MARWIN: A MOBILE AUTONOMOUS ROBOT FOR MAINTENANCE AND INSPECTION

A. Dehne*, T. Hermes, N. Möller, hochschule 21 gemeinnützige GmbH, Buxtehude, Germany
R. Bacher, Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

MARWIN is a mobile autonomous robot platform designed for performing maintenance and inspection tasks alongside the European XFEL accelerator installation in operation in Hamburg, Germany. It consists of a 4-wheel drive chassis and a manipulator arm. Due to the unique Mecanum drive technology in combination with the manipulator arm the whole robot provides three degrees of freedom. MARWIN can be operated in a pre-configured autonomous as well as a remotely controlled mode. Its operation can be supervised through various cameras. The primary use case of MARWIN is measuring radiation fields. For this purpose MARWIN is equipped with both a mobile Geiger-Mueller tube mounted at the tip of the manipulator arm and a stationary multi-purpose radiation detector attached to the robot's chassis. This paper describes the mechanical and electrical setup of the existing prototype, the architecture and implementation of the controls routines, the strategy implemented to handle radiation-triggered malfunctions, and the energy management. In addition, it reports on recent operations experiences, envisaged improvements and further use cases.

INTRODUCTION

The mobile robotic system was developed in a collaboration of the "hochschule 21" and DESY, which provides autonomous measurement tasks in the new research facility European XFEL. The project is a proof-of-concept for the recording of robot-based radiation measurements in accelerator systems. Among other things, it has to be clarified to what extent such a system can operate reliably under the given radiation load. The hardware used mostly comes from the consumer sector and is not protected against radiation.

Motivation

The need for automated systems and autonomous robot systems is steadily growing. This shows above all the current development in the field of (semi-) autonomous systems towards autonomous UAVs for parcel delivery (see [1]), self-propelled cars (see [2]) or the guideless train and bus in public transport (see [3]). Furthermore, accelerators such as, for example, PETRA III or FLASH (both at the DESY) are generally overbooked, so that beam time for researchers is limited. As the accelerators must be serviced, it is important to hold the maintenance time to a minimum.

But what must happen before a maintenance team can enter an accelerator tunnel? After switching off the accelerator, the radiation safety personnel has to measure the radiation level in the tunnel. This means that the specialists use measuring probes to control the complete tunnel at predetermined measuring points. If there is no residual radiation, maintenance can be carried out. Needless to say, the process of measuring requires time which is not available to the researchers for experiments. A useful solution is to minimize the inspection time, by automating the radiation measurements.

In addition to the time consuming aspects of the radiation measurements, there are also both physiological and psychological aspects which are usually of concern to the radiation safety personnel. A robot is unaffected by such considerations, and additionally, a measurement task performed by a robot will lead to better and to more reproducible measuring results.

Conditions

In order to increase the availability and efficiency of maintenance, repairs, inspections and fault diagnostics of scientific accelerator-based light sources, a mobile robot system is to be developed, which enables inspections without interruption of accelerator operation.

Because the spatial conditions are difficult to access, the robot platform is to be equipped with a manipulator which allows measurements and inspections to be carried out on the accelerator components. The robot is used in the European XFEL tunnel. On a route of about 3.2 km, the radiation should be measured without human intervention. As far as possible, a monitoring center should be able at all times to monitor the current status of the robot system and, if necessary, perform a manual intervention. The robot system will offer two scenarios within the project:

- Scenario 1: The accelerator is to be routinely measured by (partially) autonomous and automatic driving along the accelerator as well as carrying out radiation measurements at predefined measuring positions. Appropriate personnel carry out the configuration of the measuring positions and other parameters via a remote access.
- Scenario 2: By manually approaching certain measuring positions, the operator can perform remotely controlled and punctual measurements on the accelerator.

The switch between the scenarios should be possible at any time via remote access. The measurement data are recorded and processed by the measuring device.

* dehne@hs21.de

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STATE OF THE ART

Today's robotics technology is the result of a long development process. The first designs for robot-like machines already existed in the 15th century and were created by Leonardo da Vinci.

In the last few years, robotic technology has found more and more application areas. The technology has the potential to significantly reduce costs and risks especially in so-called 4D environments[1]. Thus, more and more industries are making use of the added value of robots as opposed to manual work in areas with hazardous environmental conditions. For example, a rail-based robotics system was installed at the world's largest particle accelerator Large Hadron Collider (LHC) in Geneva. To minimize hazardous maintenance and inspection times, TIM (Train Inspection Monorail) was put into use in 2016. As shown in figure 1, TIM moves along the tunnel in a snake-like manner on a rail system. In several wagons, TIM has grippers, sensors and camera systems [4].

