Sensors & Transducers, Vol. 268, Issue 1, April 2025, pp. 28-36

Sensors & Transducers

Published by IFSA Publishing, S. L., 2025
http://www.sensorsportal.com

Robotic Automation for Nuclear Decommissioning: Development of a Tool Carrier System with Milling and Clearance Measurement Capabilities

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Received: 11 Nov. 2024 /Revised:31 March 2025 /Accepted: 28 April 2025/ Published: 30 April 2025

Abstract: As part of the ROBDEKON [1] project, the Karlsruhe Institute of Technology's Institute for Technology and Management in Construction (KIT-TMB) is developing a robotic system designed to position two specialized tools for the decontamination and clearance measurement of concrete walls in nuclear power plants. To achieve this, a Manitou 100-VJR lifting platform has been retrofitted with essential electronic components including controllers, sensors, actuators, communication modules, and safety systems transforming it into a robotic system known as "DekontBot" [2].

In addition to the robotic platform, an automatic milling tool and an automated contamination array have been developed as tools for decontamination and clearance measurement. The system supports operation in both teleoperation and (semi-)autonomous modes. Two graphical user interfaces have been developed, one for the DekontBot and another for the contamination array. These GUIs enable intuitive control and real-time visualization of system operations using RViz2 on the ROS2 platform, allowing users to operate the systems in a user-friendly and accessible manner.

This paper presents a detailed account of the development and implementation of the DekontBot, the milling tool, and the contamination array.

Keywords: Robotic, Automation, Decontamination, PLC, Robot operating system (ROS), Nuclear power plant (NPP), Clearance measurement.

1. Introduction

On April 15, 2023, Germany shut down its last three nuclear power plants Emsland, Neckarwestheim 2, and Isar 2. Currently, there are 25 nuclear power plants and research reactors in Germany at various stages of decommissioning and dismantling [3]. Globally, approximately 297 nuclear power plants are expected to begin the decommissioning process by 2030 [4]. To date, most decommissioning and dismantling activities have been performed manually, making it a high-risk activity not only due to the high levels of radiation but also because of the physical and mental stress imposed on employees (Fig. 1).

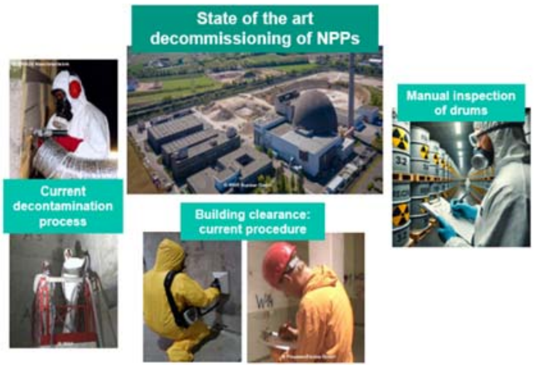


Fig. 1. State of the art in the decommissioning of nuclear power plants.

At the Institute for Technology and Management in Construction (TMB) at the Karlsruhe Institute of Technology (KIT), the “Deconstruction and Decommissioning of Conventional and Nuclear Buildings” department conducts research into topics in the conventional sector such as recycling-friendly dismantling, mechanical demolition methods and the automated separation of hazardous and non-hazardous waste. This field of research is supplemented by the dismantling of nuclear facilities. The focus here is on pilot projects designed to make the dismantling of nuclear power plants safer, more efficient and more economical for everyone involved in the dismantling process. The focus is on developing practical new dismantling technologies (pilot projects) for open problems, including large-scale testing.

However, organizations such as the OECD have noted that current technological capabilities in the dismantling process are not being fully leveraged. Increasing the use of robots and automation technologies offers the potential to reduce both costs and radiation exposure for personnel involved in the decommissioning process. Given the growing number of facilities undergoing dismantling, there is significant potential for digital and automated solutions in this domain [5].

The ROBDEKON project—commissioned by the Federal Ministry of Education and Research (BMBF)—aims to develop autonomous and semi-autonomous robotic solutions to enhance decontamination efforts in hazardous environments [6].

As part of ROBDEKON, KIT-TMB is collaborating with Karlsruhe University of Applied Sciences and Götting KG to develop a comprehensive automation chain for the decommissioning of nuclear power plants [7].

This automation chain comprises several components. One of them is the GammaBot, used for environmental exploration through geometric and radiological measurements. The collected data supports the implementation of Building Information Modeling (BIM) for digitization and detailed planning [8].

Additionally, autonomous decontamination and clearance measurement are carried out using portable robotic tools integrated into an autonomous carrier platform called DekontBot. The system also includes an autonomous forklift truck, developed by Götting KG, to handle the transportation of radioactive waste [9].

A visual representation of this integrated system is shown in Fig. 2.

