ROBOTIC SYSTEM FOR MONITORING PIPE WALL THICKNESS REDUCTION IN NUCLEAR REACTORS UTILIZING DIGITAL TWIN AND INDUSTRY 4.0 TECHNOLOGIES

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ABSTRACT: Large thermal electric generation systems based on the Rankine cycle require monitoring the reduction of pipe wall thickness caused by vapor flow due to aging processes such as erosion and accelerated corrosion processes. The inspection difficulties are related to hostile environment (50 oC and 100 % relative humidity), and spaces with complicated geometry such as pipeline curves and their support structures. This work presents a monitoring program which integrates wall thickness inspections carried out with a robotic system and Industry 4.0 technology to handle collected data and to disseminate information throughout the organization. The robotic system is developed utilizing the digital twin technology, a very realistic virtual modeling scheme which allows interaction with the real-world environment. They include equipment and all the steps to carry out the inspection process. The pipe wall thickness monitoring system is to be utilized in Angra 1 (Brazil) nuclear power plant.

KEYWORDS: robotics; pipe wall thickness; nuclear power; Digital Twin; Industry 4.0

1 I INTRODUCTION

In 2025, the Angra 1 nuclear power plant, located in Rio Janeiro state in Brazil, completes 40 years of operation and the owner Eletronuclear requested the Brazilian nuclear regulatory body to extend its operational life and renew the operating license for another 20 years. For life extension, it is necessary to carry out a wide range of plant aging management activities which may end up requiring to replace vessels and pipes which operate under high pressure and do not meet the regulatory agency's criteria to remain in service [1-3]. Large nuclear power plants have hundreds of meters of pipes under this situation and their wall inspection is among the ones more time-consuming procedures, around 300 hours. Erosion and flow accelerated corrosion processes induced by fluid flow are monitored through ultrasound inspections that seek to determine the reduction in pipe wall thickness [4-6].

This work presents the project of pipe inspection automation using a robot integrated with the Industry 4.0 technology through wall thickness measurements using the ultrasound technique. The pipes belong to the secondary system from Angra 1 nuclear power plant, which include those under high pressure connecting the steam generators, turbines, condensers and all associated instrumentation and ancillary systems. The inspection environment is hot and humid (50 degrees Celsius and 100% relative humidity). The field space has complicated geometry and access to inspection locations due to support structures. The pipes have different diameters varying from 50 cm to 65 cm some are straight, and others curved and positioned in horizontal, vertical, or inclined directions. During a shutdown, more than 50,000 measurement points are performed [7,8]

Robotic systems are used in different field applications and environments such as manufacturing activities but also in aerial inspection of structures [9], submarine inspections of structures [10,11] and even rubber tapping in plantations [7]. What they all have in common is that they feature a vehicle-handler system for inspection or other necessary on-site activity. The remotely operated vehicle contains a manipulator support platform, a robotic arm containing in its end effector with specific characteristics to carry out the activity, i.e. sensors to carry out the measure of interest [12] or the production activity as rubber tapping [13]. To enable the inspection, the vehicle is moved to the designated locations for carrying out the activity. To control the trajectory of the robotic arm, the end-effector normally has sensors for vision and contact with surfaces [14-16].

The digital twin [6] is a project realization concept in which the environment, process or a single physical object is reproduced first in the virtual world and then in the real world. In the case of robotics, its function is to map the main characteristics of the object or physical process previously via virtual simulation and subsequent real implementation whether they are system maintenance [17,18], design and manufacture of products [19–21] or processes [22].

2 I ROBOTIC SYSTEM REQUIREMENTS

It is desirable that the system has a communication interface with intelligence to process the data in the manner established by Eletronuclear and that allows identifying possible locations with thicknesses closer to acceptable limits or simply failures in the process of measuring the thickness of the pipe. In these cases, the robotic system can perform a sweep with more qualified inspection or repeat measurements.

Figure 1 shows the inspection environment in the turbine building of the nuclear power plant Angra 1. Figure 1a shows the current situation of manual thickness measurement. It is necessary to place scaffolding at the various measurement locations so that the technician has access to the measurement locations. It is seen that the environment has a flat floor that allows the movement of a vehicle. Figures 1b and 1c show pipe segments with indications of the places where thickness measurements will be taken and also the difficulty of access due to interference from other equipment and pipes in the vicinity.

