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Technical Paper

JIRO: joint inspection robot

Lucas Cruz da Silva [1]
Leone da Silva de Jesus [2]
Lucas Amparo Barbosa [3]
Iago Souza Borges [4]
Camila Silva Cavalcante Lima [5]
Diego Russo Juliano [6]
Rômulo Guedes Cerqueira [7].

1. SENAI CIMATEC, ROBóTICA, . SALVADOR - BA - BRASIL, lucas.cs@fieb.org.br
2. SENAI CIMATEC, SOFTWARE, . SALVADOR - BA - BRASIL, leone.jesus@fieb.org.br
3. SENAI CIMATEC, SOFTWARE, . SALVADOR - BA - BRASIL, lucas.barbosa@fieb.org.br
4. SENAI CIMATEC, DESENVOLVIMENTO DE PRODUTOS INDUSTRIAIS, . SALVADOR - BA - BRASIL, iago.borges@fieb.org.br
5. SENAI CIMATEC, ROBóTICA, . SALVADOR - BA - BRASIL, camila.lima@fieb.org.br
6. SHELL BRASIL PETRóLEO LTDA, PESQUISA E DESENVOLVIMENTO, . RIO DE JANEIRO - RJ - BRASIL, diego.juliano@shell.com
7. SENAI CIMATEC, ROBóTICA, . SALVADOR - BA - BRASIL, romulo.cerqueira@fieb.org.br

Abstract

The goal of the Joint Inspection Robot (JIRO) project is to develop a solution that mitigates the risks and onerous logistics inherent to current operations in cleaning and inspection of Steel Catenary Riser (SCR) flexible joints, which are structural components in floating Oil and Gas production facilities, such as Floating Production Storage and Offloading units (FPSOs). This project is an initiative of Shell Brazil and SENAI CIMATEC and aims at developing a remotely operated robotic prototype, compact enough to be transported by a commercial light work-class ROV. Its structure consists of a clamp in charge of attaching the robot to the riser, a system that unfolds and brings the instruments closer to the elastomer surface and a rotating apparatus that drives the cleaning system and the inspection sensors. The cleaning system is designed to allow removal of marine growth from the elastomer surface of a flexible joint without damaging it, by using water jet with cavitation. Moreover, the inspection system automatically gathers high-resolution and textured 3D model of the elastomer surface using a set of cameras, lights, and a laser scanner, allowing the comparison between different inspection campaigns.

Keywords: Underwater robotics. Flexible joints. 3D reconstruction. Underwater inspection

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1. Introduction

Flexible joints are the interface equipment that connect rigid risers to oil and gas floating production units, providing mechanical relief for an otherwise stressful mechanical joint. Since it is submitted to heavy axial loads, such equipment requires periodical cleaning and inspection tasks on its elastomer surface in order to mitigate the risk of structural failure and allow planned interventions in case indications of asset integrity issues are found. Currently, these cleaning and inspection tasks are performed by either heavy work-class Remotely Operated Vehicles (ROVs) and support vessels or divers, requiring complex offshore operations.

The FPSO Espírito Santo located at BC-10 (Parque das Conchas) uses a turret mooring system, in which all hydrocarbon production is transported from the seabed via rigid riser bundles, which in turn are coupled to the turret through flexible joints. The riser bundles converge geometrically to the turret in a displacement that leaves no room for heavy work-class ROVs to operate in the task of flexible joint inspection (and possibly cleaning) due to the resulting confined space. Therefore, cleaning and inspection of flexible joints in BC-10 are critical activities carried out by divers (and a support team), which execute the cleaning task manually and collect informationof the joint's elastomer in order to provide data for inspection analysis. Besides the inherent risks of the diving activity, the annual costs for cleaning/inspection missions are in the order of millions of dollars worldwide.

JIRo is an automatic tool conceived to overcome the challenges present in flexible joint cleaning and inspection in oil and gas fields, including BC-10. The robot is designed to be deployed either through the FPSO turret moonpool or overboard the FPSO using only a light work-class ROV as transport means, comprising a compact and light-weight solution proper for operations in confined spaces.

