Experience and prospects of using robotics in the nuclear power industry

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Abstract. It is impossible to imagine the modern nuclear power industry without the use of robotics. Monitoring of equipment and structures conditions, elimination of accidents and catastrophes consequences are wide application areas of robots that allow to reduce the radiation load on personnel. In the near future, the global nuclear power industry will inevitably face the need to decommission nuclear power plants that were built in the 1970s-1980s, which currently form the core of nuclear generation. This determines the high relevance and importance of developing scientifically grounded methods and approaches to decontamination and dismantling of nuclear power plant radioactive structures with the preferential use of robotic technology. A review of domestic and international experience in the field of nuclear energy allows us to assess the state and prospects of this direction, as well as to recognize the discrepancy between the existing technological level of robotic means and the promising tasks in the field of decommissioning of industrial nuclear reactors. In this case, it is considered appropriate and relevant to rapidly develop robotics as well as information simulation models that allow to provide various scenarios for dismantling of radioactive structures and equipment with the greatest involvement of modern robotic systems in this process.

1. Introduction

As of mid-2018, 31 countries operate nuclear power plants, but since the end of the 1980s, after the events at the Chernobyl NPP [1], there has been a clear global trend towards curtailing newly implemented projects in the field of using nuclear energy for peaceful purposes. The consequences of this reversal only on the territory of the USSR were both the construction suspension of a number of nuclear generation facilities (the 2nd stage of the Kalinin NPP, Rostov NPP), and the complete construction cessation of nuclear power plants (Bashkir NPP, Crimean NPP, Kostroma NPP, Tatar NPP [2]), nuclear heating plants (NHP) (Voronezh NHP, Gorky NHP), nuclear heat and power plants (NHPP) (Minsk NHPP, Odessa NHPP, Yuzhnookrainsk NHPP). Global trends in this period were generally similar to domestic ones.

At the same time, only in the last 30 years (since 1990), global electricity consumption has more than doubled and was covered mainly by the active construction of thermal and hydroelectric power generation facilities. The slowdown in the implementation of new investment and construction projects (ICP) [3,4] in the field of nuclear energy gave way to the “nuclear renaissance” [5] of the early 2000s,
but the pace of new construction does not allow us to seriously talk about a full-fledged revival of nuclear energy construction.

The global reduction in the commissioning of new nuclear power plants in the 90s and 2000s was accompanied by the active operation of existing power units, many of which, as of mid-2020, have fully or partially exhausted their resource. Numerous studies and upgrades have extended the life of individual nuclear power plants by 15-30 years, but all this does not reduce, but rather raises the issue of decommissioning nuclear power facilities (NPF) [6].

There are many financial and operational problems associated with this process. A nuclear power plant, like any engineering structure, has its own life cycle, after which the facility must be deactivated, decommissioned, and the territory made suitable for further use. In addition, given the increasing number of nuclear installations being decommissioned, it is becoming increasingly clear that there is a need to correctly assess the amount of radioactive waste during the dismantling of protective structures. This is largely due to the fact that the costs of handling, storing and disposing of tens of thousands of tons of radioactive waste can be an unbearable burden for the nuclear power industry.

The cost of RW disposal is about 1.2 million rubles/m3 for highly active, 550 thousand rubles/m3 for medium active, 130 thousand rubles/m3 for low active and 35 thousand rubles/m3 for very low active waste. Thus, the problem of induced activity of nuclear installations' protective concretes has scientific, technical, social and economic aspects [7].

In accordance with existing technologies, decommissioning of nuclear power plants is carried out according to two most popular scenarios: keeping the power unit under supervision [8] (up to 30-50 years) in order to reduce the level of ionizing radiation, or immediate dismantling [9], which allows for complete decommissioning of nuclear power plants in a short time. However, even in the second scenario, it is necessary to ensure that the reactor installation is maintained for 5 years in order to minimize radiation negative impact.

The main disadvantages that are typical of both approaches are the risk of receiving high doses of radiation by personnel, as well as the need for a sufficiently long holding of the reactor. From an economic point of view, keeping buildings, structures, and equipment of nuclear power plants under supervision for at least 5 years is extremely unprofitable, which once again underlines the relevance of developing technologies for rapid decontamination and dismantling of radioactive structures of nuclear power plants with minimal human participation in these processes.

2. Materials and methods
At the moment, some experience of such developments has been accumulated in the world practice. In 1962, the US air force, with the help of the Special Weapons Center, demonstrated robotics that can withstand high doses of radiation without harming the machine operator and electronics. However, the weight of the product developed by General Electrics reached 77 tons, which significantly limited both its scope and the range of possible work.

