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Adaptive Radiation Survey Using an Autonomous Robot Executing LiDAR Scans in the Large Hadron Collider

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Abstract. At CERN, radiation surveys of equipment and beam lines are important for safety and analysis throughout the accelerator complex. Radiation measurements are highly dependent on the distance between the sensor and the radiation source. If this distance can be accurately established, the measurements can be used to better understand the radiation levels of the components and can be used for calibration purposes. When surveys are undertaken by the Train Inspection Monorail (TIM) robot, the sensor is at a constant distance from the rail, which means that it is at a known distance and height from the centre of the beam line. However, the distance of the sensor to the closest surface of the beam line varies according to what kind of equipment is installed on the beam line at this point. Ideally, a robotic survey would be completed with online adaption of the sensor position according to the equipment present in the LHC. This new approach establishes a scan of the surface with a 2D LiDAR while moving along the tunnel axis in order to obtain a 3D scan of the environment. This 3D scan will be used to generate online trajectories that will allow the robot to accurately follow the beam line and thus measure the radiation levels.

Keywords: Hazardous environment · Autonomous inspection · LiDAR · Radiation

1 Introduction

CERN operates the world's largest accelerator complex, providing high energy particle beams to an international community of physicists. The 4 Large Hadron Collider (LHC) [8] experiments (ATLAS, CMS, LHC-b and ALICE) at the so-called collision points of the LHC proton beams offer researchers the opportunity

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to study the basic constituents of matter. Besides the injectors LINAC4, Proton Synchrotron (PS) and Super Proton Synchrotron (SPS), the 26.7 km long LHC represents the largest accelerator of the complex. Due to the planned dumping, collimation and collisions of the beam particles as well as accidental degraded beam transmission, a loss of beam particles occurs in the accelerators. These collide with other particles or matter, producing radioactive isotopes by various nuclear processes.

As a result, accelerator components, as well as liquids and air in the close environment can become radioactive. The largest source of radiation exposure of the personnel during maintenance and repair of the complex is residual radiation, which results from the radioactive decay of the induced radioactive isotopes [1]. The main objective of Radiation Protection (RP) at CERN focuses on minimizing the exposure of individuals to ionizing radiation. In addition, the reduction of the radiological impact on the surrounding environment is assigned a major role. The execution of radiation surveys of the accelerators are an essential part of CERN's ALARA (as low as reasonably achievable) approach. In the general survey, a continuous radiation measurement is carried out in the sectors of the LHC. This has two main purposes:

1. Establishment of a radiological risk assessment and dose planning for all works carried out by CERN personnel in the accelerator complex.
2. Identification of beam-loss locations and optimization of transmission.

General radiation surveys in the sectors of the LHC have historically been performed by RP personnel after a short cool down period of the machine after a beam stop. They measure the radiation dose throughout the LHC on foot or by bike. Based on this procedure, radiation levels were measured at non constant distance from the beam line and the clustered environment as well as non linear behavior of the radiation levels with respect to the distance, made it very difficult to derive accurate results. Thus, robots increase the efficiency of the operation by offering a precise and repeatable survey with respect to the sensor distance from the beam line. Furthermore, the overall downtime of the accelerator can be decreased not only by faster measurements but also due to the reason that a robot can start the scan immediately after a beam stop. Most importantly though, robots can reduce the radiation dose of personnel. In the LHC, a robotic system specialized in inspection and measurement called the Train Inspection Monorail (TIM) has been developed and installed on a ceiling mounted monorail. The main purpose of this robot consists of the functional test of Beam Loss Monitors (BLM), the visual inspections, and the execution of the general radiation survey [2,3].

TIM represents a multi-functional and efficiency-enhancing tool to perform inspections and radiation measurements in an hazardous environment. By attaching a radiation sensor to the end-effector of the robot arm present on a TIM wagon, a radiation scan can be achieved under a standardized measurement condition and timing. This paper presents the system to perform a full robotic radiation scan of the LHC, with adaptive trajectories that optimize the positional measurements of radiation along the beam line. In Fig. 1 the cross section of the LHC tunnel including TIM is shown.