Figure 1: Rail-based robot system TIM in the Large Hadron Collider (LHC)

Another field of application in the field of 4D environments for mobile robots is the exploration of rough terrain, such as for example after an earthquake (see [5]). Essential findings have been made. Also in the context of the TRADR project [6]. The Curiosity Mission (`https://mars.nasa.gov/msl/`) should also be mentioned here.

MECHANICAL SETUP

The developed robotic system uses different hardware from consumer IT sector and several industrial sensor systems, which are explained in the following. Figure 2 shows MARWIN's current appearance and its special wheels.

The drive concept is based on a mecanum drive (see [7]). This consists of four mecanum wheels. A mecanum wheel is distinguished by the freely movable rollers, which are mounted in the tread at an angle of 45 degrees. The number and size of the rollers is variable depending on the application. Important is the arrangement of the rollers in the tread. These can be aligned to the left or right. For this drive, two left and two right are required. This arrangement allows free movement in all horizontal directions. This property is advantageous for the application because the robot moves in a narrow space. In addition, it is also possible to dispense with shunting motions which could lead to collisions because of the deployed measuring arm. This drive represents the third degree of freedom of the robot.

[1] environments with extreme conditions (dirty, dull, distant and dangerous)

Figure 2: The current appearance of MARWIN in the XFEL tunnel

In figure 3 the operation of the mechanism is shown. Various scenarios in which the travel directions of the wheels are varied independently of one another enable the already mentioned freedom of movement. This is due to the orientation of the freely movable rollers. Depending on the rotational direction of the wheels, the motional forces cancel each other out and a resulting thrust force is generated. The thrust determines the direction of travel.

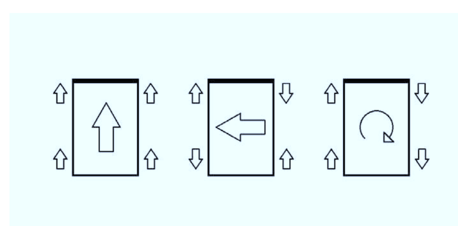

Figure 3: Three examples for the mechanical drive: left – forward, middle – sideways, right – turn on the spot

In order to be able to measure at different heights, the probe must be variable in height. Since sensitive and massive elements can be installed above the charging station, damages can be caused by contact. Therefore it must be taken into account that the robot does not exceed a height of 1.70m in its parking / charging position.

This requirement was met by a so-called scissors lift. In the extended state, the lift reaches a multiple of its overall height. This is achieved by the use of several shears (see figure 4). The lifting movement is effected by a DC geared motor. This drives a spindle, which pulls on a sled the scissors together. Over the geometry this process runs through all shears.

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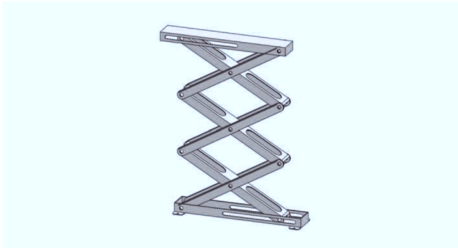

Figure 4: Schematic illustration of the scissor lift

Since it is a mobile robot which is battery powered, there are several charging stations to charge the battery. It must be taken into account that the robot operates autonomously. This means that the charging process must also run autonomously. Not to be neglected is safety. External components of the charging station may only carry current and voltage when the robot has reached the charging position.

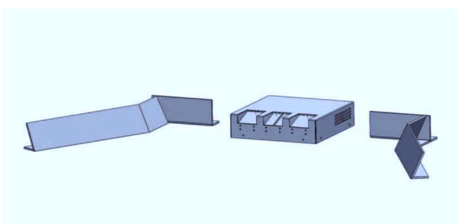

Figure 5: Schematic representation of the self-developed charging station with guide rails and charger

As shown in figure 5, drive-in aids (guide rails) are installed on the right and left of the loading station. These center the robot when entering the station and thus ensure precise positioning of the robot. The charging station is constructed such that the two inner contacts must be mechanically closed by the robot. Then the two outer contacts are released and the charging voltage is applied.

ELECTRICAL SETUP

The robot system is powered by a lithium-iron phosphate (LiFePo4) battery. It is the model "SB12V100E-ZC" from the manufacturer "Super B" with external undervoltage protection (see [8]). The battery has a nominal voltage of 13.2 volts with a nominal capacity of 100 amperes (1.320 Wh). The main advantage of this battery is the relatively large capacity with small size and low dead weight.

