A Robot for Offshore Pipeline Inspection

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Abstract-The robot presented in this paper is conceived to inspect offshore pipelines to find potential damages to the external sheath. The section of the pipeline which is subject to inspection is known as riser and connects the pipe running on the seabed to the production facility at the platform or FPSO (Floating Production, Storage and Offloading) ship.

The main advantage of the robot when compared to the actual tools used to perform such work is to be able to execute the inspection autonomously, without umbilical cable or operator assistance. The vehicle, which is called Autonomous Underwater Riser Inspection robot (AURI), uses the pipeline itself for guidance. A closed loop control system, PID based, is used to maintain constant speed during immersion. Several sensors provides multiple return conditions for safe operation, such as maximum depth, time or running distance.

The robot is suited to carry different types of inspection devices. The first prototype performs only visual inspection using a built-in camera system which provides 100% coverage of the external pipe surface. All robot vessels were designed and tested up to 100 Bar of pressure, allowing the vehicle to reach a maximum of a thousand meters depth.

This paper presents the general concepts of the robot and results from the pool trials, including some hydrodynamic parameters of the vehicle.

I. Introduction

The Autonomous Underwater Riser Inspection robot was designed to inspect the riser for potential damages. A riser is composed of polymeric cylindrical elements, reinforced by layers of helical steel wires. Its integrity is threatened by a number of processes, ranging from imperfections during manufacturing, such as diameter variation, swelling and kinks, to damage during service. The most frequently occurring failure is external sheath damage, which accounts for 25%, according to a 2001 report by MCS. When the polymeric sheath fails, the steel wires may suffer from a corrosion process which reduces the typical service life of the structure from 20 to just 2 years [1].

The main type of inspection which is presently carried out in service on this type of structure is visual examination of the outer sheath and of attachments by a Remotely Operated Vehicle (ROV) or divers on the shallow segments. This type of inpection, like any visual technique, requires an experienced operator (diver) to faithfully report the status of the riser and imply very high costs due to the expensive ROV and its Support Vessel rental costs.

In order to find a better pipeline inspection technique the robot was conceived. The main advantages compared with current established procedures are reduced inspection costs, full pipeline surface coverage, improved productivity and reliability.

The robot was design to perform a complete pipeline inspection from the water surface down to near the seabed. Once the robot is launched, the inspection is performed automatically, without any further human assistance, returning to the surface when the mission is completed. To accomplish this, the whole tool must be autonomous both in terms of power supply and control. Unlike an ROV operation the AURI inspection is executed without any umbilical cable. The current prototype can reach up 1000 m depth. Future robot versions will be able to inspect ultra deep waters, up to 3000 m depth.

This robot is driven by a pair of electrical thrusters stabilized by a PID closed loop control system in order to maintain constant traveling speed. While it may be equipped with different types of inspection devices such as ultrasound and x-ray technologies, the actual version features a camera system to perform a visual inspection of the pipeline ensuring 100% coverage of the external sheath. The images are related to time and distance so any point in the pipeline can be uniquely identified. The data is stored to an onboard hard disk for later analysis.

The autonomous riser inspection vehicle concept is covered by BR Patent PI 0605010-7/2008 registered by Petrobras SA [2].

II. The Project

The AURI robot is composed of several systems that must operate in a coordinated and seamless way in order to ensure its mission success. It must also guarantee a safe operational environment for the human operators and the riser.

One of the primary concerns of an AURI mission is eliminating the possibility that the AURI gets trapped under the Touch Down Point (TDP), the end of the catenary curve close to the seabed, and gets crushed by the weight of the riser causing damage to the pipeline. Mechanical fuses were added to specific locations on the structure so that it will break in a predicted safe way without releasing sharp hard pieces.

The robot was designed to be intrinsically safe since, in case of severe electrical failure, it will return automatically to the surface thanks to its positive buoyancy.

The vehicle is a ring-like structure that is mounted around the riser by a single latching opening having just one degree of freedom. This ensures the easy mounting of the AURI by a diver. The opening mechanism also requires just a single handle which allows a ROV to release and rescue the AURI in case it gets stuck in deep waters.

