Requirements for Safe Operation and Facility Maintenance of Construction Robots

Alexey Bulgakov[a], Thomas Bock[b], Jens Otto[c], Natalia Buzalo[d] and Thomas Linner[b]

[a]Department of Mechatronic, South Russian State Polytechnic University, Russia
[b]Department of Building Realisation and Robotics, Technical University of Munich, Germany
[c]Department of Construction Management, Technical University of Dresden, Germany
[d]Department of Information Management, Chaoyang university of technology, Taiwan
E-mail: agi.bulgakov@mail.ru, thomas.bock@br2.ar.tum.de, jens.otto@tu-dresden.de, n.s.buzalo@mail.ru

Abstract –

Construction robots are devices of increased danger and, under certain conditions, can become a source of injuries to maintenance personnel, as well as lead to the failure of technological equipment. Most of the accidents are associated with the presence of maintenance personnel in the working area during programming, configuration, training, repair and maintenance of robots. The article describes measures to ensure safety during the maintenance of robots and manipulators. The stages of preparing the construction industry for the use of manipulators, robots and robotic complexes are presented. A system of measures for preparing equipment for use and its maintenance during operation is proposed.

Keywords –

Construction Manipulators and Robots; Maintenance of Robotic Systems; Operation; Service; Safety

1 Introduction

Under certain conditions, construction robots can become a source of injuries for maintenance personnel, as well as lead to the failure of technological equipment. The main causes of emergency situations during the operation of robots and robotic complexes are mechanical damage, disruption of the drives, failure of control systems, increased positioning error, programming and tuning errors, exceeding permissible load values, occurrence of super-permissible dynamic modes, loss of the manipulated object, malfunction of safety equipment, violation service personnel operating conditions. Most of the accidents are associated with the presence of maintenance personnel in the working area during programming, tuning, training, repair and maintenance of robots [1-10].

Important in achieving the safe operation of robots and manipulators is their rational installation. Placement of robots and robotic systems (RS) should provide free, convenient and safe access for maintenance personnel to equipment and controls. The layout of the RS should take into account the shape, size and characteristics of the technological equipment, the location of the working areas, the level of automation and the degree of information support. When organizing the RS, it is necessary to have special devices that provide for the safety of staff. Enhancing safety is facilitated by safety enclosures, blocking and signaling devices, as well as the development of an information support system about the state of equipment and the environment. Protection devices must turn off the equipment when a person is in the danger zone of the workspace. The signal can only be taken by an operator who is setting up and maintaining equipment. The safety fence of the working areas of robots should not impede visual control over its work and the associated technological equipment. Safety fence is installed at a distance of at least 0.8 m from the boundaries of the working area of the robot and can be performed not only mechanically, but also on the basis of special devices: contact, power, ultrasonic, capacitive, induction, optical, etc. Automatic and automated lines and sections at enterprises manufacturing construction products should be equipped with emergency shutdown facilities equipment placed along the line with an interval of not more than 4 m.

During the operation of robots in the RS and in conditions of limited space, their working bodies are necessarily equipped with tactile sensors that are triggered by the contact of the working body with an obstacle.

The operation of robots and robotic systems imposes high requirements on the training of staff. Only persons who have undergone special training should be allowed to work on commissioning and operating robots. In addition to safety issues during the training of personnel, the device and features of the work of robots, the

procedure for controlling them, and actions of operators in emergency situations should be considered. Training in practical skills in working with building robots is preferably carried out on special simulators equipped with an automatic training system. Each operator should be given a safety note and instructions for controlling manipulators and robots. The industrial safety service of the construction firm should periodically monitor compliance by personnel with safety requirements, equipment status, and check the serviceability of safety equipment.

It is very important to have a choice of a rational mode of work and rest for staff, as fatigue can become a source of emergency situations caused by wrong actions.

2 Preparation of construction production for the use of manipulators, robots and robotic systems

The installation of robots by the construction projects and plants of the construction industry is preceded by a set of preparatory work, including a number of stages. The economic and social efficiency of robotization depends on the composition, volume, sequence and completeness of the implementation of the complex of works [11-14].

