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Development of a mobile robot group for coastal monitoring

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Abstract. In Russian Federation rich oil and half of all gas reserves are distributed along the sea shelves. Severe weather conditions, frequent storms and intense sea waves, complicate exploring and mining of new shelf deposits. Therefore nowadays stationary automated systems are used for monitoring the environment in the shelf zone of the Sea of Okhotsk near Sakhalin Island. But they provide data only for specific areas of operation. Such restrictions can be removed by using groups of remotely controlled mobile robots. Moreover, mobile vehicles should be able to operate under any weather conditions. This paper summarizes the research results of the development and creation of efficient chassis designs for coastal areas of Sakhalin Island and adjacent waters. The technique for choosing vehicle design parameters and assessing the efficiency of the system as a whole is given. Data on physical and mechanical characteristics of soil and gravel bases in the coastal zone were used for estimating vehicles' cross-country ability. To create a multi-agent coastal monitoring system we intend to use several ground, underwater and overwater robots able to exchange information in real time. We give an outline of a mobile robot group operation, the group being composed of ground, underwater and overwater robots. The use of mobile robots for performing the tasks mentioned above has the following advantages: expansion of the working area achieved by allocating the robots; highly probable accomplishment of the task due to the possibility of redistribution of targets among group members; the ability to take measurements at several locations simultaneously.

1. Introduction

Constantly growing state demands for fuel, energy, various mineral raw materials are hastening the using of ocean energy resources for the state economy development. Shelf zone plays an important role in maintaining world oil and gas production. Over the past ten years, more than two-thirds of the hydrocarbon reserves were discovered in shelf zones. The Arctic shelf is of particular importance, the total volume of its oil and gas reserves is about 413 billion barrels of oil equivalent (about 22% of the total unexplored stocks of traditional hydrocarbons in the world). All Arctic states enacted laws confirming strategic importance of the Arctic primarily in terms of hydrocarbon reserves. The Russian Federation is one of the leaders in the development and implementation of the shelf zone mineral extraction projects. The first project running on the Russian Arctic shelf in the Pechora Sea is the Prirazlomnoye petroleum deposit development. Its oil reserves are assessed at 72 million tons. The offshore ice-resistant oil production platform Prirazlomnaya has full capacity of up to 6.5 million tons per year. At present one of the most important areas of deposit active development is the Sakhalin Island shelf zone. Piltun-Astokhskoye and Lunskoye fields on the north-eastern shelf of the island are being developed by the Sakhalin Energy Investment Company Ltd [2], one of the largest oil and gas companies. To reduce production, financial and environmental risks prompt and accurate assessment of a working zone should be made at each design and operation stage. With the advancing of the projects on Russian shelf zone energy resources development ,problem of coastal zone monitoring is becoming more and more topical.

To collect information on the coastal zone, aircraft and space-based radar stations are widely used. However, common aerospace methods do not provide the required accurate and rapid information on a coastal zone concerning wave dynamics. Without such information, safe operation of shore facilities is impossible.

The main task is to monitor the wave situation in areas where oil and gas facilities are being operated using ground-based radar systems to refine the data obtained via space means. Thus, at the present development stage of radar methods for wave climate estimation it is important to observe the wave activity in the surf zone constantly, in any weather conditions.

Another way is to monitor the coastal zone using aircrafts. However, this method has a number of limitations on load capacity, safety and range.

As a result, to monitor the wave climate in the coastal zone ground vehicles moving along the bottom of the water area for are widely used [3, 4]. Currently, to detect distance to the object in coastal zone survey remote sensing methods using sensors based on the radio [5] or laser waveband [6, 7] scanning devices are considered to be prospective ones.

2. Movement conditions

Movements within coastal zones are restricted due to convertible humidity of the supporting surfaces as well as to the obstacles along the road (stones, sediments, etc.).

Analysis of movement conditions allowed to elaborate a classification of movement surfaces in coastal zones as roadways for transport and technological machines.

Sand-gravel and sandy areas, as well as snow mantle in winter prevail as supporting surfaces in coastal zones .

Figure 1 shows structure and classification characters of coastal zones.