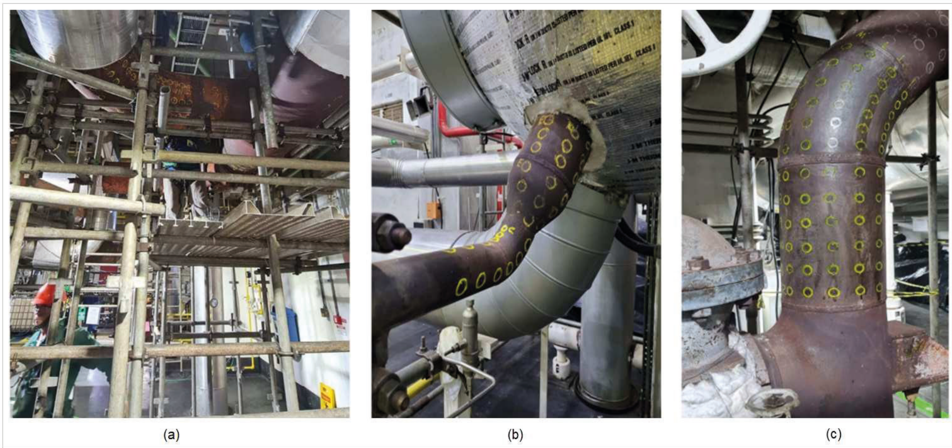

Figure 1. Environment in which measurements of the wall thickness of the pipes in the turbine building are carried out. (a) Flat floor site with scaffolding to allow access to pipes for manual measurements. (b) Pipe segment of different diameters inclined and difficult to access. (c) Piping in vertical position. The yellow circles indicate the locations where thickness measurements are performed using ultrasound.

The industrial manipulator (robotic arm) must be able to access the external wall of the pipe and position the sensor installed in the end-effector in an appropriate way to carry out the measurements. Other sensors present in the end-effector are the contact and distance sensors between the surface that act as the "vision" to avoid collisions with the pipe and the correct positioning of the ultrasound sensor for measurements. A human operator is also foreseen to provide cognitive assistance for vehicle movement and inspection actions. The thickness measurement procedure is as follows: the UROV is moved and parked at certain locations. In these places, the robotic arm moves and performs inspection on the surface and all thickness measurement procedures.

The vehicle requirements are reduced size to allow access to the different measurement locations and have mechanical strength and space to accommodate the systems of the other two units. Piping access is a great challenge because there are positions where some "elbows" are close to walls and hostile places, making it difficult to position the robotic equipment for measurements in curved surfaces.

3 I ROBOTIC SYSTEM FOR MEASURING PIPE WALL THICKNESS

The Robotic System for Measuring the Wall Thickness of the Secondary Piping of the Angra 1 Nuclear Power Plant (SRME) is composed of 3 units. The first unit, called the Remotely Operated Vehicle Unit (UROV), is a vehicle that can be operated remotely to allow displacement of the SRME to tubes of different diameters and allow thickness measurements. The second unit, called Thickness Measurement Robotic Cell Unit (UMRC), is a robotic work cell indexed in the UROV, equipped with a robotic arm that performs the movements and inspection actions and that has sensors installed that allow the movement of the measurement points and the external measurement of the pipe wall thickness. The third unit, called the Communication, Power Supply and Ancillary Services Unit (UCPA), contains all other SRME systems such as power supply cables, data transmission cables, real-time information, computers and ancillary equipment. The study on automatic thickness measurement uses the GP-7 robot from the manufacturer Yaskawa-Motoman [23]. This robot weighs 34 kg, has a reach of 927 mm horizontally and 1693 mm vertically and has a payload capacity of up to 7 kg. With these attributes, this robot can be used in the field. The robot programming is done using the digital twin technique using the Process Simulate software version 15.1.2.

The Remotely Operated Vehicle Unit (UROV), shown in Figure 2, is designed to access as many pipe runs as possible. The UROV is moved by the human operator to the closest possible location to the measurement point and makes it possible to move the end-effector via remote actuation for displacements in the x-y-z axes for the best positioning of it for carrying out thickness measurements.