Many sensor techniques can be adapted as payload for the AURI. The current prototype is equipped with a visual inspection system composed of a set of digital photographic cameras and high power white LEDs.

1. Structure

The first challenge of the project was designing a mechanism with rollers that could guide the vehicle along the riser while adapting to the diameter variations, swelling and obstacles and that could be easily handled by a diver on deployment and recovery. The structure that acts as the chassis of the AURI, shown in Fig. 1, must be rigid enough to support all the electromechanical parts during the mission, withstanding the intense water currents, while soft enough to not present any damage risk to the riser.

To obtain the positive buoyancy of the AURI, special floaters were designed employing high density resin embedded with air-filled glass micro spheres. The floaters were molded on an aluminum structure and covered with thin fiberglass plates. That way, the floaters were incorporated in the structural elements of the vehicle while maintaining a density less than the water. These slim structural elements are very rigid carbon fiber bars that work to bind the floaters together without compromising the desired aggregate density.

2. Pressure vessels

Several waterproof compartments designed to withstand pressures over 100 bar (equivalent to 1000 meters of depth) house the AURI's electronics and sensors. In order to minimize weight while preventing corrosion, they are made of fully coated hard anodized aluminium.

As this AURI version is designed to perform visual inspections, it includes twelve small pressure vessels with optical windows rated for 100 bar. Four of them house the digital cameras and have special polycarbonate optical windows. The remaining vessels house a super bright white LED each. Each vessel is also equipped with a conical shaped lens thick enough to support the pressure itself. All vessels were tested in a hyperbaric chamber before assembly in the vehicle.

3. Suspension

Eight rollers are mounted on suspension bars to allow inspections of risers having diameters ranging from 190 to 360 mm. The suspension system will absorb impacts and negotiate variations of the outer layer or possibly incrustations, preventing the AURI from getting stuck.

As the vehicle needs to be efficient in both directions, a neutral caster angle system was chosen [3]. The rollers have 100 mm of diameter and can overcome sharp obstacles of up to about 25 mm high.

Before mounting the AURI around the riser, one must perform sleeve adjustment on the suspension bars for the desired diameter. With the operating suspension range set, the forces required to fit and close the mechanism are small enough that a single diver is able to do it. The suspension adjustment also prevents the riser from escaping off the quad formed by the rollers, as shown on Fig. 2.

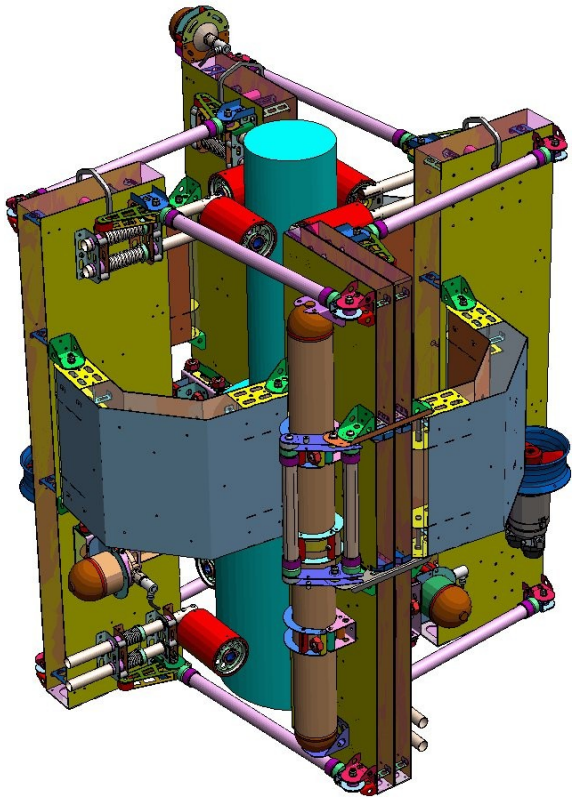


Fig. 1. General view of AURI's main structure.

