Telerobotic Radiation Protection Tasks in the Super Proton Synchrotron using Mobile Robots

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Abstract: In this paper a complete robotic solution is presented, which allows the teleoperation of the radiation survey in the Super Proton Synchrotron (SPS) accelerator at CERN. Firstly, an introduction to radiation protection is given. Subsequently, the execution of the radiation survey in person is described and the potential of robotic solutions for such missions is outlined. After providing a brief state of the art on the subject, the development of the robot base, as well as its component selection and design is shown. Hereafter, the software implementation is explained. The test procedure of this project includes the most important requirements for a correct execution of the survey, as well as the operational steps and data treatment in detail. The results underline the correct execution of the mission, and show the advantages of the teleoperated robotic solution, such as the improved and unified measurement conditions. Thus, this robotic system will allow to significantly reduce the radiation dose of the radiation protection staff. For further development, the automation of this task is planned, which presupposes the gradual autonomization of the robotic system from assisting the user to the self-reliant execution of the survey.

1 INTRODUCTION

1.1 On the Importance of Radiation Protection at CERN

CERN operates the world's largest accelerator complex to provide high energy particle beams to a worldwide community of physicists who are studying the basic constituents of matter. To this end, researchers investigate the products of collisions between high energy particles with the help of sophisticated particle detectors and analysis software. CERN's accelerator complex straddles the French-Swiss border near Geneva. The so-called injectors (LINAC4, Proton Synchrotron (PS) and Super Proton Synchrotron (SPS)) of the Large Hadron Collider (LHC) and the LHC itself successively accelerate the particles to increasingly higher energy. Finally, the two LHC proton beams are brought into collision at the so-called collision points of the four LHC experiments (ATLAS, CMS, LHC-b and ALICE) with a center of mass energy of 14 TeV (CERN, 2022).

The operation of accelerators is inevitably related to the loss of beam particles, either intentionally e.g. through collimation, dumping or collisions or accidentally by degraded beam transmission. The "lost" particles interact with other particles (collisions) or matter. Radioactive isotopes are created by various nuclear processes and in function of type and energy of the "lost" particle and the chemical properties of the matter. As a consequence, the accelerator and detector components, tunnel structure, liquids like water and gases like air become radioactive. The gamma and beta radiation fields caused by the radioactive decay of the induced radioactive isotopes ("residual radiation") represent the major source for radiation exposure of workers to ionising during repair and maintenance of the accelerators and detectors. The primary objective of Radiation Protection (RP) at CERN centers on minimizing the exposure of individuals to ionizing radiation. Furthermore, the reduction of the radiological impact on the surrounding environment is assigned an overriding role (Forkel-Wirth et al., 2013). The main principles of radiation protection

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legislation have been defined in Recommendation 60 published by the International Commission on Radiological Protection (ICRP, 1991). They are described as follows:

- Justification of the practice: Any practice involving the exposure of persons to ionizing radiation requires justification.
- Optimization of protection: Procedures that result in radiation exposure of individuals must be subject to a continuous optimization process to reduce the radiation doses received by the affected persons. In addition, the ALARA principle applies, according to which personal and collective doses must always be kept as low as reasonably achievable.
- Dose limits: The legal limits regarding personal radiation doses must be respected.

These recommendations have been fully integrated into CERN's radiation safety code (CERN, 2006).

1.2 The Radiation Protection Survey in the Super Proton Synchrotron (SPS)

Radiation surveys of CERN accelerators are a long-standing practice and part of CERN's approach to ALARA. Their purpose is twofold:

1. Measuring the radiation dose rate along the accelerator for a radiological risk assessment and input for the organisation and dose planning of repair and maintenance work.
2. Supporting beam-operation in its search for locations of beam-losses and optimization of transmission.

