SEMI-AUTONOMOUS DEVICE FOR VISUAL INSPECTION OF VACUUM BEAMLINES OF PARTICLE ACCELERATORS

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Abstract

Due to the closed structure of ultra-high vacuum beamline systems, a visual inspection of the internal pipe is hardly feasible. For instance, when opening the accelerator vacuum system, an endoscope can be used to inspect the internals. However, this proves to be impractical in case of large, curved accelerator vacuum systems with complex geometries. It is more efficient to open the system only at one or two locations and to use a mobile semi-autonomous inspection device with optical imaging. A mobile robot is currently under development in our laboratory for the planned heavy ion synchrotron SIS100 at FAIR. A multitude of vacuum chamber types with different height levels as well as gaps must be traversed reliably by the robot. We present a modular wheel-based mobile robot prototype with joints between the modules which let the robot climb to different height levels by lifting the modules successively.

INTRODUCTION

During beam experiments in the heavy ion synchrotron SIS18 at GSI in Darmstadt, Germany, beam monitors showed unexpected results which indicated a blocked beamline. Consequently, the ultra-high vacuum (UHV) pipe system of the particle accelerator had to be opened to investigate the inner pipe and to locate the section in which the trouble was likely to be caused. Eventually, a crumpled aluminum foil was found within the system, obstructing the beam path. Apparently, it was left after maintenance work or the replacement of a system component. The risk for situations like this is significant for increasingly larger accelerator vacuum systems and there have been reports from other particle accelerator facilities about similar incidents.

Inspecting the beam pipe manually, for example by using a suitably small camera which is put into the system through a flange opening, is a complex and impractical issue. The visual range of a camera is limited, especially in curved sections, which leads to the need of a significant number of flange openings in the system. More efficient could be an inspection device that is inserted at a single location of the accelerator and then moves autonomously through the beamline with an optical camera on board. Such a device could be used in each shutdown period without much effort to locate foreign objects or damaged accelerator components as well as to collect information about material conditions inside the UHV system. Due to these benefits a dedicated inspection robot is preferable for large accelerator vacuum systems like the heavy ion synchrotron SIS100 at FAIR.

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BOUNDARY CONDITIONS

The interior of the SIS100 vacuum system [1] offers a complex and delicate environment for any device that has to move along the beam path. Compared to many other pipe systems, e.g. sewers, oil and gas pipelines, an ion accelerator vacuum system has a wide range of pipe geometries and dimensions. In particular, the available space of the different vacuum chambers varies. Accordingly, an inspection device has to fit into all sections of the beamline. Due to the smallest vacuum chamber cross section, which belongs to the elliptical dipole chamber in Fig. 1 with a major axis of 120 mm and a minor axis of 60 mm, the robot height is limited to 50 mm. Its maximum width can be up to 60 mm, if we assume a rectangular robot shape.

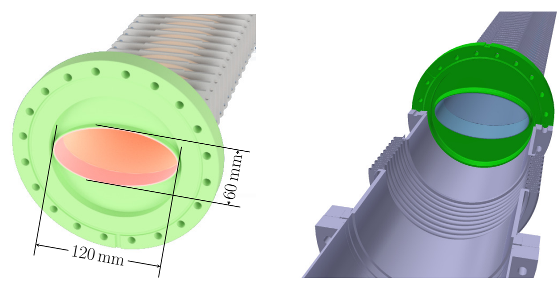

Figure 1: The dipole chamber on the left shows the smallest cross section of the beamline. The right image illustrates a typical step that occurs at the transition of two different pipe geometries.

In contrast, the robot length is generally not limited by the geometry of the beamline. However, a compact device should be preferred concerning control strategies. Furthermore, during the design process the insertion (and removal) of the robot into (and out of) the vacuum system through an empty flange has to be considered. In the SIS100 synchrotron, such flanges have a diameter of 200 mm and are mounted perpendicularly to the beamline. If the robot length is less than 200 mm, the device can be placed directly into the accelerator. A longer robot would for example need a folding mechanism that allows the robot to unfold itself or to turn into the direction of the beam path within the system.

If the robot detects an insurmountable barrier during its inspection it must be able to move backwards to the entrance where it was inserted into the system or to another empty flange. Thus, a locomotion concept is needed that can be used in both moving directions.

