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Reconfigurable inspection robot for industrial applications

A. Pistone[a]*, C. Canali[a], C. Gloriani[ab], S. Leggieri[ab], P. Guardiani[a], D. G. Caldwell[a]

[a]*Advanced Robotics, Istituto Italiano di Tecnologia (IIT), via Morego 30, 16163 Genova, Italy*
[b]*Department of Engineering and Applied Sciences, Università degli studi di Bergamo, viale Marconi 5, 24044 Dalmine (BG), Italy*

Abstract

The power generation industry, due to its importance in both general public and industrial applications, requires high standard of reliability. In the electrical power generation processes, the inspection and the adequate maintenance of the power generators are extremely important. Currently these inspection procedures are performed by dismounting the generators after a predetermined amount of operating hours. Due to the huge size and the complexity of such machines, these operations other than being time-consuming are sometimes source of mechanical and electrical damages. Furthermore, several analyses are carried on by use of manual instrumentation operated by expert workers. Consequently, a series of important tests and structural analyses other than being very expensive are highly subjective and could lack on repeatability and reliability. Moreover, not all the results of these analyses are logged or electronically stored.
Following the current trend of automation under the Industry 4.0 framework, an automated robotic vehicle has been designed with the aim of addressing the above-mentioned issues. The main features of such robot are the small dimensions, a magnetic coupling that gives the possibility to move on ferromagnetic surfaces, a reliable mechanical assembly and a wide reconfigurability in terms of mechanical add-ons and plug-and-play sensors. The housed sensors could be optical or IR cameras, ultrasonic scanner, surface analyzer, eddy currents detectors and even more. The tests conducted so far in realistic environments show that the presented system can be used to perform standard and reproducible inspections of complex machines like power generators. Moreover, due to its reconfigurability this vehicle can easily extend its range of application and be used in the inspection of other machines and infrastructures such as windmill blade, cranes, bridges beams, vessels and similar.

Keywords: Robotics and Computer Integrated Manufacturing; High Precision and Zero-Defect Manufacturing; Predictive Maintenance and Manufacturing Systems Reliability

* Corresponding author. Tel.: +39-0102896810 *E-mail address:* alessandro.pistone@iit.it

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1. Introduction

In today's world, the electric power plays a crucial role in both general public and industry fields, consequently the inspection and the adequate maintenance of the power generators in the power plants are extremely important [1]. Usually these inspection procedures are performed by removing the rotor from the generators and allowing generator test engineers to perform non-destructive testing by means of manual instrumentation. Due to the complexity and the risks that such operation imply, the data and experience gathered over the years has led to not recommending pulling the rotor for inspection, but instead to only pull the rotor for repairs [2].

Since the late 1980s robotic inspection solutions for power generators were developed [3]. Inspecting power generators using robots allows for a complete inspection without the need to remove the rotor. Usually, the inspections are carried out performing a set of procedures slot-by-slot through the generator air-gap (space between rotor and core) along the axial direction. A complete inspection is made by three main tasks:

- High definition visual inspection. Since most part of generator repairs are identified visually, this is the most important task of inspections.
- Stator slot wedge tightness assessment. The slot wedge tightness has a great impact in generator aging and reliability, in fact if the wedges are loose, stator bars are allowed to vibrate in the slot, leading to insulation abrasion and possible ground fault. The wedge tightness it's commonly provided by tapping the radial wedge with a hammer and listening to the sound produced. In the case of top tipple spring designs, the operation consists in jacking the wedge radial measuring force and displacement.
- Stator core low flux test or Electromagnetic Core Imperfection Detection (ELCID). This test is aimed to discover insulation damages which could lead to hot spot and potential core melting.

In this article, a new automated robotic vehicle based on permanent magnets with the aim of accomplishing the above-mentioned tasks is presented. The tests conducted so far in realistic environments show that the proposed system can be used to perform standard and reproducible inspections of complex machines like power generators. Moreover, due to its reconfigurability this vehicle can easily extend its range of application and be used in the inspection of other machines and infrastructures such as windmill blade, cranes, bridges beams, vessels and similar.

This paper is organized as follows: section 2 presents the state of the art of power generator inspection robots, section 3 and 4 show the mechanical design of the robot and the architecture of the inspection system, section 5 shows the prototype together with some experimental results and finally some conclusions are drawn in section 6.