Radiation surveys in the SPS accelerator have been performed by CERN personnel (Kershaw et al., 2013). A radiation protection technician in an electrical vehicle drives along the 7 km circumference of the accelerator. The dose rate is continuously measured with a radiation detector from about 70 cm distance from the machine components and at the height of the beam axis. Such a survey results in approximately 20,000 data points. This general survey is refined by a more detailed survey of the six Long Straight Sections (LSS) of the tunnel by radiation protection technicians walking along the accelerator. They measure the dose rates at 40 cm distance and on contact of the accelerator components. After visualizing the data, the results of the general survey are used as an indicator of locations of increased radiation levels and for information of the operational team on the development of beam loss points whereas the data of the detailed survey are used for job and dose planning. Typical results can be seen in Figure 1 (D. Forkel-Wirth, M. Silari (Editors), 2010).

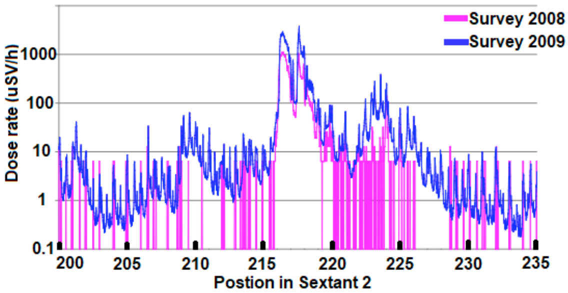

Figure 1: Radiation survey results 2008/09 realised in sector 2 of the SPS.

1.3 Opportunities and Challenges of Mobile Robotic Solutions for Inspection at CERN

Figure 2: Train Inspection Monorail (TIM).

Regarding the potential of robotic solutions for inspection it must be stated that CERN has been exploiting robots for a long time – in the beginning mainly for handling highly radioactive components like the ISOLDE targets (Catherall et al., 2017). A new type of robot had been successfully developed for the LHC, the multi-functional Train-Inspection-Monorail (TIM) shown in Figure 2 (Alessandro Masi, 2017). As the name indicates, it combines an electrical train with a monorail that already existed in the Large-Electron-Positron (LEP) Collider, the accelerator that was preceding the LHC. TIM is regularly used for visual inspections in the LHC accelerator tunnel, functional tests of the 3,600 beam-loss-monitors and radiation surveys. In the latter case, TIM performs both the general and the detailed radiation survey (Castro et al., 2018). These functions allow a considerable reduction of accelerator down-time as the tasks can start immediately after beam stop, and limits the needs of personnel carrying out this task.

TIM shows the advantages of robotic solutions, being a very versatile and promising tool for various types of inspections in radioactive environments. Robotic solutions contribute to the overall objective of optimizing inspection and maintenance tasks in the accelerator complex, both in view of radiation protection of workers and the overall efficiency increase of beam operation.

2 STATE OF THE ART ON TELEOPERATED ROBOTIC INSPECTION SYSTEMS IN HAZARDOUS ENVIRONMENTS

Complex scenarios such as accelerators, underwater facilities and nuclear plants require a high degree of knowledge in order to be able to inspect and also interact with the environment safely (Veiga Almagro et al., 2020). Sometimes the necessary knowledge to inspect a scientific facility such as the ones at CERN is not only present in a single person, so the use of a telerobotic system is mandatory (Lunghi et al., 2019).

In fact, the situation becomes even more critical when the communication channel is constrained, a challenge that can be partly mitigated by giving more intelligence to the robot, so that the operator interacts in a more supervised way, while reducing the need of communication bandwidth. This is the case of underwater robots which, once submerged, can maintain the communication link via Visual Light Communication and Radio Frequency modems at short distances, and sonar at long distances, being necessary to adjust the level of autonomy accordingly (Rubino et al., 2017).

In these kind of hazardous environments it is necessary and convenient to perform a pre-inspection of the environment, before deciding the next steps in order to perform, for example, maintenance operations. The most recent research experiments performed in this field involve the use of multiple robots, being able to cooperate in order to recover, and transport big objects (Pi et al., 2021).