This prototype, called the "Beetle", was intended primarily for installation and repair works for the engines of strategic bombers with a nuclear power unit. In parallel with the "Beetle", similar devices were developed – "Masher" and "Bat", which are the screened chassis of the M51 armored recovery vehicle and the Coleman Tow Vehicle, respectively. With the closure of the program for creating aircraft with nuclear power units, all three products were used by the National Aeronautics and space administration (NASA) of the United States, but due to the complexity of the design and low reliability of the units, their design capabilities were not realized.

The consequences elimination of the Chernobyl accident was accompanied by the active use of robotic means. The most powerful robots from Japan and Germany that arrived at the crash site were extremely inefficient. A radio-controlled amphibious bulldozer "Komatsu D-355W", that was capable of working on the sea floor, could not withstand radiation loads and quickly failed [10]. The German MF-2 and MF-3 robots, which were unable to overcome blockages and failed under the influence of high doses of radiation, turned out to be practically useless.
The advanced developments of the rocket and space industry of the USSR were also aimed at solving the problem of decontamination of premises, structures, and the area around the 4th power unit of the Chernobyl NPP. In the shortest possible time, more than 15 robots (PP‑1, PP‑2, PP‑3, PP‑G1, PP‑G2, RP, TR‑A1, etc.) with a modular layout were developed, manufactured and delivered to the accident site, which allowed them to be distributed to solve various tasks: from studying the radiation situation in the premises of the power unit (exploration) to decontamination of the territory. A significant contribution to the elimination of consequences was made by mobile robots "Beloyarets", "Mobot CH-HV", engineering robotic complex "Klin-1", specialized transport robot "STR-1".

Evaluating the overall efficiency of using robotics for the Chernobyl accident, we can confidently assert that this factor significantly reduced the potential radiation load on the accident liquidators, but a lack of understanding at the initial stage of the tasks led to the development of an excessive number of robots' types with their insufficiently thought-out design solutions and low operational reliability.

The rapid development of mechanical engineering, automation, information and communication technologies in recent decades has also led to the development of industrial robotics. A series of accidents at nuclear power facilities (The accident at the commercial nuclear fuel plant in Tokaymura in 1999 [11], the flooding of the Canadian uranium mine "Cigar Lake" [12], the accident at the Japanese nuclear power plant "Fukushima-1" [13]) stimulated the development of technical means capable of performing exploration and dismantling work in conditions of high radiation levels. Summary data on individual robotic means that have received practical application in the field of nuclear energy over the past 30 years [14] are presented in Table 1.

Table 1. Robotic means developed and used since 1990 in the nuclear power industry.

| №   | Robot assignment | Make, model       | Manufacturer                                                                 | Application experience                  |
|-----|------------------|-------------------|-------------------------------------------------------------------------------|-----------------------------------------|
| 1   | Reconnaissance   | SMERT-M           | Manufacturing science and technology center (MSTC), Toshiba Japan Hitachi, Institute for Research, Innovation and Development (IRID) (Japan) | The accident at the NPP Fukushima-1     |
| 2   |                  | PMORPH            | Hitachi, Institute for Research, Innovation and Development (IRID) (Japan)    | The accident at the NPP Fukushima-1     |
| 3   |                  | Mini Mola Mola    | Toshiba, IRID (Japan)                                                         | The accident at the NPP Fukushima-1     |
|     |                  | (underwater       |                                                                               |                                         |
|     |                  | reconnaissance)   |                                                                               |                                         |
|     |                  | PMORPH            |                                                                               |                                         |
|     |                  | (exploring the    |                                                                               |                                         |
|     |                  | continent from    |                                                                               |                                         |
|     |                  | within)           |                                                                               |                                         |
| 4   |                  |                   | Hitachi and IRID (Japan)                                                      | N/a                                     |
| 5   |                  | RESQ-A            | Japan atomic energy research Institute (JAERI/IAEA), Hitachi (Japan) Bauman Moscow state technical University (Russia) | N/a                                     |
| 6   |                  | MRK-46M           |                                                                               | N/a                                     |
| 7   | Dismantling and  | Brokk 300, Brokk 800SD | Holmhed Systems AG (Sweden)                                                    | N/a                                     |
|     | decontamination  |                   |                                                                               |                                         |
| 8   |                  | Super-Giraffe     | Mitsubishi Heavy Industries (MHI), IRID (Japan)                                | The accident at the NPP Fukushima-1     |
| 9   |                  | DX-140            | Husqvarna (Sweden)                                                             | The accident at the NPP Fukushima-1     |
The presented material clearly demonstrates a wide range of experimental use of robotic means in the global nuclear industry, but even the use of the most modern models still does not allow us to abandon human participation in the processes of operation, repair, and post-accident restoration of the functioning of nuclear power plants. This circumstance casts doubt on the possibility of implementing large-scale programs for decommissioning industrial nuclear reactors in the near future and requires accelerated development of complex robotic systems designed for long-term uninterrupted operation in conditions of high radiation load.