Preparation of building production for the use of manipulators and robots has its own distinctive features, characterized by the specificity of technological processes and the need to use new methodological foundations for their design concept. In addition, the content and scope of preparation of processes at construction sites differs significantly from the preparation of technological processes at construction plants, which are more similar in character to technological processes in mechanical engineering. The process of preparing for the introduction of robots is determined by the character of the re-equipment of production. In the case of capital reconstruction, the construction of new manufacturing divisions and plant floors in the construction industry, the basic technical solutions for process automation should be underprin at the stage of preparation of technical documentation and comprehensively linked to the design and technological features of robotics objects. With the technical re-equipment of individual production lines and plant floors and in the case of robotization of individual operations at existing plants, preparation for the introduction of robotics should begin with an analysis of the process features and the effectiveness of the existing technology, the degree of use of equipment and the identification of tight spots when performing certain operations. A variety of technologies for work on construction sites and technological operations at construction industry plants requires a systematic approach to assessing the volume of implementation of manipulators and robots, choosing the objects of robotization and drawing up a work plan. In preparing the construction industry for the introduction of manipulators, robots and RSs, special attention should be paid to the issues of specialization, typification, unification, conveyorization and improvement of technology. The system of preparation for the robotization of production processes in construction should be based on rational organization, mechanization and automation. When solving robotization issues, it is necessary to achieve the optimal technology option based on the economically feasible choice of equipment, manipulators and robots, devices and tools that provide the necessary level of mechanization and automation of production processes.

In connection with the peculiarities of the introduction of robotics in the construction industry, let us consider in more detail the volume and composition of organizational and technical measures for the preparation of technological processes for the use of manipulators and robots.

At the plants of the construction industry, robotization of technological processes can be carried out both comprehensively on the production line, site, in the workshop, and locally in individual operations. Currently, manipulators and robots are mainly introduced in separate operations with the aim of eliminating tight spots in the process and eliminating monotonous and heavy physical labor. However, due to the large capital costs, this method is ineffective. This greatly inhibits the widespread adoption of robots in the construction industry. It is possible to increase the economic efficiency of using robotics tools only by preparing the conditions for their use in the complex solution of automation and robotization of production lines and plant floors on the basis of improving technology and product design. Therefore, the robotization of technological processes in the construction industry must be carried out on the basis of comprehensive scientifically based plans for technical re-equipment, which provides for a phased transition from the robotics of individual operations to complex automation and robotization of lines and sections. With this approach, individual local control systems of operations are gradually combined into systems for controlling lines, sections, and workshops with simultaneous solutions to the issues of automation and robotization of transport-auxiliary operations. In this regard, the process of introducing robots in the construction industry is preceded by a series of preparation stages associated with the formation of plans for technical re-equipment and reconstruction of production facilities.

In order to prepare a comprehensive production robotics program, which is an integral part of these plans,

the existing production processes (Fig. 1), technologies, equipment, products and transportation relations are

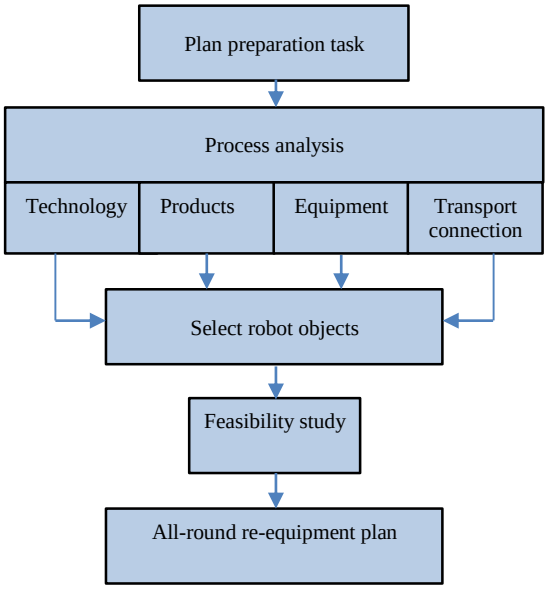

Figure 1. Scheme for a comprehensive plan for the technical re-equipment of production processes in the construction industry

analyzed. Depending on the scope of tasks for the reconstruction of production, it is necessary to analyze the entire production process, as well as its components or individual operations. The analysis reveals all the features of production, unused reserves, bottlenecks, the level of technological and design solutions, the level of mechanization and automation of individual operations, the composition and characteristics of technological equipment, organization methods and means for performing transport and auxiliary operations, transportation and storage of finished products.

