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AUTOMATION OF THE MONITORING AND CONTROL PROCESSES OF A MOBILE ROBOT FOR PROCESSING OF LARGE INCLINED SURFACES

АВТОМАТИЗАЦІЯ ПРОЦЕСІВ МОНІТОРИНГУ ТА КЕРУВАННЯ МОБІЛЬНИМ РОБОТОМ ДЛЯ ОБРОБКИ ПОХИЛИХ ПОВЕРХОНЬ ВЕЛИКОЇ ПЛОЩІ

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Abstract. The article renders special features of the design of a tracked mobile robot (MR) for moving over inclined ferromagnetic surfaces while performing specified technological operations. There is conducted a synthesis of the functional structure and selective technological parameters (such as control coordinates) of the computerized monitoring and control system (CMCS) intended for use with this MR. Application of the CMCS with the proposed functional structure allows substantially increasing the accuracy of the MR monitoring and control, which in turn provides for a considerable enhancement in the quality and economic efficiency of the operations on processing of large ferromagnetic surfaces.

Keywords: mobile robot; propulsor; clamping device; control system; positioning; sensor system; technological equipment.

Анотація. В статті розглянуто особливості конструктивної побудови гусеничного мобільного робота (МР) для переміщення по похилих феромагнітних поверхнях з одночасним виконанням заданих технологічних операцій. Здійснено синтез функціональної структури та селективних технологічних параметрів (як керованих координат) комп'ютеризованої системи моніторингу і керування (КСМК) даним мобільним роботом. Застосування КСМК із запропонованою функціональною структурою дає змогу значно підвищити точність процесів моніторингу і керування МР, що, в свою чергу, дозволяє суттєво підвищити якість та економічну ефективність виконуваних операцій обробки феромагнітних поверхонь великої площі.

Ключові слова: мобільний робот, рушій, притискний пристрій, система керування, позиціонування, сенсорна система, технологічне обладнання.

Аннотация. В статье рассмотрены особенности конструктивного построения гусеничного мобильного робота (МР) для перемещения по наклонным ферромагнитным поверхностях с одновременным выполнением заданных технологических операций. Осуществлен синтез функциональной структуры и селективных технологических параметров (как управляемых координат) компьютеризированной системы мониторинга и управления (КСМУ) данным мобильным роботом. Применение КСМУ с предложенной функциональной структурой позволяет значительно повысить точность процессов мониторинга и управления МР, что, в свою очередь, позволяет существенно повысить качество и экономическую эффективность выполняемых операций обработки ферромагнитных поверхностей большой площади.

Ключевые слова: мобильный робот; движитель; прижимное устройство; система управления; позиционирование; сенсорная система; технологическое оборудование.

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Problem statement. The problem of processing large external and internal surfaces of various types of industrial facilities is of a great economic importance to all the developed countries of the world. For its solution. it is feasible to utilize the latest high-performance technologies involving robotic technological complexes to conduct the necessary technological operations: cleaning of large horizontal and vertical surfaces and hardly accessible areas, decontamination of radioactive premises and facilities, underwater operations under radioactive pollution, installation of dowels and explosive devices, fire-fighting operations, dyeing, inspection and diagnostics, as well as welding, cutting, removal of burrs, polishing, and even desalination. All of the above are quite labor-intensive and hazardous to human life and health [1]. The use of robotic systems, both mobile and stationary ones, can substantially improve the operation productivity without decreasing its quality, as well as reduce the cost of finished products and services provided. These labor-intensive and often hazardous operations are typical of such industries as shipbuilding and ship repair, agriculture, oil and gas processing, as well as transportation, military and food industries, and the sphere of production services.

At the same time, of particular interest currently is the possibility of application of mobile robots to conduct one or more technological operations on large inclined and vertical surfaces. It is in these industrial conditions where the introduction of MRs has the most beneficial effect. In turn, these MRs are complex multicomponent technical objects that require to be accompanied with special computerized monitoring and control systems (CMCS) [2]. Complex automation of technological objects of this type provides for a substantial enhancement of their efficiency and economic indicators [2].

It is recommended to solve the problems of synthesis of the CMCS of the MR for the processing of large inclined surfaces on the basis of analysis of the major properties and technical characteristics of the processes of MR’s moving and performing a given technological operation with the selection of parameters (signals, coordinates) that are subject to monitoring and control [2].

