Amphibious Inspection Robot

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The paper presents the test results of a swimming and floor moving robot inspection system to test welds located inside a floating production storage and offloading oil tank (FPSO tank). Currently these welds are inspected manually by first emptying and cleaning the tank. This is a time consuming and expensive operation that requires operators to enter a hazardous environment. Significant cost reductions could be made by automating the inspection with robots that provide access to the welds. The simplest way to do this is to empty the tank so that only two to three centimeters of oil remain on the tank. A floor moving robot would then operate autonomously in the tank to follow and inspect the welds. A better solution is to perform the inspection in a full tank. In the first case the robot would operate in air and an explosive environment but would eliminate the need to swim the robot through a very complicated maze of partitioning walls and rows of strengthening plates that occur every 700-900 mm. In the latter case the robot would swim to a strengthening plate and operate under oil thereby eliminating the need to empty the tank. An amphibious mobile robot called FPSO is described which is capable of performing NDT in air and when submerged in liquids.

1. Introduction

An FPSO system is an offshore production facility that stores crude oil in tanks located in the hull of the vessel. The crude oil is periodically offloaded to shuttle tankers or ocean-going barges for transport to shore. FPSO systems may be used as production facilities to develop marginal oil fields or fields in deepwater areas remote from the existing outer continental shelf pipeline infrastructure (figure 1). They are used to store oil before transportation to the mainland. There are currently 70 FPSOs in operation or under construction worldwide.

For structural safety and environmental reasons, it is necessary to test the welds frequently. The main inspection task is to test the integrity of welds on plates which are used to strengthen the walls and floor of the tank (figure 2). Currently, they are inspected manually by first emptying the tank and thoroughly cleaning it; human operators then enter the tank to perform ultrasonic NDT. There is a large cost associated with the cleaning and inspection tasks. A pair of tanks are emptied, cleaned and inspected in 3-4 weeks with 60-70 man-days work. The FPSO inspection task and suitable Non-destructive Testing methods are reported in [1-3].

The aim of the FPSO project is to build a prototype amphibious robot vehicle that can carry Non-destructive Testing (NDT) sensors from an entry port in the top of an FPSO vessel tank, to the floor or sides of the tank, where the NDT sensors can be deployed from a scanner to detect either fatigue cracks in the stiffener to tank shell fillet welds, or corrosion in the shell plates.

This robot has to be amphibious, able to swim in water or oil and capable of carrying Non-destructive Testing (NDT) sensors from an entry port in the top of a FPSO vessel tank to the floor of sides of the tank, where the NDT sensors can be deployed to detect either fatigue crack in the stiffness to tank shell plates.

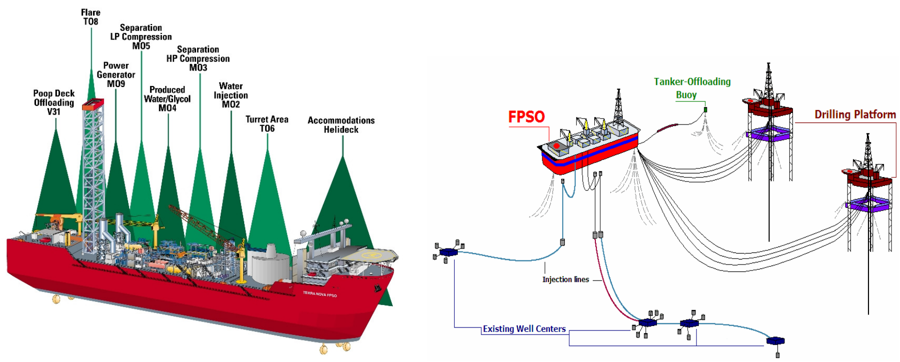

Figure 1: Floating Production, Storage and Offloading (FPSO)

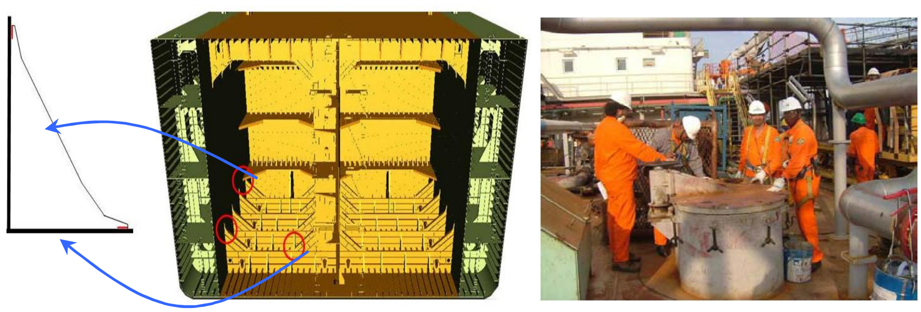

Figure 2: Left: Stiffener plates shown in a cross section of two FPSO tanks.
Right: Entry port for robot insertion

