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## COMPLEX OF TASKS FOR MONITORING AND AUTOMATIC CONTROL OF MOBILE ROBOTS FOR VERTICAL MOVEMENT

КОМПЛЕКС ЗАДАЧ МОНИТОРИНГА И АВТОМАТИЧЕСКОГО УПРАВЛЕНИЯ МОБИЛЬНЫМИ РОБОТАМИ ДЛЯ ВЕРТИКАЛЬНОГО ПЕРЕМЕЩЕНИЯ

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**Abstract.** There have been analyzed and formalized the tasks of monitoring and automatic control of mobile robots (MR) for their movement and execution of various types of technological operations on inclined and vertical ferromagnetic surfaces. Generalized structure of a mobile robotic complex is shown with consideration to its main subsystems. The paper presents critical analysis of the current state of the problem of development of universal structures of MRs for the various types of technological operations and elaboration of computerized systems for monitoring and control of MR movement. In particular, there is provided a review of wheeled, walking and tracked MRs with pneumatic, vacuum-propeller, magnetic and magnetically operated clamping devices to grip vertical and ceiling surfaces. The constructive features of the crawler MR with a magnetic clamping device capable of moving along inclined ferromagnetic surfaces are considered. The basic technical parameters of the MR are shown for the further synthesis of computerized monitoring and automatic control systems. Formalization of monitoring and control of the MR positioning at the processing of large ferromagnetic surfaces is considered from the point of view of the control theory.

**Keywords:** mobile robot; propulsor; clamping device; control system; positioning; controlled coordinates.

**Аннотация.** В работе проведен анализ и формализация комплекса задач мониторинга и автоматического управления мобильными роботами (МР) для перемещения и выполнения различных технологических операций на наклонных и вертикальных ферромагнитных поверхностях большой площади. Определены основные управляемые координаты гусеничного МР с магнитными прижимными устройствами для дальнейшего синтеза компьютеризированной системы мониторинга и автоматического управления.

**Ключевые слова:** мобильный робот, движитель, прижимное устройство, система управления, позиционирование, управляемые координаты.

**Анотація.** В роботі проведено аналіз та формалізація комплексу задач моніторингу та автоматичного керування мобільними роботами (МР) для переміщення та виконання різномісних технологічних операцій на похилих та вертикальних ферромагнітних поверхнях великої площі. Визначені основні керувані координати гусеничного МР з магнітними притискними пристроями для подальшого синтезу комп'ютеризованої системи моніторингу та автоматичного керування.

**Ключові слова:** мобільний робот, рушій, притискний пристрій, система управління, позиціонування, керувані координати.

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**Problem statement.** Improvement of labor productivity with reduction in the risks to human life, health and environment when performing various works in extreme conditions and inaccessible areas is presently an urgent issue resulting from the intensive industrial development in many countries of the world [1, 2, 8]. There are various ways to solve this problem, and one of them is the use of advanced high-technology equipment with programmable control, flexible production modules, and robotic technological complexes.

Multipurpose mobile robots appear to be the most promising solution. They are used for performing at least two different tasks from the following complex: cleaning of large and/or hardly accessible horizontal and vertical surfaces, decontamination of radioactive premises and facilities, underwater operations in a radioactive environment, installation of dowels and explosive devices, fire-fighting operations, dyeing, inspection and diagnostics, welding, cutting, removal of burrs, polishing, and ship hull desalination. All of the above are quite labor-intensive and hazardous to human life and health [1]. Most of the available solutions are based on telecommunication, but autonomous MRs that do not permanently require an operator to carry out the control activities are also on the rise. At the same time, the effective use of such MRs necessitates the development of advanced monitoring and automatic control systems. Integrated automation of multipurpose MRs allows for a significant improvement of the control accuracy and high-quality performance of technological operations.

**Latest research and publications analysis.** Over the last few years, developed countries have been conducting intensive research on the creation of mobile remotely operated robots capable of moving on horizontal, inclined or vertical surfaces using mechanical, pneumatic, vacuum and adhesive clamping devices (CDs) [1, 3–7, 10, 12–20]. However, peculiarities of the combination of propulsors and CDs pose limitations to the use of most types of such robots due to their unsuitability for complex surfaces.

To perform the works in extreme conditions with high quality and reliability, the MRs are provided with the elements of navigation (position and inclination sensors) and communication (transmitters, receivers) systems, pneumatic, hydraulic or electric drives [8, 9]. In most cases, control and communication systems are implemented in the form of onboard built-in controllers [11, 15–19]. At that, programmed and remoted types of control have become the most widespread options [3, 11, 13, 14, 16, 17, 19]. They enable the MR to tackle the following tasks: crossing and bypassing obstacles, moving along a given trajectory with account for the surface's

inclination, keeping to a specified position without slipping, taking the required starting position, etc.

The number of scientific and technical publications regarding the MRs with magnetic and magnetically operated CDs is quite limited [4–6, 14–18]. The complex of tasks for monitoring, control, and further synthesis of structures, models, control devices, and firmware for the MR control systems should be subject to a proper analysis. It is being studied by a number of research teams around the world.

