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Multiple robots (robotic centers) and systems. Remote sensing and non-destructive testing

**Роботизированные комплексы и системы.
Технологии дистанционного зондирования и неразрушающего контроля**

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RESEARCH ARTICLE

Prototype multi-agent robotic debris removal system: principles of development and experimental studies

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Abstract
Objectives. The article substantiates the relevance of the creation and the prospects of application of multi-agent robotic systems for elimination of consequences of emergency situations. The purpose of this work was to test the practical feasibility of algorithms for controlling a group of autonomous robots when performing multi-stage missions.
Methods. The theses of the finite automata theory in planning actions of a multi-agent system, methods of automatic control in organizing a goal-directed movement of robots, and methods of computer vision in searching and analyzing debris geometry were used.
Results. The principles of development, architecture, and composition are described for the software and algorithms of a prototype of the multi-agent robotic system created at RTU MIREA as part of integrated research for the creation of tools and methods of group control of robots. The multi-stage task of searching and removing debris in the process of eliminating the consequences of emergency situations is analyzed. A proposed algorithm for planning the actions of robotic agents determines the time sequence of the mission stages. Tasks are allocated among the performing robots according to assessments of their suitability. The autonomous functioning of robotic agents is determined by commands coming from the group control level, as well as an a priori embedded knowledge base with scenario models of appropriate actions. Compensation of local environmental uncertainties in the process of robot movement is based on a comprehensive analysis of visual and navigation information. Along with the main elements of the multi-agent system, the developed infrastructure of hardware and software for visual navigation and wireless communication is described.
Conclusions. The results of the experimental studies demonstrated the efficiency of the developed approaches to the creation of intelligent technologies for group control of autonomous robots on the example of debris search and removal tasks. The feasibility of the multi-agent robotic system is demonstrated by the development and integration of a number of information management and infrastructure subsystems.

Keywords: autonomous robot, intelligent control, group control, multi-robot system, debris removal

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НАУЧНАЯ СТАТЬЯ

Принципы построения и экспериментальные исследования прототипного образца многоагентной робототехнической системы для разбора завалов

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Резюме
Цели. В статье обоснованы актуальность создания и перспективы применения многоагентных робототехнических систем для ликвидации последствий чрезвычайных ситуаций. Целью работы является проверка практической реализуемости алгоритмов управления группой автономных роботов при решении многоэтапных прикладных задач.
Методы. Использованы положения теории конечных автоматов в задачах планирования действий многоагентной системы, методы автоматического управления при организации целенаправленного движения роботов-исполнителей, методы машинного зрения в задачах поиска и анализа формы завала.
Результаты. Описаны принципы построения, архитектура и состав программно-алгоритмического обеспечения прототипного образца многоагентной робототехнической системы, разработанной в РТУ МИРЭА в рамках проведения комплексных исследований развития средств и методов группового управления роботами. Рассмотрена многоэтапная задача поиска и устранения завалов. Предложенный алгоритм планирования действий робототехнических агентов определяет временну́ю очередность выполнения этапов данной задачи. Распределение заданий между роботами-исполнителями производится с учетом оценок их пригодности. Автономное функционирование робототехнических агентов определяется командами, поступающими с уровня группового управления, а также априорно заложенной базой знаний со сценарными моделями целесообразных действий. Компенсация неопределенностей внешней среды локального характера в процессе движения роботов базируется на комплексном анализе визуальной и навигационной информации. Наряду с основными элементами многоагентной системы дано описание разработанной инфраструктуры аппаратно-программных средств визуальной навигации и беспроводной связи.
Выводы. Результаты экспериментальных исследований показали эффективность развиваемых подходов к созданию интеллектуальных технологий группового управления автономными роботами на примере задач поиска и разбора завалов. Подтверждена возможность практической реализации многоагентной робототехнической системы на основе разработки и интеграции ряда информационно-управляющих и инфраструктурных подсистем.

Ключевые слова: автономный робот, интеллектуальное управление, групповое управление, многоагентная робототехническая система, разбор завалов

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INTRODUCTION

Multi-agent robotic systems (MARS) have been attracting steadily increasing interest since the early 21st century owing to the wide prospects for their application in various applied fields. The main advantage of the joint use of autonomous robots as a united group is the significant increase in efficiency gained by combining functionality and resources when organizing the necessary interactions. Although the study of problems associated with the development of technologies for group control of autonomous robots is a priority area worldwide, practical results obtained in the United States and a number of other countries are ahead of the curve [1, 2].

Up until a certain point, programs of similar works in Russia have significantly lagged behind the international level. However, the implementation of a national strategy for scientific and technological development, one of whose main goals is the transition to advanced intellectual and robotic technologies, has provided a sharp intensification of theoretical and experimental studies on this subject. These studies are carried out in a number of research centers, academic institutes, design organizations, and universities [3–5]. As regards the proposed formulations and solutions, the fundamental and applied groundwork formed against this background by the Russian scientific school is not only keeping pace with contemporary global trends, but also is gradually implemented in practical developments related to the creation of intelligent control systems for autonomous robots and multi-agent groups.

In particular, the generalization of the results obtained at RTU MIREA in the Research Project "Methods, Models, and Algorithms for Group Control of Autonomous Robots by the Integrated Application of the Apparatus of the Theory of Finite Automata" made it possible to develop an experimental prototype of MARS for testing technologies for automatic search and analysis of debris during emergency recovery.

PROBLEMS AND PRINCIPLES OF DESIGN OF A MARS FOR AUTOMATIC DEBRIS SEARCH AND REMOVAL

An analysis of natural and man-made emergencies shows that their most characteristic consequences are large-scale destruction and debris, the difficulties of recovery of which are often intensified by such aggravating factors as fires, contamination spots, etc. Under such conditions, when the involvement of human resources may be limited or impossible, the use of autonomous robots and, in particular, MARS, may become the most feasible alternative.

Multi-agent systems for emergency recovery, automatic debris removal, and performing other tasks of similar nature are formed from specialized models of autonomous robots of the corresponding type [6, 7]. Many Russian and foreign manufacturers offer a wide range of multifunctional remote-controlled mobile robots for engineering purposes (with advanced sensor equipment, a replaceable set of tools and attachments) (Fig. 1). Such robots can potentially be used in multi-agent systems for removing debris, provided that the necessary modernization of control tools is made to ensure autonomous operation including the receipt and transmission of data via wireless network communication channels.