The battery supplies the entire IT hardware with energy for a period of about four to five hours. A current consumption of 15 to 18 amperes was measured during operation.

IT hardware

The installed IT components are divided as follows:

- Two main computers,
- two single-board computers of the "Odroid XU4" type with eMMC flash memory,
- one router,
- one network switch,
- two control units and
- several sensors.

The main computers assume the actual control of the entire system while the single-board computers serve as interfaces to the installed actuators and sensors.

Redundance

The design of a redundant system is important in this application. The robot operates in an accelerator, which can cause a bit to "tip over" by ionizing radiation (single event upset). This can cause software errors. Since the measurements are sensitive data, losses must be avoided. Also, system crashes obstruct the work of the robot. For this reason, all relevant hardware components are installed in duplicate, so that a so-called SPOF (*single point of failure*) can not arise. There are two main computers that are installed as a master / slave combination. If the master crashes, it is restarted by the slave and the other way round. The measurement data is currently transmitted directly. Thus, they are not cached and no errors can occur. In the event that the transmission is interrupted, the data could be stored on three physically different memories. The parallelization of the data would lead to a minimization of the risk of data corruption.

Sensors

In order to meet the described requirements, the robot system is equipped with different sensor systems. On the front and rear of the robot, a 2D laser scanner of the "UST-10LX" type from Hokuyo is installed [9]. This takes a one-line scan of its environment, within a range of 10 meters.

These lidar sensors have three main functions:

- Providing sensory data for relative localization in the tunnel,
- detecting the orientation of the robot to the longitudinal direction of the tunnel, and
- collision avoidance.

In the case of collision avoidance in particular, the laser scanners take up all objects in two range areas. If an object is in the range of one to two meters, a warning is passed. An object that is within a distance of a meter triggers an error and stops the robot so that a collision is avoided.

Odometry sensors are mounted on each actuator or motor in the form of Hall effect sensors [10]. With them, the travel distances of the motors are incrementally recorded and can thus be used for actual variables of different control systems. This concerns the regulation of the wheels, the speed, the robot and the height of the scissor lift.

Further internal sensors are installed which are used, for example, for monitoring the power electronics or for visual remote monitoring by various camera systems.

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SOFTWARE

All computers are based on a Linux operating system. The "Robot Operating System (ROS)" is placed on them. ROS is a software framework for robots [11]. The main components of the software framework of ROS are hardware abstraction, message exchange, packet management and software libraries. The system is divided into the actual basic system ROS and a selection of additional packages which extend the basic system by individual capabilities. ROS is published under the BSD license and is thus open-source.

Localization

The localization concept consists of two parts. An absolute positional reference by the recognition of landmarks in the form of QR codes and a relative localization by the evaluation of the data of the laser scanner. The software for localization is also divided into two components, the detection of landmarks and a SLAM algorithm[2].

The ROS software package "gmapping" (see [12]) is used for the SLAM algorithm. This software creates a two-dimensional occupancy grid map from the existing laser data. To do this, the individual scans are regularly compared and added to this map. If a scan deviates to the previous one, for example by moving the robot, "gmapping" calculates the offset of the last scans and deduces the distance traveled and the current position.

QR data recognition

On the side of the robot is a CCD camera for detecting landmarks in the form of QR codes. The data encoded therein provides information to the robot system about its absolute position in the tunnel. The position information is encoded in the QR code, the edge length is 5 cm, and the average distance between QR code and CCD camera is 120 cm. The image data of the QR camera are read in and converted to an ROS format. The image is then decoded by the ROS package "zbar_ros". The result is a string that contains the tunnel position.

EXPERIMENTAL RESULTS

During the development of the robot system several test drives were carried out and data collected. The sensors could be tested and calibrated. In addition to the recording of data from the real driving mode, the parameters for suitable distances between the robot and the measured object have also been determined.

Figure 6: Incorrectly set laser data lead to curvature of the straight tunnel

[2] Simultaneous Localization and Mapping (SLAM)

As shown in figure 6, it could be seen during the first test runs that the generated map showed a curvy tunneling curve during a long journey. The distance in the figure is about 250 meters. In preliminary tests conducted in the laboratory of the hochschule 21 this problem could not be ascertained due to the short distances. By combining the individual laser scans of both laser scanners, this problem came to light. In theory, both scanners are exactly offset by 180 degrees, but the scanners are not exactly offset in the practical implementation. The error could be fixed by determining the real offset from the graph. This correction factor was then applied to the software.