This work is organized as follows. Section 2 contains the description of the robotic solution, containing the subsystems as well as the operation in order to be carried by an ROV and to complete an inspection task in the described confined environment. Section 3 describes the simulation environment and the features tested. Section 4 presents results and discussion concerning visual and 3D inspection. Finally, Section 5 contains the conclusions.

2. System description

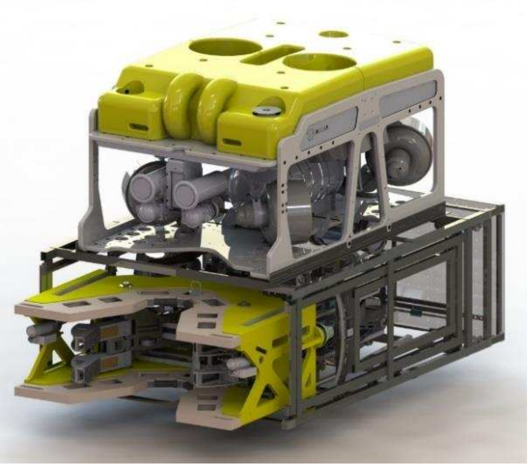
The JIRo design is a currently ongoing project which consists of two components: the skid, which is bolted beneath a third party ROV, and the Tool, which is stored in and mechanically detachable from the skid (Figure 1). The tool is a robotic system responsible for executing the cleaning and inspecting actions (Figure 2) whereas the skid enables the tool positioning on the riser and stores it back under the ROV after mission completion. The system (ROV + JIRo) is deployed in underwater environment and the ROV pilot flies it until a riser bundle is reached, from where the Tool will be extended out from the skid and attached to the riser at a location below the flexible joint to be inspected (and potentially cleaned). ROV mobility in the environment is a key feature since the Tool has no mechanism to move along the riser by itself, so the ROV pilot must be able to reach the attachment position in order to start the cleaning and inspection task. The system is designed to perform cleaning and inspection operations in assets whose angle between riser and flexible joint center axis is less than 5 degrees.

In order to achieve the cleaning and inspection goals in a flexible joint, the Tool is a robotic system containing a few actuated subsystems:

- A clamping system with pressure feedback, responsible for maintaining the Tool attached to the riser during the inspection operation.
- A folding system, which puts the tool at the operational pre-position after attachment and folds is back to the storing position. In order to fit the ROV loading capability, the tool is kept retracted (folded) while stored in the skid
- A platform containing cleaning and inspection sensors and instruments, referred to as the Instruments Table, comprising one lifting (axial) and one radial unit for fine position adjustment of the instruments and a rotational unit to reach the entire flexible joint's perimeter.

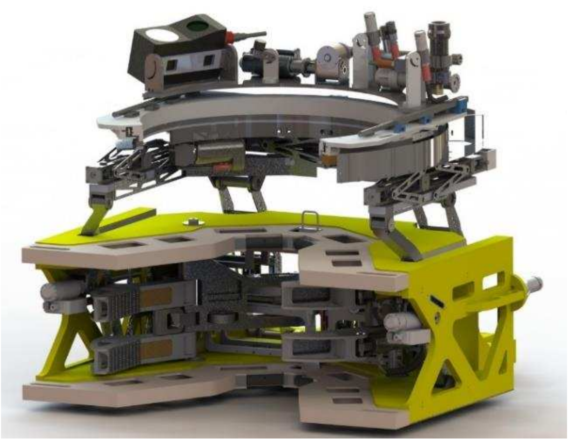
These systems and their respective designs are described in detail in the next subsections.

Figure 1 - Tool Stored in skid.



Source: produced by the authors.

Figure 2 - Tool extended.