2. State of the art

Power generator inspection robots are mainly divided in three categories, depending on the way by which the different probes are driven through the air-gap [3]:

- Cable car, the idea is to guide the different probes by means of cables placed and taut in the air-gap exploiting drives placed on each side of the generator rotor, either on the retaining ring of the shaft itself. Slot changes are made via the cable drivers placed outside the machine. The main advantage of this choice is the rapidity of the inspection, while the main disadvantage is the need to open both ends of the unit. Due to its simplicity, this was the first method proposed for power generators inspection and it is still used nowadays.
- Crawler, as suggested by the name, this solution consists in a robot equipped with on-board motors that uses the stator core and its own body to crawl through the air-gap. Using the video image feedback is possible to drive around obstacles such as rotor flux probes, resin drops and air-gap baffles and to look at a point of interest from different angles. In addition to this flexibility, the main advantage of this category of robots is that the operation requires only one end access.

- Boom or rail, in this configuration the probes are driven through the air-gap by means of telescopic beam or band. The former are moved by a drive strapped to the retaining ring, while the latter could rotate over the retaining ring for slot changes. Even this category requires only one end access and usually is used on the smaller units. The main disadvantage is the limit on the weight of the probes.

The proposed robot belongs to the crawler category. In the next section, details about the mechanical design are provided.

3. Mechanical design

The proposed robot has been designed in order to minimize its overall weight while maximizing the payload to perform non-destructive monitoring analysis on power generators: high definition visual inspection, stator slot wedge tightness assessment and ELCID measurement. The basic design is a tracked vehicle able to crawl on the stator teeth by magnetic attachment means and driving tracks.

3.1. Structure

The vehicle is made by three sub-modules, the central one houses all the probes and the on-board electronics, while the lateral ones act as motion modules. Fig. 1 illustrates the main module and two track-driven modules on each side. Since the geometry of generators (e.g.: teeth height and width, number of slots, rotor diameter) could vary a lot depending on construction parameters (e.g.: turbo or hydro, producer company), the vehicle is designed in order to adapt its geometry, according to reasonable ranges, in order to match the generator to be serviced. The vehicle design includes active and passive mechanical adjustments, the latter are adjustable tracks angle (about 20°) and driving tracks with different size, while the former are vertical alignment of wedge tightness probe and ELCID sensor. Moreover, a big set of easily exchangeable main modules with different width size has been designed.

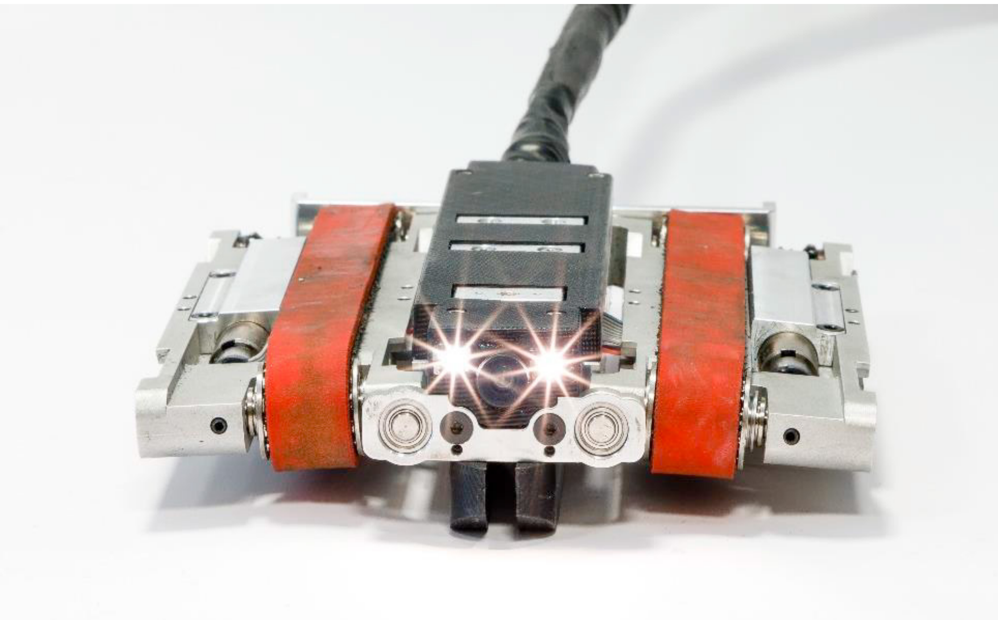

Fig. 1. Illustration of the modular crawler vehicle.