As a result of the analysis, ways to improve the production process are developed, recommendations are given for the modernization of technological equipment or its replacement, ways to change the organizational structure and increase the efficiency of the process are outlined, measures are proposed to increase labor productivity, reduce the complexity of operations and employment of workers, improve working conditions.

In the course of a comprehensive assessment of technical, technological, organizational and social factors, proposals are formed for comprehensive mechanization, automation and robotization of production processes. An important stage of this work is the preliminary selection of objects of robotization, the purpose of which is to determine the feasibility of robotization of a particular technological operation. A number of factors are used as evaluation criteria. The use of manipulators and robots in the production process can be aimed at increasing production productivity, improving product quality, improving working conditions for workers, improving labor safety, reducing the complexity of auxiliary and transport operations, ensuring a high degree of equipment load. When introducing robotic means in existing plants, the volumes of redevelopment of production facilities, modernization of installed equipment and additional costs should also be taken into account.

Preliminary selection of robot objects is usually carried out by expert experts. At the stage of preliminary selection, a group of experts determines the significance of factors for a comprehensive assessment of production and, depending on its conditions and the resulting estimates, carries out an adjustment of the composition of factors. Further, each expert gives an assessment of the measure of influence of each factor on the decision in favor of robotization, and an average and relative assessment of the significance of each factor is established. The priority of production robotization is determined by the results of a comprehensive assessment in accordance with the preference rank identified during the expert assessment. Preliminary selection of operations is completed by compiling a list of objects of robotization.

The next step is the feasibility study of the selected facilities. The feasibility study ends with the exclusion from the list of robotic objects that do not give an economic effect. In the presence of dangerous and harmful conditions for the performance of production operations, the decision on the need for robotics is made regardless of the results of economic calculations.

Based on the results of the feasibility study, in accordance with the rank of preference assigned to each object of robotization, a comprehensive robotization program is compiled. In this case, it is necessary to provide for the phased introduction of RS and automation of processes. At the first stage, the tasks of creating separate robotic positions and combining them in the RS are solved. At this stage, priority is given to automatic and semi-automatic equipment. The second stage envisages further improvements to systems for servicing RTKs and combining individual RTKs into robotic production lines. At the third stage, the issues of robotization of all auxiliary operations, operations to remove production waste and create an automated process control system are solved.

Preparation of production for the introduction of manipulators and RSs, included in the plans for its technical re-equipment, contains a set of technological, technical and design works (Fig. 2). At the enterprises of the construction industry, the implementation process begins with a detailed analysis of the object of robotization and compiling a group of technical requirements. In the process of its comprehensive critical examination, all the constituent elements of the robotic part of the production process are exposed. In robotic

workplaces, the manufacturability of product designs, its compliance with robotization requirements is additionally investigated, technical and technological documentation is studied, the sequence of operations and the movement of workers is analyzed. The cyclograms of completed operations are built, their temporal and technical indicators are determined. In addition, the nomenclature and product release program in selected areas for robotization are studied. Objects of robotization are analyzed using methods of qualitative and quantitative assessment of possible options for the construction of RS.