2. Development of DekontBot

The objective of this research is to develop universal, robot-based solutions for a fully automated decontamination process within nuclear facilities, which can be flexibly adapted to diverse and changing environmental conditions.

Fig. 2. Closed automated chain for decommissioning of NPPs.

The following sections provide a detailed description of the third and fourth steps in the automation chain: automated decontamination and automated clearance measurement, both implemented using the tool-carrier robotic system DekontBot.

2.1. Description of the Robot's Main Task

Once contamination or hotspot locations are identified using the GammaBot, these areas must undergo targeted decontamination. To address this requirement, KIT-TMB has developed an automated, robot-portable milling tool specifically designed for decontaminating concrete walls.

After the decontamination process, the affected surfaces are autonomously measured to ensure they meet the required decontamination standards. For this task, a second tool, known as the “Contamination Array” [10] has been developed.

The primary role of the DekontBot is to accurately position these two tools, operating in either teleoperated or (semi-)autonomous mode, depending on the specific operational needs.

Fig. 3. Actual State of Development of DekobtBot.

2.2. Description of Original Platform

To achieve the described objectives, the “Manitou 100-VJR” platform was further developed and automated to serve as the base vehicle for the robotic system.

The platform measures approximately 1.2 meters in length, 1 meter in width, and 2 meters in height, allowing it to pass through standard doorways and operate in a wide range of indoor environments, from large halls to relatively small rooms.

Equipped with a manipulator featuring three degrees of freedom, the system can reach working heights of up to 8 meters, utilizing a telescopic joint and a robotic arm. Furthermore, it is capable of precisely positioning tools with a maximum weight of 270 kg.

A visual representation of the platform's dimensions and its degrees of freedom is provided in Fig. 4.

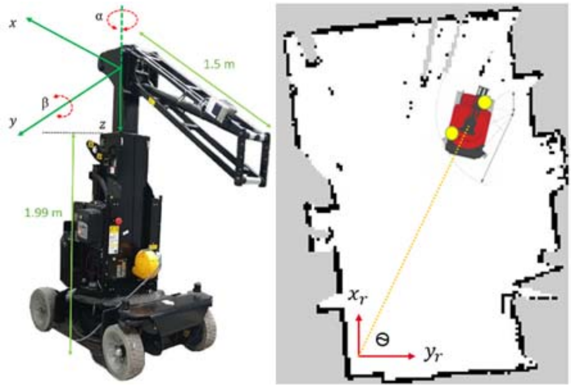


Fig. 4. Dimensions and degrees of freedom of the DekontBot.

2.3. Description of the Integrated Electronics

The foundation of the automated decontamination system is the mobile platform described in Section 2.2. To transform this platform into a fully functional automated system, it was equipped with the necessary components, as illustrated in Fig. 5.

A Rexroth CtrlX3 EtherCAT control unit (PLC) was integrated to serve as the central control system. This PLC connects to the three motor controllers, two for the traction motors and one for the pump motor, via a CAN-EtherCAT gateway. It also interfaces with various sensors to determine the position of the manipulator.

To monitor the manipulator's articulation, two inclination sensors were installed to measure the arm's orientation, and two wire-draw encoders were used to track the position of the telescopic joint and orientation of the tower.

The motor controllers provide real-time feedback to the PLC, including motor current, motor and battery voltage, and motor temperature.

For localization, the platform is equipped with two SICK microScan3 lidar sensors, which continuously calculate the vehicle's position. This positioning data is transmitted to the PLC using UDP communication.

Real-time operations such as motor control, sensor/actuator integration, and automation algorithms are executed on the PLC. Meanwhile, higher-level tasks including visualization, HMI, integration of cameras, and communication with other robotic systems and the control station are handled by a separate PC equipped with an Intel Core i7 CPU.

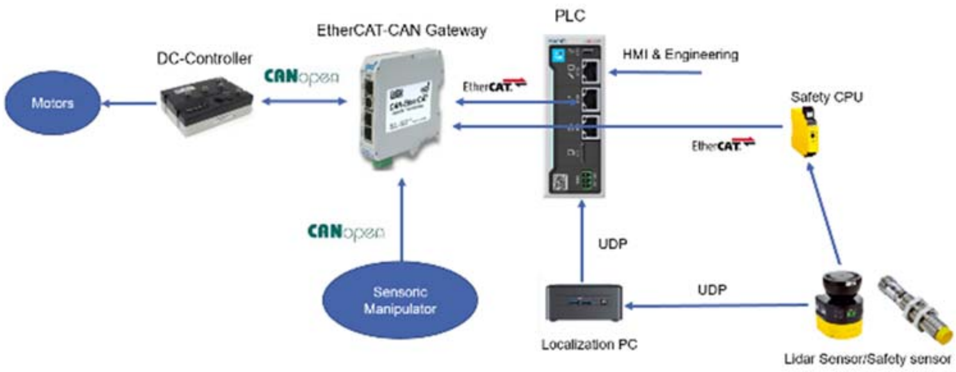


Fig. 5. Integrated electronics on DekontBot [11-14].