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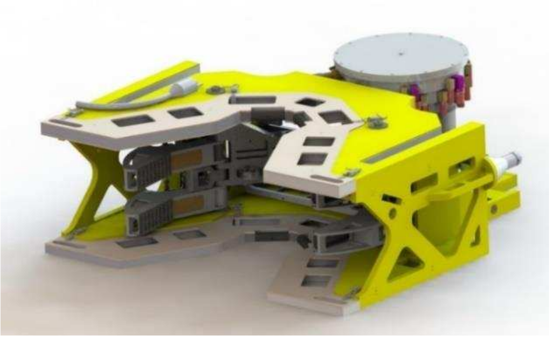
2.1. Clamping System

The clamping system is the main structure of the whole deployable part of the tool, which can be seen in detail in Figure 3. The structure is composed of different materials, mainly aluminum, stainless steel, plastics (POM, PEEK) and buoyancy foam (synthetic foam). The clamping system was designed with the following requirements:

- Gripping a range of different riser diameters (8 inches to 18 inches);
- Adjustment to irregular surface conditions of the riser (e.g. caused by marine growth).

Figure 3 - Clamping system in detail.



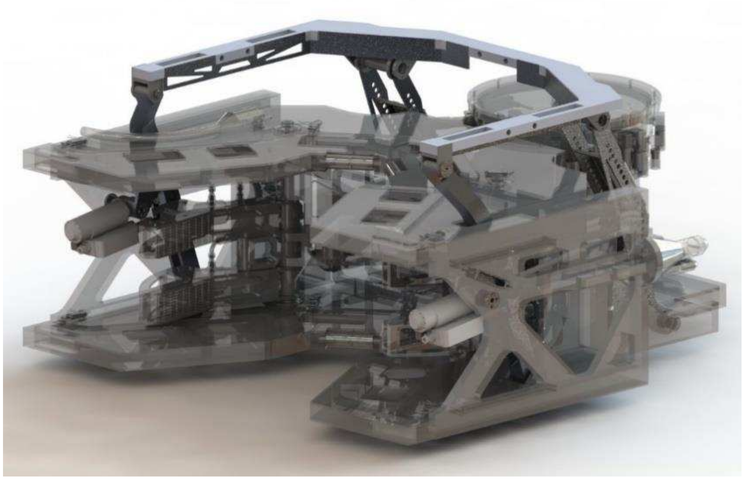
Source: produced by the authors.

Each side of the clamp forearm comprises two fingers equipped with hydraulic system on each finger, in order to reduce the impact on the riser, working as a damper and also pressure measurer.

2.2. Folding System

During both the cleaning and inspection operations, an axial arrangement of the tool is required so that the cleaning device and sensors may reach the elastomer surface in the flexible joint, whereas for storage in the ROV a horizontal arrangement is required (optimal storage and ROV control). Because of these requirements, the tool needs to be able to geometrically change its shape, and respectively its arrangement. Figure 4 highlights the folding system (a schematic view without the sensors), which provides the said morphological flexibility to the robotic tool.

Figure 4 - Folding system in detail.



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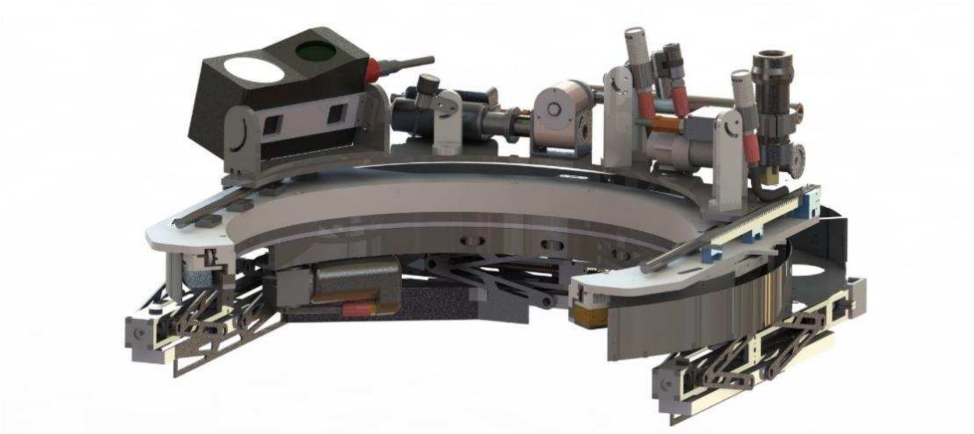
2.3. Instruments Table