2. Robot System Development

The FPSO swimming and wall-climbing robot developed for inspection is shown in figure 3. It is compact and small so that it can provide access to welds on strengthening plates on the walls and the floors of tanks in a much cluttered environment, and can be inserted through a manhole with 600 *mm* of minimum diameter. It is able to operate between two adjacent longitudinal strengthening plates separated by a distance of 900 *mm* with the transverse frames separated by a distance of 4.5 *m*. In FPSO's owned by BP, the manholes are two elliptical hatches in each cargo tank with approximately size of 900x600 *mm*. FPSO's operated by Petrobras have approximately 600x800mm openings.

Its mass is approximately 20 *kg*, so that is transportable by one or at most two operators. Both, the walls and the floor are cluttered with strengthening plates so that unhindered motion by a small robot on the walls or the floor is not possible.

Access to welds is obtained by swimming over the plates from one section of the tank to another and then landing on a wall or floor between the plates. The NDT inspection requirement is to inspect vertical welds as well as horizontal welds.

In order to deploy and mobilize itself in the complex environment of the tank interior, the designed robot travels on the floor and is able to swim. To fulfill inspection duties, it is able to carry a payload of NDT equipment. The robot can maneuver freely on the wall, move from the wall to the floor of the tank and back.

All the control systems of the robot are embedded on-board, in an air pressurized central chamber sealed to prevent the ingress of liquid through any leaks at the rotating shafts emerging from the central chamber and through NDT sensor probe cables.

Most hardware systems are placed onboard the robot. The reason for this is to reduce the size of the umbilical cord so that cable management becomes easier.

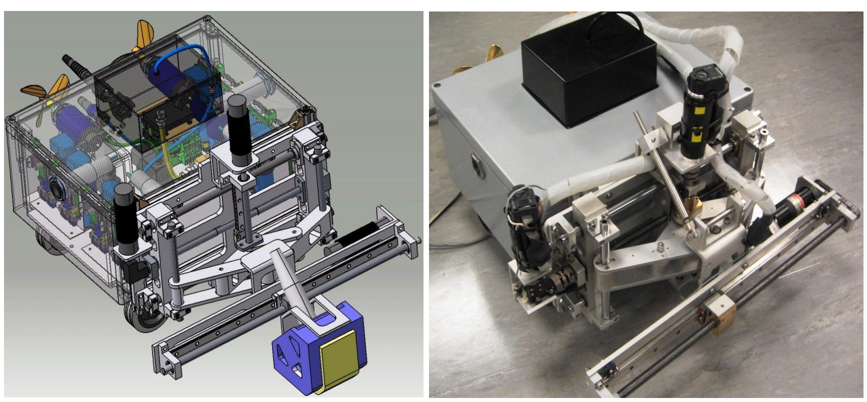

Figure 3: Amphibious robot that is designed to operate in air as well as submerged in water (at this stage) though eventually it has been made intrinsically safe to operate in crude oil (API 20 to 40).

The robot consists of a buoyancy tank on top (figure 3) that adjusts its buoyancy around neutral by controlling mass. A depth sensor provides the feedback to regulate the depth at which the robot is required to maintain its position anywhere in the tank.