Latest research and publications analysis. There are a number of publications in the scientific and technical literature on automation of the equipment for movement along inclined and vertical surfaces, in particular, of various cleaning and inspection mobile robotic installations and complexes [3-9]. Currently, the research efforts made by scientists and developers are aimed at creating designs and CMCS of mobile tele- or remotely controlled robots that can move and perform specified technological operations along horizontal, inclined or vertical surfaces with the help of various clamping devices.

In most cases, control and communication systems are implemented with the help of onboard embedded controllers [3, 5]. At that, program control and telecontrol are the most common options [3-10]. For instance, papers [3, 6, 7, 9] present specialized automatic control systems for cleaning MRs which operate according to a predefined program. Computerized monitoring and remote control systems of inspection MRs have been developed and discussed in publications [4, 5]. There are also automatic control systems for a high-pass MR’s subsystems, which utilize artificial intelligence methods [8]. However, when it comes to the MR automation for its simultaneous movement and execution of a given technological operation along a large inclined ferromagnetic surface, there are only few publications, while the tasks of development of the functional structures, control algorithms, components and elemental base of the specialized MR CMCS presently remain the subject of studies performed by several research teams both in Ukraine and abroad. This situation indicates the need for using a comprehensive system approach to take into account the special features introduced by combinations of propulsors and clamping devices of each individual MR when developing its CMCS.

THE ARTICLE AIM is to develop the functional structure and selective technological parameters (such as control coordinates) of the MR CMCS for its reliable movement and performance of given technological operations on large inclined ferromagnetic surfaces.

Basic material. ***MR’s construction.*** A large number of technological operations are commonly performed on metal ferromagnetic surfaces: elements of various facilities, structures of hulls, tanks, pipelines, etc. Therefore, we should consider the principal diagram and the main properties of an MR for moving and performing given technological operations on large inclined ferromagnetic surfaces (FS). Fig. 1 presents a layout of a mobile robot (MR) for the mechanical cleaning of a ship’s hull. In particular, the dashed lines in Fig. 1, *a* (top view) indicate the elements that are not visible from this view. The robot is built on a solid flat two-component frame (Fig. 1, *a*). Rectangular part of the frame 1 is equipped with a tracked mechanism [9]. Each caterpillar track *2* is equipped with a driving and a driven wheel, and 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 mag-