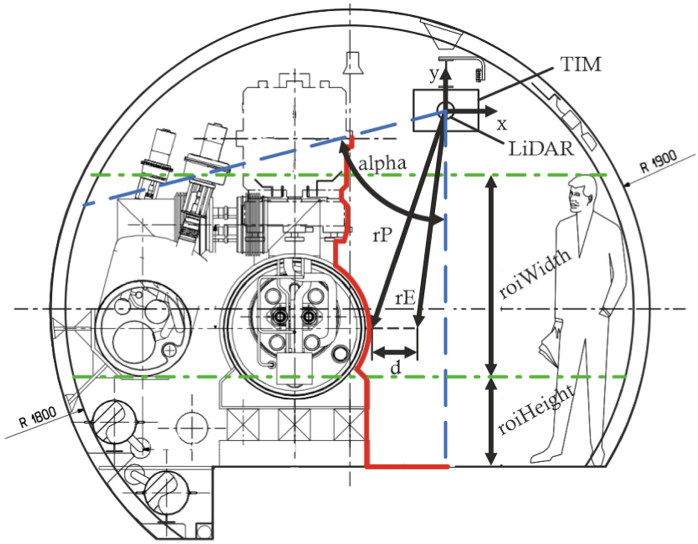

Fig. 1. Cross section of the LHC tunnel with TIM, see also [8].

2 Methodology

Currently, when TIM performs a survey, the radiation sensor is fixed with respect to the rail. Thereby, the distance between the sensor and the beam line central axis can be calculated at every point of the tunnel. However, the distance between the sensor and the closest surface of the beam line varies according to which kind of equipment is installed on the beam line. This variation is not currently taken into account by the robotic system. Future scans should instead vary the position of the sensor in order to stay at a constant distance from the closest surface of the beam line equipment.

This problem can be approached in a number of ways. As the beam line equipment installation points are pre-known, an offline trajectory can be generated from a Look-Up table. This method would be a robust solution in an ideal scenario where the position of the robot in the LHC is perfectly known. Furthermore this intervention is conducted in a semi-structured environment and hence not all obstacles (e.g. ladders, maintenance equipment or cable, etc.) are known a-priori, see Fig. 2.

Instead, an online trajectory can be computed based on feedback of the environment. The success and safety of this trajectory depends on the selection of adequate sensors to measure the environment, the robot arm state and an algorithm that can run in real time on the robot. This can be achieved through a set of different instruments such as radars, LiDARs, RGB-D cameras that are further described in Sect. 3. On the upper right in Fig. 1 TIM is visualized including the LiDAR that lies in the origin of the reference coordinate system with axes x and y. The dashed blue lines indicate the range ($alpha = 75°$) in which the LiDAR records data. The red line visualizes the recorded data representing

Fig. 2. The TIM robot in the LHC (left), the robotic wagon when the arm is deployed (middle) and obstacles that may not be modeled (right).

the profile of the installation in the tunnel and the dashed green lines indicate the Region of Interest (ROI) with the hight $roiHeight$ and width $roiWidth$. The vector $\mathbf{rP}$ represents the point of the installation profile with the highest x value, called Point of Interest (POI). The radiation sensor will be positioned at a distance $d = 400$ mm from the POI in direction x-axis, represented by $\mathbf{rE}$.

3 Robotic System

The TIM robot consists of multiple wagons, each responsible for different aspects of the system shown in Fig. 3. For the radiation survey, the robotic wagon, equipped with a robotic manipulator and gripper, is used. For complex trajectory generation, a wagon consisting of a custom 3 DOF rotation and translation stage that holds a commercial Kinova® Jaco 2 robot arm has been developed. This allows for a 9 DOF arm that has the workspace to reach the beam line with sufficient motion complexity to control the end effector pose in 3D space [7].

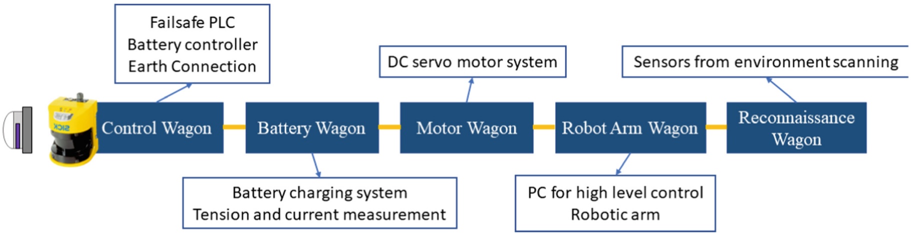

Fig. 3. Configuration of the TIM robot with the LiDAR at the front [2].

The robotic wagon is equipped with pan and tilt cameras, static cameras and RGB-D cameras. However to accurately measure the distance to the correct surface of the beam line from the radiation sensor, these cameras may not have the necessary resolution or range. For this reason, to image the beam line, a LiDAR has been used to map the environment. Through the uni-dimensional movement of the TIM base, a 3D scan of the environment can be achieved using a 2D LiDAR as in [5,6], placed in a vertical structure of the train perpendicular to the train movement as presented in Fig. 3.