2.4. Safety System

System Safety is managed by a SICK-CPU0 safety PLC. The platform is equipped with safety laser scanners that detect people and obstacles in the surrounding area. Based on the detected object's position, the system generates protective or warning signals to prevent collisions or reduce speed.

The safety zones are divided into three color-coded regions, as shown in Fig. 6:

- Red Zone: Indicates a high risk of collision. If an object enters this area in front of the DekontBot, forward motion is immediately stopped;
- Yellow Zone: Indicates a caution zone. When an object is within this area, the platform reduces its maximum driving speed to 50 %;
- Violet Zone: Serves purely as a visual warning for operators. No movement restriction is applied.

The safety system is direction-sensitive: if an object is in front of the machine, only forward motion is restricted; reverse motion remains possible, and vice versa.

To prevent tipping, additional safety features including tilt measurement system is mounted, which consist of two analog tilt sensors that monitor the inclination of the platform. The first sensor continuously measures the platform's tilt, while the second acts as a redundant monitoring unit. If the measured tilt exceeds ±10°, or if the readings between the two sensors differ beyond a defined tolerance, forward movement is blocked if the condition occurs while moving forward, and reverse movement is blocked if it occurs during backward motion.

The movement of the manipulator joints is restricted to a tilt angle of ±2° to prevent the platform from overturning, particularly when handling tools weighing up to 270 kg at a height of 8 meters. Additionally, five digital switches are installed to verify that the manipulator is in its home position, which is a precondition for allowing platform movement. Other switches monitor whether any manipulator joint is at its end position, preventing unnecessary hydraulic pressure buildup.

The positions of the wheels are measured using analog potentiometers, which serve as both end switches and inputs for visualizing the wheel orientation in a Unified Robot Description Format (URDF) model. All safety-critical signals are routed through a dedicated gateway to the main control unit. In hazardous situations, such as potential collisions or risks of overturning, the system can halt all movement immediately, wait until conditions return to a safe state, or autonomously recalculate and execute an alternative path to reach its target.

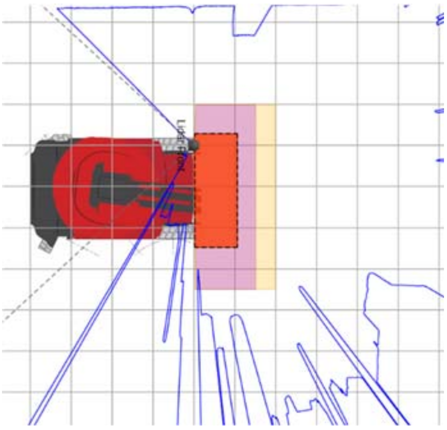
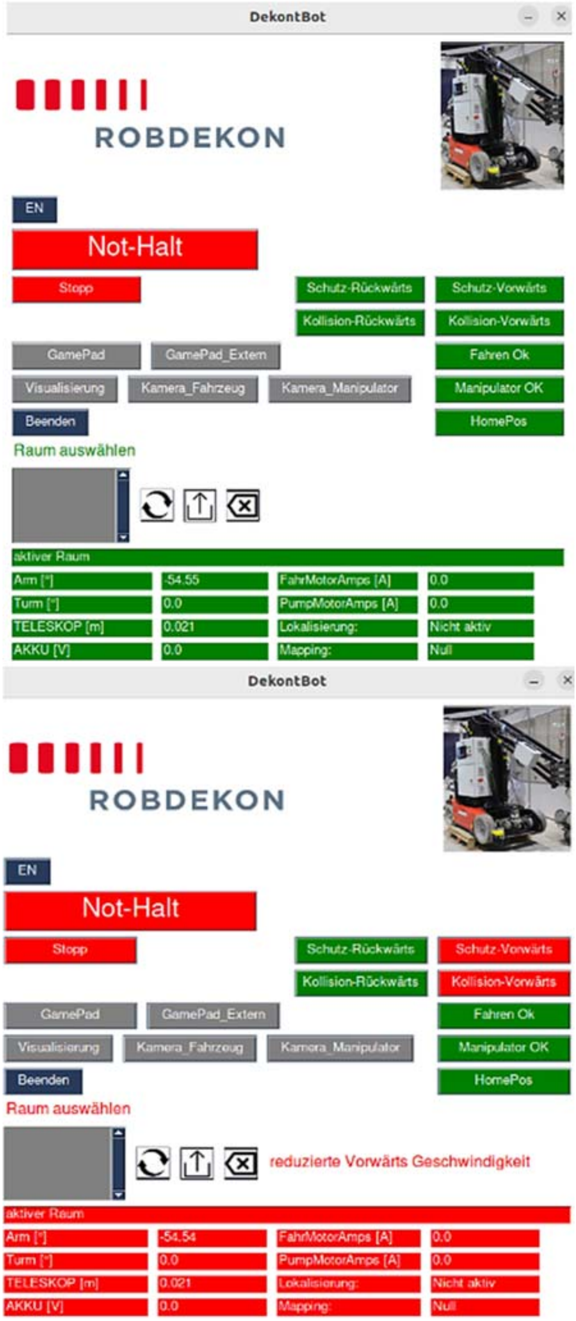


Fig. 6. Safety Zones of DekontBot: Front Safety Scanner.