As already mentioned, a particle accelerator is an inhomogeneous system constituting many different vacuum chamber types with various pipe shapes and diameters. At each transition between two pipe sections, a step to another height level

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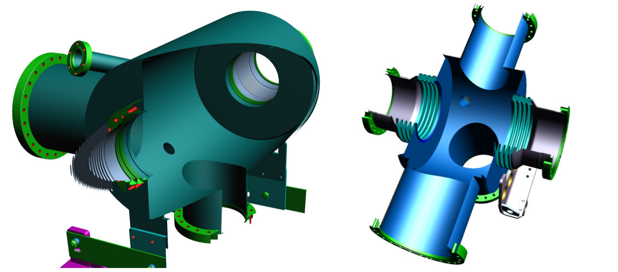

Figure 2: On the left a diagnostic chamber with a stair height of 90 mm at its entrance and its exit is displayed. The right image shows a pump chamber, which has one of the largest gaps in the SIS100 vacuum system that must be traversed by the inspection robot.

occurs as shown in Fig. 1. Thus, an inspection robot needs climbing abilities to reach a higher or lower pipe height level. Most of the height differences between two levels are about 40 mm, but for example in diagnostic chambers, illustrated on the left in Fig. 2, steps have a height of 90 mm. Hence, the robot has to overcome obstacles that are higher than its own permitted height.

Further challenging impediments are openings in the pipe surface, i.e. flange connections, which must be traversed reliably. For instance, in pump and diagnostic chambers, another pipe is located on the bottom side perpendicular to the beamline as shown in Fig. 2. Due to space restrictions within pump chambers, a robot cannot climb down and up. Instead it should be able to traverse the distance between the entrance and the exit of the chamber directly, which in this case is about 230 mm.

Single steps and gaps are the obstacles that are predominantly present in the SIS100. Therefore, the development of a first robot concept is focusing on climbing abilities to overcome these barriers.

ROBOT DESIGN

The first step in the design process of a new inspection device is to find a suitable locomotion concept. For instance, to locate damaged plug-in modules of the LHC at CERN a polycarbonate ball with a RF transmitter was developed [2]. The ball is deployed in an arc of the LHC and is moved through the vacuum system by injecting compressed air. However, this locomotion concept works only in homogeneous pipes without steps and gaps. An arc of the LHC has a length of almost 3 km and the interior height level of the vacuum system is consistent. In contrast, the distance of homogeneous pipes in the SIS100 is only about 3.5 m. Accordingly, such an inspection ball would be useless for our purpose due to the comparatively complex topography of the vacuum system.

In consequence of the dimensional restrictions, a simple design with a low number of actuators is required. Hence, we decided to develop a wheel-based robot, which allows driving on the ground surface of the vacuum pipes. To reach another height level, several driving modules are connected via pitch rotational joints. For prototyping, simple 3D printed frames are designed as chassis for a robot module as illustrated in Fig. 3. These frames allow for easy assembly of motors, sensors or other components and they are convenient for testing locomotion and climbing strategies. The height of a frame is 20 mm and its width 50 mm. Its length is variable and depends on the robot configuration. However, a module should be shorter than 200 mm to be able to deploy the robot in the UHV system.

For the drive wheels, currently low-cost stepper motors are being used which fulfill the requirements concerning motor dimensions and driving speeds of up to about 5 cm/s. 3D printed wheels with a diameter of 30 mm are directly mounted on the axles of the motors. The total width of the robot adds up to 60 mm and its height to 42 mm. A joint that connects two robot modules consists of a digital servo with an operating angle of 180°.

Figure 3 shows different configurations of the robot. The modular design allows adaptations of the robot to overcome more complex obstacles or to carry additional sensors and tools. Due to the need of a bidirectional moving concept, the robot is built symmetrically. To perform climbing tasks, a minimum of three modules in a robot configuration is required. When a module is lifted, the robot must always be in a balanced state so it cannot tilt under any circumstances. Therefore, a minimum of four wheel pairs are necessary to provide stability. Generally, each module carries one pair of wheels. Only the minimum configuration requires two pairs for the central module.

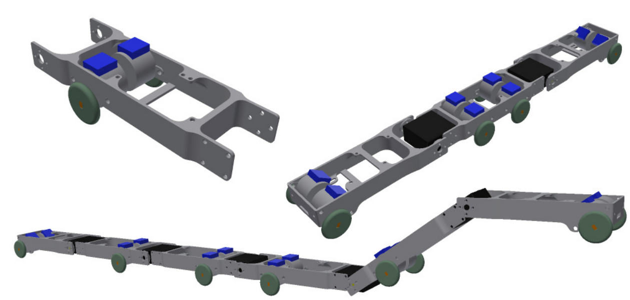

Figure 3: CAD model of the modular robot. On the top left, an example of a single module is displayed. The model on the top right shows the minimum robot configuration of three modules. The robot below consists of six modules.

A further important design aspect is the position of the outer wheels. They are placed closely to the edge of the module so that the wheels slightly protrude beyond the frame. During climbing to another height level, this design ensures contact of the robot with the pipe surface only with the wheels and prevents touching and scraping of the chassis on the pipe surface. The wheel position in the second and the second to last module is relevant while traversing gaps. Therefore, the distance between the outer wheels and the wheels of the next module should be chosen to be larger than the gap length. Independent of the robot configuration, the robot has then either contact to the pipe with at

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least three wheel pairs before or after a gap or with at least one pair on each side of a gap. The prototype depicted in Fig. 4 was successfully used in extensive tests within various vacuum dummy chambers and already offers most of the necessary climbing abilities for real-world accelerator vacuum environments.

