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LHC TRAIN CONTROL SYSTEM FOR AUTONOMOUS INSPECTIONS AND MEASUREMENTS

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Abstract

Intelligent robotic systems are becoming essential for inspection and measurements in harsh environments, such as the European Organization for Nuclear Research (CERN) accelerators complex. Aiming at increasing safety and machine availability, robots can help to perform repetitive or dangerous tasks, reducing the risk for the personnel as the exposure to radiation. The Large Hadron Collider (LHC) tunnel at CERN has been equipped with fail-safe trains on monorail able to perform autonomously different missions as radiation survey, civil infrastructures monitoring through photogrammetry, fire detection as well as survey measurements of accelerator devices. In this paper, the entire control architecture and the design of the low-level control to fulfil the requirements and the challenges of the LHC tunnel are described. The train low-level control is based on a PLC controller that communicates with the surface via 4G through VPN, where a user-friendly graphical user interface allows the operation of the robot. The low-level controller includes a PLC fail-safe program to ensure the safety of the system. The results of the commissioning in the LHC are presented.

INTRODUCTION

Industrial as accelerators experimental areas have the needs of being remotely inspected by robots because of dangers for humans, time or space constraints.

Operating robots for maintenance in hazardous environments on often expensive machines requires skilled and well trained and dedicated shift operators. This is costly and highly time -consuming and is mainly caused by the not intuitive human robot interfaces present on industrial robots.

The European Organization for Nuclear Research (CERN) [1] is the world largest high-energy physics laboratory in the world. At CERN, there are more than 50 km of underground-unstructured accelerators areas with thousands of different items of equipment that need to be inspected and maintained. Due to the presence of human hazards, mainly produced by radiation and high magnetic fields, the accelerators equipment at CERN needs to be inspected and maintained remotely, possibly using robots.
CERN unstructured environments present also more constraints like accessibility, long distances, objects with various pose and occlusion in cluttered areas. These aspects require a safe robotic system that can travel long distances, possibly with a user-friendly human-robot interface (HRI) allowing its use by accelerators operators without a too specific training for use of robots.

Figure 1: TIM in the LHC.

The Large Hadron Collider (LHC) [2] at CERN, built in a 27 km long underground tunnel, is the most powerful machine in the world. It needs to be inspected during few days long technical stops, and machine shutdowns. There are several challenges in applying autonomous robotic systems in harsh and hazardous environment (Table 1), like the CERN accelerators complex. The control system of a robotic inspector must be designed to overcome these challenges in a safe way, as it is detailed in the following sections of this paper.

The LHC tunnel has been equipped with the fail-safe Train Inspection Monorail (TIM) (Figure 1) systems, able to perform autonomously different missions as visual inspections, radiation survey, civil infrastructures monitoring through photogrammetry, fire detection as well as survey measurements of accelerator devices as collimators [3] and superconducting magnets [4].

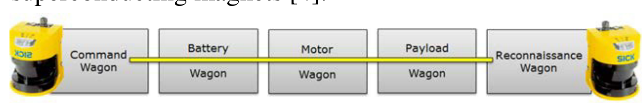

Figure 2: TIM train wagons composition.

TIM is a battery powered train composed by different wagons (Figure 2) and connected to a monorail linked to the ceiling all around the LHC tunnel structure. Thanks to its mechanical design, it can be adapted to different I-beam profiles used as monorail. Due to the dimensions of the LHC ventilation and sector doors, the cross section of TIM is limited to 30 x 30 cm (Figure 3). According to the mission' configuration different mechatronic systems (e.g. robotic arms) are deployed. Thanks to a precise on-board positioning system, when the train passes narrow areas, the autonomous fail-safe control automatically retracts all the deployed mechatronic systems into safe positions for avoiding collisions. Moreover, the train is equipped with

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different environmental sensors, like oxygen monitoring, temperature and radiation sensors. In addition, thermal cameras, 2D cameras and pan-tilt-zoom cameras on both ends guarantee a full visual inspection of the environment all around and below the train. Installed on both ends of the train, the control of SIL3 SICK [5] laser scanners, coupled with safety bumpers, guarantee collision free operation and adaptable speed in case of obstacle presence. In this paper, a novel fail-safe control system for autonomous inspection and measurements is presented. The system has been integrated on the TIM, its performance has been validated and it is currently in operation in the LHC. In the next sections, the control system architecture of the TIM inspectors of the LHC is presented.