3. GUI, HMI, Visualisation and Data Transfer

To enable intuitive user interaction, a user-friendly interface has been developed, allowing operation of the system without requiring in-depth technical knowledge. The interface supports language switching between German and English. (Fig. 7).



Arm [°] -54.55
Turm [°] 0.0
TELESKOP [m] 0.021
AKKU [V] 0.0
FahrMotorAmps [A] 0.0
PumpMotorAmps [A] 0.0
Lokalisierung: Nicht aktiv
Mapping: Null

reduzierte Vorwärts Geschwindigkeit

Arm [°] -54.54
Turm [°] 0.0
TELESKOP [m] 0.021
AKKU [V] 0.0
FahrMotorAmps [A] 0.0
PumpMotorAmps [A] 0.0
Lokalisierung: Nicht aktiv
Mapping: Null

Fig. 7. Top: No Safety Warning Signal, Down: Collision Signal.

The decontamination process is based on a contamination map generated in advance by the GammaBot. This map includes a two-dimensional layout for localizing the DekontBot, as well as a three-dimensional point cloud enriched with radiological information. Using this data, the DekontBot can identify contaminated areas, calculate the optimal trajectory from the starting point to the contamination sites, and position the required tools for decontamination or clearance measurement accordingly. All relevant information is transmitted automatically from the GammaBot to the DekontBot via a TCP server/client architecture using the ROBDEKON VPN.

The 2D map will be converted, processed, and the localization information will be transmitted from the PC to the PLC (Fig. 8).

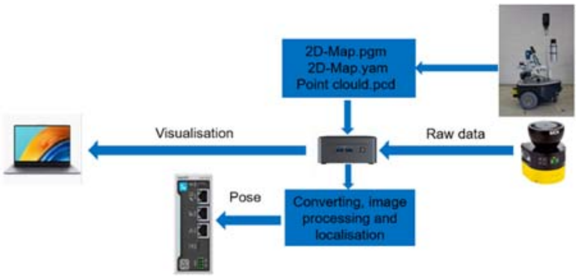


Fig. 8. Information Processing: From Transport to Localization and Visualization [11].

Through the graphical user interface (Fig. 7), users can select or delete existing contamination maps, start or stop system operation, and switch between teleoperation and automatic mode. The interface also displays key safety and system parameters, including collision risks, manipulator joint positions, battery voltage, motor currents, and localization status. Changes in system status are visualized through color transitions, from green to yellow or red along with corresponding warning messages.

To enhance spatial awareness, the selected contamination map is visualized in RViz2 using ROS 2. This includes both the 2D map and the 3D point cloud of the building, overlaid with a dynamic URDF model of the DekontBot (Fig. 9), providing real-time visualization of the robot's position and configuration.

For additional situational awareness, the platform is equipped with two USB 3.0 cameras: one for monitoring the vehicle's surroundings and another for observing the manipulator during operation.

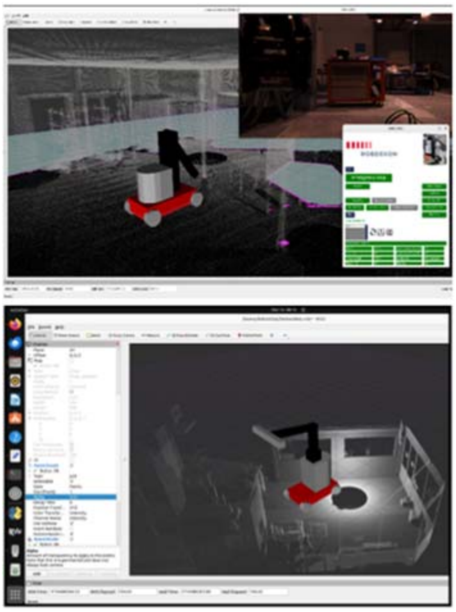


Fig. 9. Visualisation of point cloud and URDF model.

4. Developed Tools

As previously mentioned, the primary task of the DekontBot is to position two end-effectors: a milling tool for decontamination and a contamination array for clearance measurements, at the designated target positions. The following section provides a detailed description of the goals and development of these tools.