A significant state of the art on teleoperated robots for exploration and inspection is also represented by the latest developments of the lunar rover as part of the YUTU-2 mission. In February 2022, several small intact spheres of translucent glass were discovered and inspected. This glass can contain information about the moon's history, including the composition of the lunar mantle and impacts (Michelle Starr, 2022).

Another indispensable application of telerobotic systems involves radioactive environments. Robots are increasingly taking over tasks at nuclear plants to simplify inspection procedures or reduce the radiation exposure of the personnel. One example is the LAROB underwater robot, which can remotely inspect reactor vessels in nuclear power plants under laser guidance. LAROB contributes to carrying out the mandatory inspections more efficiently, while reducing the operator's workload. As a result, the system has the potential to drastically reduce the critical path of reactor vessel inspection (Kim et al., 2014).

3 A MOBILE ROBOTIC SOLUTION FOR RADIATION PROTECTION OPERATIONS

3.1 Hardware

3.1.1 Omnidirectional Robot Base

For the SPS radiation survey, a new robot has been designed at CERN. An omnidirectional base was chosen, using four mecanum wheels located in parallel (Prados Sesmero et al., 2021). The omnidirectional behavior of the platform is created by the passive rollers attached to each wheel. The movement of these in combination with the rotary motion of the four wheels results in a force transfer in another direction, in such a way that sideways and diagonal movements, as well as rotations around the center of the base, are made possible. The rubber rollers are protected by the wheel frame. Depending on the ground conditions, a different movement behavior can be observed. Especially on smooth or slippery surfaces, a slippage of the wheels and the rollers can occur, which results in a misalignment in any direction (Park et al., 2010).

The frame structure and arrangement of the mecanum wheels in the longitudinal direction at the bottom corners of the frame provides several advantages. First of all, the design is simplified, offers sufficient and equal space for motor mounting and allows the connection of these motor sets centrally within the frame. Moreover, this structure is compact and allows all required sensors and other hardware to be housed within the frame, so that only the wheels extend from the frame. This offers significant advantages in maneuverability when traversing narrow passages or limited spaces. Another benefit is the redundancy of the system. Thus, even in the event of a motor failure, it is still possible to complete the robot's tasks through controlling the three remaining wheels. In addition, adjustment and correction algorithms in the kinematic model can compensate for such an error.

However, this locomotion arrangement presents some disadvantages that need to be considered: The aforementioned slippage of the mecanum wheels results in a positioning error that can falsify the odometry. It is therefore crucial that the localization of the robot is not based on the motor encoder values alone, but rather supported by additional sensors such as cameras (visual odometry), LiDAR's (LiDAR odometry) or IMU's. Another disadvantage concerns the energy efficiency of the wheels, that is significantly lower than of conventional ones, which translates into increased battery consumption. This can be compensated for by sufficient battery planning, as well as a reduction in the maximum speed, which must be applied in any case due to the safety regulations within the tunnel system of the accelerator complex.

3.1.2 Sensor and Component Selection

The following devices were selected for equipping the omndirectional base (Prados Sesmero et al., 2021):

- 3 cameras (Axis F44 main unit / F1035-E sensor units) providing a high definition camera stream for teleoperation
- an inertial measurement unit (VMU931), contributing to the localization accuracy of the robot base
- a radiation sensor (Atomtex BDKG24) to measure the radiation dose rate
- a 4G LTE Wi-Fi router (Teltonika RUT240) allowing external access over a client in a different network, as well as local communication for testing
- a robot arm that moves the radiation sensor into the optimal measurement position and also permits a detailed visual inspection with the attached gripper camera. The Kinova® Jaco 2 is used.

Moreover, the robot features a small form factor PC for the execution of all processes. The cameras, as well as the Kinova® robot arm, are connected to the network interface of the PC via an Ethernet hub.

3.1.3 Mechanical Design

The main structure of the mechanical design is characterized by the use of aluminum profiles. These give the system robustness and rigidity. Furthermore they guarantee the protection of the internal components.