**THE ARTICLE AIM** is to analyze and formalize the complex of tasks for monitoring and automatic control of the MR for its movement and execution of various types of technological operations on large inclined and vertical ferromagnetic surfaces.

**Basic material.** Research and development of robots for vertical movement are carried out at the laboratories and research centers of technologically developed countries [8, 9]. An MR can be presented as a set of three major subsystems: a transport subsystem, a specialized subsystem, and a control subsystem (Fig. 1) [8].

*The transport system* (Fig. 1) is a platform intended for the delivery of specialized and technological equipment to the work site. The transport platform consists of an undercarriage, a main body, and a power plant. As a rule, the control system is installed inside the main body. Depending on the type of the operational environment, the MR may have a tracked, wheeled, wheel-tracked, semi-tracked, walking, or wheel-walking undercarriage and a water jet or gas jet propulsor. The appearance of the ground MR is primarily determined by the type and design of the propulsor used to convert the force derived from the engine into the traction effort that drives the transport platform.

Selection of the propulsor's type and dimensions is very complicated. It is virtually impossible to create a universal design of the propulsion system, which would give the MR an opportunity to move equally steadily under various conditions. Numerous types and properties of the soil, terrain complexity, and the need to move over the elements of structures and inside buildings are the reasons for creation of a large number of layouts for the robots equipped with propulsors of different types. The developers are focused on various modifications of wheeled and tracked propulsors, with less attention being paid to the walking ones and least to the other types. The latter include rotor-screw propulsors, air cushion vehicles [8] and so on, i.e. those designed for movement on the surface with specific physical and mechanical properties (wetlands, shallow water, or deep snow). Therefore, each type of propulsors corresponds to a particular range of ap-

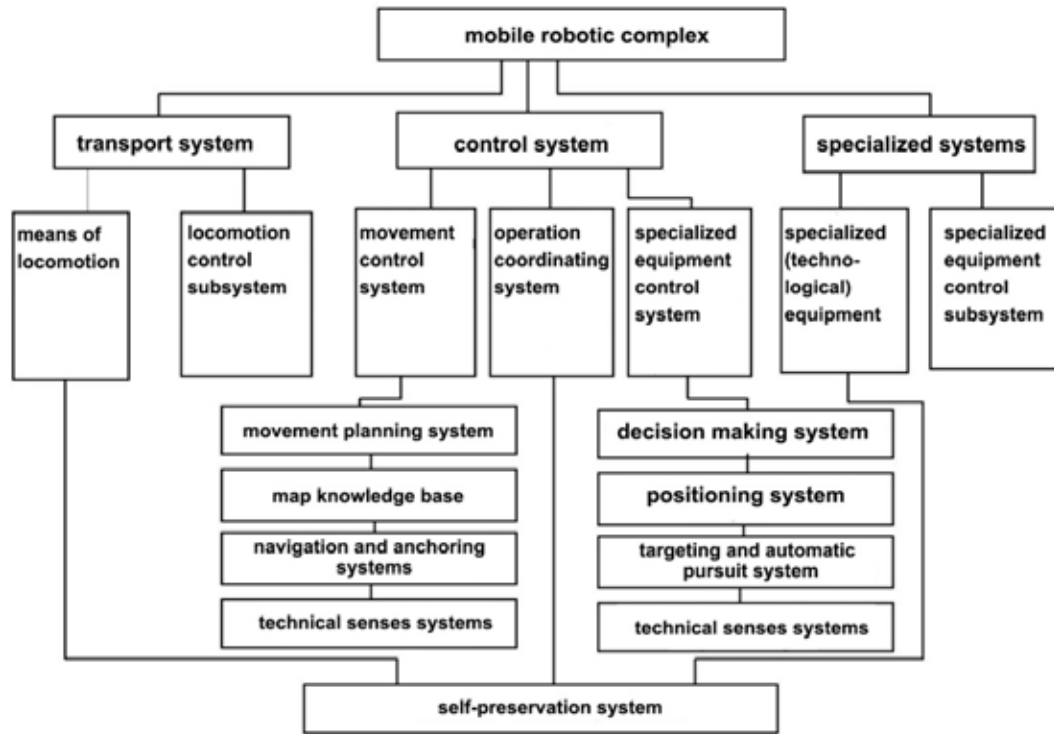


Fig. 1. Generalized structure of a mobile robotic complex

plications. For instance, a multipurpose MR intended for use on uneven terrain is fitted with a tracked undercarriage as the most versatile one. However, when an MR is predominantly used on roads or other fairly even surfaces, the wheeled option appears to be more attractive [8].

Under the conditions where the speed of a wheeled or tracked robot is lower than the speed of a walking one, it is advisable to use the latter (for example, in a mountainous terrain or the site of destruction). When designing conventional vehicles, the propulsion parameters are optimized for the most typical operational conditions and surfaces. However, such optimization for a mobile robot is a very complex problem due to the uncertainty of the operational conditions. This is why the MR propulsors are currently constructed adaptable to the operating surface [1, 2].