4.1. Milling Tool

The structure of the milling tool is shown in the Fig. 10.

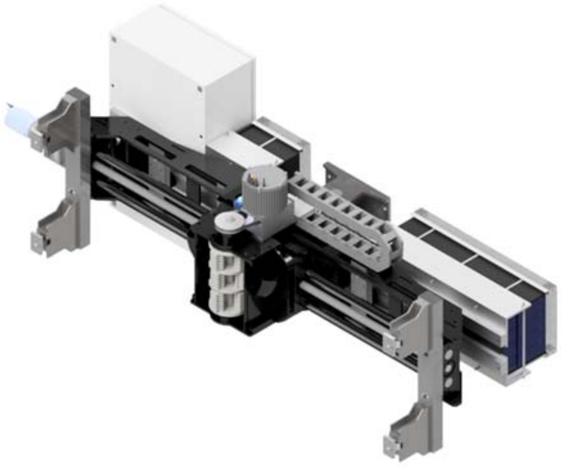


Fig. 10. The structure of the milling tool.

The mechanical components of the milling tool were developed by Contec, GmbH [15], while the electrical cabinet (Fig. 11), battery, motors, sensors, and corresponding software development were handled by KIT-TMB.

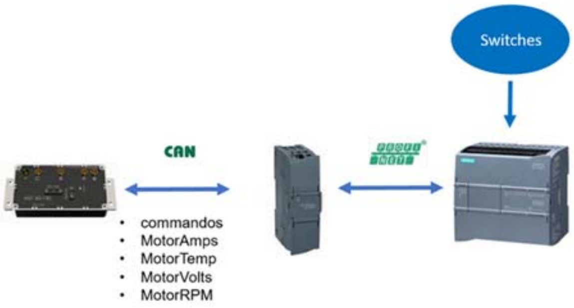


Fig. 11. Integrated electronics on milling tool [16-18].

The milling tool is equipped with 2 degrees of freedom, facilitated by two motors. The first motor, with a power of 2.2 kW, drives the milling head and executes the cutting process. The second motor, with a power of 0.4 kW, is responsible for the lateral motion of the milling head.

Four digital switches are mounted at the front of the machine. Once the milling tool makes contact with the surface, all four switches are activated, and the machine begins operation. This mechanism is primarily for safety and to reduce power consumption, preventing the tool from operating when it is not in contact with the surface.

Additionally, two sensors are mounted on the sides of the milling tool. When the milling head reaches the end of its trajectory, these sensors are activated, prompting the lateral motion of the milling head to shift in the opposite direction.

To control the lateral velocity of the milling head and ensure optimal milling performance, a current sensor is installed to measure the current of the milling motor. When the motor's current is low (i.e., during free-run operation), the lateral velocity is high, indicating that there is little to no resistance and the head is not cutting material. If the current remains low, the tool will stop cutting.

Conversely, when the milling motor's current increases, the lateral velocity decreases. This increase in current indicates that the milling head is encountering material to cut, leading to higher torque and a reduction in lateral speed to optimize the cutting process.

The milling tool is equipped with a Siemens CPU, which communicates with the motor controllers via CAN protocol using a Profinet/CAN gateway. The entire milling tool is powered by a 48 V, 120 ampere-hour battery.

Communication between the milling tool and the DekontBot is established through UDP and TCP protocols. This integration allows the milling tool to be monitored and controlled via the GUI. Sensor data, such as motor speed, motor currents, and battery voltage, is transmitted via UDP, while commands such as Release or Stop are sent using TCP.

Additionally, the milling tool is equipped with a suction unit for efficient dust and debris collection during the milling process.

Fig. 12 shows the milling result of the tool on a concrete wall.

Fig. 12. Milling result.

4.2. Contamination Array

To achieve the step of autonomous clearance measurement, a robot-portable, battery-operated tool known as the ‘contamination array’ was developed at KIT-TMB.

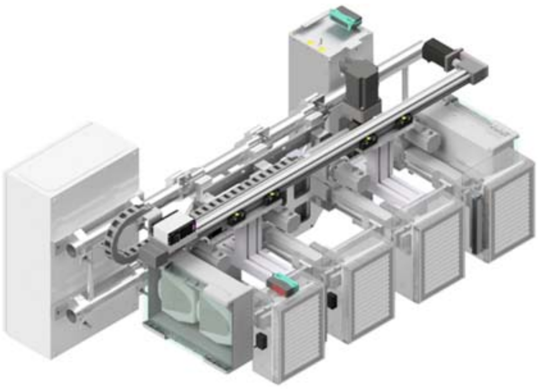


Fig. 13. The structure of the contamination array.

As shown in Fig. 13, the contamination array consists of four contamination detectors mounted in parallel. It is crucial to prevent the detectors from making contact with surfaces, as this could damage them or cause them to become self-contaminated, leading to inaccurate measurements.

