as AB18 (66.7°N, 162.6°W), Tiksi (71.3°N, 128.5°E), KIR0 (67.5°N, 21.0°E), and NNVN (61.4°N, 44.9°W). Many researchers note also testify the GNSS system failures to operate during the Aurora [19]. GPS navigation algorithms can be used to construct models with ionospheric effects, but such models are not always sufficient to compensate ionospheric effects in the presence of large TEC gradients [20].

2. The absence of wide-band satellite functional supplements of GNSS type SBAS (Satellite Based Augmentation System) in high latitudes.

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* Correspondence Author

Alexey Lagunov *, Department of Fundamental and Applied Physics of the Higher School of Natural Sciences and Technologies Northern (Arctic) Federal University named after M.V. Lomonosov, Severnaya Dvina Emb. 17, Arkhangelsk, Russia, 163002.

Alexey Orlov, Telecommunications Saint-Petersburg State University of Telecommunications (branch in Arkhangelsk), Papanina Str. 24, Arkhangelsk, Russia, 163062,

The SBAS GNSS system allows you to improve the positioning accuracy of standard GPS. Users obtain correction factors for GNSS SBAS systems via geostationary satellites (GEO). In the Arctic, these satellites are visible very low above the horizon. Therefore, SBAS data reception is either not possible or received with a large amount of noise. Above 78-degree north latitude, reception from GEO becomes impossible [21]. Therefore, SBAS performance at high latitudes is significantly lower than at lower latitudes. The main reason is the long distances between base stations in a remote area of the Arctic and the dense clouds that cover the circumpolar region. The above limitations very often do not allow the use of GNSS in the robots created. Researchers can be left without a robot if it loses orientation.

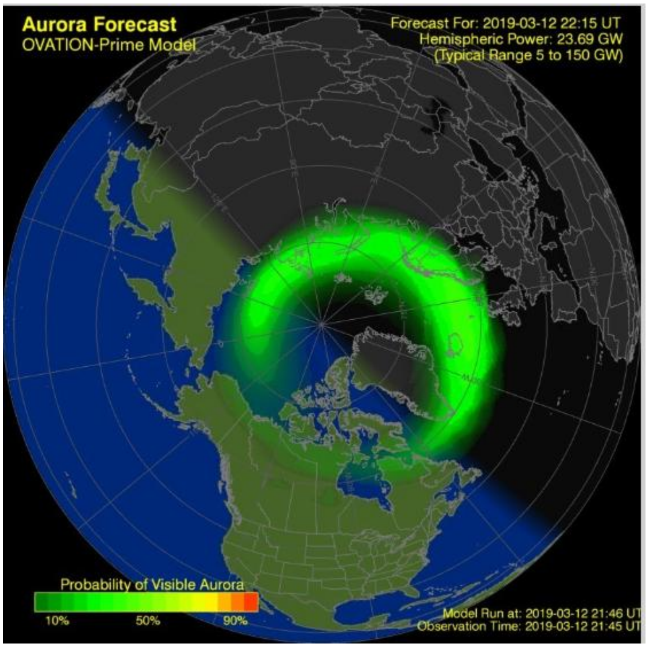

Fig. 1.Aurora Forecast [22].

The purpose of this study was to clarify several aspects of robot navigation in the Arctic. In such conditions, we propose to use inertial navigation in robots [23] for work in the Arctic as an alternative. The project is being carried out within the framework of cooperation of the Northern (Arctic) Federal University named after M.V. Lomonosov (NArFU) [24] and the Swedish Foundation for International Cooperation in Research and Higher Education (STINT) [25] under the ASIAQ: Arctic Science Integration Quest [26].

II. MATERIAL AND METHODS

A. Navigation module requirements

We have formulated the following requirements for the robot:

1. The robot navigation system must be a functionally complete module containing sensors and a computing device that calculates the navigation parameters and orientation parameters of the robot.

2. The navigation module should be a strap-down inertial navigation system based on micromechanical sensors, which ensures the autonomy of the work, small dimensions, weight and power consumption of the module.

3. The dimensions of the module should be no more than 10x10x5 cm, and its mass should not exceed 0.5 kg to be able to be installed on a small-sized robot.

4. The power consumption of the system should not exceed 5 watts.

5. In the case of straight-line movement, the robot's error in determining the coordinates should not be more than 10% of the distance traveled.