The main characteristics of the design are the following:

- Four lead acid batteries, placed on the sides. The capacity of these are 15 Ah, which guarantees about 4 hours of operation, depending on the velocity of the base as well as the robot arm usage
- A magnetic connector that facilitates the correct launch of the charging process
- Four possible localization for cameras or LiDAR's behind the wheels, placed where the field of view is sufficiently large
- A support for the radiation sensor attached to the end effector of the robotic arm

The main dimensions of 526 × 360 × 190 mm, were chosen to allow the passage of the robot through the cut-out gaps of the security doors that are separating the various accelerator sectors. The weight of the robot amounts to approximately 45 kg, including the robot arm and all necessary components. The reach of the mounted robot arm including the radiation sensor is approximately 1100 mm (Prados Sesmero et al., 2021). The robotic arm has been placed so that it can fold down below the height of the base to allow maneuverability in low-profile environments, such as the secure gate cut-out. The gripper camera serves as a visual guidance for the operator. Besides the radiation surveys, the combination of robot arm and camera allows a wide variety of additional teleoperation tasks. Visual inspection of accelerator components and infrastructure, leak repair, drilling, component replacement welding, as well as visual, variable checking (measuring oxygen concentration or temperature) and many more, can be performed by replacing the end effector tool. Figure 3 shows the fully equipped robot.

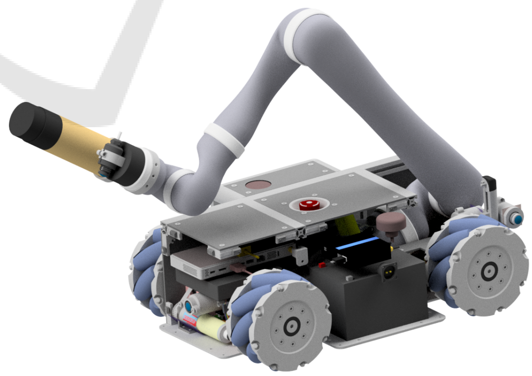

Figure 3: Cross-section of the omnidirectional robot base with Kinova® Jaco 2 robot arm.

3.2 Software Implementation

3.2.1 The CERN Robotic Framework (CRF)

The Cern Robotic Framework represents an innovative modular architecture for robotic inspection and telemanipulation in harsh and semi-structured environments (Di Castro et al., 2018). It covers all aspects of robotic interventions at CERN, from the specification and operator training, the choice of the robot and its material best suited for an environment with radiological hazards, to the realization of the intervention, including procedures and recovery scenarios. Thus, it can be described as a multidisciplinary toolbox that represents a complete in house software solution and is indispensable for the operation of ongoing interventions as well as the development of new robotic projects at CERN. Figure 4 shows the scope of this framework.

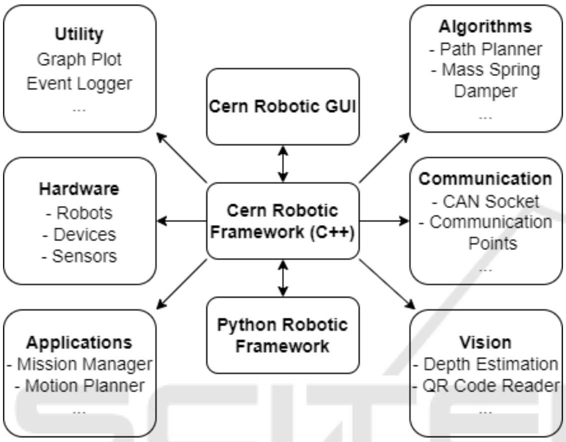

Figure 4: Modules of the Cern Robotic Framework (CRF).

3.2.2 Overall Architecture

The overall architecture of the robotic control system is shown in Figure 5.