To address this, the first step in the measurement process involves scanning the surfaces using a laser scanner mounted on a linear drive to detect any obstacles. Fig. 14 illustrates the scanning area and the scan profile.

Using this information, each contamination detector will be positioned accurately using separate linear drives. This ensures that the detectors not only measure surface activity from a pre-defined distance but also avoid collisions with detected obstacles. Once the detectors are properly positioned, the radiological measurements will begin, lasting approximately 10 seconds.

In the next step, the entire system will move sideways to cover the areas between the four contamination detectors, as shown in Fig. 13, and to position the detectors in areas between any obstacles.

Additionally, external laser distance sensors are mounted on the tool to measure the positions of the machine within its own coordinate system. The final output of the contamination array will be a digital documentation file containing all necessary information, such as radiological measurements, positions, time, and date.

Similar to the DekontBot, a GUI has also been developed for the contamination array, as illustrated in Fig. 15.

Using this GUI, the user can start or stop the measurements, monitor the radiological measurement values, track the positions, and view the scan profile of the surfaces.

Additionally, users can initiate zero-effect measurements to assess background radiation for calibrating the detectors. Similar to the milling tool, the system also includes an interface to transfer information between the contamination array and the DekontBot.

5. Results and Further Developments

The mechanical and electrical expansion of the DekontBot and its two tool has been successfully completed, and the platform is now fully operational for teleoperation. All degrees of freedom of the original platform are controllable through the integrated electronic components. The required system operation values are measurable via selected sensors, and the platform's safety hardware is fully integrated.

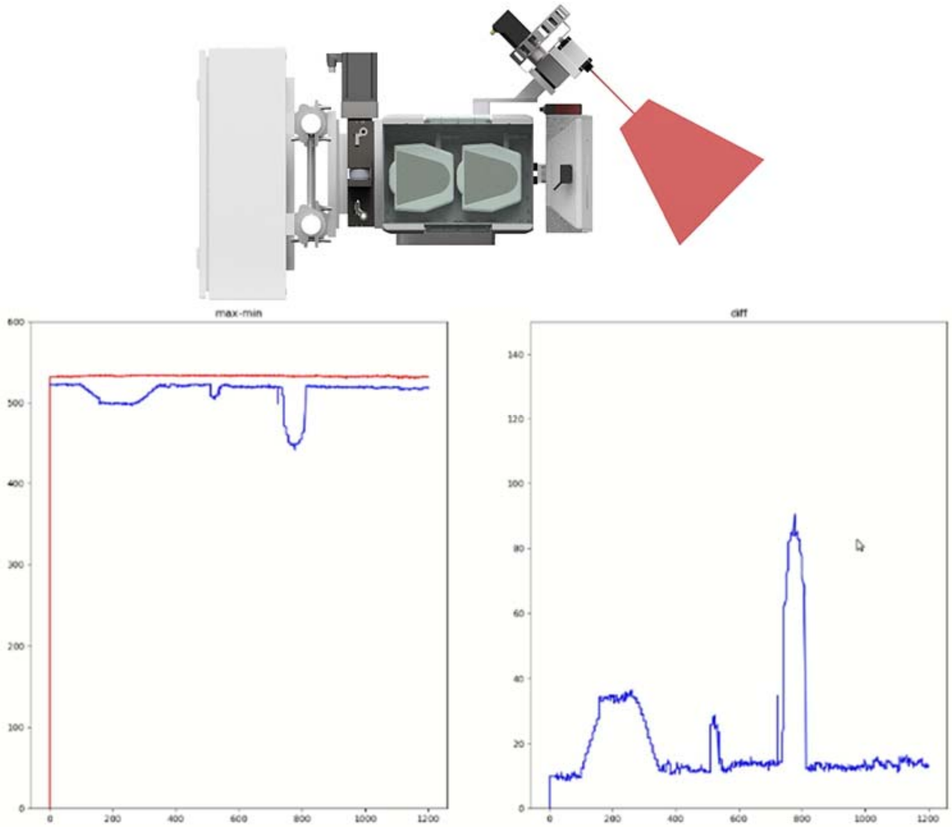


Fig. 14. Scanning area and the scan profile.

Kontamat 1 [µSv]: 0.144
Kontamat 2 [µSv]: 0.207
Kontamat 3 [µSv]: 0.23
Kontamat 4 [µSv]: 0.095
Laser 1 [mm]:
Laser 2 [mm]:
Laser 3 [mm]:
Laser 4 [mm]:
Laser 5 [mm]:
Laser 6 [mm]:

Pos-Kontamat 1 [mm]: 50.0
Pos-Kontamat 2 [mm]: 50.0
Pos-Kontamat 3 [mm]: 50.0
Pos-Kontamat 4 [mm]: 50.0
Pos-LaserScaner [mm]: 1199.96
Pos-Array [mm]: 0
Null1 [cps]:0.31 Null2 [cps]:0.53 Null3 [cps]:0.36 Null4 [cps]:0.5

Fig. 15. GUI of contamination array.