6. Components of the robot should allow its operation in the Arctic.

B. Designing a navigation module

Designing a navigation module can be divided into several stages:

1. The study of the orientation parameters of a solid body, the choice of the most appropriate parameters for the navigation module in terms of ease of use and amount of calculations.

2. The study of the kinematic equations of rotational and translational motion of a rigid body.

3. Selection of the most appropriate methods for solving equations from the viewpoint of both accuracy and volume of calculations.

4. Compilation of mathematical models of sensor readings for obtaining primary information on their readings, and for their calibration.

5. Determining the order of execution of calculations in the system, drawing up a block diagram of the navigation module.

7. Selection of specific sensor models for the developed module.

8. Development of the navigation module hardware.

We studied the parameters of the orientation of a solid body and investigated the kinematic equations of rotational and translational motion of a solid body (points 1-2) in 2015-2016. We presented the results of our work at the 2017 4th International Conference on Manufacturing Engineering and Technology for Manufacturing Growth [27].

C. Mathematical model

We need to build a mathematical model of the readings of three-axis micromechanical accelerometers and gyroscopes. When building a model, we must take into account the set of parameters that the sensors have. The accuracy of the results obtained depends on the following: zero offsets, scale factor, its non-linearity, axis intersection, axis non-orthogonality, and their asymmetry, sensor parameters dependence on temperature and supply voltage, the effect of linear accelerations acting on the gyroscope readings [28].

We introduce the sensor basis B and the transition matrix P from the orthonormal basis N to the basis B in order to take into account the non-orthogonality and cross-connections of the axes. Separately forms the transition matrix P from the orthonormal basis N to the basis D.

We will assume that the position of the sensitivity axes of the sensor is constant. Cross-links manifest themselves linearly and do not change. As a result, we obtain that the matrix P is constant. The diagonal matrix K will contain the scale factors of the model.

We will write the zero shifts in the form of column vector S. We will introduce the rotation matrix A. This will allow reprojecting the acceleration from the associated basis E into the basis N.

We get the following expression for the accelerometer:

$$r_a(p_E)=K_a(T,u,p_E)\cdot P_a\cdot A_a\cdot p_E+S_a(T,u)\quad (1)$$

where the column vector consists of the following: pE is the apparent acceleration acting on the accelerometer in the basis of E, ra is the accelerometer reading; T is the sensor temperature; u is the sensor supply voltage.

We convert the expression (1). As a result, according to the accelerometer readings, we get the formula for calculating linear accelerations:

$$p_E(r_a)=A_a^{-1}\cdot P_a^{-1}\cdot K_a^{-1}(T,u,p_E)(r_a-S_a(T,u))\quad (2)$$

We can write, similarly to (1), a model for a gyroscope. We can represent in the form of the dependence of the scale factor on the acceleration effect of linear accelerations on the sensor:

$$r_g(\omega_E)=K_g(T,u,\omega_E,p_E)\,P_g\cdot A_g\cdot\omega_E+S_g(T,u)\quad (3)$$

where the column vector is: ωE is the angular velocity acting on the gyroscope in the basis E, rω is the gyroscope reading.

We can transform the expression (3) and get the formula for calculating the angular velocities for the gyroscope.

D. Hardware development

As a result of the review of the currently produced micromechanical sensors for the designed navigation system, the LSM330DL sensor from STMicroelectronics [29] was selected, which contains a three-component accelerometer, a three-component gyroscope, and a thermal sensor. The sensor has several ranges for measuring linear accelerations and angular velocities. The system performs data exchange in digital form. It uses protocols (12 C, four-wire SPI, three-wire SP1). Table I contains the basic typical sensor characteristics.

Here, the LSB is the least significant rank. The maximum resolution of the accelerometer is equal to 12 bits; the gyro is equal to 16 bits, the temperature sensor is 8 bits. According to the main characteristics, including the range of temperature changes, this sensor is suitable for work in the Arctic.

The hardware contains Atmega8 - 16AU microcontroller manufactured by Atmel Corporation (since 2016 — Microchip Technology [30]). The basis of this microcontroller is the 8-bit AVR core. This core has high efficiency and low power consumption, which is very important when working in the Arctic, where energy is always not enough. The microcontroller has 512 bytes of non-volatile memory for the system, 8 KB of flash memory for programs, 1 KB of RAM for data. It also differs from analogs in a large set of integrated peripherals. The microcontroller has 32 outputs, is made in a miniature package for surface mounting type TQFP. The sensor receives power from the power source 3 V, and the microcontroller from a power source of 5 V.