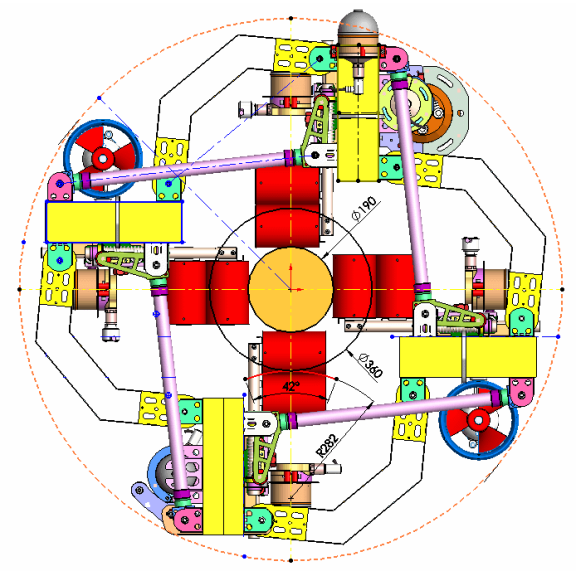


Fig. 2. Top view of suspension enclosing the riser.

4. *Propulsion*

AURI is propelled by two 1350 Watt electrical thrusters that can provide 56 kgf of total force, Fig. 3. Only part of this propulsion power is needed to keep the speed constant during normal operation, but the vehicle has enough force headroom to negotiate unexpected obstacles.

Part of the propulsion force is used to overcome a positive buoyancy of 14 kgf (about 140N). The other forces involved are due to various friction effects (dynamic, viscous and cinematic) that may depend on current speed. The target submersion speed is 0.5 m/s and, while returning, the emerging speed can be as high as 1.2 m/s.

5. *Onboard sensors*

The AURI prototype is fitted with several sensors: (i) four Firewire cameras, (ii) a pressure transducer, (iii) two odometers, (iv) a digital compass, (v) an inclinometer and (vi) five thermometers.



Fig. 3. Electrical thruster.

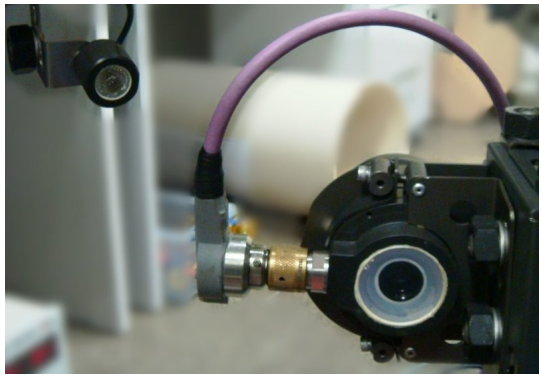


Fig. 4 LED spot (upper left) and camera detail.

The four cameras are used to acquire the images of the riser. The power white LEDs lighting system is necessary due to the lack of light in the underwater environment. LED and camera are shown in Fig. 4. LEDs are off most of the time and are only lit for a brief period which is synchronized to the camera's shutter in order to not waste energy.

The lens for the camera and LED modules has been designed to optimize the illuminated area and the focus distance. In particular, the design for the camera module had to take into account the different diffraction coefficients of the air inside the module, the glass and polycarbonate of the window and the seawater.

Because the vehicle might inadvertently spin around the riser during the mission, a digital compass was added to allow the exact positioning of the acquired images. The compass is connected to the onboard computer using a RS-232 link.

The pressure transducer is meant to provide the computer with information about the current depth. The maximum depth is one of the parameters set on the vehicle before starting a mission. Because of the uncertainty of the pressure sensor measurement (about 5 meters), the depth value cannot be used to reference the images. For that purpose, two odometers are used instead. These have been installed on two of the eight rollers of the AURI. The redundancy of the two odometers allows the distance to be accurately measured even in the case of slippage of some rollers.

The importance of the odometers is twofold: (i) the traveled distance triggers the image acquisition system, allowing for a predefined superposition between shots to ensure 100% coverage and (ii) they are also part of the closed loop which controls the tool speed. Using the odometer feedback, the onboard computer will adjust the power of the thrusters to maintain the immersion speed approximately constant.

6. *Embedded computer*

The entire system is powered by two sets of batteries. One is used for all the control systems, computer and sensors and the second is used only for the power circuits of the electrical thrusters.