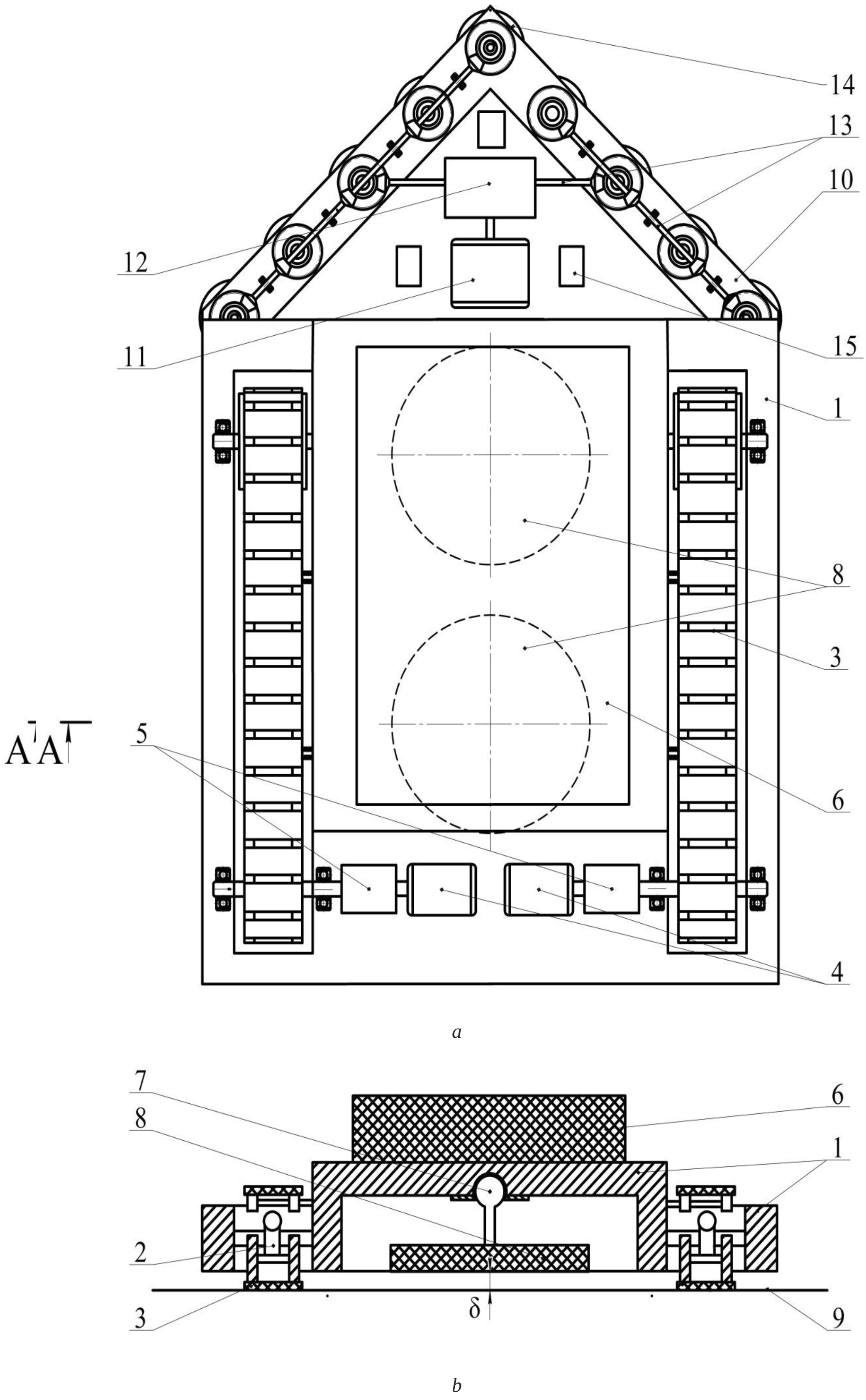

Fig. 1. Layout of the MR for mechanical cleaning of FSs:
a — top view; *b* — cross-section A – A

nets *8* between the left and right caterpillar tracks with a proper gap δ to the operating FS 9 (Fig. 1, *b*). The second part of the frame has a triangular shape (labeled *10* in Fig. 1, *a*). 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 MR is installed on the ship's hull in such a way that the main permanent magnets are oriented through the gap δ along the FS 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 MR'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 gear units *5*. Thus, the MR starts moving along the surface of the ship's hull and mechanically cleaning it from algae and other aquatic organisms. The 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 MR 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° to 360° 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 δ 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.

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, and 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 [11, 12].

The monitoring and control system must provide 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 subsystem with the environment [10].

The monitoring and control system comprises the information-control part (MR's control unit, sensors, machine vision and data pre-processing microprocessors), located on the robot; the MR 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 MR [10]. For instance, the system for monitoring and control of technological equipment (as part of the MR CMCS) 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 [6, 10]. Accordingly, the functions of the movement control system include permitting the interaction with operators, planning the path to cover the area to be cleared and checking the quality of the processed surface using the data obtained from intelligent cameras (for example, when using two cameras, one is placed in front of the cleaning tool and the second one behind it [7]). The movement control system should also provide planning of movement under non-deterministic conditions on a cartographic basis. It takes into account the information being continuously supplied to the control system from the technical sensory organs and the navigation system. The complexity of the control system is determined by the complexity of the problem to be solved, the degree of uncertainty of the external environment and the required degree of the robot's autonomy. It is the development of control systems that defines the development of robotic complexes in general [10].

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 vector of the parameters of the MR's spatial motion; monitoring and automatic control of the value of the clamping force created by the MR clamping magnets; monitoring and automatic control of the vector of the parameters of specified technological operations performed by the MR (cleaning, cutting, welding, inspection, etc.); monitoring and automatic control of the vector of the operating parameters of the technical equipment of the MR's propulsor; monitoring and automatic control of the vector of the operating parameters of the technical equipment of the MR's clamping device [10].