With the developed GUI and visualization tools, the systems can be operated without prior knowledge of robotics or programming, making it highly user-friendly for its intended users.

The next phase involves integrating path planning and control algorithms to automate the systems further. Additionally, to ensure more precise tool positioning, particularly for the decontamination and clearance measurement of inclined walls, floors, and ceilings, further degrees of freedom will be added to the end effector, as shown in Fig. 16.

To achieve this, an additional joint will be designed and built at KIT-TMB, enabling both end-effectors to rotate ±90° around their axis. Two parallel-mounted analog laser distance sensors will be used to measure the inclination of the surfaces. The 0.24 kW motor will be controlled via a motor controller, which will be connected to the central PLC using the CANOpen protocol.

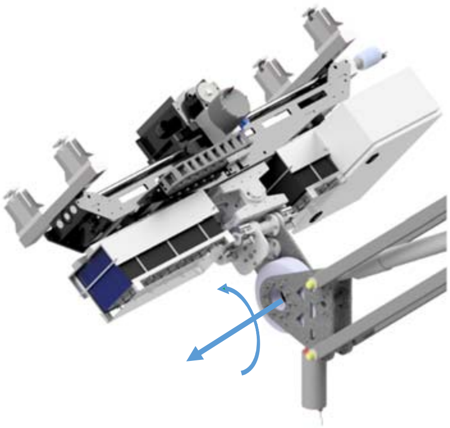


Fig. 16. Swivel module for expanding the degrees of freedom of the end effector.

The safety system also requires enhancements to meet the TÜV (Technical Inspection Association) testing and verification standards. Additional optimizations are necessary, such as improving the quality of point clouds, refining details in the URDF model, and ensuring robust communication between the DekontBot and the control center. These improvements will ensure that the DekontBot and its tools are fully prepared for initial testing within a nuclear facility.

6. Conclusions

It has been demonstrated that automation and robot-based solutions hold significant potential in the decontamination processes of nuclear facilities. These solutions not only alleviate the physical burden on personnel, who typically carry heavy tools and wear uncomfortable protective suits, but also significantly reduce the radiation exposure to their bodies and minimize the generation of secondary waste.

As a result, the DekontBot and its two end-effectors were developed specifically for decontamination and clearance measurement of concrete walls in nuclear power plants. In collaboration with partners like Karlsruhe University of Applied Sciences and Götting, who are developing the GammaBot and the automated forklift, the automated decontamination chain will soon be completed and made available to users.

With the integration of this automated chain, the effort and associated risks of these tasks can be substantially reduced. There is considerable interest from operators of nuclear power plants in adopting autonomous solutions or robotic systems for decontamination operations.

Furthermore, the DekontBot can also serve as a tool carrier for a variety of tools weighing up to 270 kg. After discussions with relevant personnel, it was determined that one potential application for the DekontBot would be in conventional decontamination work (non-nuclear), such as chemical decontamination removal.

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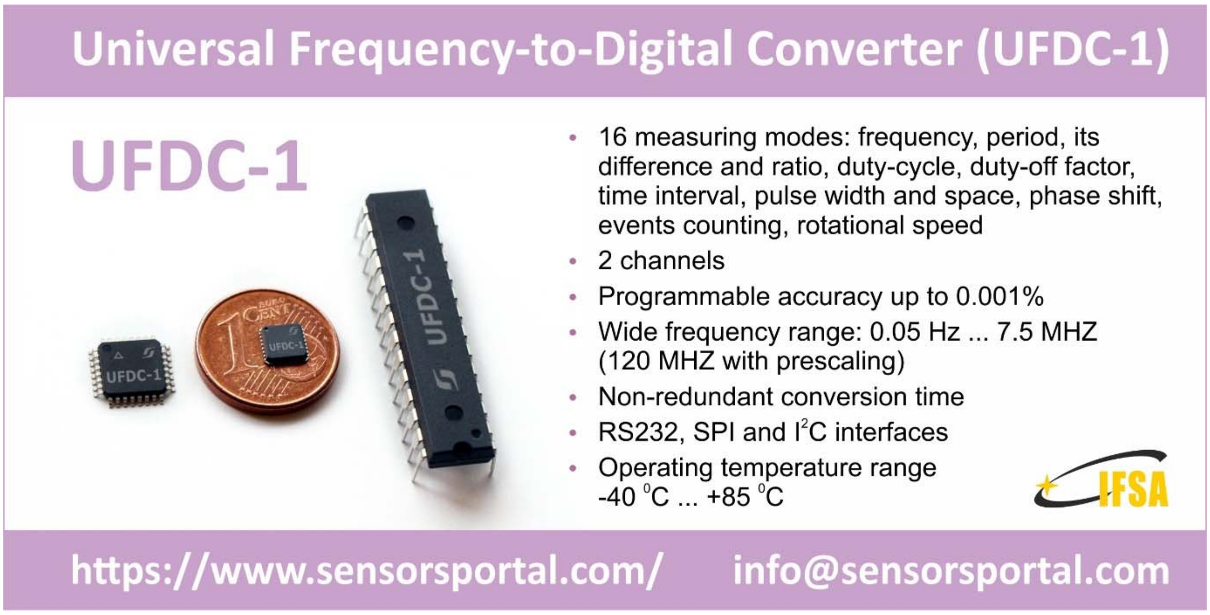