After the vehicle is deployed on the water, the only human interface with the system is a single magnetic switch. The

switch is a small Hall sensor positioned in a well defined spot of the vessel. The diver has to hold a permanent magnet to this spot during three seconds to start the mission. This startup mechanism has no moving parts, does not require the vessel to be open and is robust against non intended triggering.

Before the diver starts the mission, the AURI is in a very low power consumption mode. Both the computer and the high voltage supply for thrusters are completely shut off. The only circuit which remains powered is a micro controller that watches the magnetic switch command.

When AURI is started, an embedded computer is powered up ans takes control of the system. The computer module is a commercial product targeted for real time image acquisition and processing applications. It is the decision center of the tool, managing all the tasks related to camera and sensors acquisition, thruster control and storage of the inspection data in an 80 GB hard disk.

The batteries employed in the AURI are rechargeable Ni-MH (Nickel-metal hydride), chosen due to their high current discharge capabilities.

The vessels are interconnected by electrical cables and special high pressure connectors. These connectors were terminated using both epoxy resin and polyurethane to provide anchoring for the cables. All parts were tested in a hyperbaric chamber for a work pressure of 100 bar.

7. Software

The embedded computer provides an Ethernet connection that has multiple uses: (i) software upgrade, (ii) on-the-fly testing capabilities of all sensors and actuators (iii) mission parameters setting and (iv) inspection data download.

The AURI's control software is composed of several tasks to control the sensors and peripherals, store the inspection data and logs, manage the Firewire bus, command the return of the vehicle and run the closed loop speed control.

The firing of the camera shutters and LEDs is controlled to micro second resolutions. This resolution is critical to ensure that enough light is provided to the camera's CCD in a reduced exposition period required to avoid blurring the images because of the vehicle's movement.

The maximum downward speed is also determined by the Firewire bus because of the transfer time from the cameras to the CPU. Considering the camera resolution and Firewire's synchronous bandwidth, the maximum image acquisition and storage is about 3.75 frames per second. As each camera shot covers about 300mm of the riser's length, the target speed of 0.5 m/s is within the capabilities of the acquisition system. A small superposition between acquired images allows seamless joining of the data in the post-processing stage.

A lot of care was devoted to creation of robust and safe end-of-mission logic, that is, when the AURI decides it is time to revert its thrusters and return to the surface. The mission is considered complete when one of the following conditions is met: (i) maximum pressure on depth sensor is reached or (ii) the specified traveled distance is achieved or (iii) maximum mission duration time is exceeded or (iv) maximum allowed tilt is detected by the inclinometer. In other words, the AURI may decide to return based on depth, traveled distance, predefined timeout or proximity to the TDP (the catenary inclination). All these parameters can be set by the operator before the start of a mission.

The embedded computer is also continuously monitored by a watchdog circuit. In case of failure of the computer, the microcontroller will shutoff all systems, including thruster's power supply, forcing a return by buoyancy. Even if the batteries get totally exhausted the tool will return naturally to the surface, effectively working as a deadmans safety mechanism.

III. LAUNCHING PROCEDURE

The AURI is transported in a metallic tubular structure (a cage) to the inspection area. A crane must be used to deploy the equipment into the water because the entire structure weighs more than 200kg. Once in the water, it has slightly positive buoyancy and can be easily moved to enclose the riser. The AURI is fixed around the riser and the transporting cage is removed.

During the entire launching sequence, the LEDs will blink every 3 seconds to show that AURI is in standby mode waiting for a command. The mission may then be started by means of the magnetic switch.

The power-up and self testing sequence of the computer and sensors takes about one minute. After this a fast flashing sequence of the LED modules (3 Hz during 30 seconds) will inform the operator that the AURI is ready to start moving. At this point, the diver must take a safe distance from the vehicle because the thrusters will be powered soon.



Fig. 5. Preparation for a pool test, AURI mounted on the pipeline..