Functional structure of the computerized system for the MR monitoring and control. One more drawback of the existing technological equipment for movement along large surfaces in accordance with the reliable maintenance requirements is the low level of automation that leads to its inefficient use, inability to work under optimal modes and, consequently, lower quality of the obtained services. This is because the specialized MRs, which are used for the implementation of technological equipment movement on curved surfaces, are complex multicomponent control objects with randomly changing conditions of functioning. Measurement, monitoring and control of some their operating parameters cause a number of difficulties due to the peculiarities of the required technological process. Thus, the given MRs have to use the advanced monitoring and control systems (typically with a hierarchical branched structure) based on the data received during the execution of technological processes in real time mode [13, 14] for the effective operation with high energy and economic indicators. Automated operator posts, process controllers, industrial computers, programmers, as well as facilities for the implementation of industrial networks, are the main components of such systems. Besides, software compatibility with most digital controllers available on the market is an important problem arising at designing of the MR monitoring and control systems. So, the user has a wide range of hardware to choose the appropriate set integratable with one or multiple operating systems. Nowadays, supervisory control and data acquisition (SCADA) systems [14–17] are successfully utilized in this role.

Intensive development of computer technologies and automatic control theory, as well as practical results of automation of complicated technological processes in the industry, has led to the rise of the SCADA concept [14, 15]. A high level of automation is achieved by applying the SCADA technology when solving the tasks of designing of monitoring and control systems, such as data acquisition, transmission, processing, display and storage. Human-machine interface (HMI) is an important part of any SCADA system. HMI user-friendliness is provided by the clarity and completeness of the information appearing on the screen, the presence of control tools, the possibility of using the help system and prompts, etc. Due to the above advantages of SCADA systems, the efficiency of dispatcher interaction with the system increases, and the number of its possible critical control errors reduces substantially.

Therefore, it is recommended to use the specialized CMCS proposed by the authors in order to implement the above-mentioned formalized tasks of automatic control and monitoring of the MR moving and performing given technological operations on large inclined FSs. Its multilevel branched structure is displayed in Fig. 2. The developed functional structure of the computerized system for monitoring and control of the MR positioning is presented in Fig. 2, where the following notations are adopted: GES – group of environment sensors; GAS – group of additional sensors; FS – force sensor; AS – angle sensor; DS – displacement sensor; CD1, CD2 – the first and the second clamping device; P1, P2 – the first and the second propulsor; MCU – movement control unit; CFCU – clamping force control unit; PPCU – positioning program control unit; TCU – trajectory control unit; HMI/MMI – human-machine/man-machine interface; $\mathbf{G}_{MR}$ – influence of the MR on the working environment; $\mathbf{G}_{WE}$ – influence of the working environment on the MR; $\mathbf{P}_{WE}$ – main parameters of the working environment; $\mathbf{P}_{MR}$ – main parameters of the MR; F_{MR} – the MR's clamping force acting on the FS; φ_{MR} – the MR's angle of rotation; S_{MR} – the MR's linear displacement; F_{CD1} – clamping force of the MR's first clamping device; F_{CD2} – clamping force of the MR's second clamping device; S_{P1} – linear movement of the MR's first propulsor; S_{P2} – linear movement of the MR's second propulsor; $\mathbf{U}_{PWE}$ – GES output signals corresponding to the main parameters of the working environment; $\mathbf{U}_{PMR}$ – GAS output signals corresponding to the main parameters of the MR; u_{FS} – output signal of the sensor of the MR's clamping force acting on the FS; u_{AS} – output signal of the sensor of the MR's angle of rotation; u_{DS} – output signal of the sensor of the MR's linear displacement; u_{CD1} – control signal of the MR's first clamping device; u_{CD2} – control signal of the MR's second clamping device; u_{P1} – control signal of the MR's first propulsor; u_{P2} – control signal of the MR's second propulsor; $\mathbf{U}_{CFS}$ – output signals of the clamping force sensor; $\mathbf{U}_{CFCU}$ – control signals for the MR's clamping force control unit; $\mathbf{U}_{MS}$ – output signals of the MR's movement sensors (angle sensor and linear displacement sensor); $\mathbf{U}_{MCU}$ –control signals for the MR's movement control unit; $\mathbf{U}_{P}$ – output signals of the MR's main operating parameters; $\mathbf{U}_{PPCU}$ – control signals for