The main requirements for the functionality of MARS are related to the need to analyze the assigned applied task, its decomposition into a set of subtasks or composite technological operations, and their subsequent execution in autonomous mode by the joint efforts of individual performers, which coordinate their actions [8–10]. The creation of such systems that fully meet the requirements imposed on them involves the solution of the following key problems:

- organizing a developed human-machine interface, which allows for the prompt formulation of a common applied task;
- organizing the appropriate interaction between individual agents in the interests of performing a common applied task;
- ensuring the autonomy of agents and the system as a whole.

In turn, the problem of organizing the appropriate interactions between active elements of MARS contains two major subproblems:

- planning coordinated actions of agents (based on the analysis of the assigned applied task, the process of its implementation, and available resources) with subsequent formulation and assignment of appropriate tasks;
- ensuring information-logical interaction and compatibility of agents (both at the level of using common formats of presentation of data, message systems, commands, and target designations, and at the level of technical channels for their transmission).

An analysis of the identified problems shows that the integration of potential approaches to their solution within a single system implies the need to build this system in accordance with the following principles:

- commonality of goals for the functioning of agents;
- adequacy of the logical and functional capabilities of agents to the complexity of the tasks being performed;
- common information space of the system;
- mutual information-logical compatibility of agents.

When creating and implementing MARS solutions, the most acute problems are experienced when determining the sequence and methods for the joint

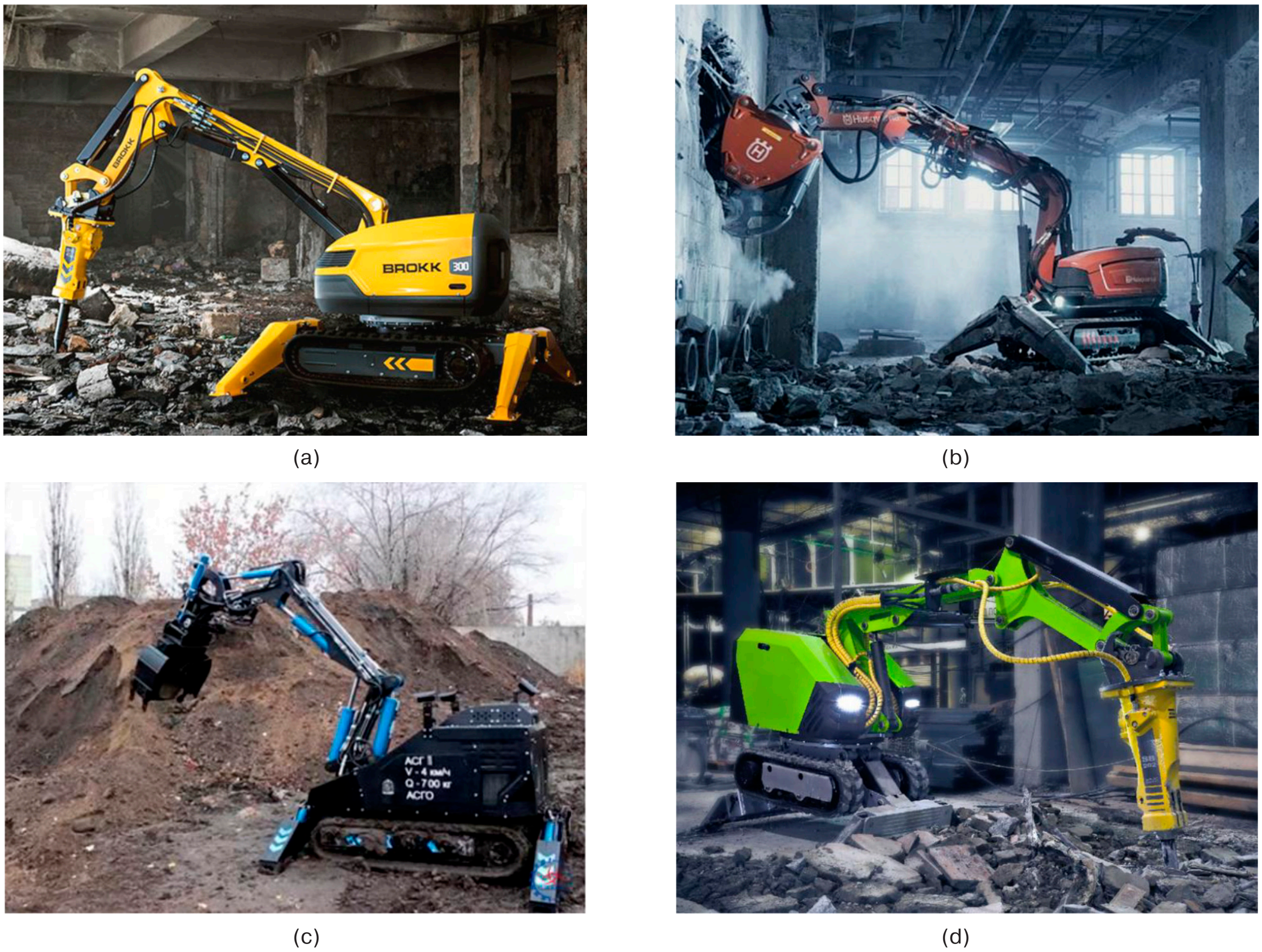


Fig. 1. Models of specialized teleoperator-controlled engineering robots: (a) Brokk 300 (Brokk, Sweden), (b) Husqvarna 310 (Husqvarna, Sweden), (c) ROIN R-070 (Intekhros, Russia), and (d) Betonolom 2000 (Robotekhniks, Russia)

use of autonomous robots [9, 11] in combination with the development of an adequate set of the software and algorithms of group control with their subsequent testing and debugging.

SEQUENCE AND METHODS FOR THE TARGETED USE OF THE MARS SYSTEM FOR AUTOMATIC DEBRIS SEARCH AND REMOVAL

The effectiveness of the targeted use of MARS is generally determined by the rationality of its actions for performing the required applied task. The corresponding scenario for determining the sequence and methods of using MARS for automatic search and analysis of debris (Fig. 2) involves the phased implementation of the following set of necessary operations:

- movement of existing robots to the designated assembly point in the emergency zone from the places of their prompt delivery or permanent placement;
- reconnaissance of the general situation, assessment of the destruction centers, and determination of the parameters of their location using one or more specialized search robots;
- targeted movement of MARS to the zone of the detected debris;
- automatic layer-by-layer analysis of the debris with the allocation of recognized operations between individual MARS agents.