PRESENT AND FUTURE USE CASES

MARWIN is designed to operate inside the accelerator tunnel of the European Free-Electron Laser XFEL even during beam and RF operation. Presently, MARWIN is equipped with an off-the-shelf, remotely controllable pan and tilt camera for visual inspections and two radiation detectors including

- A standard gamma radiation dose rate meter (Geiger-Müller tube 6150AD from Automess, see [13]) mounted at the tip of MARWIN's robot arm. It can be moved to any position within the range of MARWIN's chassis and robot arm is dedicated for radiation safety measurements of the static radiation originating from beam-activated accelerator components.

- A combined gamma and neutron dose rate meter (LB 6419 from Berthold Technologies, see [14]] aka Pandora) mounted on MARWIN's chassis. It is suited for pulsed radiation and can be used for measurements of direct and indirect radiation originating from beam losses or field emission processes in the superconducting RF-cavities.

The data measured by both radiation detectors are continuously recorded, time-stamped and stored in the data archive of the XFEL control system along with the robot position. Figure 7 shows the radiation profile measured with MARWIN's Pandora device during a test run in the XFEL accelerator tunnel between the two docking stations at 1069 m and 280 m, respectively. Locations with an increased radiation level can be identified easily.

Besides visual inspections and radiation measurements other use cases for maintenance and inspection robots might be envisaged in future including e.g.

- Recording thermographic images with an infrared camera do localize temperature hot spots e.g. at insufficient screw connections of powered cables,

- Localizing leaks in pressure pipes using directional microphones or gas sensors

- Manipulating manual valves and switches,

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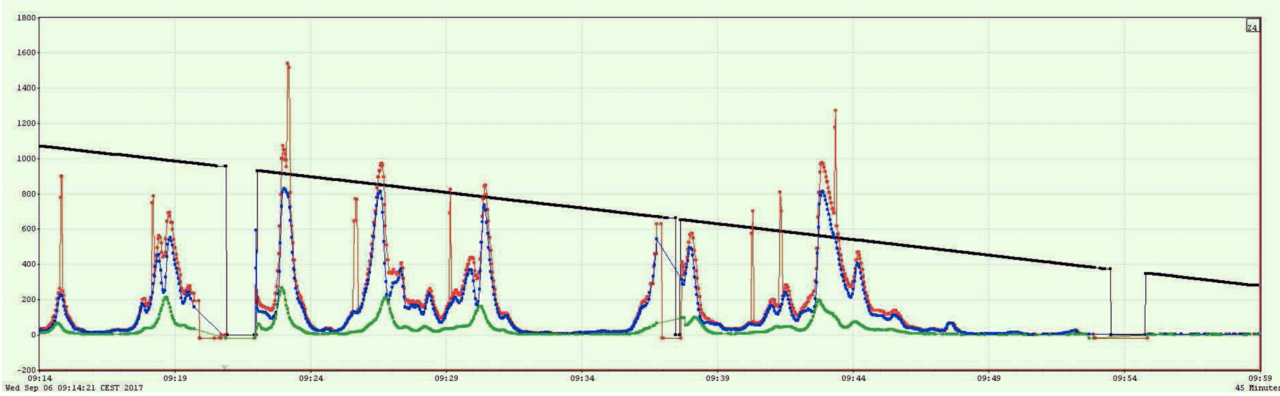

Figure 7: Radiation profile measured with the Pandora device alongside the XFEL accelerator (test run between the two docking stations at 1069 m and 280 m, black: robot position [m], red: dose rate [µSv/h], blue: averaged gamma dose rate [µSv/h], green: averaged neutron dose rate [µSv/h], missing data: wireless data connection temporarily lost)

- Replacing broken electronic boards housed in the cabinets underneath the accelerator modules during beam operation,
- Performing in-situ x-ray inspections of the interior of vacuum components.

CONCLUSION

The first attempts to measure the radiation of the tunnel were carried out. The project was successfully implemented and was also well received in other departments at DESY. Thus, initial discussions gave incentives for further development stages of the robot system in order to be able to incorporate more functionalities. For example, the scissor lift could be extended by one or two 6-axis robotic arms with appropriate tools in order to carry out further maintenance and inspection procedures.

A project extension could be achieved in order to develop a further identical robotic system and to use it in the further course of the tunnel. The XFEL accelerator tunnel is divided in two separate areas by a safety door and therefore requires a second robot. In addition, minor adjustments will be made with regard to the mobility of the measuring probe, since more complex geometries of the measuring object are present in the rear tunnel area. In this context we also have to improve the reproducibility of the positioning system.

In the long term, attempts are being made to launch a larger cooperation with other project partners and to push the project forward and to reach the next stage of development.

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