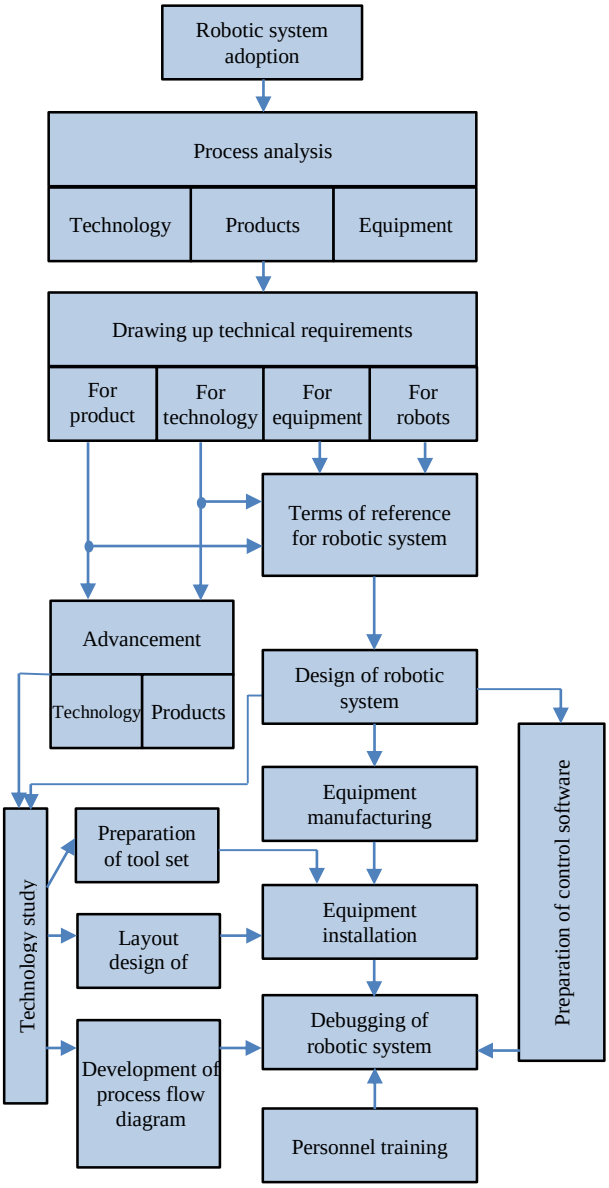

Figure 2. A set of works on the introduction of RS in the construction industry

Based on the analysis, technical requirements are formed for the technology, the main and auxiliary equipment, manipulators, tooling, control systems. The main requirements for the developed RS are set by technological, operational and economic indicators. The first determine the functional characteristics of the robot necessary for its inclusion in the RS, the second determine the ease of maintenance, maintainability, and other operational indicators, and the third establish the capital and operating costs that provide the necessary economic effect.

The formulated requirements serve as initial data for the preparation of technical specifications for the development of the RS and the implementation of works to perfecting the designs of products and their manufacturing technology. On the basis of the technical specifications, RSs are designed, preliminary they are developing a new technology and layout of the complex. When developing a project, when choosing technical means, it is necessary to take into account the productivity of each unit of equipment included in the complex, its mutual coordination with respect to constructive and technical performance. Particular attention should be paid to increasing technical productivity, which takes into account technical interruptions in the operation of the equipment. During the design process, a robot, additional equipment and working bodies are selected. The model of the manipulator or robot is selected based on a comparison of economic indicators for specific operating conditions. In the absence of robots that satisfy the task, it is being maid up the terms of reference for the development of a special design.

Particular attention in the design is given to transport-technological schemes and means of delivery of components and materials. At the design stage of the RS, safety and security equipment, magazine devices, special containers and facilities for the disposal of industrial waste are developed. Based on the results of a preliminary study of the operating technology of the PC, technological equipment is developed and manufactured that meets the basic requirements for the operation of the complex.

An important stage of preparation for implementation is the layout of the RS. When compiling it, much attention is paid to the optimal location of the main and auxiliary equipment, taking into account the technology of work, the safety of maintenance of this equipment and the possibility of its repair.

The final stages of preparation are the manufacture and installation of the RS, the development of process maps, the preparation of control programs, the debugging of individual equipment and the entire complex. Maps are drawn up in accordance with the general rules for the technological preparation of enterprises in the construction industry, determined by the Building Norms and Rules (BNaR).

Installation and debugging of the RS includes the development of an installation plan, the execution of work, the manufacture of an experimental batch of products and acceptance tests. Technological maps are developed after the final selection of the main and auxiliary equipment, means of its automation and tooling design. During production robotization, simultaneously with the design, manufacture and installation of the RS, the issues of personnel training for their maintenance should be addressed. Persons who have undergone special training are allowed to work on servicing robots and RS.