An analysis of the scenario shows that the implementation of the last stage involves the development of specialized software tools that not only process visual information to determine the parameters of the position of the observed elements of the debris, but also to automatically synthetize a scenario model for dismantling its upper layer.

GENERALIZED ARCHITECTURE OF THE MARS SOFTWARE FOR AUTOMATIC DEBRIS SEARCH AND REMOVAL

The developed suite of software and algorithms, the architecture of which is shown in Fig. 3, provides all the necessary functions for information processing and intelligent control of MARS that are focused on performing operations of automatic search and removal of debris and formed from among autonomous mobile

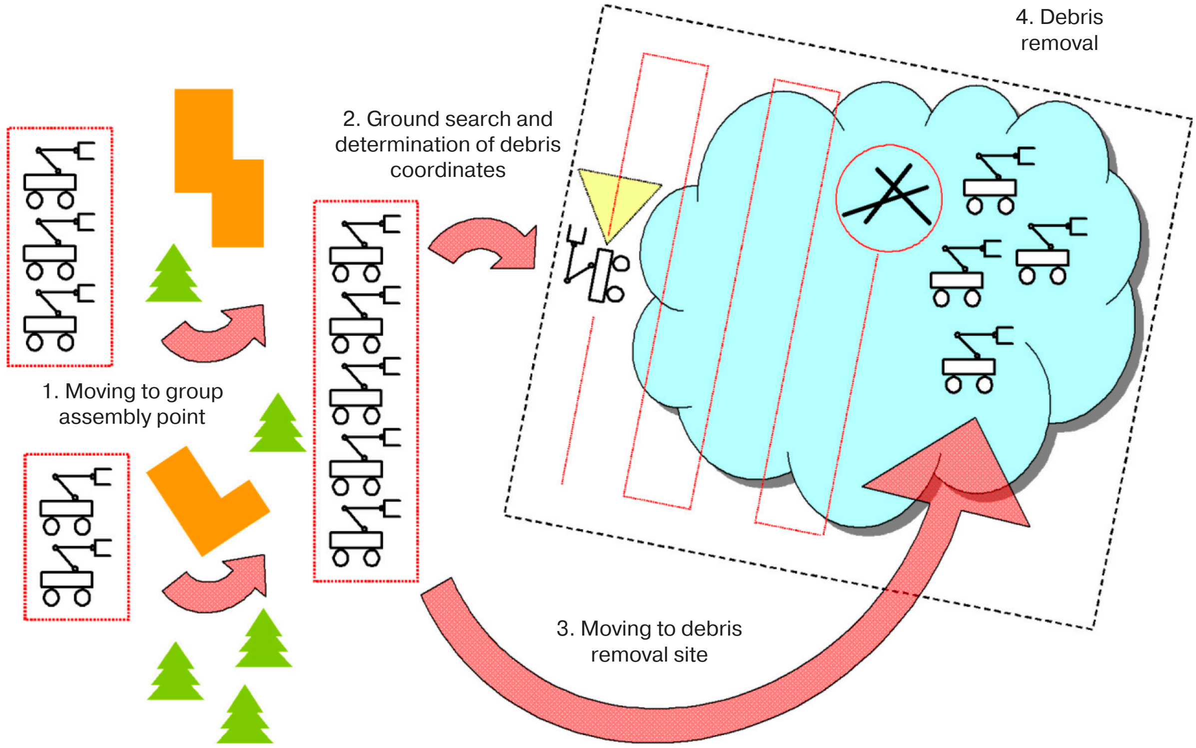


Fig. 2. Generalized scenario of the MARS functioning in performing the tasks of automatic search and analysis of debris in emergency recovery measures

robots (AMR) with an onboard manipulator and advanced sensor equipment. The main structural elements of the suite, which is built on a block-modular principle based on modern knowledge processing technologies, are the human–machine interface subsystem, the subsystem for intelligent planning and task allocation in MARS, as well as the subsystem for intelligent control of autonomous robots.

The software for the intelligent task planning subsystem of MARS includes the following set of main functional modules:

- knowledge base with scenario models for performing applied tasks created according to the description of the operator [9, 10] or in automatic mode (based on information on the structure of the observed debris) [12] using the apparatus of finite automata;
- module for summarizing sensory information for constructing a structural model of the observed debris;
- module for the dynamic construction of scenario models for layer-by-layer removal of detected debris based on the apparatus of finite automata [12];
- module for intelligent planning of stages and operations for testing scenario models of assigned applied tasks [9, 10];
- module for allocating tasks between robots from the united group using algorithms for multi-criteria assessment of the usefulness of potential performers [9].

In turn, the subsystems for intelligent control of autonomous robots of MARS have the following common software composition:

- knowledge base with a priori embedded scenario models for executing individual operations, which are built on the basis of the apparatus of finite automata;
- module for intelligent planning of appropriate actions based on the processing scenario models for performing certain operations [13];
- library of software tools for planning movements of the mobile platform and the manipulator (by the selective use of a number of specialized algorithms, such as A*, potential fields, rapidly exploring random trees (RRT), etc.), and for solving mapping problems (using SLAM algorithms) [14];
- a module for integrating odometric information and data of the external navigation system;
- a module for processing and summarizing sensory information from the onboard video camera and the laser scanning rangefinder for assessing and recognizing the external environment.

Onboard subsystems for controlling the actuating devices of autonomous robots ensure the executing of the set of commands generated by the higher-level subsystem.

The human-machine interface subsystem combines a wide range of software and tools for monitoring the performance and current state of MARS, setting goals