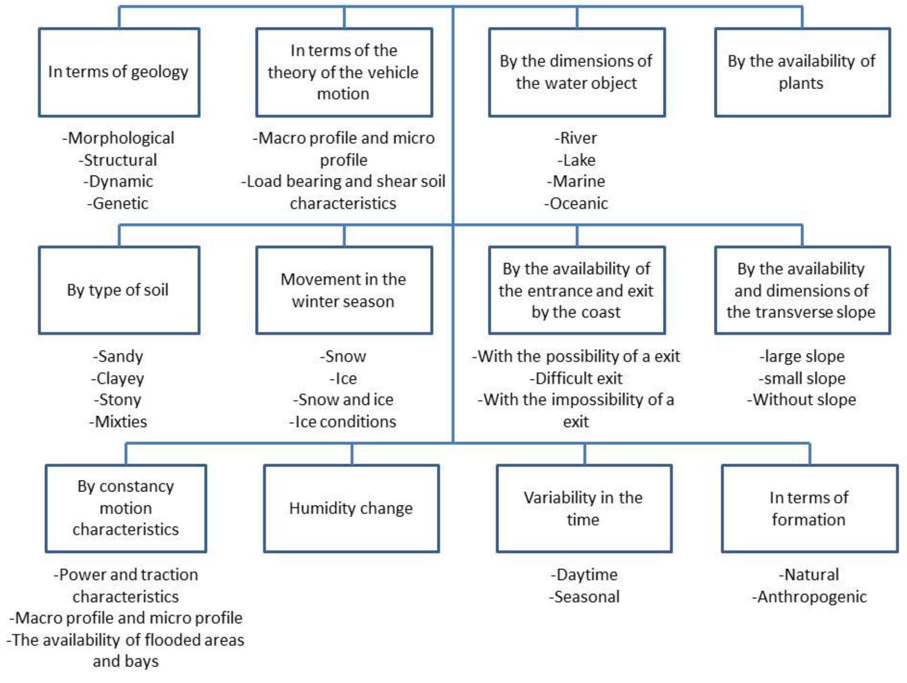

Figure 1. Structure and classification features of coastal zones.

In 2016 and 2017 the authors carried out research of the coastal zone of the Sea of Okhotsk, Mordvinov Bay [8, 9].

The most convenient mathematical model for sand-gravel supporting surfaces is given in the works of Y.S.Ageikin and N.S.Volsky [10]. Normal and shear stresses calculation is made according to the dependencies given below:

$$q_\beta = \left[\frac{(H_G - z)}{b(1+1{,}75\varphi_0)\left(k_{\beta_1}\cdot b\cdot\rho\cdot X_1 + k_{\beta_2}\cdot c_0\cdot X_2 + k_{\beta_3}\cdot\rho\cdot X_3\cdot z\right)\cdot\cos\beta} + \frac{a\cdot b}{E\cdot z} arctg\frac{(H_G - z)}{a\cdot b\cdot\cos\beta} \right]^{-1} \quad (1)$$

$$\tau = \left[q_\beta\cdot tg\varphi_0 + c_0\left(1 - \frac{S_{t_0}}{S_t}\right)\right]\left[1 - \exp\left(-\frac{S_{t_0}}{k_\tau}\right)\right] \quad (2)$$

где $k_{\beta_1} = \dfrac{\pi - 4\cdot\beta\cdot tg\varphi_0}{\pi + 4\cdot\beta\cdot tg\varphi_0}$, $k_{\beta_2} = k_{\beta_3} = \dfrac{3\cdot\pi - 2\cdot\beta}{3\cdot\pi + 2\cdot\beta}$, $X_1 = \dfrac{1 - X^4}{X^6}$, $X_2 = \dfrac{1{,}3\left[X^2 + 1\right]}{X^4}$, $X_3 = \dfrac{1}{X^6}$

где $X = tg(\pi/4 - 0{,}5\varphi_0)$

Dependences for calculating the generalized functions of resistance and friction are determined on the basis of the values of the stresses arising in the elemental area with subsequent integration over the contact area.

$$\Phi_f = bM_a^{-1}\int_0^{h_G} pdh, \quad (3)$$

$$\Phi_\varphi = bM_a^{-1}\int_A \tau dA. \quad (4)$$

Figure 2 shows calculation schemes for wheeled and track movers.