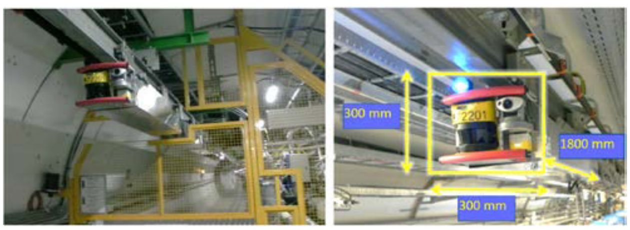

Figure 3: TIM in the LHC tunnel passing sector doors (left) and the dimensions of one wagon (right).

CONTROL ARCHITECTURE

The underground tunnel areas of the CERN accelerator complex require long times for inspection and maintenance. The human access to an accelerator tunnel, like the LHC, is restricted to programmed machine technical stops or long shutdowns.

A robotic system can perform inspections in shorter time with respect to humans, and avoiding the exposure of personnel to the hazards present in the accelerator tunnels. Even in the periods in which the access for personnel is forbidden, the robotic system can still be used for inspection and measurements if the machine has stopped its operation for a short time.

The TIM control architecture allows the robot to perform autonomous missions while the data can be monitored in real-time, and then autonomously come back to its safe position when the mission has finished.

The deployment of robotic systems in underground areas presents several challenges in terms of communication, big spaces and long distances, energy autonomy and poor light conditions. In addition to these, the CERN accelerator complex presents other specific challenges such as the expensive and delicate machine equipment, high magnetic fields and radiation.

Along with oxygen deficiency hazard that can be present in the LHC tunnel, these challenges make necessary to build a robotic system that is totally fail-safe and can recover automatically without the need of human intervention.

The main challenges in doing inspection and measurements in CERN's harsh environments are listed in Table 1, including the TIM feature designed specifically for each challenge.

Table 1: LHC Challenges for Robotic Inspection and TIM Features

Challenge	TIM feature
Limited intervention time (< 1 hour) in very long distances (km)	Multiple systems and high speeds.
Unexpected obstacles	Safety scanner systems integrated in the control
Precision localization during environmental measurement (<few cm)	Precise on board absolute positioning systems including detection of reference markers placed along the tunnel
Delicate equipment	Anti-collision systems and recovery scenarios
Permanent obstacles	On-board obstacle database, speed reduction, safe position of all payloads
Poor light conditions	Controllable lights on both ends of TIM
Big depth of field to be inspected	HD pan-tilt-zoom cameras on both ends of TIM
Loss of communication signal	Control through SMS, notifications/alarms via SMS
Robot autonomy	Energy management system, power rail and robotic charging arm system for battery charge all around the LHC tunnel whenever needed
High radiation or magnetic disturbance during LHC operation	TIM parked in a safe tunnel bypass during LHC operation, safe from radiation and magnetic disturbances

In order to overcome the challenges presented above, the robotic solution should be modular, reusable, safe and redundant. Furthermore, an autonomous system is of great advantage since it reduces man power needed to operate and increases the machine up-time.

This section presents the proposed control system architecture (Figure 4) of the Train Inspection Monorail, including the communication, the graphical user interfaces and the web data publication.

Control System Design

The TIM embedded autonomous control is based on a fail-safe PLC and on an industrial control for monitoring purposes. The communication of the fail-safe part is based on PROFISAFE [6] while the rest of the control is based on TCP/IP. The control system is designed in layers, in which the hardware abstraction layer (HAL) and the supervision layer are the main parts (Figure 5). These two control layers are then composed by different sub-layers guaranteeing modularity, reusability, and portability.