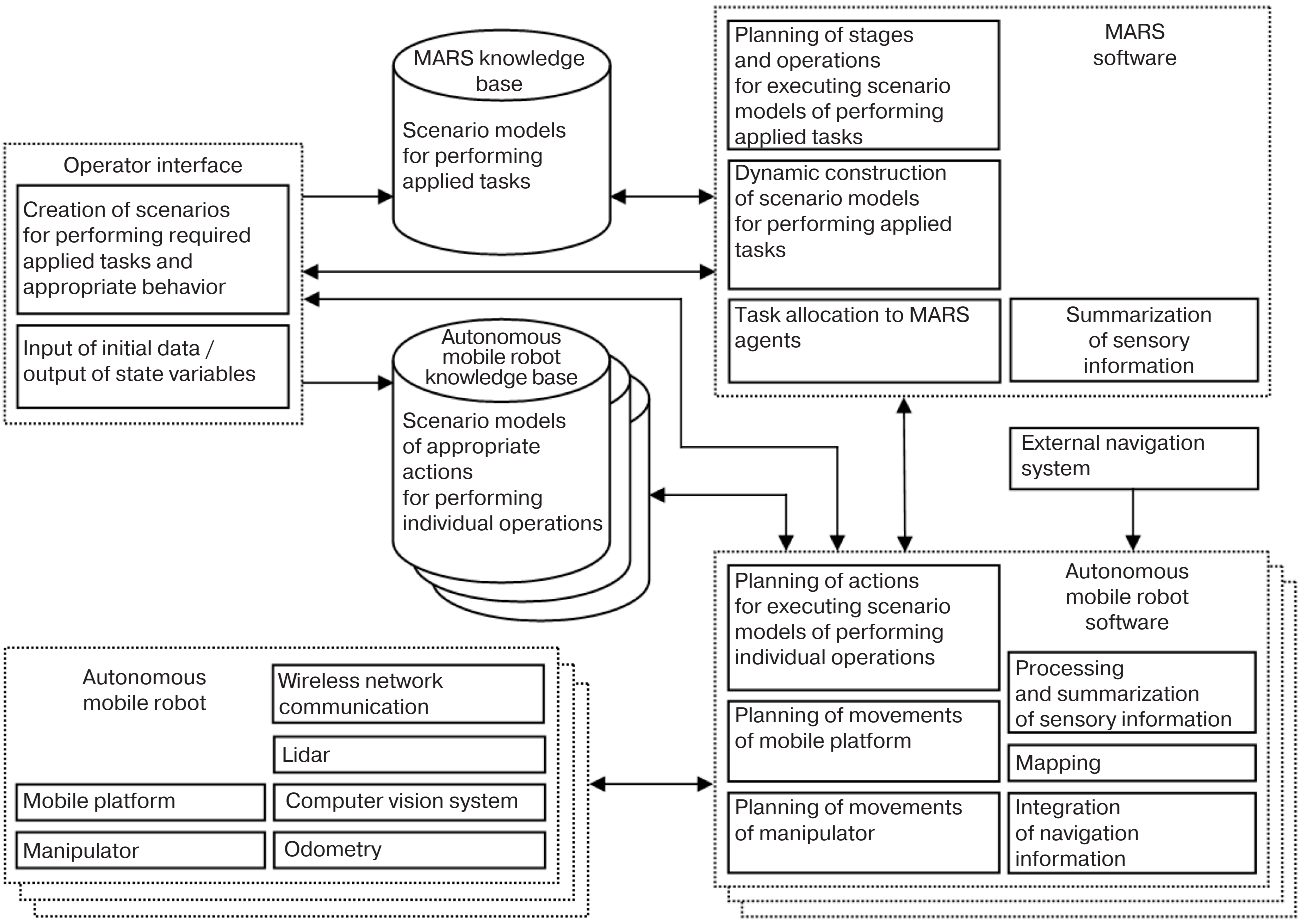


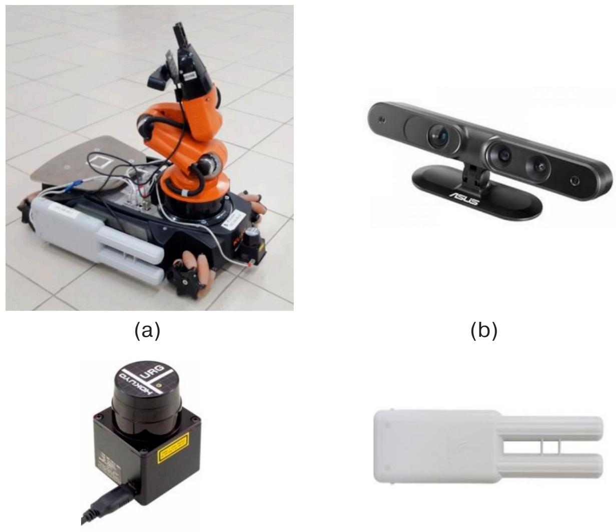
Fig. 3. Generalized architecture of the suite of software and algorithms of a demonstrator of MARS for automatic search and analysis of debris

and objectives for its operation, constructing scenario models for performing tasks and controlling robots, as well as monitoring telemetric information on the progress and results of their operations [15].

DEMONSTRATION MODEL OF THE MARS FOR AUTOMATIC DEBRIS SEARCH AND REMOVAL

The creation of the demonstrator of MARS was aimed at the fundamental testing of intelligent technologies for group control of autonomous robots on the example of automatic search and analysis of debris during field experiments with imitation of the corresponding conditions at a specialized test site. The prototype autonomous robot was represented by the KUKA youBot mobile platform (KUKARoboter, Germany). Designed as a mobile-base manipulator. This model is equipped with a laser scanning rangefinder, a stereo video camera, wireless network communication devices (Fig. 4), as well as software and algorithms for supporting modes of autonomous operation and group control.

The closed rooms of the test site were equipped with a set of 16 Beward BD3670M IP video cameras (NPP Beward, Russia), which were placed uniformly under



(a) (b) (c) (d)

Fig. 4. (a) KUKA youBot mobile robot with an onboard set of information and measurement tools: (a) autonomous transport platform, (b) Asus Xtion PRO live RGBD video camera (AsusTek Computer Inc., China), (c) Hokuyo URG 04LX UG01 laser scanning rangefinder (Hokuyo Automatic Co., Japan), and (d) MikroTik OmniTIK UPA-5HnD wireless access point (MikroTik, Latvia)

the ceiling at a height of 4 m. As well as providing direct determination of the coordinates of observed moving objects within the common integrated navigation field (Fig. 5), these were used for emulating satellite navigation systems. The information interaction of autonomous robots of the united group was performed via wireless network communication channels in accordance with Wi-Fi technology standards using TCP/IP protocols. The unity of the common information space of MARS was ensured by the integration of the network infrastructure of the hardware and software components, related to the wireless communication and the external visual navigation systems (Fig. 6).

The prompt formulation of an applied task and control over the progress of its implementation is carried out using specialized options on the operator interface panel (Fig. 7) on the monitor screen of the central computer.