Ratio analysis for the generalized functions of resistance and friction allows assessing chassis's ability to move in coastal zone over sandy and sand-gravel support surfaces and defining such values of design parameters when chassis will remain movable. In accordance to this, we developed a methodology, its block diagram is shown in Figure 3.

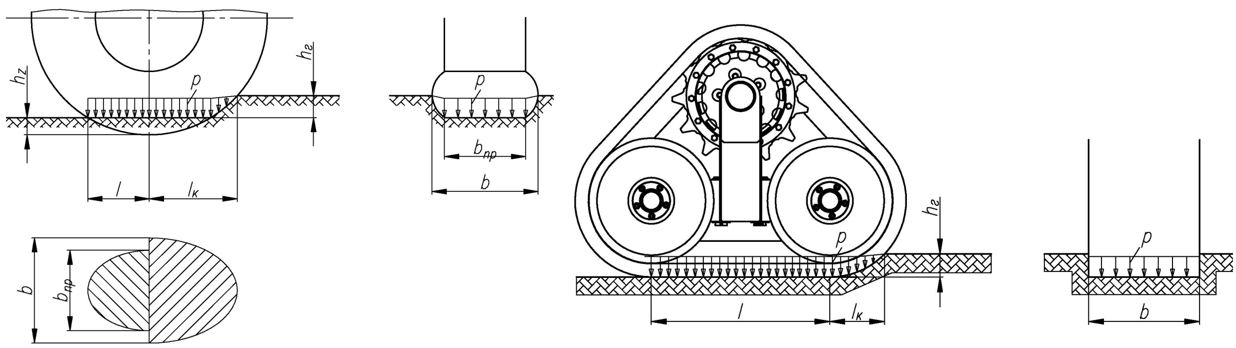

Figure 2. Design diagram of wheeled and track movers' interaction with soil.

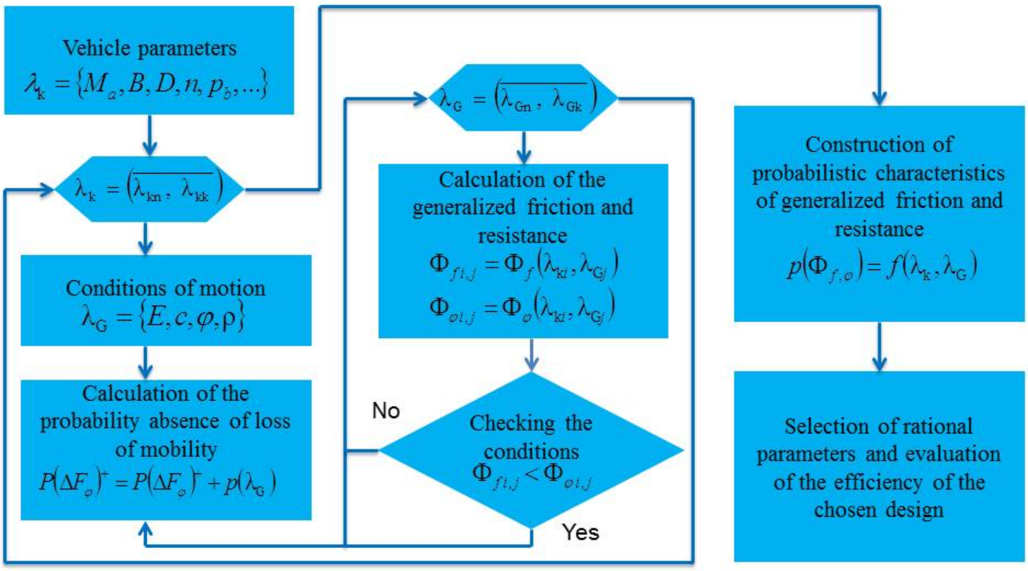

Figure 3. Block diagram of the methodology for evaluating the structural parameters of the chassis and efficiency criterion defining.