Based on a detailed review of the stages of preparation for production at the enterprises of the construction industry, it should be noted its features in the robotization of processes at construction sites. The main feature of the robotization of operations at the construction site is the non-stationary nature of the performed works, the temporary nature of the installation of equipment, possible changes in the layout and technology when changing construction. In this regard, it is advisable to implement robots and RSs at construction sites based on the use of standard projects for the robotization of certain types of work. Such projects are developed by a specialized organization for the construction of mass buildings based on an analysis of typical technologies for the construction process (Fig. 3).

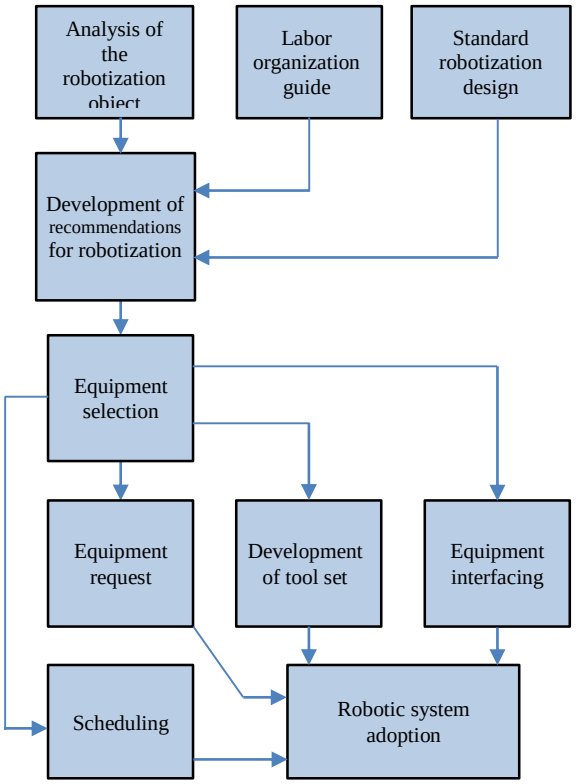

Figure 3. Scheme for the development of standard projects for the robotization of construction works

Typical projects include diagrams of the robotoization process, the composition of the recommended equipment, operation cyclograms of equipment, standard technological maps and basic labor protection measures when working with robots and RS.

The development of standard projects is preceded by a comprehensive analysis of the existing technologies of the robotic type of work and the organization of the construction process. Based on the results of the analysis, recommendations are made for improving the technology. Based on these recommendations and the results of the analysis, the objects of robotization are pre-selected and their feasibility study is carried out, technological schemes of operations are developed, the recommended equipment is selected, typical layout schemes, cyclograms and routings are drawn up. Based on the results of this work, a typical robotization project for this type of work is drawn up. To provide technical assistance to construction organizations on the implementation of manipulators, robots and RSs, it is advisable to prepare labor management guidelines for builders on the basis of standard designs when using robotics.

The process of preparing the construction for the implementation of manipulators, robots and RS during the construction, restoration, repair and reconstruction of buildings and structures begins with an analysis of the construction and technological characteristics of the robot object (Fig. 4). On the basis of this analysis, as well

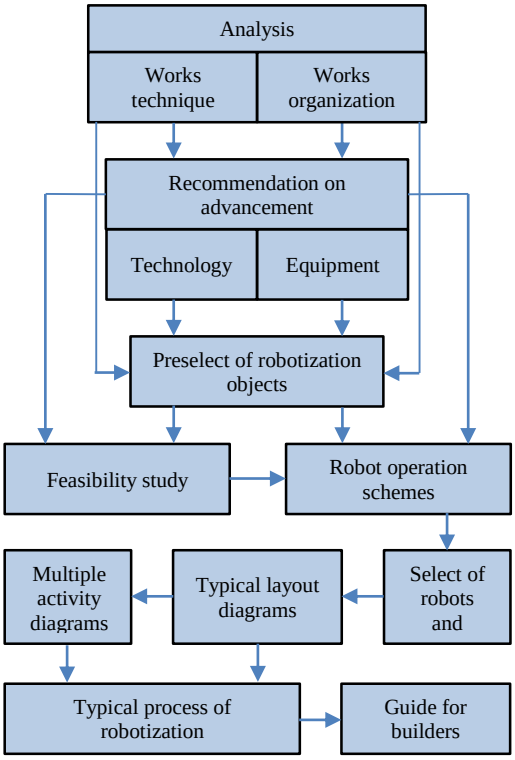

Figure 4. Scheme of works on the robotization of construction processes based on standard projects