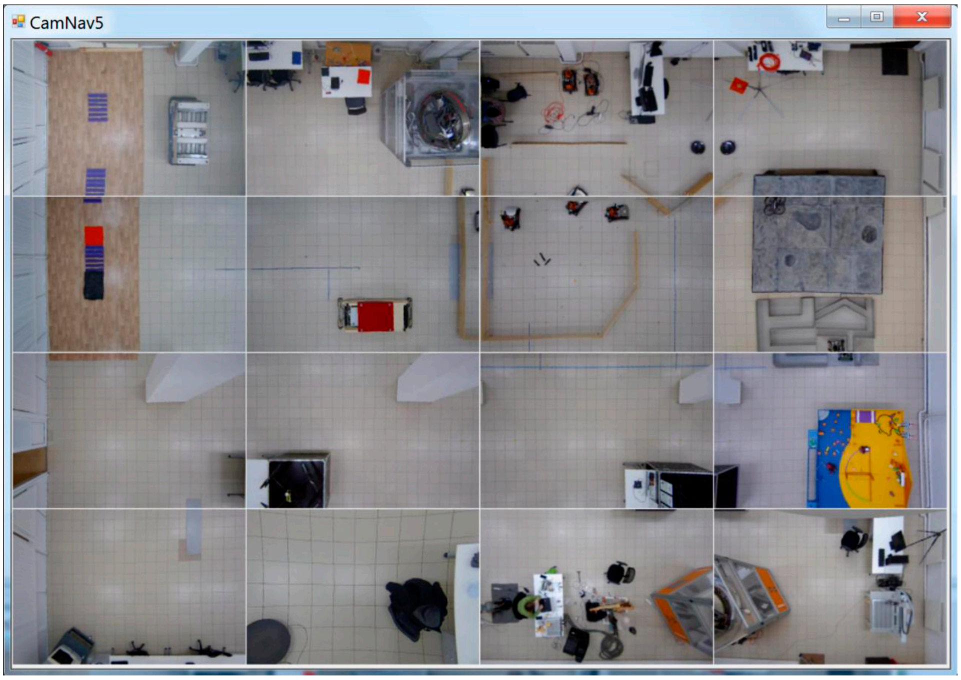


Fig. 5. Integrated field of the visual navigation system

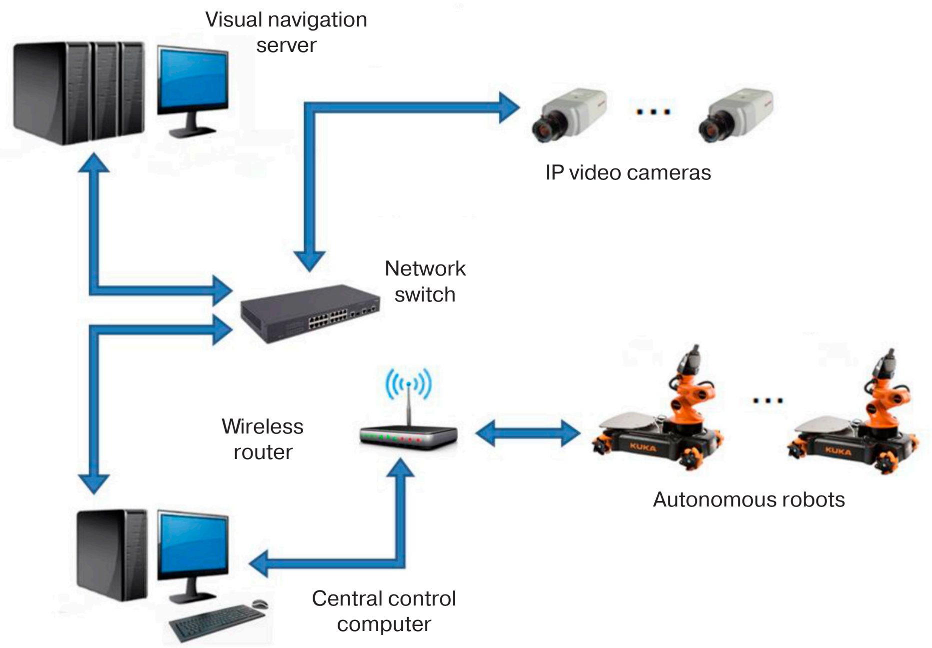


Fig. 6. United network infrastructure of the hardware and software of the visual navigation and the wireless communication systems

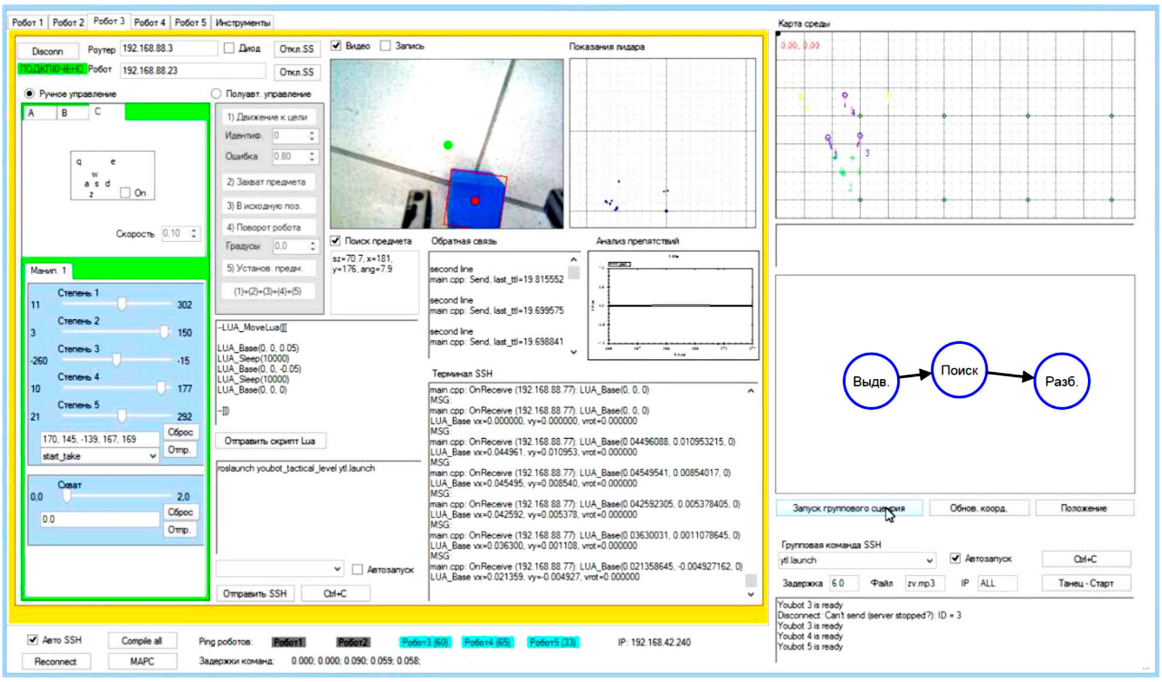


Fig. 7. Interactive operator interface panel of the demonstration model of MARS for automatic search and removal of debris

FIELD TESTING OF INTELLIGENT CONTROL TECHNOLOGIES OF THE MARS FOR AUTOMATIC DEBRIS SEARCH AND REMOVAL

A series of planned experiments for field testing of the software and algorithms for group control of autonomous robots for automatic search and removal of debris was carried out by the example of imitation of consequences of an emergency with conditional imitation of a zone of destruction and debris (Fig. 8) at a specialized test site of the Institute of Artificial Intelligence of RTU MIREA.