The suggested methodology uses loop with a counter (searching), base parameters of the chassis $\lambda_k = \{M_a, B, D, n, p_b, ...\}$ change their value from the specified initial value λ_{kn} to the final value λ_{kk} with some step $\Delta\lambda_k$ the loop body is executed once for each parameter. The initial values of the parameters λ_k are preset on the basis of engineering experience and the design requirements provided by the requirements specification. In this paper we analyze the change in the parameter values by 20% from the average:

As data on the characteristics of the supporting surface $\lambda_G = \{E, c, \varphi, \rho\}$ the values, as well as their statistical characteristics, are set, which are set using a cycle with a counter (enumeration). The basic parameters of supporting surface λ_G change their value from the specified initial value λ_{Gn} to the final value λ_{Gk} with a certain step $\Delta\lambda_G$, the loop body is executed once for each parameter.Meanwhile, each value λ_G corresponds to its own probability density $p(\lambda_G)$.

For each parameter ratio λ_G and λ_k, the values of the generalized resistance Φ_f and friction Φ_φ functions are calculated.If $\Phi_f < \Phi_\varphi$, we calculate the coefficient that takes into account vehicle's mobility being preserved under practicability condition with λ_G and λ_k given. By varying the parameters of the ground λ_G and obtaining the values of Φ_f and Φ_φ, we represent dependencies which take into account the probabilistic characteristics in the form $p(\Phi_f) = f(\lambda_G, \lambda_k)$ and $p(\Phi_\varphi) = f(\lambda_G, \lambda_k)$ for given values. λ_k [11].

To estimate and choose rational parameters of the movers for the developed chassis when operating in snow-covered terrain , we used mathematical models described in [12, 13].

The method serves for the development of mobile ground complexes for monitoring coastal zones, which are necessary for ensuring activity in coastal areas and adjacent water areas. The block diagram is shown in Figure 4. Using this method one can recommend a certain chassis design (choose mass and dimensions parameters, dimensions of the mover), evaluate the effectiveness of the selected algorithms for controlling the movers' power distribution flow, determine the fields of the chassis's efficient use for wheel and track movers in warm seasons and in winter [14, 15].

The sequence of actions is as follows. The requirements for the place and time of monitoring and research equipment specification are developed in terms of safety requirements for this or that activity. Knowing place and time of monitoring, one is able to qualify the surface on which the research complex will operate. It can be either sand-gravel or snow-covered terrain. Additional sample probes of the coast can be taken as needed. Equipment specification defines the dimensions of the chassis and the weight of cargo being transported. It will determine the basic parameters for the chassis on the basis of regression equations for the vehicles ratio. Having chosen the initial data, we analyze the constructions and choose design parameters optimal for the set operation conditions. At first, we evaluate the design from the point of view of its cross-country ability and choose the most reasonable alternative. Then, we make estimates and select algorithms for controlling the movers' power distribution flow. Using the obtained data, we can estimate autonomous travelling time for the vehicle with lowest fuel consumption. The mobility of the chassis is evaluated reasoning from its potential travelling time during the winter with cross-country ability preserved. Thus, the sequence of actions given helps to suggest chassis designs optimal for mobile monitoring sets operating in coastal zones.