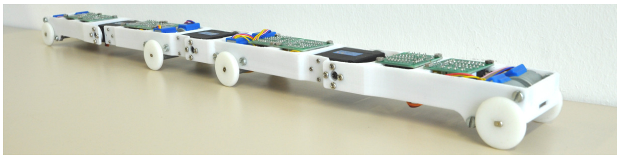


Figure 4: 3D printed prototype of the inspection robot.

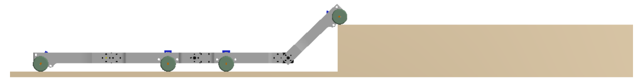
CLIMBING ABILITY

In this chapter, the motion steps necessary to climb on a higher pipe surface level are described for a typical robot configuration consisting of four modules. Descending to a lower surface is almost the same in reverse order. In case a step is detected, for instance by a distance sensor, the robot stops close to the obstacle and raises its first module to a height so that the front wheels are slightly above the upper ground level. Then, the robot moves forward until the front wheels are directly above the upper surface as Fig. 5a shows. By aligning the first module horizontally and simultaneously lifting the second one in Fig. 5b, the front wheels get traction on the step and stabilize the robot. With wheels on both height levels, the robot drives forward again until the first joint is directly over the edge of the step. Then, analogously as before for the first and second module, the second module is aligned with the first, while the third module is raised. Only the first and the last wheel pair are having ground contact now. The robot drives forward again and stops when the second joint is over the edge of the step, illustrated in Fig. 5c. At this point, the second wheel pair is located on the top surface, too, or slightly above. Aligning and lifting the third and the last module and driving to the last joint (see Fig. 5d) shows that this sequence can be repeated for an arbitrary number of modules. Next, the last module is raised to a horizontal position, so that it is aligned with the rest of the robot. Finally, driving forward brings the entire robot onto the surface of the new height level and the climbing maneuver is completed successfully.

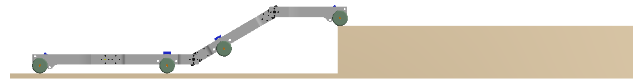
The possible height level differences, which the robot can overcome, depend on the wheel radius r, the height of the joint axle above the ground surface z and the dimension of an outer module described by the horizontal distance d between the outer wheel axle and the next joint axle. If we assume that the first module is raised about 90° to reach an upper level, the maximum step height can be calculated by

$$h_{\text{max,first}} = z + d - r. \tag{1}$$

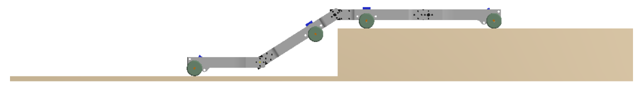
It must be taken into account that the wheel axle is mounted at least a bit below the chassis. If this would not be given, the frame would bump against the step before the wheels are



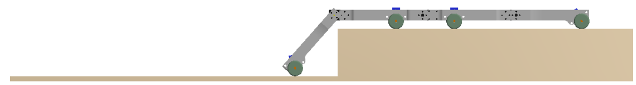
(a) First module is raised.



(b) Second module is raised and the first is aligned horizontally.



(c) Both the first and the second wheel pair have ground contact.



(d) Three of the modules are already on the upper surface.

Figure 5: Movement sequence of climbing on a higher ground level for a robot with four modules.

above the top surface. Additionally, the last module, which has the same dimensions as the first one due to symmetrical design, has to be considered. If we consider a situation like in Fig. 5d and assume an angle of about −90° of the last joint, the maximum step height can be derived as

$$h_{\text{max,last}} = r + d - z. \tag{2}$$

Comparing Eq. (1) and Eq. (2) shows the difference in the signs of the wheel radius and the joint height. Generally, the positioning of the joint axle is higher compared to the wheel axle which means $z > r$ and $h_{\text{max,last}} < h_{\text{max,first}}$. It follows that $h_{\text{max,last}}$ gives the correct maximum step height.

CONCLUSION

We present a basic and expandable concept of a modular inspection robot for the SIS100. The mobile device is capable to reliably traverse simple steps and deep gaps of vacuum pipe systems. Further essential developments of the modular concept are foreseen which shall enable the inspection robot to be deployed in a multitude of accelerator vacuum systems. Specific topics like battery management, sophisticated movement and control optimizations as well as corresponding simulations are currently under development. Furthermore, due to the fact that an exterior mobile device has to be inserted into a clean UHV environment, measures must be undertaken to prevent or at least to minimize abrasion and outgassing of abraded material.

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