At the top of the structure stands the Human Robot Interface, which allows the operator to take control of all necessary components of the robot, while being informed about the current status. In this case, the operator can control the robot base and robot arm independently via keyboard or controller input. For visual orientation, the four video streams of the cameras attached to the robot are displayed. In addition, the current radiation dose measured by the radiation sensor attached to the robot arm and the current velocity of the base are indicated. Using the local network connection, the client connects to a virtual private network to which the server in the robot is also connected. This allows a remote launch of the Robot Arm - and Robot Base Communication Point on the server PC. The communication points establish the connection between the Graphical User Interface and the robot. For this purpose, the Transmission Control Protocol (TCP) is used. The communication points start the control loops for the robot base and the robot arm and thus the mecanum wheels of the robot base

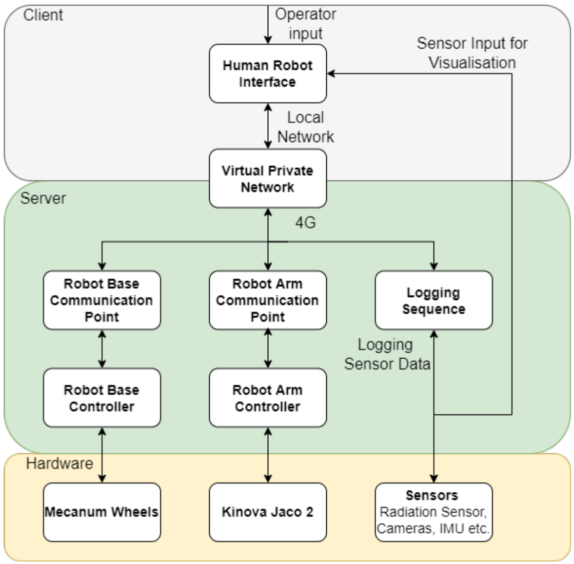

Figure 5: Overall architecture of the teleoperated robot for the robotic radiation survey.

and the joints of the Kinova® Jaco 2 can be teleoperated by the HRI on the client side. Furthermore, the logging sequence can be launched. It accesses the built-in odometry of the robot base, as well as the radiation sensor data. The collected data are subsequently stored locally on the robot's PC.

4 EXPERIMENTAL EVALUATION

4.1 Test Procedure

4.1.1 Preliminary Requirements

In order to carry out a successful radiation survey, several requirements need to be considered during the operation. Worth pointing out are the safety measures, such as the secured operation without human interaction, as well as the importance of protecting the equipment and machines in the tunnel from any damage that might be caused through robotic operation.

Considering this early test phase, it was therefore decided to start the operation after the regular working hours, and in consultation with the CERN Control Centre (CCC), which gave clearance to use the robot for a robotic intervention inside the tunnel of the SPS. Furthermore, two operators carried out the mission in order to guarantee a review of the execution steps and to gain a better overview of the overall situation. The maximum velocity of the robot during the survey was limited to 1.5 m/s. This measure ensured a safer operation by limiting the probability of potential crashes with structural elements or equipment in the tunnel of the SPS.

Since the aim of the robotic radiation survey, as in the manual survey, described in section 1.2 , is to measure the radiation dose rate along the SPS machine, it is therefore also necessary to comply with the requirements given by this inspection process. This includes respecting a maximum distance of 70 cm to the beam axis when taking the survey measurements. Furthermore, the operation time shall not exceed 2 hours, in order not to significantly disrupt maintenance activities in the SPS. An additional difference between the teleoperated execution of the survey compared to the existing procedure concerns the 19 security doors, which are normally opened manually by the personnel, but have to be passed with the robot through a cut-out rectangle measuring 30 cm x 40 cm.

4.1.2 Operation Steps

The mission starts by activating the robotic system. The charging is interrupted and the communication points of the robot base and the robot arm are launched. By using the CERN Robotic GUI, the robot is then moved out of the charging station, and the robot arm is brought into an upright position so that the radiation sensor is aligned with the beam axis. After this, the system is ready for operation. To start the survey, the closest security gate is approached to provide a precise localization point at the beginning of the data recording. The security gates are passed by folding the robot arm back in such a way that the arm is below the height of the robot base like shown in Figure 6. The camera on the end effector is used for guidance through the cut-out in the gate. Directly after passing the gate, the robot arm is brought back into the operation pose illustrated in Figure 7. The logging sequence for measuring the radiation dose is subsequently launched and the data is saved locally on the storage medium of the PC. The data set includes the measured radiation dose, as well as the odometry data of the motor encoders integrated in the mecanum wheels. In the following data analysis, this allows the mapping of the measured radiation value to its position in the SPS tunnel.