3.2. Equipment

In terms of measurement sensors, commercial devices have been chosen for the visual inspection and the ELCID probe, while for the wedge tightness assessment a custom tool has been designed. The vehicle is equipped with brushed DC motors, coupled with proper gearboxes and encoders, and the tracks are made by Linatex® rubber. The magnetic adhesion force is provided by commercial available neodymium magnets (15mm x 15mm x 8mm) placed above the tracks, in order to be no more than 3mm far from the stator core. It is important to note that the ratio between the magnets weight and the total weight of the vehicle is about 15%, allowing the crawler to carry payload up to 1kg. After many tests, an alternating polarity configuration has been chosen as the best appropriate configuration compatible with the geometrical constraint given by the generators geometry. Thanks to these choices, the vehicle has an adjustable speed up to 10cm/s, a positioning accuracy of less than 5mm and the maximum occupied volume is around 150mm x 140mm x 25mm.

The crawler works for both cases when the rotor is in place and when it is removed. Before starting a slot inspection, the tracks of the vehicle have to be aligned with the stator teeth.

3.3. Challenges

Besides the fact that the crawler design has been invented from scratch, building such a compact and sophisticated device was also a challenge. One of the most critical aspect was the selection of the tiny visual cameras and the choice of their positioning in order to optimize the visual effect. Other difficulties were related to the fitting of the on-board electronics into the limited dimensions of the robot body. Concerning the motion module, the biggest challenges were: the choice of motors and gears that are coupled to the track belts, the selection of the belt material and its shape design and the trade-off between the magnetic adhesion force and the torque of the above-mentioned motors. Finally, the design of the main module different sizes was critical in order to cope with the wide range of generators with different rotor diameter, stator teeth size and teeth to slot width ratio. Finalizing the size of the several mechanical adjustments required a continuous process, which included a frequent update between the theoretical design and the actual machine data acquired during the application of the in-situ inspection practices.

3.4. Reconfigurability

Although the robot has been designed for power generators inspection, a great effort has been made in order to have a wide reconfigurability. The housed sensors could be optical or IR cameras, ultrasonic scanner, surface analyzer, eddy currents detectors and even more. Therefore, this robot can easily extend its range of application and be used in the inspection of other machines and structures.

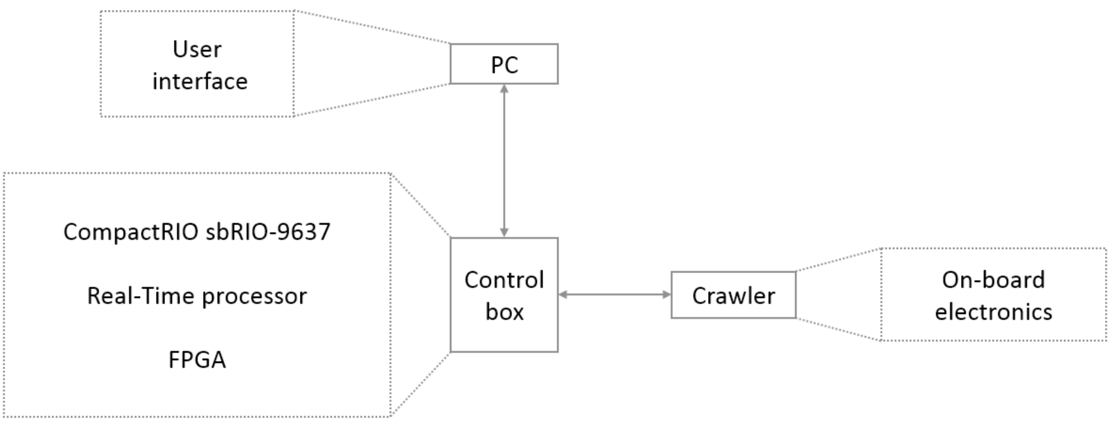

Fig. 2. Overview of the architecture of the inspection system.