The insignificant presence of domestic developers’ products among the presented robotic means makes us recognize the extreme dependence of the modern nuclear industry in Russian Federation on world leaders in the field of creating remotely controlled machines.

3. Results
Summarizing the review of domestic and international experience in the use of robotic means in the nuclear industry, the main directions of their application should be highlighted:

- ensuring the implementation of processes for the safe manufacture, processing and disposal of nuclear material, as well as the management of solid radioactive waste and equipment exposed to radioactive radiation;
- consequences elimination of accidents and natural disasters at nuclear power facilities;
- ensuring the implementation of projects for nuclear facilities decommissioning.
The greatest complexity and scale for both researchers and organizations operating nuclear reactors now is the decommissioning approach. This occurs due to the inevitable exhaustion of the resource. The world practice currently has no experience in decommissioning large-capacity nuclear power plants. In some countries, these technologies are at the stage of conceptual development and pilot implementation on low-power reactors.

The processes of dismantling the structure and equipment of channel-type water-cooled graphite-moderated reactor, the most common of which is the RBMK-1000 reactor, are particularly difficult for domestic specialists in this case. The main problem is that any open reactor creates high radiation doses even for robotic devices. Due to its own design features, the RBMK reactor cannot be quickly dismantled in parts (like the VVER reactor), which requires a long dismantling process of structures directly in its core. The most obvious way to solve this problem is to use heavy mounted radiation protection for robots. However, this solution significantly complicates the process of delivering technical equipment to the workplace and limits its production characteristics.

Dismantling of equipment and structures is inevitably preceded by a complex of exploration work, which makes it possible to obtain up-to-date data on the state of technical systems and structural elements of the reactor compartment. In this case, robotics, remotely controlled by the operator, is indispensable and allows you to carry out:

- systematic monitoring of the radioactive radiation level for timely detection of threats of radioactive contamination;
- decontamination of premises to ensure conditions for the safe production of research work by personnel;
- examination of the nuclear facilities current state using scanners, cameras and sensors;
- construction of a multidimensional model of a building in accordance with its current state in order to develop a comprehensive work program for dismantling structures and equipment.

However, when working with remote-controlled mechanisms, it is necessary to take into account the requirements and conditions for such work:

- possibility of the working tool remote replacement;
- the ability to replace main components and units without manual detailed disassembly;
- use of quick-release connectors;
- use of electromechanical and relay control systems with a minimum amount of electronics;
- absence of hard-to-reach cavities and places of radioactive substances accumulation in dangerous quantities on the instrument;
- possibility of equipment decontamination from radioactive contamination.

These conditions should be taken into account both in the design of robotic complexes and in the development of projects for decommissioning nuclear power facilities. The most valuable experience for the domestic nuclear industry decommissioning of nuclear facilities will be provided by the implementation of two major projects in the near future:

- dismantling of AMB-100 reactor structures at Beloyarsk NPP [15];
- metal structures dismantling during the decommissioning of the AV-1 UGPR at the Federal State Unitary Enterprise "PO" "MAYAK" [16].

An important feature of these projects is the preliminary development of an interactive simulation model for dismantling the graphite masonry of the reactor [17] by joint efforts of the "Kurchatov Institute" and AO "NEOLANT".
Modeling the processes of dismantling AMB-100 reactor structural elements at the Beloyarsk NPP using a BROKK robot allowed researchers to identify a number of structural and technological problems of the project and develop measures to solve them. The most significant of these problems were:

- Unreliability of the system for automatic change of working mechanisms attachments due to graphite dust deposition on the device contacts;
- Insufficient visibility of fixed cameras that control the process of performing operations;
- Failure to extract more than 30% of the reactor's graphite masonry blocks using the developed "carousel" design, which ensures the robot's operation in the reactor shaft space.
- When using the accepted robotic mechanisms, it is impossible to remove the melted and stuck parts of the graphite masonry from the reactor's body [15].

In this case, simulation modeling made it possible to increase the efficiency of the project development for decommissioning the AMB-100 reactor, and provided a conceptual understanding of the prospects and possibilities of using robotic systems for dismantling the structures of channel water-cooled graphite-moderated reactors.

4. Conclusion

Summing up the research, it is necessary to say that in the nuclear power industry there is a systematic experience accumulation in using robotics that allow monitoring nuclear facilities, performing radiation reconnaissance and dismantling structures and equipment in conditions of a high radiation background.