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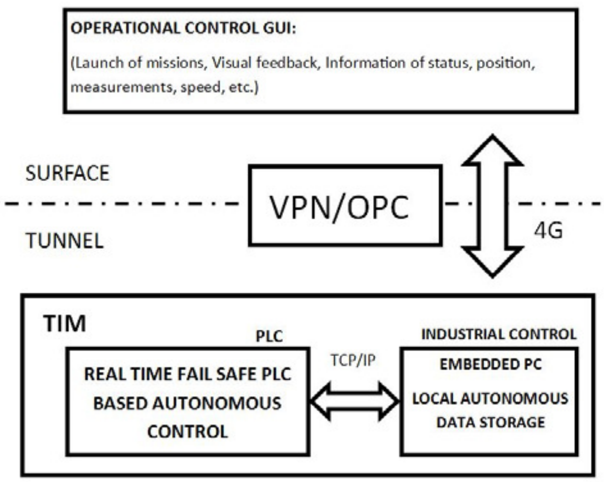

Figure 4: Overview of the control system with communication in between surface and tunnel.

The lowest sub-layer of the HAL contains the PLC and the Safety PLC inputs and outputs, where the system communicated directly with all sensors and actuators at the lowest level. Then, the hardware abstraction layer contains the low-level functionalities of the system, such as the positioning, motion, vision and communication. In the supervision layer, the managers are the functions in charge of the main functionalities. In the application framework layer, the autonomous missions, recovery scenarios and artificial intelligence form the highest level of the on-board control.

The interface with users and operators is done through the graphical user interface, the e-mail notification and the SMS control in case of emergency.

This architecture allows changes and additions in the very low level that will never affect the rest of the system.

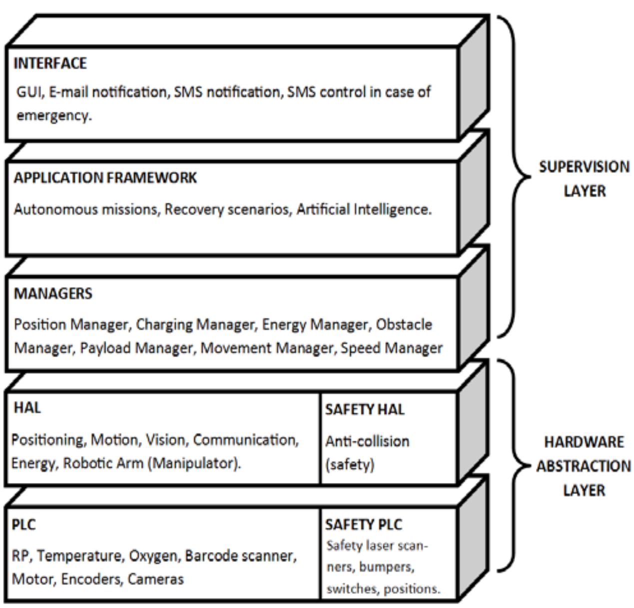

Figure 5: Control system design in layers.

All the data, obtained from a survey with one of the TIM trains, must be collected along with the time and their precise position in the order of the cm. For this, the localization of the robots in the LHC tunnel is fundamental.

Fail-safe System

The fail-safe system is guaranteed by different features, such as the safety program in LAD programming logic. The laser scanners are connected directly to the speed encoder and the PLC in order to regulate the velocity of the train in case of obstacles. Safety bumpers are also connected to the fail-safe PLC and included in the safety program. Different safety switches distributed along the train ensure that all mechatronic systems are in safe position in case of obstacles or during the passage through tunnel sector doors.

Odometry System in the LHC

The positioning system of the TIM trains consists of a positioning wheel connected to an incremental encoder, with which the increment in position (in mm) during movement is calculated by the PLC. Since this system can reduce its precision after few tens of kilometres because of friction and slippage in between the traction wheel and the monorail surface, the trains are featured with a position correction system. Every 100 meters, on the LHC monorail is installed a tags localization system. The tags are read from the trains through a barcode laser scanner, and converted into absolute position. Thanks to this correction system, the position precision of TIM in the whole 27 kilometres of the LHC tunnel is ±1 cm.

Speed Regulation

The fail-safe system provides information about the environment in case an obstacle or an unexpected object is detected in the way of the train. According to the distance at which the object has been seen by the safety scanners, the speed of the train is autonomously regulated and eventually reduced. In the case of the obstacle being too close to the train, the safety system stops train and retracts all mechatronic systems that may be deployed for measurement purposes.