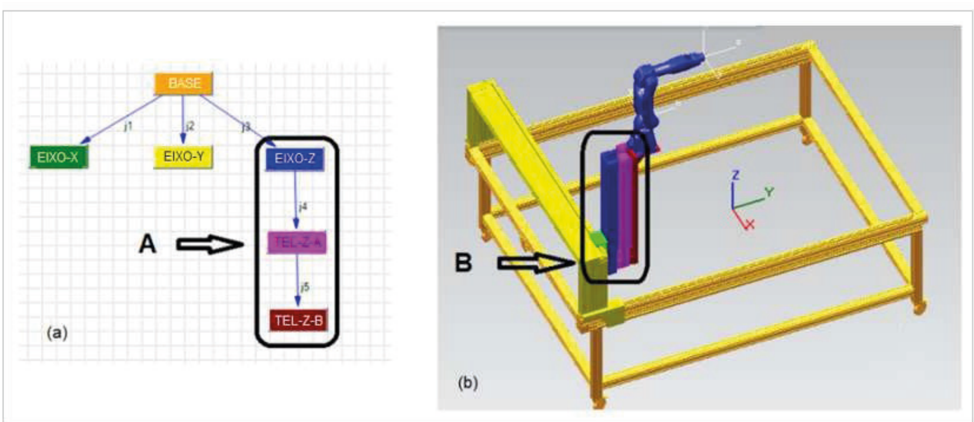

Figure 2. Unit Remotely Operated Vehicle (UROV) with caster system: (a) The X-AXIS describes the horizontal translation movement of the mechanism in the X direction, the Y-AXIS in the Y direction and the Z- AXIS describes the vertical translation movement of the mechanism in the Z direction. The TEL-Z-A-AXIS describes the vertical translation movement of the mechanism in the Z direction with retractable or telescopic articulation and the TEL-Z-B AXIS describes the vertical translation movement of the mechanism in the Z direction with retractable or telescopic articulation telescopic after displacement of the AXIS-TEL-Z-A. (b) In this figure, the yellow color describes the horizontal translation movement of the mechanism in the Y direction, the green color describes the horizontal translation movement of the mechanism in the X direction, and the blue color describes the horizontal translation movement of the mechanism in the X direction. Y direction. In figures "A" Mathematical modeling in x-y-z by means of horizontal movements, x and y, and telescopic elevation in z with two additional prismatic movements and "B" the corresponding movement of the end-effector on the robotic arm with five degrees of freedom of the measuring robotic cell with teleoperation system.

Figure 3 shows the URMC Robotic Thickness Measuring Cell Unit with a robotic arm having six degrees of freedom to reach a 65 cm diameter pipe and the end-effector. After marking with points offset by 30 degrees, thickness is measured on a 144-point grid. A reservoir installed at the base of the robotic arm with coupling liquid that varies according to the type of material, but is essential to perform the thickness measurement.

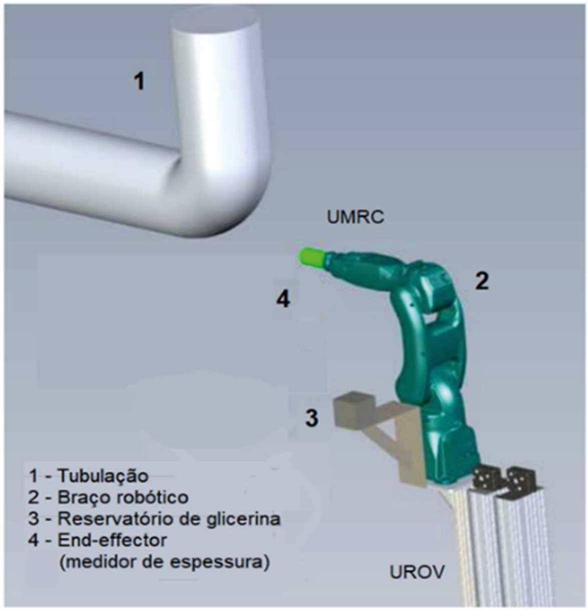

Figure 3. Thickness Measurement Unit (URMC): 1) Piping is where the process of measuring thickness using the ultrasound technique is concentrated and requires the preparation of the surface of the external piping to carry out the measurement, instrumentation, specification and calibration of the ultrasound measurement system point transducer type and surface scanning type ultrasound. 2) Robotic arm and end-effector. 3) Reservoir with coupling liquid. 4) End-effector (thickness gauge) can accurately and quickly measure the thickness of the walls of the pipes at the determined points.

The design challenge consists of integrating thickness measurement, analysis, treatment and storage of information in a safe and reliable way. The industrial robot needs to receive measurements from the electronic transducers of the system that performs the measurement and store them in variables. These variables need to be defined and the technologies that enable Industry 4.0 follow data security protocols and interface communication that can be customized according to the needs of the company, in this case, Eletronuclear.

Robotic manipulators have positioning problems, speeds and forces applied in any type of movement. The definition of the trajectory of the GP-07 robot in three-dimensional space, called direct kinematics, is done with the SIMULATE software. Figure 4 shows the relationship of programming via Digital Twin with the SIMULATE software and the movement of the robotic arm that determines the location of the end-effector. This software uses the

Denavit-Hartenberg notation to assign to the robotic system an orthonormal coordinate system for each link of the kinematic chain [4,5,24].