Along with the consequences elimination of the accidents and catastrophes at nuclear facilities, remotely controlled mechanisms are indispensable in the implementation of projects for decommissioning nuclear power units. However, the involvement of robotic means in this case should be accompanied by both appropriate training of working personnel and the development of multidimensional simulation models that allow working out possible operating scenarios and solve potential problems of a constructive, technological and organizational nature at the development stage of the decommissioning project.

Special attention should be paid to taking into account features of nuclear facilities decommissioning at the stage of designing the object and creating its construction information model. At this stage, it is possible to provide a number of solutions for the design and technological plan, which subsequently allow the process of dismantling radioactive equipment and structures with the lowest costs, greater efficiency and the minimum impact of ionizing radiation on working personnel. An example of such accounting can be the reactor compartment layout of a nuclear power plant from hybrid units-modules of high factory readiness [18], which provides for the possibility of subsequent dismantling of the building by cutting it into initial blocks and transporting them to specialized sites for fragmentation and decontamination.

References

[1] Nigmatulin B I 2019 Nuclear industry in the world State and forecast up to 2050 St. Petersburg State Polytechnical University Journal Physics and Mathematics 25(4) 6-22
[2] Zausaeva Y D 2015 Institucional'nye faktory razvitiya nesostoyavshihsya atomnyh gorodov Demoscope Weekly 631-2 12
[3] Morozenko A A and Voronkov I E 2018 Analytical calculation of the reliability of participants in investment and construction projects as elements of the organizational structure Scientific and Technical Volga region Bulletin 8 27-9
[4] Voronkov I E 2018 Evaluation and improvement of the reliability of organizational structures of ICP by the method of hierarchy analysis IOP Conference Series: Materials Science and Engineering 365 062035
[5] Chernyakhovskaya Y V and Korolkov D L 2012 Public-private partnership in nuclear energy: the USA experience Bulletin of the Financial University 21 1(97) 91-105
[6] Bochkarev V V, Abakumova A S and Kryanev AV 2018 Justification of the choice of decommissioning option for nuclear facilities Nuclear and Radiation Safety Journal 2(88) 24-8

[7] Bylkin B K, Engovatov I A, Kozhevnikov A N and Sinyushin D K 2018 Data bank on activation characteristics of radiation shielding concrete of nuclear plants Vestnik MGSU 13 2(113) 213-21

[8] Berela A I, Fedotov A G and Tomilin S A 2013 Manufacturing equipment for NPP units withdrawal Global Nuclear Safety 1(6) 58-66

[9] Engovatov I A and Adiyatullin R F 2020 Providing rationale for the possibility of decommissioning Bilibino nuclear cogeneration plant based on the in-situ disposal option Proceedings of universities Nuclear Energy 2 73-84

[10] Ovchinnikov V V, Batanov A F and Mingaleev S G 2019 Robotics in Chernobyl Civil security technologies 16 4(62) 70-8

[11] Omelchenko E V, Stepanova M R and Bibik A A 2017 The danger of industrial radiation Ecology and life safety 114-9

[12] Dotdueva Z S and Beslaneeva D A 2015 Nuclear power engineering in sloving problem of power consumption: safety and value Modern problems of national economic development 79-86

[13] Fitkullin R Z 2019 The global aspect of nuclear energy security (on the example of Japan after the accident at the Fukushima-1 nuclear power plant) Age of Globalization 2(30) 86-97

[14] Lakutin N A and Oganesyan V S 2019 The line of robotic means for decommissioning nuclear power plants Politechnical student journal 3(32) 6

[15] Bylkin B K, Kononov V V, Bunto P A, Gulyaev O V, Sviridov D V, Trifonov V E, Tikhonovsky V L and Chuyko D V 2012 Experience of using a simulation model of the dismantling of the reactor graphite stack AMB-100 Beloyarsk Research of the Science City 2(2) 59-64

[16] Belkin D Y, Ivanov I A and Tananaev I G 2016 Concept for decommissioning of industrial uranium-graphite reactors (PA "Mayak", Chelyabinsk region) Vestnik Dal'nevostochnogo otdeleniya Rossijskoj akademii nauk 3(187) 58-65

[17] Bylkin B K, Chuyko D V and Tikhonovsky V P 2016 Interactive simulation 3D model as a tool supporting personnel radiation safety at decommissioning activities Nuclear and Radiation Safety Journal 1(79) 28-32

[18] Morozenko A A and Voronkov I E 2014 Improving the efficiency of organizational and technological solutions in the construction of nuclear power plants based on modern Russian and foreign experience Industrial and civil construction 10 74-9