After the area is cleared from obstacles in the field of view of the train, TIM is allowed to continue its movement. However, the speed is reduced until all wagons of the train have abandoned the critical area.

Variation of the Speed with Respect to Position

The very precise positioning system of TIM allows the possibility of mapping all the permanent known obstacles of the LHC. A database with all the obstacles positions and the recommended speeds, including if the mechatronic deployed systems must be retracted into safe position or not, is featured in the on-board PLC. When the train is approaching an area with known obstacles, the speed is regulated according to the speed stated in the database. This regulation assures that the train always sorts the known obstacles in a way that is safe both for itself and for the accelerator's equipment.

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Energy Management

TIM is a battery powered vehicle, so in order to improve its autonomy and reliability of operation, the energy stored in the battery must be used in the smartest possible way. The energy management of TIM is in charge of three main functions: computing an accurate State-of-Charge (SOC) estimation of the battery, estimating the amount of energy needed for completing a mission and optimizing the overall consumption of the train. The SOC algorithms of TIM are featured with power optimization models that takes into account not only the dynamics of the train motion, but also its mechanical frictions and contacts with the monorail.

The batteries of TIM were chosen taking into account the power needed to feed all the on-board electronic devices, which require a stable voltage within a determined range, as well as to ensure the longest possible operation duration. TIM is powered with two 12 V lead acid batteries mounted in series. The SOC represents the amount of energy remaining in the battery with respect to its rated capacity, expressed in percentage. A novel SOC estimator was designed specifically for TIM's energy management, based on the Current Integration Method [7] [8]. This method has the advantage to take into account the variation of the battery capacity according to the discharge current, which leads to an increased accuracy of the estimation. The SOC estimation method has been programmed and integrated on the TIM PLC and it runs in real time without the need to interrupt battery operation.

The amount of energy needed for completing a mission is calculated taking into account the length of the movement, the speed and the slope of the tunnel. A speed based optimization algorithm modulates the speed during the missions to increase the TIM autonomy. If the energy available in the batteries is not enough for performing the selected mission, the operator will be notified and TIM will wait for further instructions, such as the selection of a shorter mission or the command to start or continuing charging.

Payloads

The modular design of TIM and its control system architecture, makes possible to have different configurations of the robotic system. TIM can be equipped with several different payload wagons, according to the needs of the mission to perform, and its design allows new types of wagons to be easily added in the future without major changes to be implemented in the system.

The payloads already developed for TIM are listed below:

- Radio protection: this payload wagon includes a two-axis robotic arm that places a radiation probe at the beam height for measurements along the LHC machine.
- Tunnel structural monitoring: a photogrammetry system takes high definition pictures of the tunnel while TIM runs and compares current and previous images to detect tunnel degradation signs like walls cracks and deformations.
- Multi-axis robotic arm: a novel wagon designed for featuring one multi-axis robotic arm that can move in space using precise position control, placing sensors or cameras in a desired position with respect to the LHC equipment to inspect. In the future, these wagons could be used for tele-manipulation with single or multiple robotic arms.
- Collimator alignment survey: includes the sensors, cameras and mechatronic systems for detecting collimator misalignments in the LHC using photogrammetry.
- Fire extinguisher: payload wagon featuring a fire extinguisher and a robotic arm that can activate it in case of fire in the LHC, without the need of the fire brigade to intervene until the fire has been extinguished from TIM.
- Vacuum leak detection: a wagon equipped with a robotic arm that activates a nozzle connected to a helium bottle to flush helium on vacuum equipment searching for vacuum leaks.

Human Robot Interface

The Human Robot Interface (HRI) is used by operators from the surface, who can set up the type of operation or mission to perform and follow the progress and information live from the trains (Figure 6). Visual inspections are performed from the HRI's displays of all the on-board cameras. The user-friendly design of the HRI allows operators to make an intuitive use of the trains successfully after a very short training.

Figure 6: TIM Graphical User Interface.

The HRI communicates from the surface with the TIM trains in the tunnel through 4G or 3G. Even if most of the times the communication signal is stable, it can happen that in some areas of the tunnel the signal is lost for some moments. In case of emergency recovery and no communication, TIM can autonomous return to the garage position or be controlled from the surface through SMS to recover to a safe position and charge the battery. Operators can also choose to receive e-mail and SMS notifications about the status of the missions or the remaining energy in the battery, in case they are not constantly following the feedback from the HRI.