The assembly of the hardware of the robot navigation module was carried out in two stages: the first stage is the manufacture of printed circuit boards; the second is the installation of radioelements on the board [31].

We made a printed circuit Board from foil fiberglass. Fig. 2 contains a photo of the appearance of the navigation module PCB.

Table I. Typical LSM330DL sensor specifications

Parameter	Value	Units
Linear acceleration measurement range	±2, ±4, ±8, ±16	g
Angular velocity measurement range	±250, ±500, ±2000	°/c
Accelerometer Sensitivity	1,2,4, 12	10^{-3}g/M3P
Gyro sensitivity	8.75, 17.5, 70	10^{-3o}/(c·M3P)
The effect of temperature on the sensitivity of the accelerometer	±0.05	%/°C
The effect of temperature on the sensitivity of the gyroscope	±2	%
Accelerometer Zero Shift	±60	10^{-3}g
Gyro Zero Shift	10	M3P
The effect of temperature on the zero shift of the accelerometer	±0.5	10^{-3}g /°C
The effect of temperature on the zero shift of the gyroscope	±0.03	°/(c·°C)
Accelerometer Noise Density	220	10^{-6}g/√Hz
Gyroscope noise density	0.03	°/(c·√Hz)
Temperature range of temperature sensor	-40...+85	°C
Temperature sensor sensitivity	-1	°C/M3P

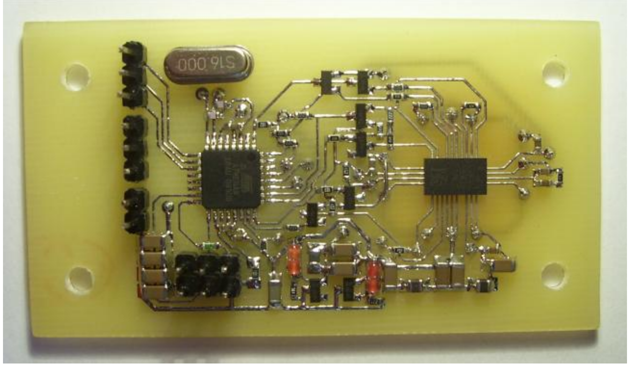

Fig. 2.Navigation module circuit board.

E. Software development

The robot's navigation module has firmware written in C and assembler. The program is implemented using free software only.

We wrote the software in the integrated development environment Code::Blocks. In the implementation and assembly of the program used avr-gcc, avr-binutils, and avr-libc, which are versions of GCC, GNU Binary Utilities and libc for AVR microcontrollers. Avr-gcc - a set of compilers, contains compilers of C and C ++ languages. Avr-Binutils contains a set of tools for working with object code, assembler and linker. Avr-libc is the standard C library for AVR microcontrollers. The assembled program was recorded in the program memory of the microcontroller by the avrdude program (AVR Downloader / Uploader).

When implementing the software, a problem arose: the resources of the microcontroller are not enough to calculate the navigation parameters. To solve this problem, we decided to calculate the navigation parameters using Ubiquiti Bullet M2 hp Titanium wireless access point installed on the robot for wireless control [32].

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This router is based on a 32-bit Atheros MIPS 24KC microprocessor with a clock speed of 400 MHz, has 8 MB of flash memory for storing data and programs and 32 MB of RAM. We can increase the memory up to 64 MB by replacing the memory chip with a more capacious one.

The access point has a shockproof, waterproof case, operating in the temperature range from -40°C to +70°C. It has a frequency range of 2.4 GHz. We can provide a communication range of 50km when a directional antenna is installed on the base station and there are no major obstacles in line of sight. These parameters are sufficient for work in the Arctic. The access point can work under control of various firmware. The official Ubiquiti firmware does not allow to utilize the capabilities of the router fully, so at the moment it has the OpenWRT 18.06 firmware installed on it - a special Linux distribution for network devices [33]. We compiled the OS from the source code with the necessary capabilities.