as typical projects of robotoization of this type of works, recommendations are developed to improve the technology of robotic operations and modernize the equipment used with the goal of being able to interface with robotic mechanisms. At the next stage of work, it are selected the main and auxiliary equipment, automation tools; it are developed applications for their supply; it are prepared technical tasks for the design of technological equipment; it are developed equipment, devices and means of pairing old equipment with new one. After the completion of design work, equipment is manufactured and adjusted. The final stage of preparation is the development of a project for the production of works. Technological maps for the robotic operations that are part of the project are developed on the basis of standard ones with specific reference to the construction site and local construction conditions. Particular attention should be paid to the development of labor protection measures [15-20].

3 Maintenance of robotic systems

Manipulators, robots and RSs are complex technical devices, the effectiveness and reliability of which largely depends on the organization of maintenance. The low level of this service leads to a significant decrease in the efficiency of the use of automation and robotic means for construction and production processes, and in some cases it can even nullify the effect of their use. The correct construction of a maintenance system for manipulators, robots and RSs and their precise organization lead to an increase in the operating time, reduction of downtime, enhance reliability and, as a result, contribute to the growth of their operation in the production process.

Construction robots and RS as objects of maintenance have a number of characteristic features. They are distinguished by increased complexity, the presence of mechanical, electromechanical, hydraulic, measuring, electronic and other components and devices, which increases the risk of working with them. Therefore, high demands are placed on the labor protection of service personnel. The introduction of robots and manipulators requires not only appropriate technological preparation of production, but also changes in the activities of the technical and technological services of the enterprise, professional and psychological training of workers and engineering personnel.

The use of robots and RЬI at construction sites sets the task of creating a special repair and maintenance service that can provide maintenance of complex equipment directly at the site of construction vn work.

In the general case, maintenance of robotic devices includes a system of measures for preparing equipment for use and its maintenance during operation. In accordance with this, the following main stages of maintenance of robots and RTKs can be distinguished:

- the period of preparation of equipment and control systems for operation,
- preventive maintenance of devices during operation,
- restoration of the operability of devices in the event of failures.

The block diagram of the maintenance of robots, reflecting the listed stages of maintenance, is shown in Fig. 5. It can be seen from it that each stage includes a

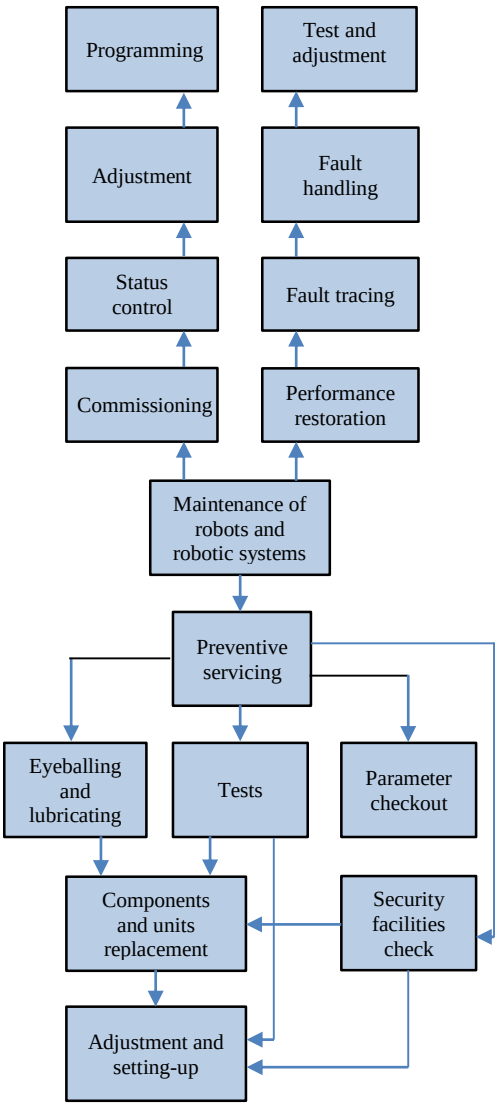

Figure 5. Block diagram of robots and RSs technical maintenance

group of measures necessary to ensure operability, the required reliability and durability of the equipment. So, the period of preparation of robotic facilities for use includes monitoring the status and performance of devices, their configuration and programming. Preventive maintenance includes periodic inspections of