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Autonomous Missions

The intelligence of TIM is able to perform complete missions and safely recover to a garage position afterwards, without need of human intervention or teleoperation. The operator configures the mission by simply selecting the sectors to inspect, the type of mission and the option of recovery after it has finished inspecting.

TIM autonomously can move to the mission start position, deploys all mechatronic systems and sensors needed, and starts moving towards the end position while taking the measurement data. The operator can follow the mission at all times through the HRI's indicators and camera feedbacks, but does not need to intervene. Once the mission has finished, the data will be published on a website, and the operator and LHC equipment responsible will also receive the data from the mission attached to a certified e-mail.

Data Collection

The embedded industrial PC (IPC) is in charge of collecting all the data from the missions (Figure 7), save it in a certain format and publish it on the designated TIM website when the communication signal is stable enough.

While all sensors data is taken from the PLC, the PLC communicates with the IPC though Ethernet sharing all the data form the trains. The IPC's application starts saving data when a mission starts, and once it has finished it shares the data with the operators, both by e-mail and by publishing it on the website.

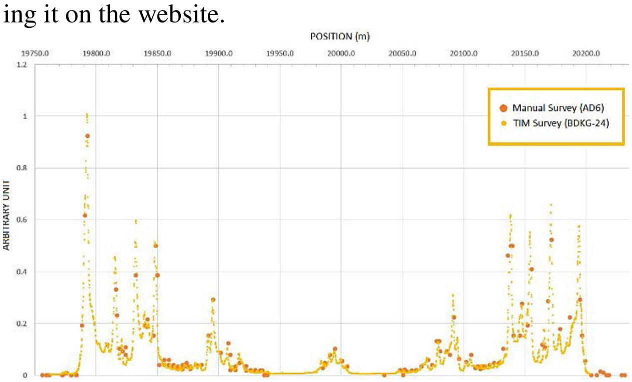

Figure 7: Example of radiation mapping of an LHC area.

Web Interface and Data Mining

In order to provide to the machine responsible a live view of the TIM operation a web interface has been created (Figure 8). This web interface collects and displays live data from TIM in the LHC. Therefore, at all times, the machine responsible can monitor the position of the robot as well as the sensors readings such as radiation, oxygen level, temperature and camera feedbacks.

The web interface provides also the connection to the database where all the collected data from TIM is stored. The data, coupled with its position in the LHC, is matched with the equipment in that position. The web interface allows also to perform some data comparison of the data taken in different times.

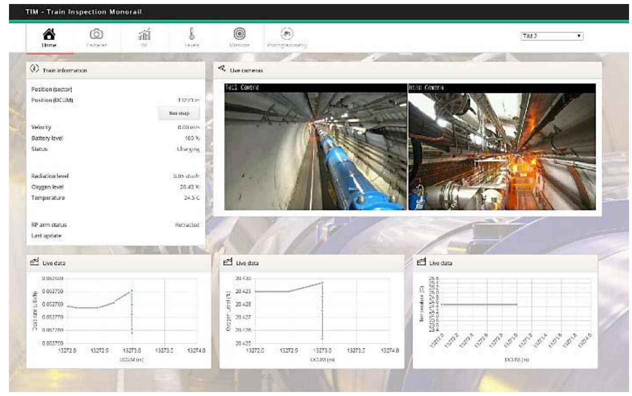

Figure 8: TIM webpage used for live monitoring and measurements databases access.

CONCLUSIONS

The control system presented in this paper was successfully deployed on the TIM trains for inspection of the LHC. In 2017 there are two TIM units in operation in the LHC, that in the past years have run more than one thousand kilometres and performed more than 50 successful missions, including radiation dose measurements, temperature, oxygen and tunnel structure monitoring with HD cameras.

TIM has productively replaced humans in tasks such as radiation measurements, visual inspections and tunnel structural monitoring, reducing the exposure of personnel to hazards and increasing the machine uptime of the LHC. The results obtained with the several missions already performed in the LHC have proven that the control architecture formulated in this paper works successfully deployed on different TIM trains for different robotic tasks.

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