III. RESULT AND DISCUSSION

A. System calibration

We tested the robot's navigation system on a wheeled chassis. The chassis has four wheels with a diameter of 0.125 m and four engines ME-255 with a rated power of 20 watts. The robot gets power from 2 batteries of 12 V with a capacity of 7.2°heach connected in parallel. Dimensions 36x25x18 cm, weight with batteries 9.87 kg. Fig. 3 contains a photo of the robot's appearance and chassis. On top of the chassis is a platform with shock absorbers for attaching the navigation system. All electronics were installed on metal fittings.

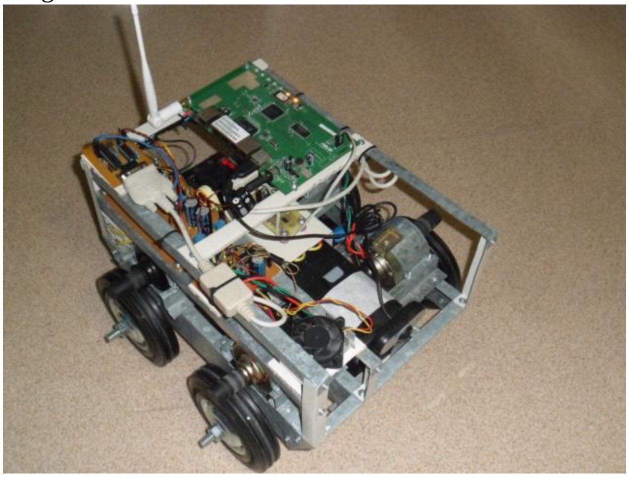

Fig. 3.The appearance of the robot on the chassis.

Before testing, we calibrated the sensors. Calibration of sensors is necessary to identify their parameters. The accuracy of the navigation system depends on the calibration quality. We used two calibration methods.

In the first orientation method, we installed a stationary accelerometer so that one of its sensitivity axes (calibrated) could coincide with the geocentric vertical. In this case, the accelerometer will show the value of the acceleration of free fall of the Earth along this axis with the opposite sign. The axis to be calibrated must be strictly vertical. The readings of the other two axes control this moment. Their testimony should be zero. With this method of calibration, readings are taken six times for each value of voltage and temperature - twice for each axis under opposite effects. This method allows you to determine the shifts of zeros and scale factors.

The second calibration method – calibration of the centrifuge. We used this method to determine the nonlinearity of the scale factors, since this method allows us to set any centripetal acceleration acting on the accelerometer. Fig. 4 is an external view of the test stand. The centrifuge consists of an engine 1 mounted on a support 2, rotating a wooden rail 3, a control module 4 and a tachometer consisting of a disk 5 with transparent and opaque marks and an optocoupler 6. The data from the navigation system is transmitted by infrared waves; the radiation receiver 7 we attached above the centrifuge.

Fig. 4.Test bench with a centrifuge.

As a result of the accelerometer calibration, we found that zero shifts and scale factors do not depend on the supply voltage of the sensor, and the nonlinearity of the scale factor is negligible. At the same time, the effect of the sensor temperature on the scale factors and zero shifts of the accelerometer was revealed (Fig.5).

As a temperature value, direct readings of the built-in thermal sensor are used (a smaller value corresponds to a higher temperature). We calibrated the gyroscope using a centrifuge. The shifts of gyro zeros are set equal to the readings of the gyros at rest. We can neglect the rotation of the Earth since in this state the effects on the gyroscopes are zero.

We performed the determination of the parameters of gyroscopes in a centrifuge, similar to the calibration of accelerometers in the gravitational field of the Earth. In this case, we installed the calibrated axis of the gyroscope parallel to the axis of rotation of the centrifuge. We shot the data six times in groups of three for each axis. In this case, the opposite effect was carried out to identify the nonlinearity of the axis in both directions. We took readings at two points located at different distances from the axis of rotation to more accurately determine the effect of linear acceleration on the gyroscope readings.