The formulation of the task by the operator using interactive tools of the human-machine interface (Fig. 7) involves the construction of a scenario graph, whose nodes and edges represent the composition and sequence of the main stages of the applied mission to be performed. Each of the nodes of the constructed graph is assigned a dataset that determines the parameters of the corresponding stage. If necessary, the assigned data may contain references to the involved algorithms or names of nested scenario graphs.

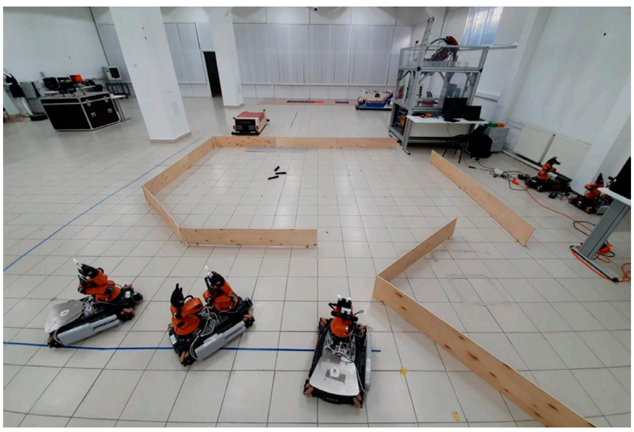


Fig. 8. Stage model for making experiments for automatic search and removal of debris using MARS

The preparation and specification of scenario graphs ensures the automatic construction of a formalized model of the applied task to be solved in the form of an appropriate network of finite automata. This approach ensures the implementation of the control and monitoring functions while planning the behavior and appropriate actions of MARS autonomous robots.

In particular, the formulation of the applied problem for MARS within the ongoing experiments required the construction of a scenario graph with the sequential inclusion of the stages of movement of robots to the assembly point, search, and subsequent removal of debris (Fig. 8).

It is important to note that the parameters for conducting the second stage (ground search) provide for two possible outcomes: a negative search result leads to the completion of the entire mission, whereas the detection of debris causes a transition to the next stage of the task.

In turn, the last stage is specified by a nested scenario graph with cyclic repetition of operations for recognizing the structure of the upper layer of the debris, as well as dynamic model synthesis and planning of dismantling operations up to the last constituent element.

The final stage of setting the task is the initialization of robots, indicating their network addresses and operating parameters, and entering the coordinates of the assembly place and the zone of subsequent work.

The launch of MARS, which is carried out at the command of the operator, initiates the direct execution of the assigned applied task in automatic mode in accordance with the operationally introduced and a priori embedded scenarios of autonomous and group control.

Figures 9–11 present the main fragments of one of the test-site experiments for testing methods and technologies for group control of autonomous robots of MARS in the co-execution of the common applied task of automatic search and removal of debris.

Figures 9a–9d illustrate in detail the execution of the first stage of the task, which is the advance of autonomous robots to the designated assembly point. While their targeted movement is routed using the A* [16] and RRT [17] algorithms, the movements associated with maintaining convoy formation are planned using the algorithmic implementation of the method of potential fields [18] and the apparatus for processing visual, ranging, and navigational information. The algorithms are chosen based on the scenario for performing the assigned task at the level of the corresponding references established during the specification of the parameters for this stage. The arrival of robots at the designated assembly place, confirmed via wireless network communication channels, serves not only as an actual confirmation of the successful completion of the current stage of the task being performed, but also as a signal for the transition to its next phase. The current status of the robots and the task they perform is displayed on the operator interface panel.

Figure 10 illustrates the second stage of the task, which is the area reconnaissance and the search for debris.

A robot for these purposes is selected according to the criterion of a suitable functional or the smallest serial number (other conditions being equal). The completeness of the inspection of a given area is determined by the scenario of planning and testing search movements using the A* algorithm and available means of processing visual, ranging and navigation information. The sequence of necessary actions is regulated by the scenario for performing the task, as well as the scenario for conducting search operations, which is a priori embedded in the knowledge bases of intelligent control systems for autonomous robots.