individual devices, components and units of equipment, tests, verification of basic parameters and characteristics, replacement of elements and components, as well as verification of safety equipment. In the process of preventive maintenance, lubrication and adjustment of both individual elements and the equipment as a whole are performed. Faults and failures in the operation of nodes and blocks arising during the operation of robots are eliminated by carrying out restoration work, including troubleshooting, their elimination, as well as the verification and adjustment of devices.

Important indicators of robots and RS as service objects are maintainability, recovery efficiency and time spent on troubleshooting.

Maintainability characterizes the degree of adaptability of robots and manipulators to the prevention and detection of causes of failures in work and the elimination of failures. This characteristic determines the readiness of the equipment for work and is taken into account at the design and development stages. From the point of view of maintainability, robots and systems created on their basis should have handling devices, control systems, information support tools and technological equipment that meet the requirements of convenient access to elements, units and modules when troubleshooting and eliminating failures. The maintainability of robots and RSs depends on unification, interchangeability, availability of troubleshooting systems, as well as the level of preparation of diagnostic tests.

For robots servicing, determining the category of complexity of their repair, as well as evaluating the length of the overhaul period, is of particular importance. These indicators are determined depending on the design characteristics of robots, load capacity, degrees of mobility, complexity of control systems, type of drives, positioning accuracy and other indicators. A major role in robotic servicing is played by troubleshooting time. It is determined by a group of components and includes the time intervals necessary for detecting a failure, preparing a tool, finding a faulty unit and element, troubleshooting, after-sales adjustment and tuning. The time spent on troubleshooting depends on both technical and organizational factors, and primarily on the degree of maintainability, the level of organization of maintenance, training of maintenance personnel and the availability of diagnostic tests.

Carrying out repair work is also characterized by the efficiency of the restoration of failed nodes and systems of robots and technological equipment that is part of the RS. This indicator depends on the quality and reliability of the restoration, its cost, labor costs of maintenance personnel, as well as losses associated with untimely equipment repair.

When using robots in the construction industry, much attention is paid to the preparation period. This maintenance phase is especially important for robots used on construction sites where there are no special conditions for repair service and maintenance. In this case, it is advisable before sending the equipment to a new construction site under stationary conditions of the repair and maintenance service to monitor its condition and operability, to carry out the necessary adjustment and configuration of units and blocks, as well as programming based on the technological maps of the work at this object.

A prerequisite for the performance and reliability of construction robots is the organization of their preventive maintenance. It includes a system of preventive measures that reduce the likelihood of failures. Preventive measures are planned based on an analysis of the particular features of the functioning of all devices and systems of the robot. The choice of the timing, volume and sequence of these measures depends on the nature of the failures, the amount of restoration work, the requirements for reliability and operability of both individual components of the work, and the entire equipment complex. When planning work on preventive maintenance of robots, it is necessary to take into account the nature of failures of individual nodes and elements. Their planned replacement is carried out in case of failures due to wear and tear and for elements subjected to aging. For elements, blocks and devices having a specified service life, a plan for their replacement is drawn up in accordance with the achievement of the maximum operating time. Elements for which the service lives are unknown are replaced by the results of periodic control tests, during which the technical parameters are checked. If limit values are reached, the elements unsuitable for further operation are replaced. Parts subject to rare occasional failures must be replaced if they fail. Their planned replacement is non-forest-like, since it can lead not to an increase, but to a decrease in the reliability of the equipment. Their planned replacement is impractical, since it can lead not to increase, but to reduce the reliability of the equipment.

4 Conclusion

To ensure safe working conditions for construction robots and manipulators, a set of measures is provided that is implemented at the design, installation and operation stages.

The complication of production associated with the introduction of robots, raises the need to address in the process of preparing a set of issues on the organization and operation of robotic systems. In this case, special attention should be paid to ensuring labor safety during the operation of manipulators and robots.