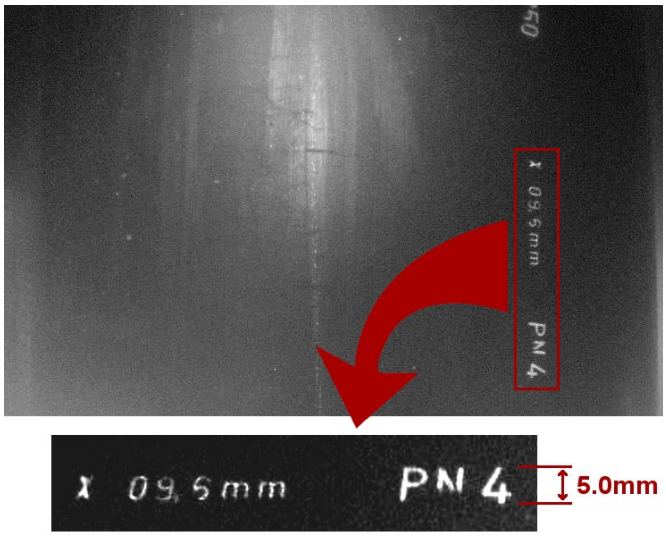


Fig. 6. Detail of a text marking on the pipeline. The image was acquired by AURI using its underwater lighting system.

When the mission is considered accomplished by the control software, the AURI will automatically enter the returning mode. Although the buoyancy is positive, the AURI may decide to revert its thrusters in order to aid the emerging and overcome any obstacle that is encountered.

IV. Testing

So far, the AURI has only been tested in a pool environment with offshore tests scheduled for later this year.

The testing setup included a 6 meter deep pool, load lifting facilities a movable platform for tool assembly and operation, and long electrical cables for real-time instrumentation.

The Fig. 5 shows the AURI mounted on the pipeline on tests preparation.

The following tests were performed:

1.General system checklist: tests each subsystem functionality individually, including sensors, lighting system and image acquisition.

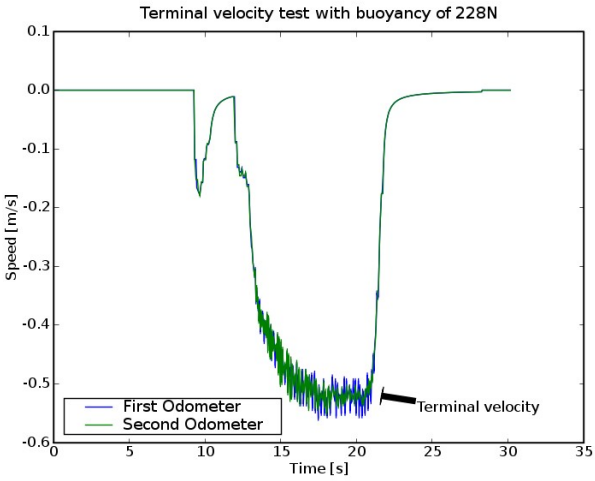


Fig. 7. Emerging speed test with net buoyancy of 228N.

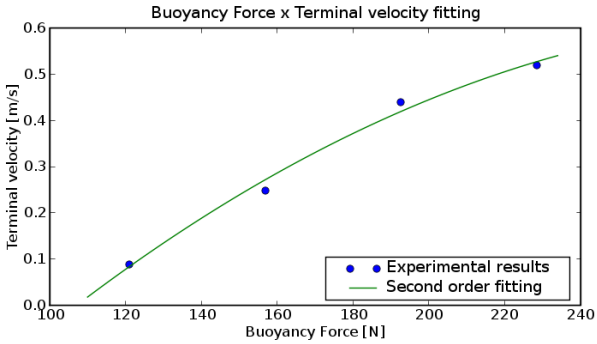


Fig. 8. Second order fitting of the speed x buoyancy experiments.

2.Balancing and buoyancy: the vehicle is fine tuned with extra weights added to the lower part of the structure. The center of mass must be set precisely below the center of buoyancy so that it stays in a straight upright position and applies no lateral forces to the pipeline. The difference between buoyancy and weight is adjusted to meet the project target of 140N positive.

3.Thruster measurements: the force produced by each thruster is measured using a load cell between the AURI and the crane. The electrical current is recorded to check if autonomy requirements can be met with the available battery power.