The chosen LiDAR is a 360°C omnidirectional laser range scanner placed upstream of the robot arm, in a static position on the TIM. The robotic arm holds the radiation sensor, a dosimetric detection unit type BDKG24 from Atomtex® that measures gamma radiation in the range from 30 nSv/h–1 Sv/h with a measuring frequency 50 Hz at a baud rate of 19200 bps. To acquire and process the sensor information, an onboard PC is present, which also runs the control algorithms for the robotic arm on the wagon.

4 Data Acquisition and Processing

To test the feasibility of the described method, a scan of an LHC tunnel section was performed. The robotic platform was moving at a constant speed v_R while recording the raw data from the LiDAR scans.

The maximum speed of the robotic platform v_R depends on the LiDAR frequency and the maximum displacement of the LiDAR during one turn. Thus, the maximum train speed can be written as

$$v_{R,max} < d_{max} f_{LiDAR}, \tag{1}$$

with the maximum train speed $v_{R,max}$, the maximum LiDAR displacement per turn d_{max} and the LiDAR frequency f_{LiDAR}. For the feasibility test, the TIM ran a section of 3167 m at an average velocity of 1 m/s. Data was recorded every second. This results in approximately 3200 points of raw data, visually depicted in Fig. 4.

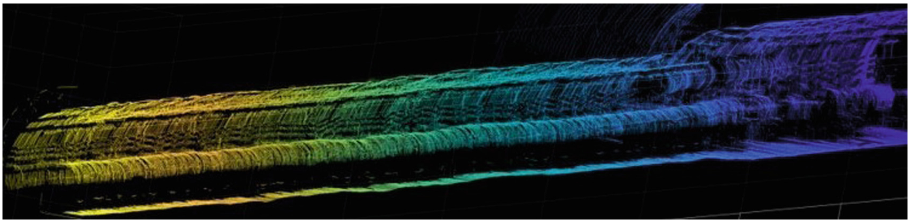

Fig. 4. Raw data of 100 m of the LHC tunnel.

After the raw data was recorded with the LiDAR, the data undergoes a linear and rotational transformation in order to compensate offsets due to the mechanical placement of the sensor. Then a next step of filtering removes the outliers present in the raw data. Outliers are points that exceed the known diameter of the tunnel. This is only possible if the LiDAR sensor is not exactly directed perpendicular to the tunnel walls. A rotation of the sensor can not be detected and thus the recorded points would suggest an increase in tunnel diameter, which is not the case in the whole complex. These outliers and all data points recorded during the same revolution of the LiDAR sensor will be removed. This ensures a reduction of noise even for the circular area with a diameter less then the tunnel diameter. Later, a gaussian filter is applied to reduce noise in the remaining data. In a final step, the data will be reduced to a set of points that lie in a Region of Interest (ROI), defined by a rectangle as shown in Fig. 5.

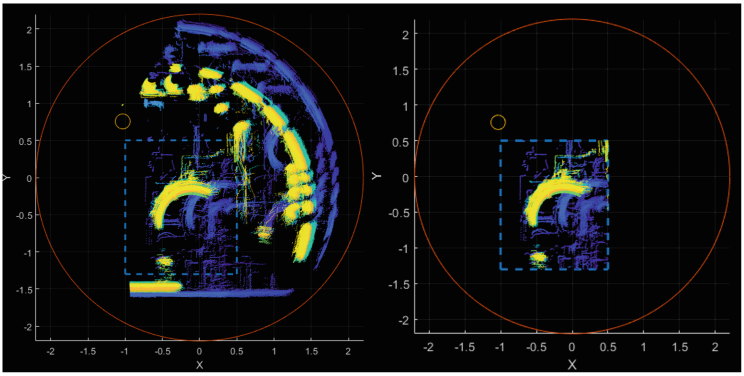

Fig. 5. Obtaining the ROI of the section. This process reduces computational cost and focuses on the necessary parts of the scan.

Once the ROI is obtained, the relevant control points for the trajectory are extracted. These must be 40 cm from the closest surface of the beam line, at the beam line height.