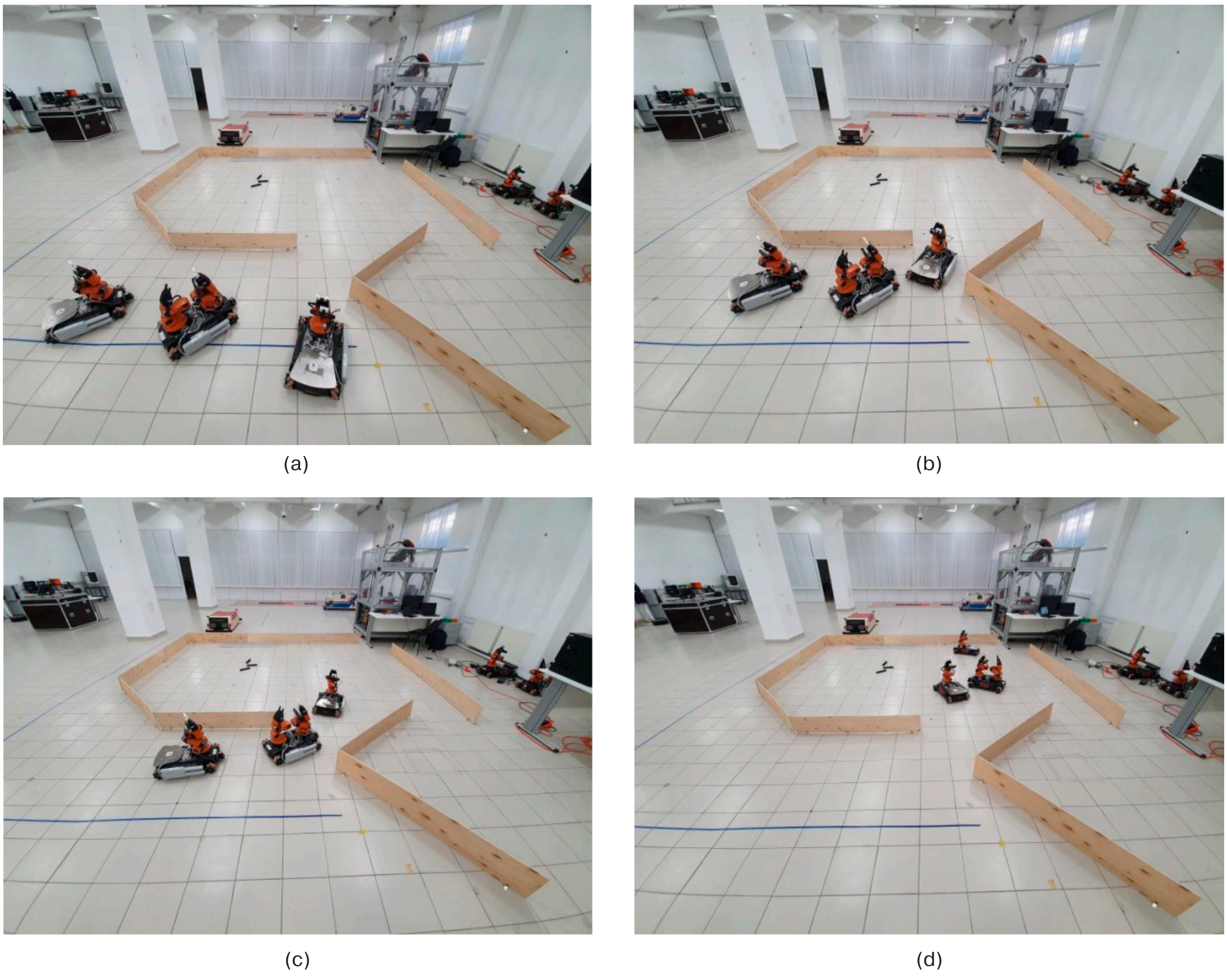
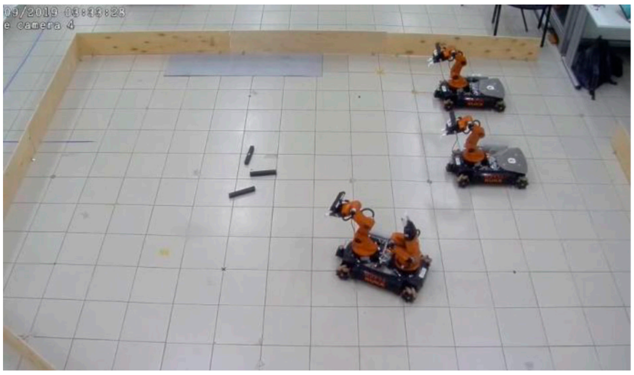
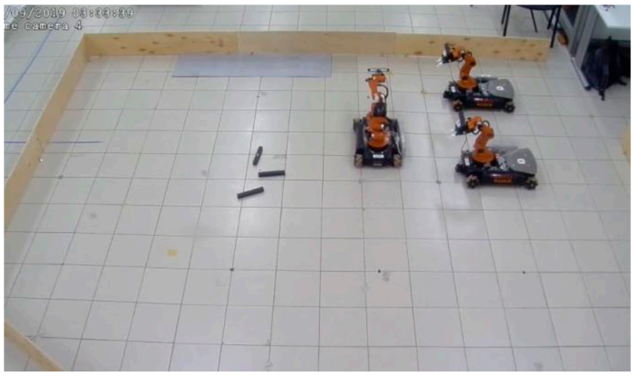


Fig. 9. Movement of a group of autonomous robots maintaining a convoy-type formation configuration toward the designated MARS assembly point



(a)



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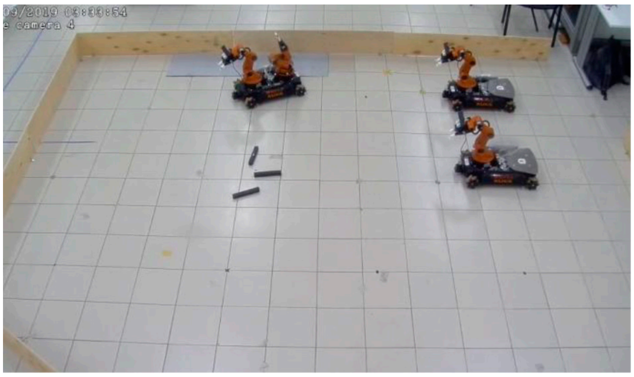
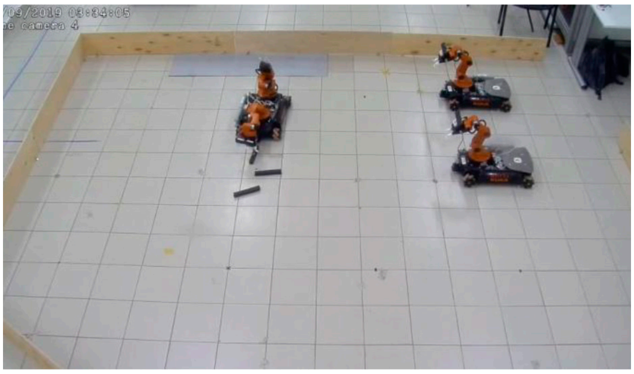


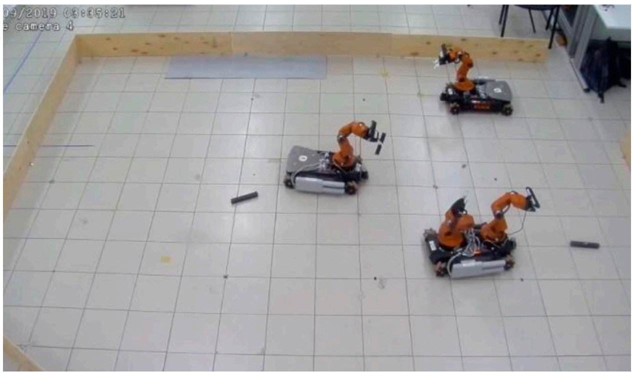
(c)

(d)

Fig. 10. Operation of MARS during the ground search: (a, b) the selection of a robot to search for debris, (c) search movements of the robot during ground search, and (d) the detection of debris based on the results of processing the images from the onboard camera of the robot