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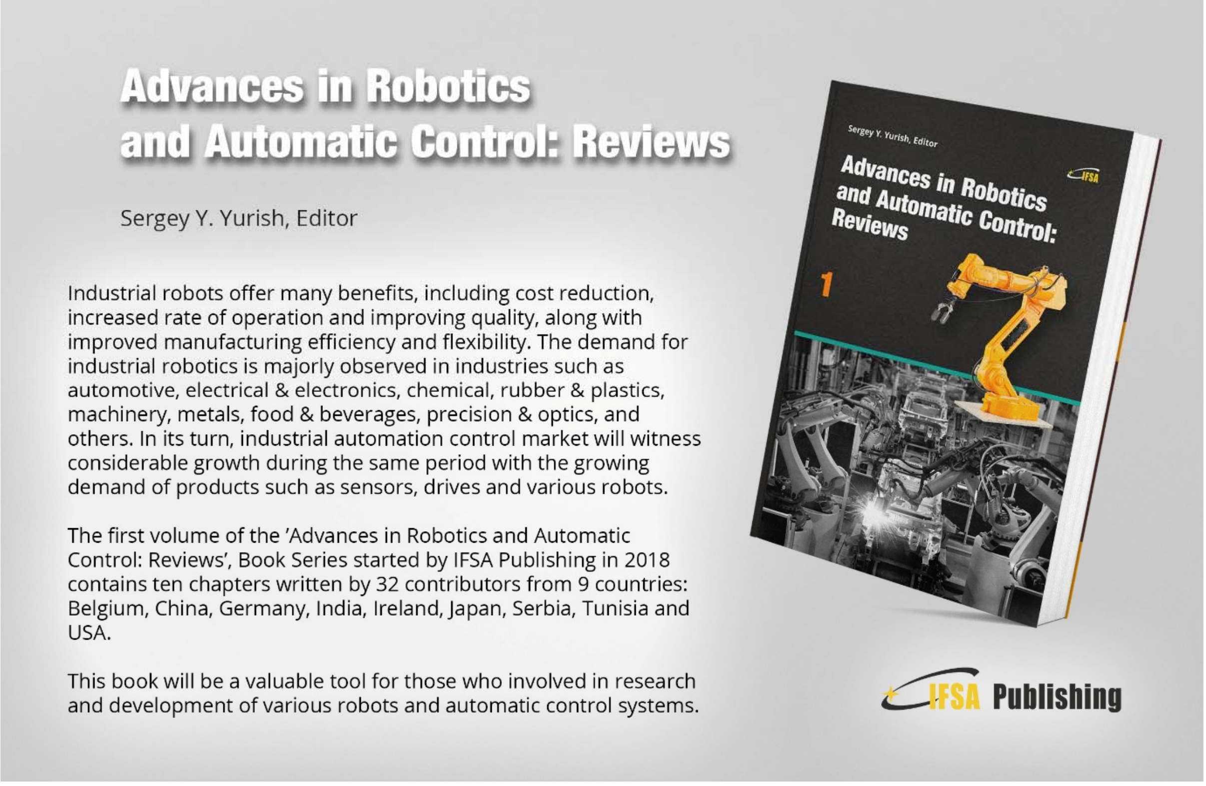

Advances in Robotics and Automatic Control: Reviews

Sergey Y. Yurish, Editor

Industrial robots offer many benefits, including cost reduction, increased rate of operation and improving quality, along with improved manufacturing efficiency and flexibility. The demand for industrial robotics is majorly observed in industries such as automotive, electrical & electronics, chemical, rubber & plastics, machinery, metals, food & beverages, precision & optics, and others. In its turn, industrial automation control market will witness considerable growth during the same period with the growing demand of products such as sensors, drives and various robots.

The first volume of the 'Advances in Robotics and Automatic Control: Reviews', Book Series started by IFSA Publishing in 2018 contains ten chapters written by 32 contributors from 9 countries: Belgium, China, Germany, India, Ireland, Japan, Serbia, Tunisia and USA.

This book will be a valuable tool for those who involved in research and development of various robots and automatic control systems.

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