5 Online Trajectory Planning and Control

The data points identified in the ROI are split up along the beam line longitudinal axis in equidistant segments of length SL, see Fig. 6. Within each segment the point with the most significant impact to the radiation will be identified. Then, a smooth path, using a sinusoidal method, see [4,9], will be defined. This method creates a smooth response to a step input that is differentiable until the fourth derivative and thus ideal for mechanical system with gear elasticity. The maximum first derivative of the sinusoid path ν_S can be found considering two other constraints, the maximum end-effector velocity of the robotic arm v_E and the maximum speed of the robotic platform v_R, to ensure the trajectory can be achieved by the robotic system. This can be written in the form

$$\nu_S = \frac{v_E}{v_R}. \tag{2}$$

Considering all constraints it is now clear that the survey time per meter τ is a function of v_R, v_E and the segment length SL and thus can be written as

$$\tau = f(v_R, v_E, SL). \tag{3}$$

To follow a step of e.g. 0.7 m with an end-effector speed of 0.25 m/s, it was found that a train speed of 0.2 m/s was required, which is achievable with the robotic platform. The path according to the above mentioned parameters and constraints is visualized in Fig. 6.

The control algorithm to ensure that the arm accurately follows the generated trajectory is presented in Fig. 7. Since there is a time disparity between the

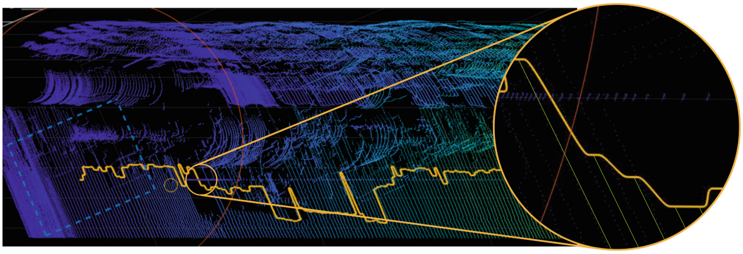

Fig. 6. Recorded online trajectory over 100 m. The green lines indicate the segments with length SL.

collection of the data and when it will be required by the arm, the block diagram is divided into 2 different frames: t and $t+k$, where k is the time for the train to move the arm to where the LiDAR recorded the data. The calculated trajectory is added to the execution list and carried out when the arm reaches the start of the trajectory. Previously executed trajectories are deleted.

The time k must be sufficient to allow the system to do the necessary calculations and extract the trajectory before arriving to the execution position. If the necessary time for the calculations is bigger than k, the results can be appended to the full trajectory. From here, they can be fetched when the train arrives to the exact position, and executed through the control loop.

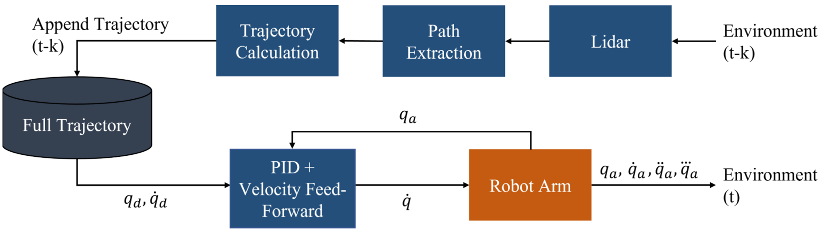

Fig. 7. Block diagram of the full control system.

The arm control loop is a velocity feed-forward [10] type. After the calculation of the trajectory in $t+k$, the system waits until t to execute it. The desired next point of the trajectory $(q_d, \dot{q_d}, \ddot{q_d})$ is extracted, and sent to the control loop to follow.

6 Conclusion

This paper presents the concept of a completely automated and adaptive system for robotic radiation surveys along the LHC tunnel. The rail guided system, combined with a six degree of freedom robotic arm, establishes a constant distance to the closest beam line surface, allowing for precise surveys to be conducted. The use of a 2D LiDAR on the robotic system can be meshed to create a 3D scan of the tunnel environment which is used to generate an online trajectory planner that adapts to changes in the semi structured environment of the LHC tunnel. The calculations for simple sinusoid path planners are feasible in the required control loop time frames using embedded PCs, and create smooth trajectories for the robotic arm.

The first simulations using recorded data from the LHC tunnel have shown great improvements in survey times, reliability and accuracy with respect to the real activation of installation material in the tunnel. Future proof of concept studies will review and validate these simulated results in the real environment using the TIM robot. The system can also be adapted to be used on ground based mobile robotic platforms for radiation surveys in other experiments at CERN where no monorail is installed. The orientation of the tangential plane on the POI will be taken into account in order to establish the optimal orientation of the radiation sensor. These systems will lead towards the creation of automatic, repeatable and precise radiation surveys across the full accelerator complex at CERN. Evaluation of the repeatability and accuracy of the positioning system as well as the resulting accuracy of the radiation measurements compared to non adaptive trajectories will be subject to future work.

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