The instruments table is the system that contains the cleaning device and the sensors responsible for the respectively the cleaning and inspection task. In order to accomplish the mentioned tasks, this system enables actuation in axial direction (adjusting the distance between instruments and elastomer surface), radial direction (moving the instruments either closer or farther from the riser) and rotational direction, so that the entire area of the elastomer surface may be submitted to the operation. Each of the mentioned direction has independent actuation. Moreover, the rotation around the riser is accomplished by stop-motion type of movement, meaning that the instruments are positioned at different sections of the riser circumference throughout the operation. The instruments table is depicted in Figure 5, in a representation detached from the robotic tool.

The cleaning operation is carried out by a cavitation water jet pointed at the elastomer surface during operation. The cavitation process produces bubbles of vaporized water, which implode on collision against the surface of the elastomer. The jets of water toward the surface of the elastomer, after the implosion of the bubbles, have enough energy to remove the marine growth.

Figure 5 - Instruments table in detail.



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The inspection task relies on a few sensors, comprising an HD camera for high definition photomosaic and a laser scanner for 3D point cloud representation. These sensors are backed up by LED lights and a surveillance camera, meant to observe the cleaning and inspection task. This system's design was conceived to meet the following requirements:

- Precision of rotational steps: maximum error of 98 mm for the Laser Scanner and 46 mm for the photomosaic camera;
- Steps necessary to achieve the minimum acceptable overlap of 3D data for the stop motion scenario: 12 steps;
- Steps necessary to achieve the minimum acceptable overlap of photomosaic data for the stop motion scenario: 24 steps;
- Distance range of the camera to the elastomer: 460-900 mm;
- Lifting adjustment of approximately 300 mm for the acceptable variation of attachment to the riser.

3. Methodology

The robotic system is planned to perform automatic procedures triggered by an operator, who may decide upon new cleaning and/or inspection tasks on a same flexible joint as they see fit. In order to achieve automatic instrument usage and provide system modularity, the JIRo system (skid and robotic tool) was developed using the Robotic Operating System (ROS), consisting of a framework comprising several software libraries for robot programming (Quigley et al. (2009)).

The system as simulated in virtual environment using the software Gazebo (Koenig and Howard (2004)) and UUV Simulator as physical engine and OpenSceneGraph (Wang and Qian (2010)) for graphic rendering (Manhães, Scherer, Voss, Douat and Rauschenbach (2016)). This environment allows for kinematic and dynamic simulation, so that control of joints and links in the robot as well as trajectory planned can be calculated and tested prior to deploying the software in the real robot. The simulation environment was used to verify several features of robot modelling, software integration and robot operation. Examples of the tested features are listed below:

- ROV operation;
- Virtual flexible joint (mockup);
- Camera view from the ROV perspective;
- HD Camera view in JIRo’s instrument table ;
- Laser scanner view in JIRo’s instrument table.

The simulated sensors enabled the testing of algorithms for riser inclination angle prior to attachment, photomosaic creation and 3D point cloud reconstruction, the latter two based on the data acquired at the virtual flexible joint. Moreover, the simulation environment enabled the development of trajectory algorithm.

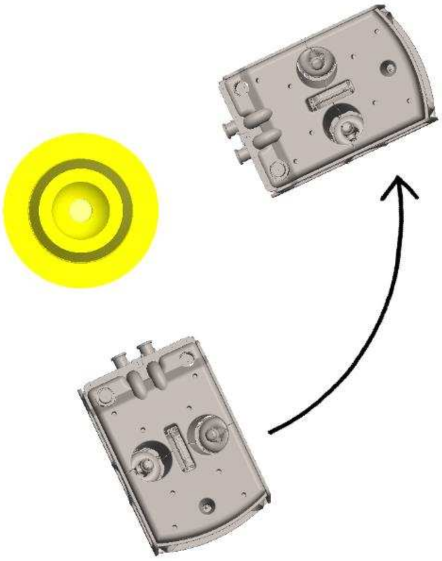
Besides the simulated environment, flexible joint mockups were designed to validate the algorithms run in simulation environment using actual data from JIRo’s sensors. A bench mockup was developed for testing trajectory and single sensor response, whereas an underwater mockup was built to assess sensor response and algorithm performance in underwater environment.