*The specialized systems* are directly designed for the execution of specific works. They comprise the required set of technological equipment, which is determined by the type of the problem being solved and the purpose of the MR.

*The control system* provides control of the movement and operation of the technological equipment, as well as adaptive control of the undercarriage and power plant with account for interaction of the transport system with the environment.

The control system comprises the following units:

- the data control unit located on the mobile robot (robot control equipment, sensors, machine vision system, data pre-processing microprocessors);

- the mobile robot operator’s post (control panel, video monitoring devices, computer for data processing);
- the receiving and transmitting equipment kit providing the transfer of data from the robot to the operator’s post and control commands from the operator’s post to the mobile robot.

The control system should also provide the robot’s movement planning in nondeterministic conditions based on the map database and the data continuously coming to the control system from the technical senses and the navigation system. The complexity of the control system is determined by the intricateness of the problem being solved, the degree of uncertainty of the environment, and the degree of the robot’s autonomy. It is the development of control systems that determines the development of robotic complexes as a whole. Researchers pay a lot of attention to the study of dynamic processes and control systems with the feedback on position, strength, and acceleration [2]. At present, designing of the control systems employs the advances on optimizing the locomotion, control algorithms and programs with the use of intelligent technologies for the robots’ movement under extreme and nondeterministic conditions in order to increase their mobility and autonomy [1, 11].

***Special features of mobile robots of various functional purposes, which are capable of moving along inclined and vertical surfaces.***

To move along external surfaces of buildings and facilities, mobile robots can be equipped with vari-

ous types of clamping devices: mechanical, magnetic, adhesive, pneumatic, vacuum, and magnetically operated ones. Their peculiarities pose limitations to the use of most types of MRs due to their unsuitability for complex surfaces. Let us consider each type of MR CDs individually, together with appropriate control systems.

*Vacuum CDs based on seals.* The vertically moving robots mainly employ pneumatic devices with universal seals for gripping vertical and ceiling surfaces; the seals are suitable for any surface material [1, 3, 9, 13, 17]. For instance, cleaning MRs can be fitted with a wheeled undercarriage and a descender [17], a mobile wheeled system with a telescopic lever (Fig. 2) [13], or a walking undercarriage with pneumocylinder propulsion [3]. The weight and dimensions of robots can be reduced through the use of multipurpose CDs, which allow both holding on to a given position and effectively cleaning the operating surface. In this case, the gripping effort of the vacuum device should be sufficient to keep the robot at a given position on the vertical surface and provide the normal force required for its movement. If the vacuum's clamping force is too low, the robot will fall off from the vertical surface; if the clamping force is too high, the robot will be difficult to move [1].



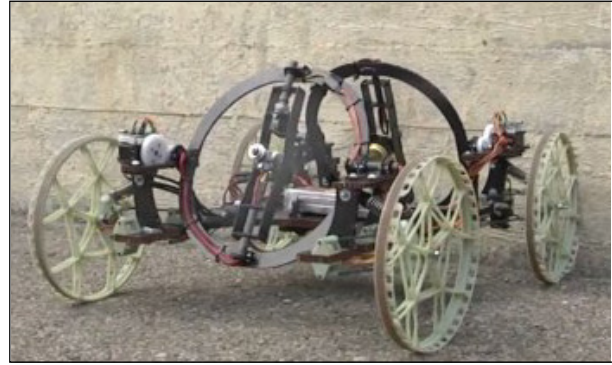
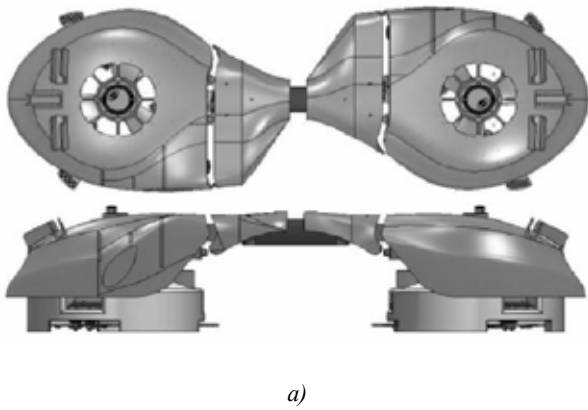
**Fig. 2.** Cleaning MR based on a wheeled complex with a universal CD and a telescopic lever

Therefore, MRs of this type are poorly controllable, they move slowly, with jerks, which often leads to the need for re-cleaning of the skipped areas. In addition, the vacuum clamping devices are unreliable when operating on heterogeneous surfaces (such as welded joints) that deform the vacuum seal and make the robot fall off. It is rather difficult for such an MR to perform any works other than paint stripping and almost impossible to move at high speeds, which is essential for enhancement of its performance at cleaning operations [1]. While the vacuum devices provide the required clamping force, they are sensitive to the quality and heterogeneity of the surface and call for considerable expenses aimed at intense maintenance and frequent replacement.