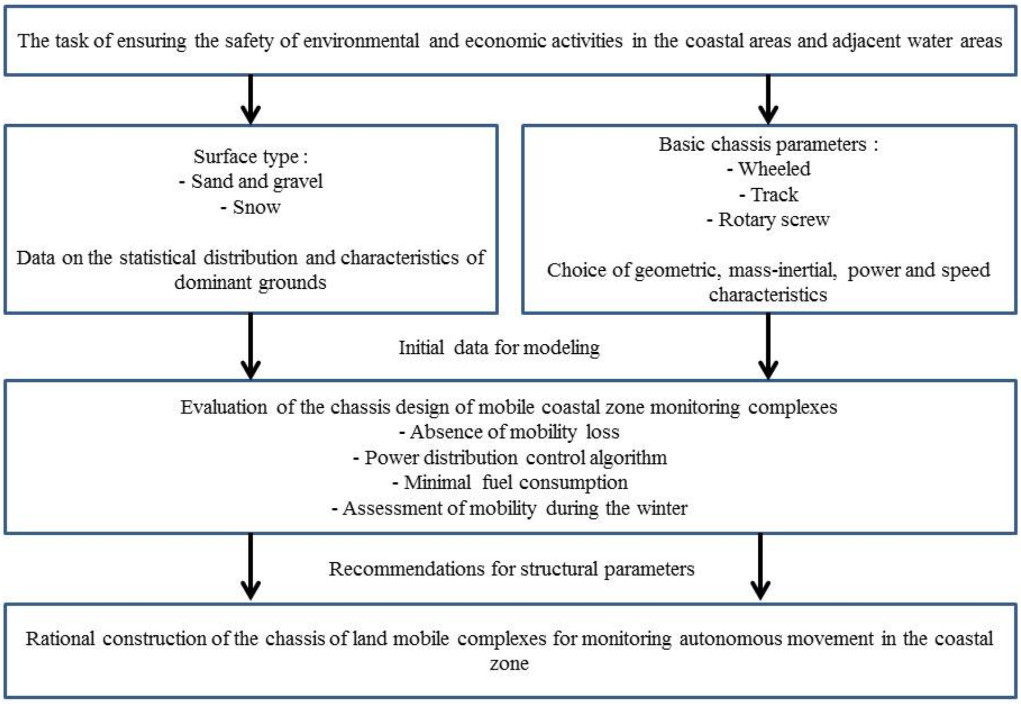

Figure 4. Block diagram of the method for designing the chassis of mobile monitoring sets.

3. Mobile robot group

In accordance with the proposed method, various technological vehicles and mobile robotic complexes were developed, including an autonomous mobile robotic complex [16, 17, 18, 19] for coastal zone monitoring. Experimental researches of this complex carried out on the coast of Sakhalin Island in May and June 2016 made it possible to evaluate the efficiency of the worked out technical solutions and algorithms for the mobile monitoring systems operation in coastal zones.

However, using single robot for research work is inefficient. For this purpose, we suggest creating a group of mobile robots capable of monitoring the wave conditions in the shelf zone and transporting measuring equipment for complex research. Methods based on using of a group of remotely controlled mobile robotic means are free of many faults mentioned above, and proved their efficiency in the course of experimental researches [20, 21, 22].

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Within this project we suggest an approach to coastal wave climate monitoring ,based on employing a telemetrically connected group of ground, above-water and underwater robots.

This approach allows us to expand the research area significantly.

The scheme of the group interaction and the possible scheme for carrying out the experiment is shown in the Figure 5.

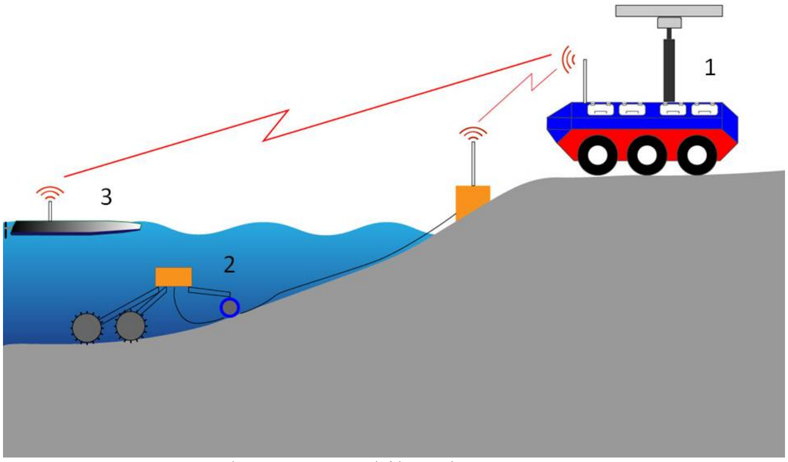

Figure 5. Mobile robot group.

This scheme consists of ground (1), underwater (2) and above-water (3) robots. The ground and above-water complexes exchange information on wave strength and the investigated area bathymetry detailed data. The underwater robot uses a cable to transmit data on wave strength from a string sensor in the researched area,the data is received by a stationary base installed on the shore. Further, the information is transmitted via wireless communication to the ground robot computer for processing. Now, we'll examine each type of robot.