The measurements are always recorded from one safety gate to the next, resulting in a total of 19 data sets. The path between the start and end point is completed in one continuous run at a constant speed of 1.5 m/s. The maximum distance to the beam axis of 70 cm is maintained, using line markings as a reference during the operation through the gripper camera. Special attention has to be paid to the connection status between the robot and the 4G repeaters in the tunnel system of the SPS. By monitoring the ping development between client and server pc, conclusions can be drawn about connection problems before the complete loss of control occurs. If in exceptional cases there may be a temporary loss of control, the velocity of the robot is automatically set to 0. However, the robot base has no brakes, therefore the wheels will coast before coming to a complete stop. In addition, the ground conditions must be taken into account during teleoperation. As the floor is often inclined, counter steering is required in order to maintain a constant distance to the magnets. In addition, especially in the vicinity of the 6 access points, the operator must be aware of any cables, maintenance tools or other objects in the way and navigate around them. Once the 7 km circumference of the SPS tunnel has been covered and all 19 secure gates have been passed, the robot arm can now be brought back into the parking pose and the base will be driven into the charging station. Subsequently, the locally saved measurements are transferred to the client PC and the charging process is launched. In the most recent surveys, a total operation time of 1h 40’ - 1h 55’ was measured, and therefore, the limit of 2 h was respected.

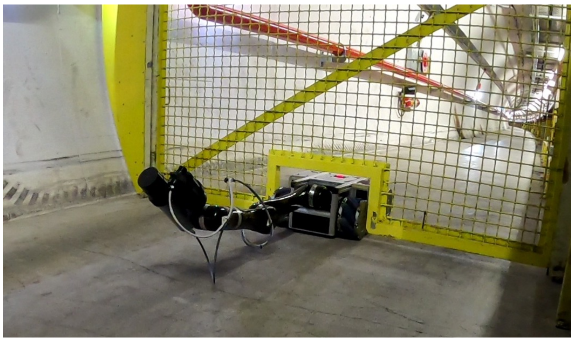

Figure 6: SPS robot passing one of the 19 secure doors.

Figure 7: SPS Robot taking radiation measurements.

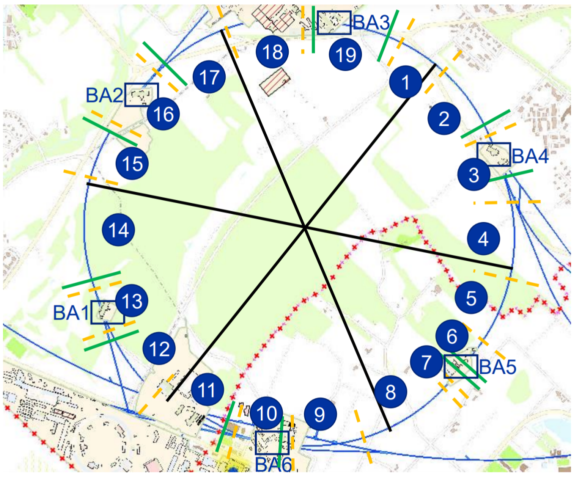

Figure 8: Data partitioning map of the SPS.

4.1.3 Data Treatment

The post processing of the data serves two main purposes for this survey. On the one hand, the mapping between the position of the measurement and the measured value must be carried out, including the correction of the positioning error, and on the other hand, modifications are made to optimize the visualization of the results. The odometry data of the robot base provides the distance travelled or the so-called "distance cumulée (DCUM)", which approximates the circumference of the SPS. As can be seen in Figure 8, the SPS is divided into 6 sextants. Within these 60° sectors, the unit of arc minutes is used for precise positioning. The dashed yellow elements along the circumference of the SPS represent the position of the secure gates. The 19 individual measurements are then merged into 6 sextant data sets.