3.1. Measurement of riser inclination angle

The angle between riser and flexible joint’s center axis was the subject of a detection algorithm planned to be executed prior to the robotic tool`s attachment. It uses the information provided by the cameras of the ROV.

Since the angle between the riser and the flexible join may occur in any sector of the circular section of the flexible joint, it is necessary a few takes of the asset to estimate correctly the inclination angle. The procedure consists in flying the ROV around the riser in a sufficient angle in order to have all possible angle projections between riser and flexible joint. This procedure is depicted in Figure 6.

Figure 6 - ROV moving around the riser for inclination angle estimation.



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3.2. Photomosaic generation

One goal of the inspection task is to provide high definition images so that certain types of flaws in the elastomer surface can be readily identified by inspectors. The algorithm for joining (stitching) consecutive images taken form the elastomer surface in a complete turn around the riser was tested in simulation environment and with real flexible joint data.

The stitching process consists of the following steps:

1. Images preprocessing;
2. Feature selection / extraction;
3. Feature matching;
4. Image warping estimation;
5. Image blending composition.

OpenCV, a library for computer vision (see Culjak, Abram, Pribanic, Dzapo and Cifrek (2012)), was employed. All the steps (after the preprocessing) are performed automatically by OpenCV methods, which were adjusted by setting parameters focused in JIRo challenges.

3.3. 3D point cloud

Besides high definition images, the inspection task also comprises a 3D point cloud acquisition for assessment of physical integrity in the elastomer surface regarding damage in the surface profile. Data acquisition was carried out according to the previously described stop-motion takes and the Registration algorithm (the process of forming a complete 3D image from sections data) was tested in simulation environment and using the actual sensor under a flexible joint mockup.

The registration strategy consists of the following steps:

1. Normalization of partial point clouds by means of principal component analysis (PCA) (see Dougherty (2013));
2. Alignment of adjacent clouds based on the odometry data from the instruments table;
3. Refinement of the final point cloud using Iterative Closest Point (ICP) method described in Besl and McKay (1992).