*Vacuum CDs based on propeller screws.* The clamping devices based on propeller screws may serve as an alternative to the above mentioned CDs (Fig. 3, a). They are placed in a closed suction chamber and do not rely upon the material of the operating surface [19]. Due to their multifunctionality, they can adjust the direction and speed of the mobile robot under water, allowing it to reach the surface if the adhesion to the ship's hull is lost. However, these CDs have large weight and dimensions due to the presence of a geared DC motor in their structure. The shafts should be sealed carefully for underwater operation. To provide for the semi-autonomous operation without monitoring, the control system of the walking cleaning robot contains encoders on each rotating part, accelerometers, differential pressure sensors for measurement inside the suction chamber, an absolute pressure sensor for depth measurement, and elements for the exploration of the local environment.

The MR control system [19] is hierarchical and comprises three levels. The basic, top-level unit calculates the path the robot must follow to clean an object effectively. The configuration of this unit may vary depending on the applied strategy (random or based on the layout of the robot's main body). The middle-level reactive system is responsible for autonomous crossing of obstacles and performing of local maneuvers (based on sensory data). The bottom-level controller is realized with the use of the Simatic S7-300 PLC; a GUI operator has been developed for the regulation of the engine's operation. The controller may be directly available to the human operator for operational monitoring.

Another MR, VertiGo, is based on a frame made of lightweight carbon fiber [20]. The robot has four wheels, and the front two can be rotate like the front wheels of a car. The VertiGo robot can move along vertical surfaces due to its two propellers driven by electric motors mounted on a movable suspension (Fig. 3, b). The robot's frame accommodates a microcontroller that receives in-



**Fig. 3.** Mobile robots based on vacuum clamping devices:  
*a* — underwater walking cleaning robot; *b* — ground wheeled robot

formation from inertial sensors and two infrared sensors. The sensors continuously provide information on the robot's current position in space and the distance to the obstacle to be crossed. Using these data, the processor calculates the propeller angles and rotational speeds necessary for the creation of the air flow to reliably hold the lightweight robot, pressing it to the vertical surface. Such MRs can be used to conduct a survey of the structure integrity regardless of its material, particularly in inaccessible areas of buildings and facilities. More energy-intensive operations are still beyond their capabilities.

*Magnetic clamping devices.* Fig. 4, *a* presents a model of the underwater cleaning and inspecting MR with permanent magnets on its tracks (Fugro, Aberdeen, GB [14]). The robot has a hydraulic drive and is controlled remotely (from the surface) with the help of a laptop. Cleaning is carried out through a combined effect of water jets and rotating brushes on the processed surface. The quality of the cleaning and diagnostics control is enhanced by means of HD stereo cameras and ultrasonic thickness gauges, cathodic protection monitoring, surface thickness measurement, cracks detection, 3D Sonar visualization, and laser scanning. The advantages of such an MR are its high operational speed, mobility and maneuverability due to the large area of adhesion with

the operating surface. The disadvantages are a low reliability and short service life due to the continuous shock mechanical collisions of the permanent magnets with the operating surface during the caterpillar tracks movement, which leads to demagnetization and gradual destruction of the magnets. Besides, the energy efficiency of the robot's movement is quite low, since each subsequent elementary (unit) displacement of the device equivalent to the width of a track's permanent magnet is accompanied by separation of the latter in the opposite direction, which leads to the emergence of additional resistance to the robot's movement and extra energy loss.

Wheeled MRs with permanent magnets are widely used for diagnostics and inspection in inaccessible areas; Fig. 4, *b* shows the Magnetbike model [12], and Fig. 4, *c* shows the HR-MP20 model [6]. The former is equipped with roughness and thickness sensors, instrumentation for measuring oxygen concentration, and wide-angle CCD high-resolution cameras. Navigation of the inspection robot is provided by means of an integrated miniature gyroscope XSENS MTi and a directed coordinate system (AHRS). The low-power internal signal processor implements 3D drift orientation of the MR without energy consumption and calibrates 3D acceleration, turning course, and magnetic field data of the earth.



**Fig. 4.** Wheeled MRs with permanent magnets:  
*a* — for cleaning; *b, c* — for inspection

The remotely controlled robot HR-MP20 is aimed at diagnosing hidden defects and cracks in the metal structures of wind generator turbines [6]. It is made on the basis of a four-wheeled cart. Due to the powerful neodymium magnets installed in the wheels, it can freely move along the vertical surfaces of turbine supports and curved surfaces of the blades (Fig. 4, c). In some cases, the wind turbine should not be stopped completely for its inspection, since the force of magnets and the power of electric drives of the robot allow it even to grip the surface of rotating blades, overcoming the impact of centrifugal forces. Five neodymium magnets ensure the robot's operation on flat and curved surfaces with a radius of curvature up to 1.2 m in any direction selected by the operator at the maximum speed of 13.3 m/min.