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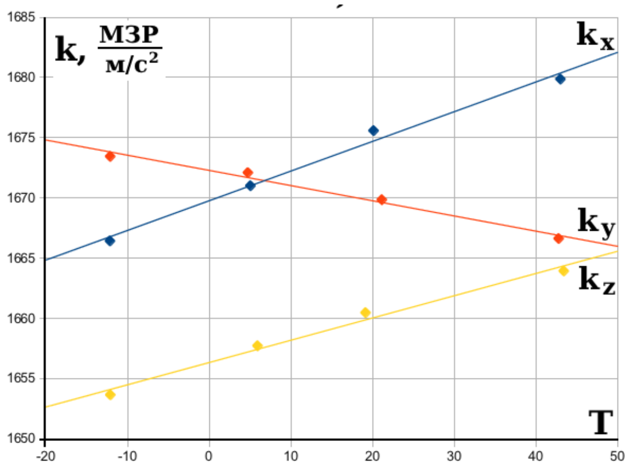
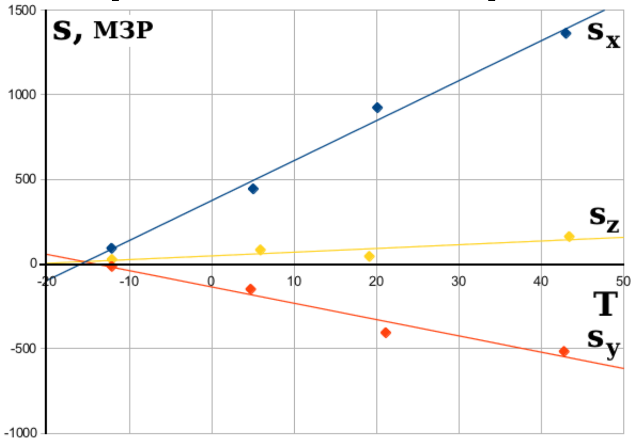


a - dependences of scale factors on temperature



b - dependence of zero shifts on temperature

Fig. 5.The effect of temperature on accelerometer parameters.

We found that when calibrating gyroscopes, their parameters do not depend on the supply voltage. At the same time, the nonlinearity of the scale factor is rather small. We did not find the dependence of the readings on the linear acceleration. At the same time, the dependence of the scale factors on temperature was revealed (Fig.6).

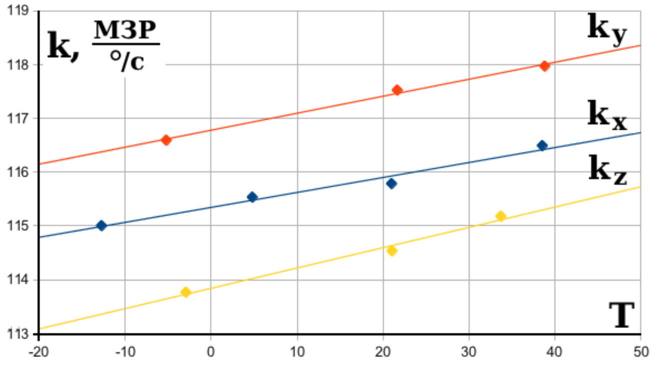


Fig. 6.Appearance of the centrifuge.

When the navigation system is at rest, we can easily calculate the values of zero shifts. We have not found that the value of the zero offset depends on the temperature change. In the Arctic, there are very large temperature differences, so we will not observe the zero shift when the temperature changes and robot navigation will be more accurate.

We found that the parameters of the sensors change over time. We assume that this is due to the residual deformation of the elastic elements. In this regard, there is a need to recalibrate the sensors periodically. We found that the accuracy of accelerometers immediately after calibration is about 1.5% with a confidence level of 0.95. After seven days of work on the robot, the error increased to 3.4%.

B. System testing

The test of the robot was carried out in 2 stages: test indoors (similar to the method [34]); field test.

When testing in the room, we used a measuring ruler. At the same time, without the use of tachometers, with the rectilinear movement of the robot over distances up to 3 m, the error in determining the coordinates after stopping the robot did not exceed 10%. We found that while moving along a complex trajectory without stopping, the error reaches 30% of the distance traveled (in 30 s the robot passed 31.2 m). We found that when using tachometers, the error in determining the coordinates did not exceed 5%, regardless of whether the robot was moving with or without stops. Field tests were carried out on the island of Mudyug (64.55°N, 40.16°E). Fig. 7 shows the robot's route on the island.

Fig. 7.Robot's route on the island Mudyug.

We left the route of the robot (red line) Google map (acquisition date: 06/26/2018). Mudyug island is located in the White sea (Russia). The white sea has a connection through the Strait to the Arctic ocean.

The island stretches from north to south; its length is about 15 km, the width (at its widest point) is 3.5 km. The formation of the relief of the island occurred under the influence of two currents, sea and river. Therefore the island consists mainly of washed sand. It is pronounced sandy manes and waterlogged depressions between them.