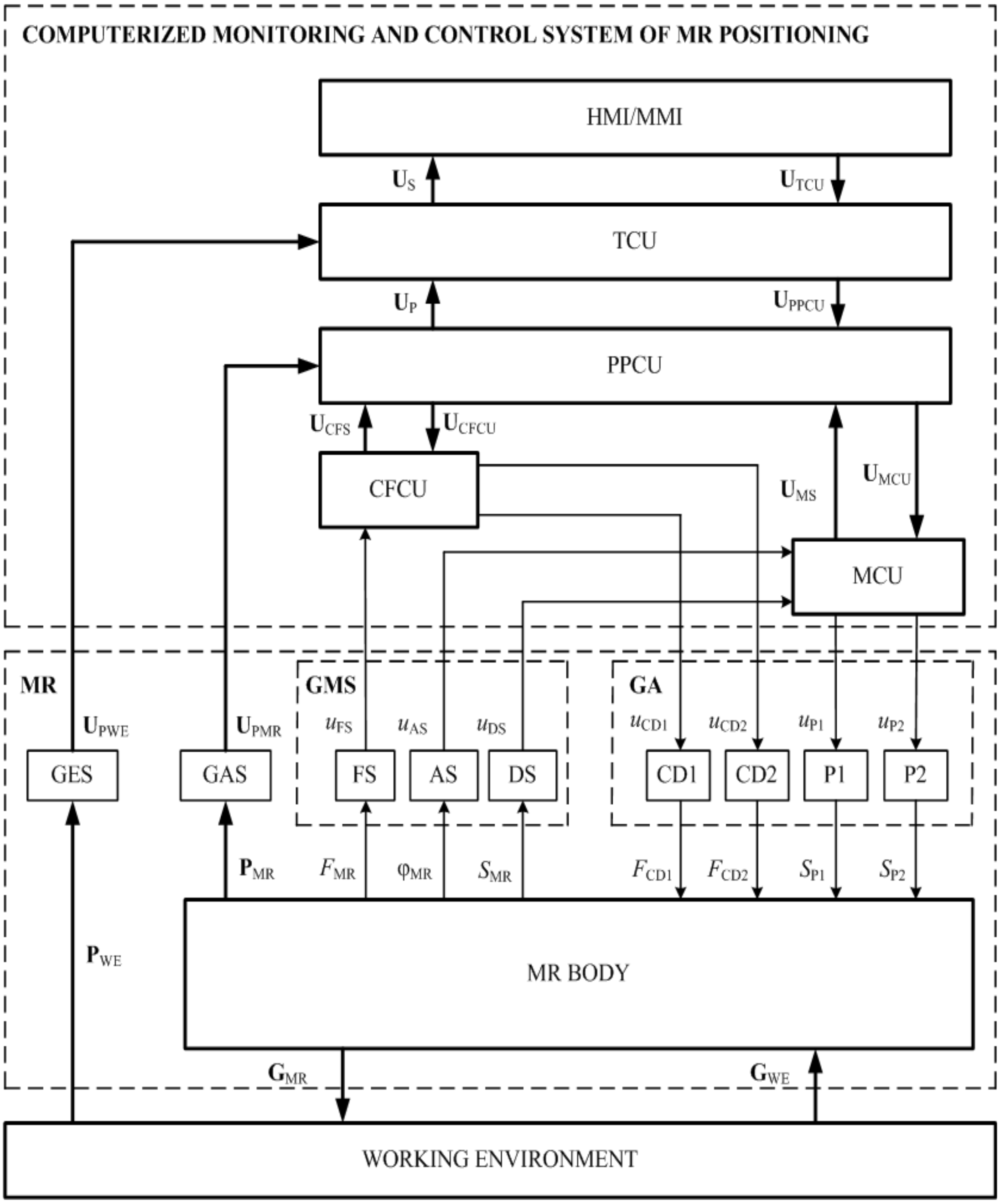

Fig. 2. Functional structure of the computerized system for monitoring and control of the MR positioning

the positioning programming control unit; $\mathbf{U}_S$ – output signals of the sensors of the MR's main operating parameters considering the state of the working environment; $\mathbf{U}_{TCU}$ –control signals for the trajectory control unit.

The functional structure of the MR is designed for monitoring, automatic control and visualization of the MR's main process parameters in real time mode. In accordance with Fig. 2, the proposed MR operates as follows. First, the operator specifies the required MR moving trajectory by using the HMI/MMI editing tools and means. After this, the TCU calculates the individual required MR movement points for the given trajectory ($\mathbf{U}_{PPCU}$ signals). Next, the PPCU converts the received coordinates and generates the corresponding control signals for each point of the MR movement ($\mathbf{U}_{CFCU}$ and $\mathbf{U}_{MCU}$ signal vectors). These signals are perceived by the CFCU and the MCU, which directly control the current values of the clamping force (F_{CD1} and F_{CD2}) and displacement (S_{P1} and S_{P2}) of the MR. It should be noted that clamping force control is possible in case of using clamping electromagnets to provide for the reliable MR holding on FS.