The inspection MRs with magnetic clamping devices are characterized with a high passability and can work autonomously, but they have a limited scope of application due to the low load capacity.

Publication [17] considers a wheeled cleaning MR M2000 with permanent magnets. It weighs 216 kg and is made of corrosion-resistant materials, such as titanium, stainless steel, and various plastics. The engines, sensors and electrical connectors are fully sealed, so that the entire robot can be poured over with water or even immersed in it for a short period of time. The M2000 contains two large magnets fixed under its front and rear axles. The robot is intended for stripping the paint up to 6.3 mm thick, which corresponds to the largest gap between the magnet and the steel surface. The large normal clamping force of the magnet allows the MR to move safely on smooth, wet and even oil surfaces. The robot is directed with the help of an industrial radio control unit. The built-in microcontroller converts the signals from the control unit's joystick and input buttons into the corresponding signals for the MR actuators and air valves. The low-level microcontroller subsystem also addresses

the safety issues, which includes an automatic stop in the event of any firmware malfunction and automatic closing of the cleaning device's nozzles when the robot stops. The surface stripping speed is determined by a computer vision system that photographs the stripped surface and compares the photo with static images of the steel surface stored in the memory. The system then decides to increase or decrease the speed of the MR movement.

Therefore, magnetic clamping devices are a very promising option for the works on ferromagnetic surfaces. They are applied even in large MRs. Yet, these CDs do not provide for the control of the clamping force and suggest a limited number of cycles of collision with the operating surface in some structural arrangements (for example, when mounted on the robot tracks) [5].

*Adhesive CDs.* Chemical and molecular adhesion is one of the ways to secure a robot on the surface. A walking robot that employs molten plastic to move [7] can be fixed on vertical surfaces with a load that may exceed its own weight. The robot's legs are equipped with heating elements. When in action, these elements melt a special polymer composition, which then fills even the smallest cracks and displays of roughness of the operating surface (Fig. 5, a). Each cycle (step) of the robot involves heating the material, attaching the leg to the surface, slightly cooling the material, movement and strong cooling, which allows the legs to separate from the surface. The MRs of this type can be used as front scouts in mining rescue services, assistants in the construction of high-rise buildings, or instruments for the decoration (artistic finishing) of vertical walls and facades. However, the heating, melting and further cooling of the adhesive polymeric mixture call for substantial energy expenditure. In addition, a part of this mixture remains on the operating surface, so the robots have to be additionally equipped with a spare tank of this material. It should also be noted that the strength of chemical adhesion tends to decrease



a)



b)



c)

**Fig. 5.** Walking mobile robots: a, b — equipped with adhesive CDs; c — equipped with magnetically operated CDs

after several applications due to the presence of dust on the surfaces [1].

It is promising to make use of molecular gravity forces (also dubbed as the Van der Waals force), as does the Abigaille robot [10] regarded as an outer space robot (Fig. 5, b). It is capable of moving along vertical and horizontal surfaces by using the principles of gripping the surface like a gecko lizard does. The surface of the robot's legs is covered with millions of dry tiny fiber-glass setae ending with flat surfaces. It is modeled after the toes of a gecko, which is able to move along absolutely smooth vertical surfaces without the use of adhesives. Flat ends of the millions of setae come into contact with the material of the surface and allow holding a fairly large load. The advantage of such a technology is its suitability for use in vacuum, under sharp temperature changes and other extreme conditions of the open space. The only drawbacks of such CDs are the manufacturing complexity and high cost.

*Magnetically operated CDs.* Fig. 5, c presents the ship cleaning MR of the walking type with manual, semi-automatic and automatic control [18]. The combined clamping devices are based on permanent NdFeB magnets, and additional electromagnets prevent the accumulation of ferromagnetic dust during the robot's operation. These electromagnets also separate the MR legs from the operating surface at the movement through creating magnetic fields opposite to those of the permanent magnets. Such clamping devices allow adjusting the value of the clamping force when necessary. The robot's architecture is based on two four-legged frames or modules connected by a complex of joints that move relative to one another by means of a pneumatic actuator. This is how the robot's movement on the ship's hull is provided.

The control system comprises two major parts: an onboard control system and a movement control system. The former checks the sensors and makes real-time decisions regarding the state of the executive mechanisms. The latter is located in the base station on land. The movement control system authorizes the interaction with operators, plans the path to cover the area to be cleaned, and checks the surface treatment quality using the data obtained from two intelligent cameras. At that, one camera is in front of the cleaning tool, and the other is behind it. The two subsystems are connected via the communication line. The entire control system includes four levels of control, one on the robot and three on the base station.