3.1. Ground robot

In the interaction scheme, the ground segment is represented by an autonomous mobile robotics facility developed by research team from NNSTU n.a. R.E. Alekseev [23, 18]. The complex,which shown in Figure 6, can have different types of movers installed, add-ons for actuating devices of control drives and hardware.

The hardware consists of two LMS511Pro LIDARs, a GNSS antenna, a weather station, a wi-fi antenna, a video camera and all-round surveillance radar MRS-1000.

The robot collects information on wave activity in the investigated zone. Software unit collects information and outputs it graphically. During the tests the data is all held on the on-board computer.

Figure 6. Ground robot.

3.2. Underwater robot

The underwater segment in the scheme is represented by an amphibious modular vehicle (AMV) (Figure 7) [14]. AMV is a three-support system consisting of several basic components: support platform, sealed container for measuring equipment, adjustable arms, step motors, driving wheels and a supporting wheel.

Figure 7. General view of AMV [14].

The complex collects data using a video survey system and a hydrostatic wave recorder with a string sensor mounted to the stationary casing support. The operation of the string sensor is the work of the capacitor coatings between the insulator, water and copper wire being conductors[14].

AMV has adjustible gravity center for stability increasing when driving on steep slopes of the seabed or suffering significant hydrodynamic exposure. To adjust it vertically one changes the length of each of the support arms in the range of 770-920 mm, or changes the angle between support arms of the driving wheels in the range of 40°- 120° if horizontal adjustment is needed. When the position of the mass center in the two above-mentioned planes changes, the motion axes of the driving wheels diverge. This leads to disalingment of propelling forces, drag forces increase and loss of complex controllability. To avoid this problem we use an adjustment unit that allows changing the direction of the motion axes of the driving wheels and setting them parallel to each other with accuracy of ± 1 degree.

The AMV electronics consists of control and power units. A single-board computer makes the core of the control part,all other sensors are connected to it. These are tilt sensor based on MPU-6050 gyroscope, string sensor for recording wave height and videocamera. They are controlled remotely from the shore via Ethernet cable or wi-fi if the cable is connected to a buoy floating in the water. The power part consists of two stepper motors with reducers (1:10) and stepper motor drivers. Lithium battery 48V 10Ah is a power supply providing 4 hours of continuous operation which satisfies several submersion experiments.

3.3. Above-water robot

The autonomous remote-controlled research boat is designed to carry out detailed bathymetric measurement of the observable water area. It allows us to create a depth map promptly using a multibeam echosounder.

The development of an autonomous remote-controlled research boat was carried out by the engineers of Special Design Office for Automation of Marine Research of the Far Eastern Branch of the Russian Academy of Sciences (SRBA MR FEB RAS) who have wide experience in creating research complexes and conducting oceanological research, studing hydroacoustic, hydrophysical and hydrodynamic processes, the atmosphere and ocean interaction, marine hazards and marine safety.

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For the positioning of the boat, the Trimble SPS461 GNSS receiver is used, the IMU-108-30 SMC is used to determine the boat's tilt parameters. Bathymetric data is collected by a multibeam echosounder. Protected computer with a separate power supply 12V 15Ah processes the data and controls the boat. Power plant includes two DC motors, BTS7960 drivers and an arduino nano controller. The boat is controlled remotely, maneuvering is performed through the right and left motors manipulating. Extended-range Wi-Fi module based on the MikroTik 2SHPN point of presence provides communication with the boat .

4. Experiment

We undertook three expeditions to various parts of the Sea of Okhotsk coastal zone at Svobodny Cape of Sakhalin Island and carried out AMV and AMRC tests in July 2017.
The coastal zone relief is characterized by shallow water depth of 2-4 meters over several hundred meters far from the shore. The AMV was plunged into water to the depth of about 2 meters using remote control at a distance of about 50 meters from the shore. At the same time, we collected data on wave activity using a ground robot placed near the AMV (Figure 8). The data from the string sensor was transmitted to a base station installed on the shore, and then to AMRC, that made equipment calibration possible, and we got information on wave strength in the zone with the help of radar.