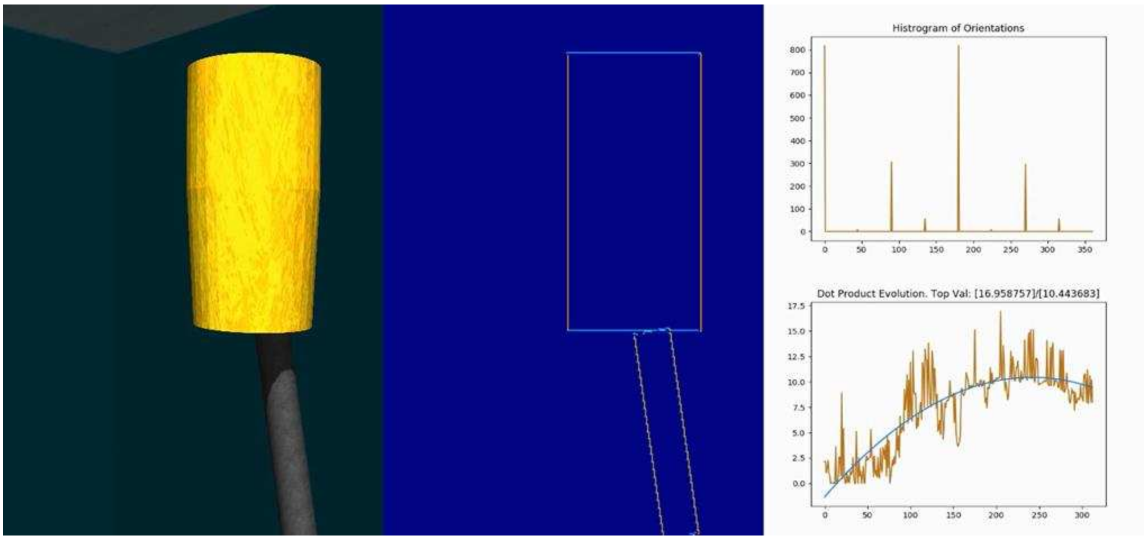
4. Preliminary results

The following subsections describe the results obtained for riser inclination measurement, photomosaic pictures and 3D point cloud acquisition.

4.1. Measurement of riser inclination angle

Figure 7 shows the angle estimation algorithm and a typical example in simulation environment. The pair riser + flexible joint is segmented into two distinct polygons. The angle between these two polygons' normal vectors, represented by the dot product between them, is measured for each image provided by the ROV as it surveys the asset (as in Figure 6). Each image provides a certain angle, corresponding to the projection of the 3D angle in the current image taken. A 2nd order polynomial regression is applied to the sequence of angle measurements, and the maximum value is considered the measured angle between the riser and the flexible joint.

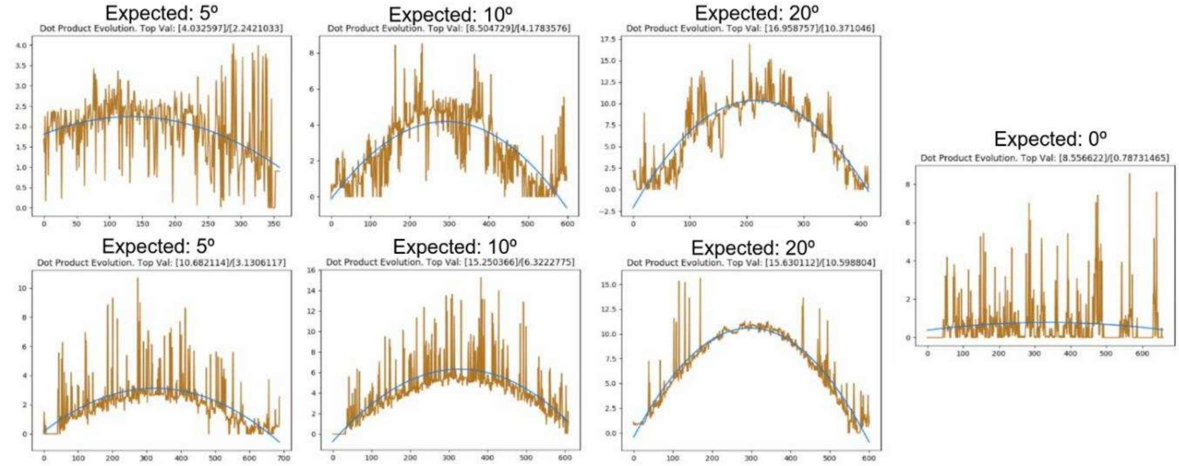
Figure 7 - Algorithm for inclination measurement.



Source: produced by the authors.

Figure 8 shows preliminary results of the detection algorithm for several simulated angles (in degrees) between riser and flexible joint. The peak in each polynomial fit (in blue in each graphic) represents the measured angle. The algorithm estimates the angle at about half the expected value, therefore a correction factor must be applied to the final result.

Figure 8 - Angle estimation.