The onboard MR control system is based on the microcontroller PIC24HJ256GP206, which is designed for operation under industrial conditions. It communicates with the base station via the bus with the RS485 interface

to receive instructions and transmit the sensor data. The system includes four types of sensors. Linear sensors measure the position of the pneumatic drive and allow for a real-time calculation of the robot's kinematic configuration. A three-speed accelerometer measures the local gravity, estimates the robot's spatial orientation, and adjusts the estimate of the robot's position on the ship's hull. Finally, two video cameras are used for the surface treatment quality monitoring and additional positioning of the robot [18].

The movement control subsystem is built on a regular personal computer (PC) with the RS485 interface for communicating with the robot control subsystem and the appropriate input for the data transmitted from the video cameras tracking the cleaning quality. The movement control is based on three hierarchical levels that correspond to three different modes. Lower levels are subordinate to upper levels. The operator can access any level via the graphical user interface where (s)he can choose the manual, semi-autonomous and autonomous mode for the robot's operation.

The advantages of such an MR are its high passability and reliability of adhesion to a ferromagnetic surface provided by the additional electromagnets. The disadvantage is the limited scope of application, since it can handle only the outer surfaces of the ship's hull due to the large amount of wires and cables [1].

Paper [15] proposes an interesting concept, namely, the inspection mobile robot SCID fitted with two powerful clamping electromagnets. It does not have a drive but moves under the impact of gravity along any trajectory. The control strategy is to modulate the frictional force between the electromagnet and the surface to obtain a given trajectory. The MR employs two types of sensors. Thus, two potentiometers (standard, single-turn, linear) measure the angle position, while the ADXL 202 accelerometer determines the absolute angle of the robot's deviation from the course. The MR is equipped with a hybrid fuzzy-digital microcontroller ST52E420, which controls the robot's movement autonomously, according to a pre-recorded program. This MR has a high energy efficiency and a small weight. At the same time, its application is limited because it can only move from top downwards, which does not allow operating on ceilings. Moreover, the system is characterized with a low reliability; the robot may slip uncontrollably and move on complex vertical surfaces unsteadily.

The marine wheeled MR Octopus (French) [16] is capable of moving on vertical, horizontal or inclined steel surfaces with the help of powerful magnets. The Hie system can be pre-programmed to follow a specified path or to be controlled remotely (via a joystick) in real

time. The robot has low speed and passability because of the wheels' small area of adhesion to the operating surface.

As evidenced by the critical analysis of most types of available MRs, the most promising option is a tracked MR equipped with magnetic or magnetically operated CDs.

***Layout and basic properties of a mobile robot for vertical movement along inclined ferromagnetic surfaces.***

Fig. 6 presents a layout of a mobile robot for the mechanical cleaning of a ship's hull. In particular, the dashed lines in Fig. 6, a (top view) indicate the elements

that are not visible from this angle. The robot is built on a solid two-component flat frame (Fig. 6, a). Rectangular part of the frame 1 is equipped with a tracked mechanism [5]. Each caterpillar track 2 is equipped with a driving and a driven wheels; tape 3 made of a friction material is stretched in between. Each driven wheel is connected to drive motor 4 and gear unit 5. The rectangular part of the frame also accommodates zero buoyancy tank 6 and spherical hinges 7 (on the lower surface) securing the main permanent magnets 8 between the left and right caterpillar tracks with a proper gap  $\delta$  to the operating ferromagnetic surface 9 (Fig. 6, b). The second part of the frame has a triangular shape (labeled 10 in Fig. 6, a).