4. Architecture of the system

A schematic view of the architecture of the system is reported in Fig. 2. The control and data acquisition circuitries are based on a commercial Single-Board Controller by National Instruments. The CompactRIO sbRIO‐9637 is an embedded controller that integrates a Real-Time processor running NI Linux Real‐Time, a user-reconfigurable FPGA and analog and digital I/O on a single printed circuit board (PCB). The CompactRIO board is placed inside a control box that communicates by means of cables with both the control pc, that houses the user interface, and the vehicle, that houses all the measurement sensors. The latter are powered and read by a vehicle onboard custom PCB. The human-machine interface based application, as well as the Real-Time and FPGA applications, are built in LabVIEW environment.

5. Prototype and experiments

According to the concepts presented in the previous sections, a prototype has been successfully designed, built and tested. The test process started with a simple displacement on a metallic wall, in order to verify the adhesion and tractive force, in trajectories that were both perpendicular and parallel to gravity. A lot of documentation showing the operation of the robot has been recorded, Fig. 3 shows the crawler vehicle resting on a metallic door.

In the next step, the vehicle was tested on mock-up and actual generators, where the rotor was removed. As above-mentioned, the results obtained during this phase have been used for further improvement of the design and implementation. Fig. 4 shows the vehicle crawling on the stator of an actual generator with the rotor removed.

Finally, the vehicle was tested in a real scenario performing an inspection of a power generator in a real plant. Fig. 5 gives an overview of how the crawler is operated and how the visual images are displayed when inspecting on a specific machine. The video image can be stored for offline analysis purpose. Fig. 6 shows pictures taken by the on-board camera from an actual generator air-gap. Following an idea of reconfigurability and flexibility [4,5], the presented vehicle has been designed in order to crawl on many kind of metallic surfaces. An example of its versatility is shown in Fig. 7 where the crawler is resting at the top of an iron beam close to our laboratory.

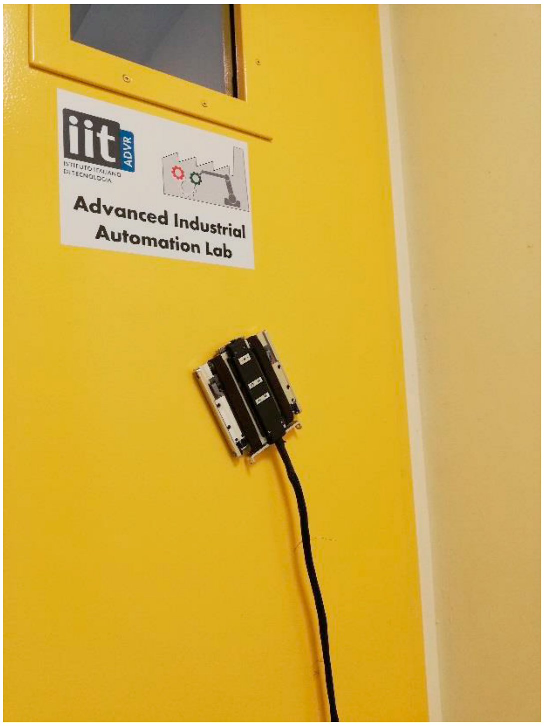

Fig. 3. The robot prototype resting on a metallic wall in the lab at the IIT (Genoa, Italy).

Fig. 4. The robot prototype crawling on the stator of an actual generator with the rotor removed.

Fig. 5. Visual inspection testing with the crawler vehicle on a specific generator.

Fig. 6. Typical visual inspection results from an actual generator.

Fig. 7. The robot resting at the top of an iron beam. The vehicle can climb up to 20m from the control box.

6. Conclusions

In this paper, a novel crawler vehicle for power generator inspection without removing the rotor has been presented. The modular design can adapt to a set of generators with various geometry, in terms of stator teeth width, teeth to slot width ratio and rotor diameter. The prototype has been tested in both mock-up environment and in real generators. At the current stage, the minimum air-gap size that can be crawling through is 25 mm with the rotor diameter about one meter and half.

The chosen magnetic attaching approach allows the robotic vehicle to easily extend its range of application. Therefore, the presented crawler can be used in the inspection of other machines and infrastructures such as windmill blade, cranes, bridges beams, vessels and similar.

Thanks to the versatility of the chosen software framework, other than performing standard and reproducible measurements, the robot can be easily teleoperated and programmed for autonomous functions.

Finally, there is the possibility to assemble two or more vehicles attached to each other in order to carry several probes and sensors.

Future research and development has been proposed for miniaturizing the crawler to reach even smaller air-gap while keeping on-board all the probes and the cameras.

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