4.Mission testing: the AURI return condition is set to less than the pool depth to simulate a complete image acquisition mission.

5.Terminal velocity measurements: final return speed of the tool is recorded for several buoyancy configurations using onboard electronics. This experiment allows for determination of viscous friction coefficients which are very difficult to obtain from computer simulation.

1. Results

The pool testing has successfully verified that the mission control logic works for different returning criteria. The AURI was configured with a 4 meter depth mission to record images of the pipeline and then return without any user intervention.

The illuminating settings for underwater image acquisition were tested and found to be appropriate, as well as the shutter settings to ensure sharp and good quality images. The images were clear enough for a small 5 mm text on the pipeline to be easily read, as shown on Fig. 6.

The forces produced by the thrusters were measured and found to be in agreement with manufacturer's specifications.

Experiments were performed to find out the dynamic and viscous friction coefficients of the vehicle. Each test was executed using a different set of weights attached to AURI. The vehicle is placed on the bottom of the pool and then set free to return to the surface. The emerging speed was recorded by onboard electronics and odometers. The Fig. 7 shows the result of one such experiment with a net buoyancy of 228N.

Estimation of the friction coefficients involved is possible by performing emerging speed tests with several buoyancy

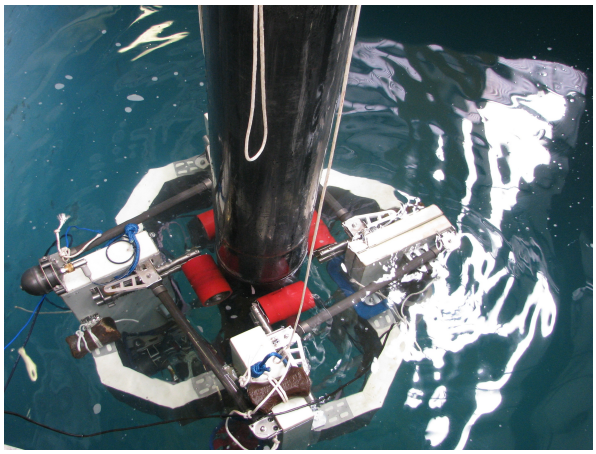


Fig. 9. AURI immersion during pool test.

values. Some friction forces, like those due to the suspension rollers, have no dependence on speed. Therefore, the dynamic friction force can be separated from viscous friction effects after fitting the experimental data to a second order polynomial, as shown in Fig. 8.

It was found that the dynamic friction of the rollers was much higher than expected, requiring more buoyancy than 140N to reach the emergency hydrostatic return speed of 0.6m/s. This was due to a problem in the suspension design. A new round of tests was performed two months later with a new suspension design installed on AURI. This time the dynamic friction was considerably smaller and project's specifications were met.

The total mission time to inspect 1000 m of riser is calculated to be 44 minutes, including return time. The onboard available energy allows for a significant safety margin of autonomy twice this value, considering the thruster's current consumption required to maintain 0.5 m/s.

V. Conclusion

The AURI project provides formidable challenges in terms of electronics and mechanical engineering to create a new robot capable of autonomous riser inspection.

The tests performed so far confirm the viability of the system for that application. The robot has the potential to drastically reduce the current riser inspection costs improving productivity and reliability. The vehicle will be used as a platform for new types of inspections using other techniques that are currently unavailable in the field.

Offshore tests on riser pipelines are scheduled to take place later this year. A few adjustments are currently being performed on the equipment based on results obtained during pool tests to improve the hydrodynamics and the ease of operation of the robot.

Acknowledgment

The development team would like to acknowledge our Petrobras partners for the concept, motivation and funding. Our thanks to the LNDC/Coppe laboratory for providing the testing facilities.

References

[1] O'Brien, P. and Picksley, J., 2001, “State-of-the-Art Flexible Riser Integrity Issues”, MCS International

[2] Marnet, R. V. and Silveira Jr, E. L., 2008, “Equipamento para limpeza e inspeção de risers flexíveis em catenária livre”, Patent number PI0605010-7. Petroleo Brasileiro S.A.

[3] Gillespie, T. D., 1992, “Fundamentals of Vehicle Dynamics”, SAE International.