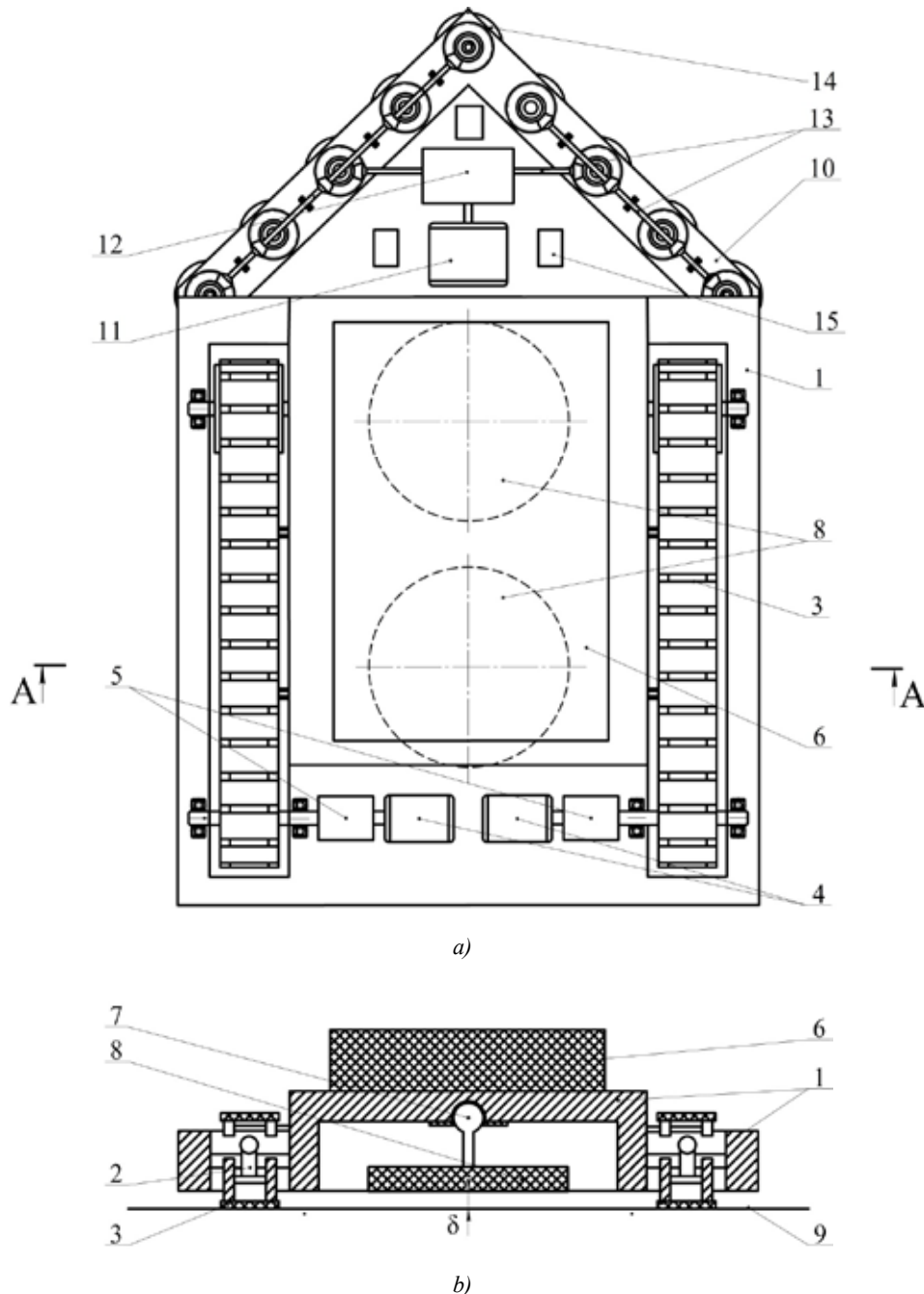


Fig. 6. Layout of the MR for mechanical cleaning of ferromagnetic surfaces

It contains electric motor *11* kinematically connected through gear unit *12* and shaftings *13* to the steel tooling with cleaning brushes *14*. Apart from that, additional clamping permanent magnets *15* are evenly placed on the entire lower surface of the triangular part of the frame.

The MR for the mechanical cleaning of a ship's hull operates as follows. First, a cleaning mechanism (tooling with steel brushes) is set at 1.5–2 mm above the surface to preserve the primer and painted layers of the ship's side. Then the mobile robot is installed on the ship's hull in such a way that the main permanent magnets are oriented through the gap  $\delta$  along the ferromagnetic surface to provide the required clamping force. Afterwards, electric motor *11* is launched, and the cleaning procedure begins. Thereat, brushes *14* rotate in different directions on the left and right sides of the triangular part of the frame. It allows balancing the torque (rotating) moments of the tooling and eliminates the mobile robot's misalignment (tilting) at its movement and operation.

Next, electric motors *4* are powered to rotate the driving wheels together with caterpillar tracks *3* through the gear units *5*. Thus, the mobile robot starts moving along the surface of the ship's hull and mechanically cleaning it from algae and other aquatic organisms. Cleaning can be performed both underwater and in a floating or dry dock. For effective underwater treatment, the shafts of the gears and motors are made watertight with composite ferromagnetic and gland sealing, and the robot is fitted with zero buoyancy tank *6*.

The mobile robot moves automatically on the surface of the ship's hull in the direction specified by the program at a speed appropriate for the execution of a particular technological operation (in this case, cleaning of the ship's hull). The speed of stripping can be controlled by a human operator or a specialized computer system according to the quality of treatment of the operating surface. Apart from that, two twin motors *4* with gear units *5* operate autonomously, independently of each other, which allows the robot to make any turn from  $0^\circ$  to  $360^\circ$  or move backwards. When the robot is moving along a rough surface, permanent magnets *8* secured with spherical hinges *7* deviate from the vertical axis of the hinge within the gap  $\delta$ , and thus set the holding force vector perpendicular to the surface of the ship's hull. In this way, the uniform distribution of the maximum clamping force between the magnets and the ship's surface is ensured along the entire operating plane of the magnets.

The use of separate holding magnets to create a clamping force and the installation of spherical hinge joints securing the magnets between the tracks on the underside of the MR frame improve the reliability of adhe-

sion of the device to the operating surface by increasing the magnetic holding force of the robot. The main vector of the clamping force generally acting on the polar magnet facet and its components are calculated in [4].