The current values of the clamping force formed by CD1 and CD2, the angle of rotation and the displacement of the MR are measured using appropriate sensors. The obtained measurements are used for correction of control impacts on the MR's propulsors and clamping devices. Besides, the system performs measurement of additional MR parameters, such as the current in the drive motor windings (for P1 and P2), the amplitude of the robot's main body vibration, and the quality indicators of the operations performed by the robot. The main environmental parameters affecting the trajectory planning are also measured using the GES. These may include unaccounted disturbance, substantial damage or structural features of specific FSs and other robotic devices.

The measurements performed on the MR's operating parameters and the working environment are taken into account in the corresponding units of the functional structure (Fig. 2). In this case, the most important ones are displayed through the HMI/MMI on the operator's computer screen. The HMI/MMI additionally contains means of visualization of the MR's operating parameters in the form of tables and charts. Also, the HMI/MMI has the ability to record the measurement history to the database for further processing, modification of control algorithms, etc. [14].

Thus, the proposed system provides visual display of information on the state of the MR's main components with clear indication of current states and emergencies. Furthermore, the system allows for automatic data sending to all the users of the enterprise network in case of emergency. Also, it has an advanced, highly integrated programming environment that is sufficiently flexible and easy to extend, as well as flexible network designs and possibility of connection to the online expert system for more detailed data analysis.

It is noteworthy that according to Fig. 1, the main actuating mechanisms of the MR include drive motors (P1 and P2 in Fig. 2), clamping magnets (CD1 and CD2) and necessary technological equipment (optional). These actuating mechanisms are to be powered from the AC mains via contactors and a thyristor or transistor converter [11].

For hardware implementation of the above system for monitoring and automatic control of the MR's main working parameters, we suggest using modern gauges and transducers. Ready-to-use solutions based on program logical controllers (PLCs), microcontroller-based development boards, and input/output (I/O) modules allow accelerating the designing process and reducing the number of errors at testing procedures. Usually, such devices have standardized current, voltage and discrete inputs and outputs and are used as data acquisition modules for the analog and discrete input signals, or for actuating automatic control mechanisms. Also, they may provide USB to RS-232/422/485 and vice versa converting for the module connection to PC at testing and debugging of the whole system [16, 17].

Accordingly, we suggest installing a TCU on PC, a PPCU on PLC, and also CFCU and MCU based on microcontroller or I/O modules in the current system for the experimental setup development. As the main operating unit, the PLC has a high-capacity processor and includes VGA, Ethernet, USB 1.1, RS232, RS485 and RS482 interfaces for communication with PC and I/O modules. The respective data acquisition modules then convert the analog signals u_{FS}, u_{AS}, u_{DS} into proper digital ones, which are transmitted to the PLC via RS485 bus with DCON protocol. The PLC has specialized software to process the data obtained from the sensors. The information on the current values of the clamping force acting on the FS, the MR's angle of rotation and linear displacement are displayed on the screen of the operator's PC with the help of a specialized HMI. All the control algorithms [17] of the system under development may be implemented using the SCADA TraceMode 6 software.

As can be seen from the MR's functional structure in Fig. 2, the computerized system for monitoring and automatic control of the MR positioning on large FSs should consist of the following multi-coordinate subsystems: propulsor monitoring and automatic control sub-system, CD monitoring and automatic control subsystem, TE monitoring and automatic control subsystem. The effectiveness of the above subsystems is substantially enhanced through the application of intelligent technologies in the development of their functional structures, control algorithms and devices [10].

CONCLUSIONS. This paper presents the development of the functional structure and selective technological parameters (such as control coordinates) of the CMCS for an MR moving along large inclined FSs and performing given technological operations.

Application of the CMCS with the proposed functional structure enables complete automation of the processes of control and monitoring of such robotic complexes. In turn, it can substantially improve the quality of the operations performed, increase labor productivity and reduce the expenditures for processing a unit of the working surface area, which in general increases the efficiency of operations and economic indicators of these complexes.

Further scientific research should be focused on the synthesis of mathematical models of the MR and individual elements of its CMCS, realization of the MR's mechanical movement along vertical surfaces with the help of different methods, intellectualization of the MR through installing appropriate sensors and arranging feedbacks, development of special algorithms for scene analysis, accumulation of databases on the external environment, and automatic decision making.

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