Thus, both robotic devices were combined into united local network. Then, the data on wave height was collected and displayed in real time for 60 minutes.

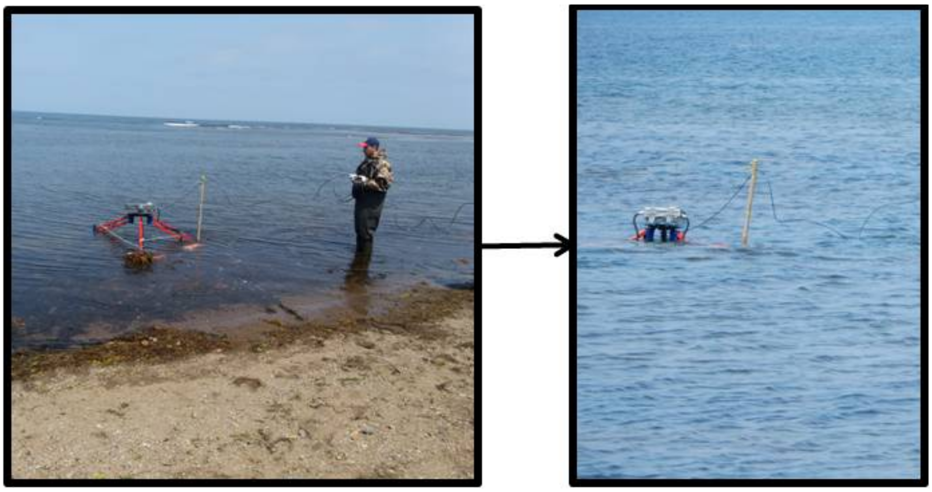

Figure 8. AMV's submersion into water.

On the basis of the experimental researches undertaken , the following conclusions were made.

The developed AMV can be used to verify data received from a radar station installed on a large-scale research chassis when using a group of mobile ground and above-water robots for detailed study of wave dynamics.

Primordially, a string wave sensor was used, but this sensor has a number of shortcomings.It can be used only in a slightly rough sea and there is a risk that marine growth affects the delicate wire. In this connection , we plan to refine the AMTS design and use bottom pressure sensors, which do not have these drawbacks.

We made coastal supporting surfaces classification and elaborated an approach to the development of functional chassis designs for coastal and adjacent water areas.

A technique for selecting optimal vehicle parameters and basic vehicles requirements,depending on the type of terrain, have been developed.

We suggest brand new approach to sea waves rating with the help of a group of mobile ground, underwater and above-water robots. Unified approach will help expand the observable zone significantly and verify data received from robots.

For the summer 2018 we are planning an experiment involving all three types of robots integrated for better control into a local network with real-time data processing. Currently, software for shared control of a group of robots is being developed. We are planning to refine the system by increasing underwater robot mobility.Using the buoy with WiFi transmitter instead of underwater cable is possible. This solution requires underwater robot's connection to the buoy via cable, communication with other robots of the group will be established with the help of a Wi-Fi transmitter floating in the water. It will make the experiment less restricted since transmitter installation ashore and cabling won't be needed. It is also possible to install GNSS inside underwater robot, attaching the receiver antenna to the buoy, as a result this will improve the accuracy of robot's positioning.

Nomenclature

a	coefficient characterizing the attenuation of stresses in the soil	
b	tire contact width with soil	[m]
k_τ	coefficient of tangential elasticity of soil	
S_t	grousers step	[m]
S_{t_0}	grousers shear	[m]
β	angle between the load vector and the normal to the soil surface	[radian]
ρ	volume density of soil	
E	modulus of deformation	
φ_0	angle of internal friction	
c_0	internal friction in the soil	
H_G	thickness of soft layer	
z	immersion	
λ_k	basic chassis parameters	
λ_{kn}	initial value of basic parameters	
λ_{kk}	final value of basic parameters	
λ_G	basic soil parameters	
λ_{Gn}	initial value of basic soil parameters	
λ_{Gk}	final value of basic soil parameters	
$\Delta\lambda_G$	step values of basic soil parameters	
$\rho(\lambda_G)$	probability density	
Φ_f	generalized resistance function	
Φ_φ	generalized friction function	

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