The presence of an appropriate gap between the main permanent magnets and the surface allows increasing the speed and passability of the robot, since it provides the possibility of orienting the outer plane of the main clamping magnets in relation to the ship's hull. The proposed tracked MR consumes less power because there is no additional resistance to movement, which means that there is no need for a cyclic separation of the permanent magnets from the ferromagnetic surface during movement like that described in [4, 14].

**Major tasks of monitoring and automatic control of the MR.** In order to ensure reliability of the MR movement and continuity of the high-quality cleaning of the ship's hull surface (or other technological operations), these processes should be automatically controlled with the appropriate level of precision, all the operating parameters of ongoing operations should be monitored and checked for compliance with the declared level of quality. In addition, it is necessary to keep track of the current operational parameters of the robot and its technical equipment [2].

Let us regard the robotic complex under consideration as a multi-coordinate control and monitoring object. Then, there can be formulated the following major tasks for its monitoring and automatic control:

- monitoring and automatic control of the  $\mathbf{Y}_{MR}$  vector of the MR spatial motion parameters;
- monitoring and automatic control of the  $F_{MR}$  value of the clamping force of created by the MR clamping magnets;
- monitoring and automatic control of the  $\mathbf{D}_{MR}$  vector of the parameters of specified technological operations performed by the MR (cleaning, cutting, welding, inspection, etc.);
- monitoring and automatic control of the  $X_{YMR}$  vector of the operating parameters of the technical equipment of the MR propulsor;
- monitoring and automatic control of the  $X_{FMR}$  vector of the operating parameters of the technical equipment of the MR clamping device.

The functional structure of the MR as a multi-coordinate control object is shown in Fig. 7. In the diagram, TE stands for the technical equipment of the MR, which is used for the implementation of specified technological operations;  $\mathbf{U}_{TE}$  is the vector of the signals of the MR TE control;  $\mathbf{U}_p$  is the vector of the signals of the MR propulsor control;  $\mathbf{U}_{CD}$  is the vector of the signals of the MR CD control;  $\mathbf{Z}_p$ ,  $\mathbf{Z}_{CD}$ ,  $\mathbf{Z}_{TE}$ , and  $\mathbf{Z}_{MR}$  indicate the vectors of the

disturbing impacts acting on the MR propulsor, CD, TE, and main body, respectively.

Thus, the given mobile robot for vertical movement along inclined ferromagnetic surfaces is a complex multi-coordinate control object, and its effective functioning necessitates a developed multi-coordinate monitoring and automatic control system. As can be seen from the functional structure of the MR, the system should consist of the following multi-coordinate subsystems:

- 1) propulsor monitoring and automatic control subsystem;
- 2) CD monitoring and automatic control subsystem;
- 3) TE monitoring and automatic control subsystem.

The effectiveness of the above subsystems is substantially enhanced by the application of intelligent technologies in the development of their functional structures, control algorithms and devices.

**CONCLUSIONS.** The paper present the analysis and formalization of the complex of tasks for monitoring and automatic control of the MR capable of moving along large inclined and vertical ferromagnetic surfaces in order to perform various technological operations.

Analysis of the special features of most types of modern MRs capable of moving along inclined and vertical surfaces renders the complex of problems related to the development and operation of the CDs, control of the drives, as well as different ways of their solution.

Magnetically operated CDs are most suitable for moving along ferromagnetic surfaces. They provide the MR with the highest speed and insensitivity to changes in the structure and temperature of the surface. Addition of permanent magnets to the CD improves the reliability of the robot in the event of a power system malfunction.

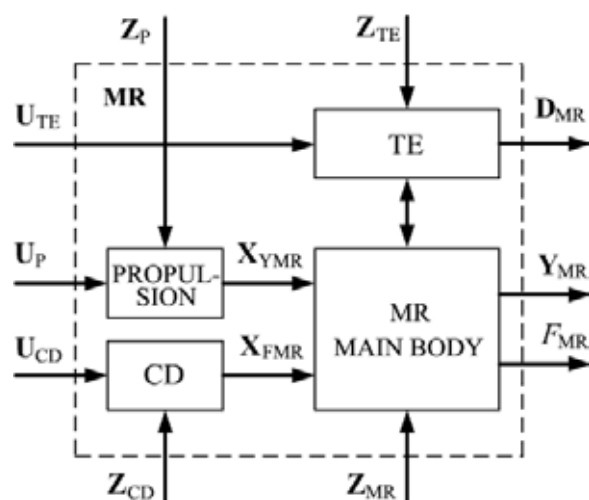


Fig. 7. Functional structure of the MR as a multi-coordinate control object

Automatic control of the MR employs the same principles as those used with other equipment. At that, program systems with telecontrol have acquired the most widespread application. Another common option is advanced computer tools, including built-in controllers that simplify and significantly accelerate the control processes.

Further research should be conducted in the sphere of synthesis of functional structures and mathematical models, mechanical movement of MRs along vertical surfaces by means of different methods, intellectualization of MRs through installation of appropriate sensors and establishment of feedback, development of special algorithms for scene analysis, accumulation of databases on the external environment, and automatic decision making.

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