The unit of the radiation measurements is micro Sievert per hour. In addition to these adjustments, the position error of the measurement is corrected. This is necessary due to the fact that mecanum wheels tend to slip during acceleration and deceleration, which means that the registered traveled distance is higher than the real value. However, since the exact location of the security doors is known, the position error can be subsequently compensated by homogeneously applying the absolute percentage error to the measured odometry in one segment run.

4.2 Results of the Robotic Radiation Protection Survey

In Figure 9 the results from the December 2021/January 2022 robotic RP surveys in Sextant 2 of the SPS are shown:

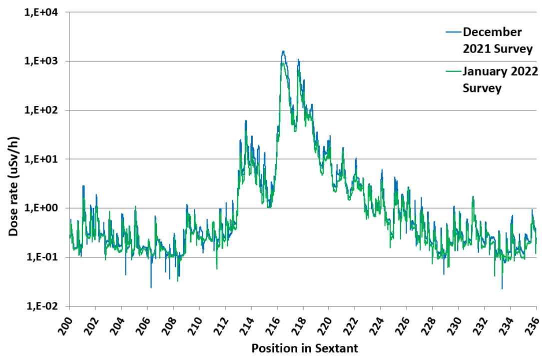

Figure 9: Robotic radiation survey results December 2021 / January 2021 realized in sector 2 of the SPS.

The graph has a clear similarity to the 2008/2009 survey presented in section 1.2 . The increased measuring frequency of the radiation sensor of 50 Hz results in an overall lower noise level. In direct comparison to Figure 1 , slightly higher radiation doses were recorded than in the manual procedure. The reason for this lies in the optimized positioning of the radiation sensor on the robot arm at the level of the beam axis, as well as a constant distance of the robot towards the magnets of the SPS. A total of approximately 500,000 data points were recorded in each of the two teleoperated surveys, which roughly corresponds to one measurement point every 14 mm.

5 CONCLUSION AND OUTLOOK

In summary, it can be concluded that a complete robotic solution has been developed, which allows the radiation survey to be carried out in a teleoperated manner. In particular, the absence of personnel in the tunnel of the SPS during the survey is the main advantage of this system. Consequently, the radiation dose of the staff, which carries out the survey in person under the current terms, can be saved. Moreover, the functional advantage of more precise measurements due to optimized conditions is also a significant advancement. The next major change is the construction of a second identical robot including an additional charging station. This change provides more flexibility in the execution of the survey. For instance, the operation time in the tunnel can be reduced to half if each robot covers 3 sextants and switches to the opposing charging station at the end of the operation.

The greatest potential of the project development lies in the gradual autonomization of the robot. Whereas at the current stage the operator's attention is indispensable for the execution of the task, the goal for the future development will be to increase the assistance level so that the operator's workload is progressively reduced until only potential intervention is required. The first step of gradual autonomization describes an assisted operation (Florian Petit, 2020). All repetitive tasks are performed automatically. In this case, the robot arm poses for achieving the parking position, operation pose or even the folding procedure as shown in Figure 6 will be performed autonomously. Furthermore, safety strategies concerning collisions or communication loss are being implemented. Level 2 describes an autopilot that is capable of independently performing certain tasks under optimal conditions. Applied to this project, this means the autonomous navigation of the start to the end point of the measurements, whereby more complicated processes, such as crossing security gates and navigating through environments with obstacles, will not be included yet. Therefore the operator is required to monitor the situation at all times. Level 3 describes a completely autonomous execution of all steps of the operation. The user is only informed in critical situations and is also given a buffer time to react appropriately to the situation. Thus, this stage of development would include all tasks of the survey, from mission preparation, measurement acquisition and security gate crossing to the successful completion of the survey and deactivation of the robot. In addition, security strategies will be developed to take effect in case of execution errors and will either correct the problem itself or give the user time to intervene.

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