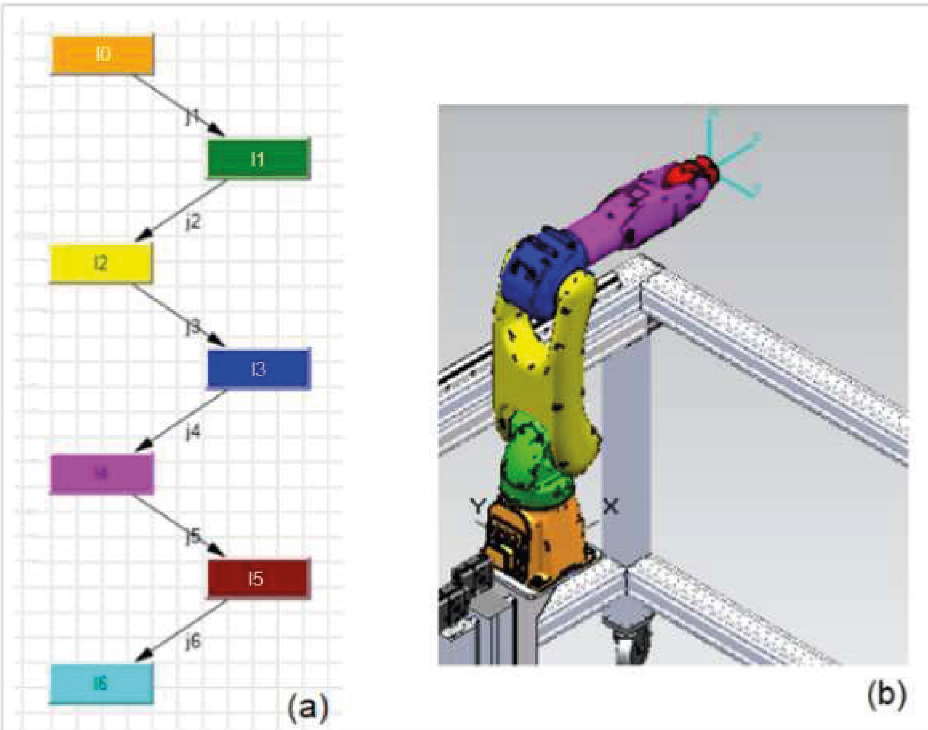

Figure 4. (a), Symbols l0, l1, l2, l3, l4, l5 and l6 in a chain representing the homogeneous transformation matrices according to the Denavit-Hartenberg notation from the base of the robot to axis six, respectively. The symbols J1, J2, J3, J4, J5 and J5 represent the links between the rotation joints of the six degrees of freedom of the robot, respectively. (b) In this figure, the colors of each physical joint of the robot correspond to the same colors as the matrices in figure (a).

The development of the kinematics is done after obtaining the Denavit-Hartenberg parameters of the GP-07 robot [5]. This robot has a reach of 927 mm horizontally and 1693 mm vertically with a payload capacity of up to 7 kg. Once this coordinate system for adjacent links is established, it can be represented by a homogeneous coordinate transformation matrix. With this information, the kinematics of the robotic movement is built, precisely defining the position and orientation of the end-effector next to the surface for carrying out the measurement.

The method used to obtain the results of direct kinematics in virtual space (Digital Twin) showed good precision performing joint, linear, circular and spline interpolated trajectories.

4 I CONCLUSIONS

To ensure that the prototype results are suitable for the effective use of SRME in Angra 1, all prototype design requirements must take into account the environment where thickness measurements take place in the Turbine Building. This article presents a work stage that considered important aspects of the Angra 1 power plant project. It was possible to model the virtual commissioning activities, transfer all information and project data automatically to the physical project of the SRME. Access to the measurement sites occurs through two movements: the UROV and the UMRC. The UROV is moved by the robotist to the closest possible location to the point of movement. From this point, via remote actuation, the robotist can move the support base of the robotic arm in x-y-z by means of horizontal movements, x and y, and elevation, z.

The second movement is provided by the UMRC robotic arm. This allows greater access to the pipes. The movement of the support base of the robotic arm has a mathematical model with a telescopic concept of the z axis. It is expected a significant productivity gain in this process, as the entire programming of the physical robot, an important part of the project to carry out the process of measuring the thickness of the pipes, is transferred directly from the virtual project (digital twin) to the real robot.

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