For the selection of objects of robotization in each case, the priority of the set goals is established. First of all, during robotization, attention is drawn to labor-intensive, traumatic and harmful to human health operations, and secondly, to low-prestige, auxiliary, etc.

The main tasks of the maintenance of robotics tools are periodic monitoring of the technical condition of the equipment as a whole and its individual parts, timely detection of precautionary conditions, troubleshooting and restoration of equipment performance.

The effectiveness of the use of robots and RTK in construction largely depends on a clear organization of repair services. At the same time, planning and calculating the nomenclature and the number of spare parts is of paramount importance. During operation, robots and RTK are equipped with spare elements, blocks, replaceable modules. Repair service is provided with the necessary set of tools and devices. The troubleshooting process involves several steps. It begins with finding the failure by external signs and compiling, on the basis of logical analysis, a list of faults that can cause the observed set of failure. After that, the optimal sequence of checks is determined, allowing to find the faulty module, block, functional unit. Then a faulty element is searched. Diagnostic tests allow to simplify the troubleshooting task and quickly find a failed item.

References

[1] Cousineau L. and Miura N. Construction robots: the search for new building technology in Japan. – ASCE Press, 1998. ISBN 0-7844-0317-1

[2] Bock T. and Linner T. Robot-Oriented Design, Design and Management Tools for the Depolment of Automation and Robotics in Construction; Published since May 2015.

[3] Bock T. and Linner T. Robotic Industrialization. Automation and Robotic Technologies for Customized Component, Module, and Building Prefabrication; Published since August 2015.

[4] Bock T. and Linner T. Automated/Robotic On-Site Factories; Published since October 2015.

[5] Bock T. and Linner T. Construction Robots. Elementary Technologies and Single-Task-Construction Robots; Available February 2016.

[6] Bock T. and Linner T. Robotic Ambience. Automation and Robotic Technologies for Maintenance, Assistance, and Service, Available 2017

[7] Delgado J.M. D. et al. Robotics and automated systems in construction: Understanding industry specific challenges for adoption. Journal of Building Engineering Volume 26, November 2019, 100868 doi.org/10.1016/j.jobe.2019.100868

[8] ISO 13482:2014(en) Robots and robotic devices — Safety requirements for personal care robots.

[9] ISO 10218-1:2011, Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robots.

[10] ISO 10218-2:2011, Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration.

[11] Seward D. and Zied K. Graphical Programming and Development of Construction Robots. Journal of Construction Engineering and Management (2004), ASCE. 65.

[12] Everret, J.G. Automation and Robotics Opportunities Construction Versus Manufacture. Journal of Construction Engineering and Management (1994), ASCE. 120(2), pp. 443- 452.

[13] Balaguer C. and Abderrahim M. A Trends in Robotics and Automation in Construction. University Carlos III of Madrid, 2008.

[14] Bock T. Special Issue on Construction Robotics. Autonomous Robots. Volume 22. Number

[15] Cousineau L. and Miura N. Construction Robots: The Search for New Building Technology in Japan. American Society of Civil Engineers. 1998.

[16] Taylor M. and Wamuziri S.Automated Construction in Japan". Proceedings of ICE. 2005.

[17] Giretti A., Carbonari A., Naticchia B., DeGrassi M. Design and first development of an automated real-time safety management system for construction sites. Journal of Civil Engineering and Management. Volume 15. Issue 4. 2009.

[18] Bock T. CAR: Construction Automation Robotics. - In: 22nd International Symposium on Automation and Robotics in Construction (ISARC), Ferrara, 11.-14.09.2005.

[19] Bock T. Affordable and Adaptive Housing for Socio-technical Innovation by Construction Automation and Robotics. Journal of Industrial and Civil Enginnering, Russian Engineering Academy of the Russian Society of Civil Engineers, ISSN:0869-7019, pp. 5-10, Vol.10, 2014.

[20] Linner T. and Bock T. Automation, robotics, services evolution of large-scale mass customization in the Japanese building industry. In: Mass Customisation and Personalisation in Architecture and Construction: A Compendium of Customer-centric Strategies for the Built Environment , Edited by P. A.E. Piroozfar & F. T. Piller, London & New York: Routledge/ Taylor & Francis Group, June 2013, pp. 154-163.