(a)



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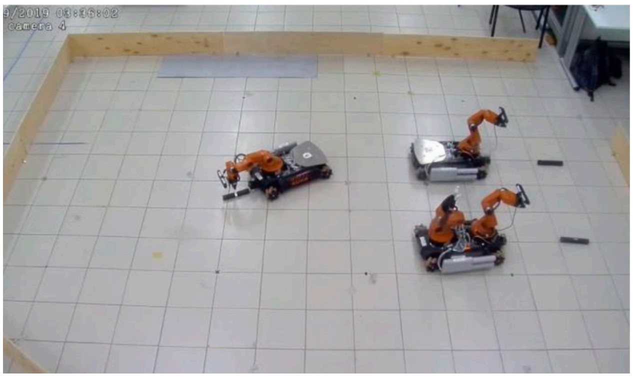

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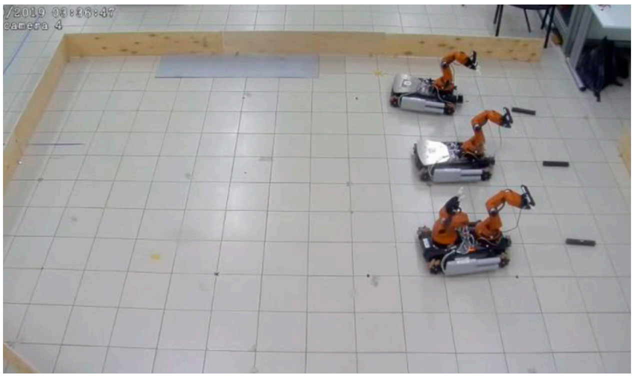

(d)

Fig. 11. Operation of MARS performing debris removal operations

The criterion for detection of debris is the excess of the critical number of destruction elements per unit area, which is found from the results of processing the data from the onboard set of information and measurement tools of the robot.

Following the detection of debris, the third stage of the task involving the removal and evacuation of the found objects can be initiated (Figs. 11a–11d). The nested scenario of its implementation includes the cyclic repetition of image processing procedures, the analysis and restoration of the structure of the upper layer of the debris, and the dynamic construction of a scenario model for dismantling the selected elements.

The construction of such a model based on the use of the apparatus of finite automata makes it possible to plan the layer-by-layer removal of the debris with the prompt issuance of an ordered set of subtasks, indicating the elements to be removed and the parameters of their spatial position.

The tasks are allocated between robots based on assessments of their current occupancy and distance from the place of the corresponding operations. The generated allocations are transmitted via wireless network communication channels to selected addressees from MARS. The execution of the received tasks is regulated by a set of scenario models that are a priori embedded in the onboard knowledge base of the intelligent control system of each of the robots and determine the procedure for carrying out the necessary operations to capture and evacuate the indicated elements of the debris based on the combined use of a number of appropriate algorithms. For example, the local movements of the mobile platform and the manipulator installed on it are planned on the basis of the algorithmic implementation of the RRT method. The targeted movements of the mobile platform are routed using the A* algorithm. Bypassing moving obstacles during the movements of the robot in a dynamically changing scene is controlled by the algorithmic implementation of the method of potential fields. The entire set of problems of planning the movements and controlling the movement of the robot is solved on a real-time basis using the means of processing visual, ranging, and navigation information to take into account the specifics of the environment.

Objective control of the results of testing each component of scenarios of each level on the basis of processing the readings of information and measurement tools of individual robots ensures the transition to the next stage of the task or its completion with all necessary information displayed on the interactive operator interface panel.

The means and methods for group control of autonomous robots, whose coordinated interaction is ensured by the combined use of various information strategies, was practically tested by creating the MARS demonstrator and carrying out its field tests:

- strategies of centralized control in planning the stages of performing a given applied task with the allocation of subtasks to individual robots for performing the necessary operations;
- strategies of autonomous control in planning appropriate actions and coordinating the movements of robots during their joint functioning in performing the assigned tasks.

Note that the principles of constructing the set of hardware, software, and algorithms of the MARS demonstrator allow for its scaling according to the total number of robots in the group. The implementation of such properties makes it possible to increase not only the fault tolerance of the system, but also the degree of its universality in application to various practical problems, the complexity and extent of whose solution may require a prompt change in the required number of involved robots.

In this context, of special interest is the question of the amount of information transmitted via wireless network communication channels during the operation of MARS. As the analysis showed, the intensity of information flows in the data transmission network of the developed MARS configuration with five robots does not exceed a critical level (Table).

Thus, the conducted field experiments convincingly demonstrated the feasibility of MARS solutions focused on performing various applied tasks, including automatic search and removal of debris during emergency recovery.

Table. Intensity of information flows in the wireless data transmission network of MARS

Data	Frequency, Hz	Size of one message, kB	Number of devices	Total transmission rate, kbps	Content
Navigation	5	102	16	65 280	Images from IP cameras
Navigation	5	0.5	1	20	Line with coordinates of detected robots
Navigation	1	0.1	5	4	Lines with coordinates of each robot
Control	1	0.1	5	4	Tactical-level robot control commands
Control	1	0.05	5	2	Confirmation of execution of tactical-level commands
Interface	10	25	5	10 000	Image from onboard video camera
Interface	10	2	5	800	Data from onboard lidar

CONCLUSIONS

The creation of the MARS prototype enabled the integrated testing not only of group control methods and algorithms, but also technologies for processing the necessary knowledge along with human–machine interface tools for the prompt setting of the applied tasks to be performed. The results of experimental studies performed by the example of tasks of automatic search and removal of debris confirmed the efficiency of the developed software and algorithms, the current version of which implements the centralized strategy of group control of autonomous robots constituing the united group. Proposals for further development of the system include supplementing its structure with bulletin board mechanisms to support decentralized strategies for the functioning of autonomous robots at the level of coordinating their behavior plans and interactions.

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Authors' contributions

S.V. Manko has developed algorithms for planning and distributing tasks between MARS agents; proposed a formalized description of the scenario of the specified applied problem in the form of a network of finite automata.

V.M. Lokhin has developed the MARS architecture and the generalized structure of its autonomous robotic agent; proposed the concept of a full-scale experiment to search for and eliminate the blockage, and controlled the stages of its implementation.

S.A.K. Diane has developed vision algorithms for autonomous robotic agents in the MARS; programmatically implemented key algorithms for planning, distributing tasks, and processing information in MARS.

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