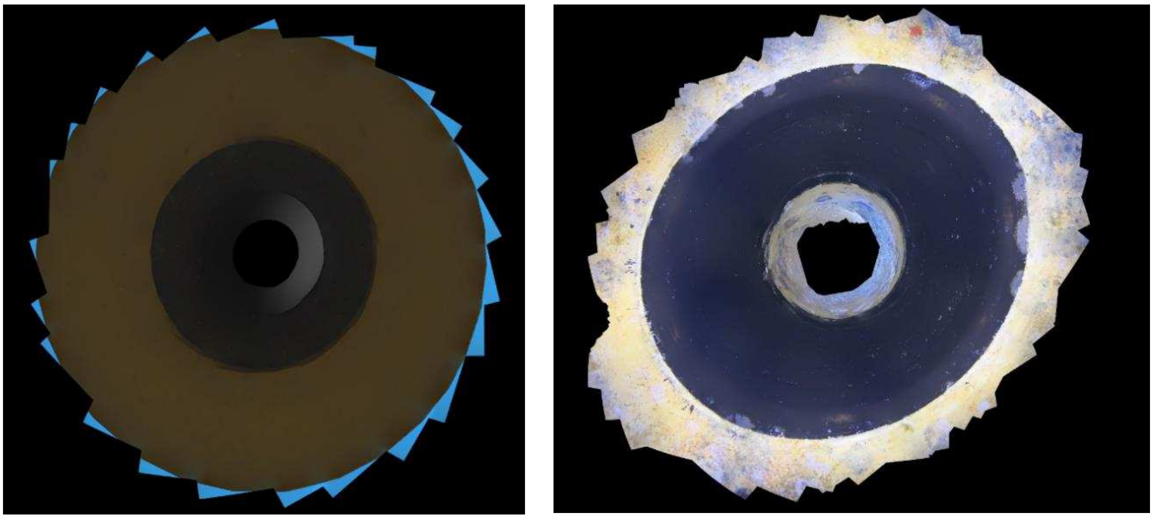


Source: produced by the authors.

4.2. Photomosaic

The results for both simulated and actual data can be seen in Figure 9, where the blurred boundaries between consecutive images can be noticed in the center and outer circumferences in both photomosaic images, as a result of the merging algorith

Figure 9 - Photomosaic results for simulation (left) and actual (right) data.



Source: produced by the authors.

In order to achieve better precision and reduce warping in photomosaic representation, the algorithm matches one image with the 2 next images (the last with the first and second). The code was adapted to support this project need, reducing the false positive between distant pieces, as the elastomer images present high similarity.

The simulated photomosaic result in Figure 9 was obtained with a set of images containing between 1100 and 1200 features, whereas the photomosaic image based on real data was obtained with images containing 1400 to 1500 features.

4.3. 3D point cloud

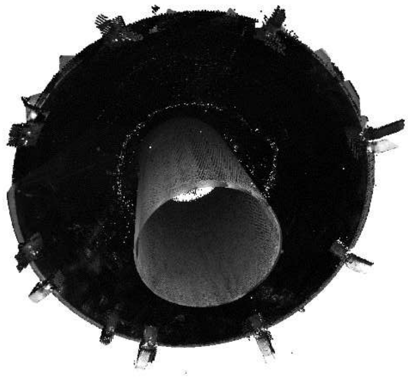
The results for simulated data can be seen in Figure 10, whereas Figure 11 presents the result for acquired data from a flexible joint mockup .

The registration of simulated data resulted in a point cloud containing 53832 points. Since the actual sensor produces a denser output than the simulated one, the corresponding 3D point cloud for real data resulted in 3158394 points after the registration step.

Figure 10 - 3D point cloud (left) and representation after mesh generation (right) obtained for simulated flexible joint.

Source: produced by the authors.

Figure 11 - 3D point cloud of life-size flexible joint mockup.



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5. Final remarks

This work presented the concept of a robotic tool designed to overcome the challenges of the inspection task in flexible joints on service in confined space under turret-moored FPSOs. Current commercial solutions cannot carry out the task using light workclass ROVs, for which the presented solution has been designed. The description of the system was presented, showing a general view of the robot and a detailed description of the main subsystems, respectively responsible for attaching to the riser, storage under the ROV and analysis of the flexible joint`s elastomer surface.

The preliminary results concerning simulated and real sensor data were presented for the inspection capabilities of the robot. Aspects of detection of riser inclination relative to the flexible joint, photomosaic representation of the elastomer surface and 3D point cloud reconstruction of the flexible joint were shown, and the results summed up to the system design indicate that JIRo is a suitable robotic solution for the target inspection task.

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