The robot moved from West to East. For field tests, we had to replace the smooth wheels with combed ones because the robot could not move on the sand with smooth wheels. During the test, the robot moved to a distance of 4.2 km. Since the island is flat, the height change was 1 m. The maximum slope of the relief did not exceed 1.6%.

To control the coordinates, we placed a GPS receiver on the robot with the ability to record a route. We compared the obtained coordinates and the data that were recorded by the robot. Fig. 8 contains the results of the comparison.

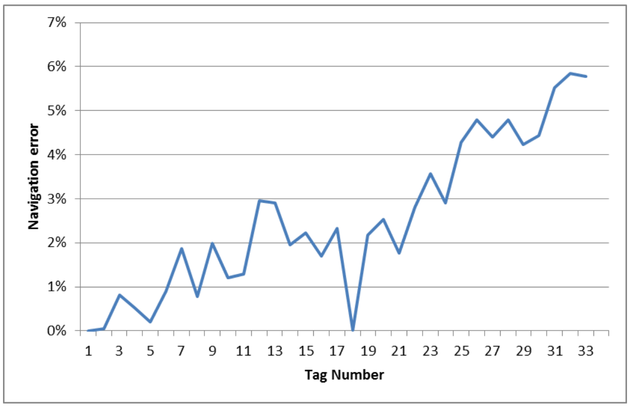


Fig. 8.Dependence of navigation error on tag number.

Navigation error during the whole testing trip did not exceed 6%. On the chart, you can see that the error in the movement gradually increases. At point 18, the robot was trapped and could no longer move. We pulled the robot out of the trap, because it could not get out on its own, and again set the coordinates.

In general, the tests were successful. The navigation module showed that it is capable of performing tasks using inertial navigation in the field. The problem was with the base, which was placed on a mobile navigation system, as the wheelbase on four wheels was not very high permeability. We plan to move to six wheelbases.

We see further work in building a robot platform on a six wheelbase with protection from adverse conditions that could work in the Arctic.

IV. CONCLUSION

The purpose of the current study was to determine the possibility of using inertial navigation to build a prototype robot in the Arctic. The developed algorithms for the functioning of the inertial navigation system and its hardware have shown full performance in practice. Thanks to the described calibration methods, it was possible to achieve a low error in the primary navigation information measured by the sensors, which had a positive effect on the accuracy of the entire system (the error did not exceed 6%).

Indoor tests and field tests on an island in the White Sea have shown the reliability of the system. Wheelbase problems can be solved using the 6th wheel system or the caterpillar system. The navigation system was tested at temperatures down to -20°C. Hardware components can operate at temperatures up to -40°C. Large randomized controlled trials could provide more definitive evidence.

The findings of this study have some important implications for future practice. Such conditions allow the constructed model to serve as a prototype for creating specific copies for work in the Arctic. Most of the recent advances in swarm robotics have mainly focused on homogeneous robot swarms and their applications [35]. Further research might explore the building of the robotic swarm for work in the Arctic.

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AUTHORS PROFILE

Alexey Lagunov, Associate Professor of the Department of Fundamental and Applied Physics of the Higher School of Natural Sciences and Technologies Northern (Arctic) Federal University named after M.V. Lomonosov. Educational qualifications: mathematics, State Pedagogical Institute, Arkhangelsk, RUSSIA. PhD, Author of 24 publications. Area of scientific interests: research and construction of telecommunication systems in the Arctic, the study of the possibility of using alternative energy systems to operate in high latitudes, data analysis and construction of information and telecommunication systems for monitoring the environment of the North, the construction of hardware and software systems to protect human life and health in the Arctic, the construction of medical devices.

Alexey Orlov, Teacher of Telecommunications Saint-Petersburg State University of Telecommunications (branch in Arkhangelsk).
Educational qualifications: engineer, Northern (Arctic) Federal University named after M.V. Lomonosov, Arkhangelsk, RUSSIA. Master of physics, author of 5 publications. Area of scientific interests: computer, radio engineering, programming, data analysis, sensor networks, satellite communications, Arctic, telecommunications. programming in the construction of telecommunication systems in the Arctic, configuration and programming of alternative energy systems for operation in high latitudes, data analysis and construction of information and telecommunication systems for monitoring the environment of the North, construction of hardware and software systems for the protection of human life and health in the Arctic, writing software for medical devices.