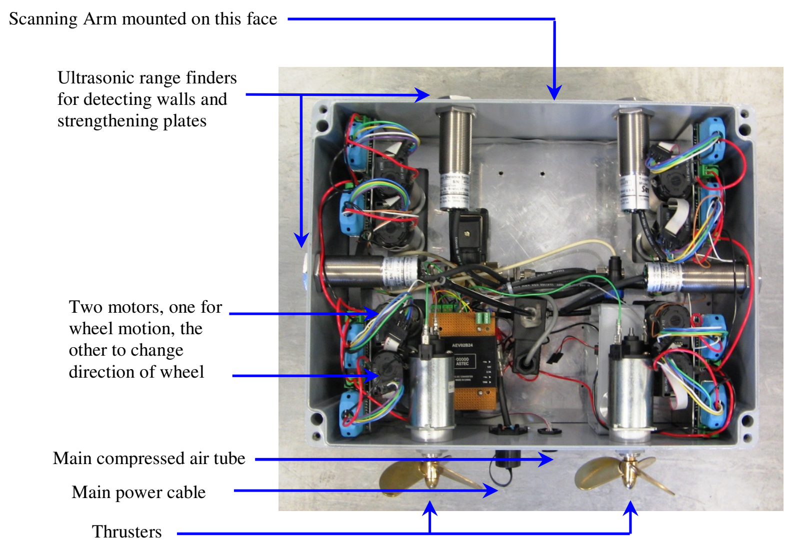

Figure 4: A single pressurized box housing all the on-board servo controllers, motors and sensors for the amphibious FPSO Robot.

Thrusters control the horizontal motion of the swimming robot. The navigation system to control the robot's orientation when operating on the floor of the tank consists of four ultrasonic range sensors operating at 10 KHz that profile the surrounding strengthening plates and tank walls. These sensors are used to align the robot and to guide it autonomously along welds between the floor and strengthening plates and the toe ends of the plates. The sensor range is 40mm to 1040mm, resolution is 0.086 mm max., repeatability is nominal 0.1% of range in constant temperature and is affected by target, distance or environment. The sensor protection is to IP68. The sensors communicate with the controller using RS-232, RS-485: 6 bytes, 9600 baud, 8 data bits, 1 stop bit, no parity. Up to 32 sensors can be wired together for operation in the same area

Wheel angle sensors: 4 magnetic sensors determine home position (zero degree) of the four wheels which can individually turned and pointed in different directions. For example, changing the angle by 45 degrees from home enables the robot to be rotated on its own spot.

The Cartesian scanner shown in figure 3 carrying an ACFM probe scans the welds after the robot has been positioned correctly.

3. Robot Trajectory For Weld Inspection

Robot trajectory (figure 5) in a constrained space for precise weld following around plates and side walls requires motion that is straight-line along welds, 90º rotation to present the scanner arm correctly when going from a plate to a side-wall and back onto the next plate. Special mechanisms have been designed to rotate all four wheels through turning angles between ± 180º and to independently control the speeds of all four wheels.

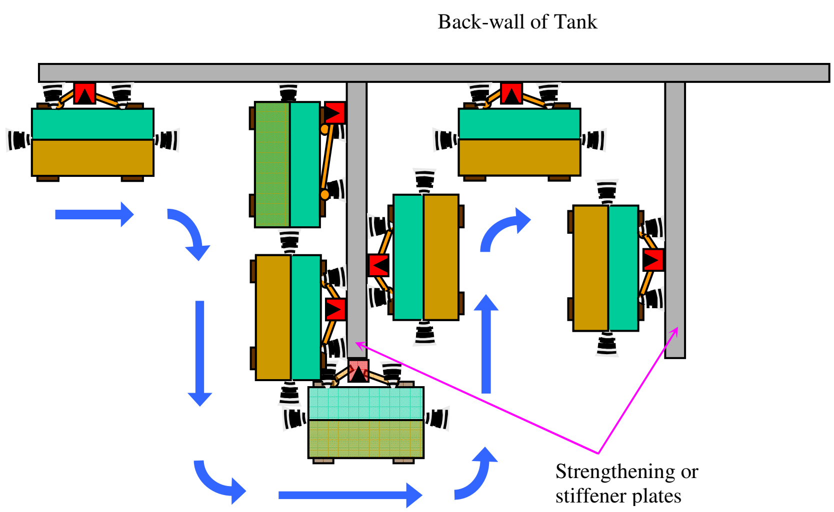

Figure 5: Trajectory and robot orientation for following welds around stiffener plates. Four ultrasonic range sensors are used to locate the plates and enable the robot to apply the NDT probe to the weld.

The robot is made highly maneuverable by designing a special mechanism to independently twist the facing angle of the four wheels of the robot. For each wheel two motors are used in the configuration shown in figure 6 to twist the facing angle of the wheel and to rotate the wheel. Foe example, rotating the wheels at an angle of 45 degrees from the home position enables the robot to rotate on the same spot. Similarly, the robot can move at 90 degrees to its previous trajectory to follow the weld from a back wall to a stiffener plate.

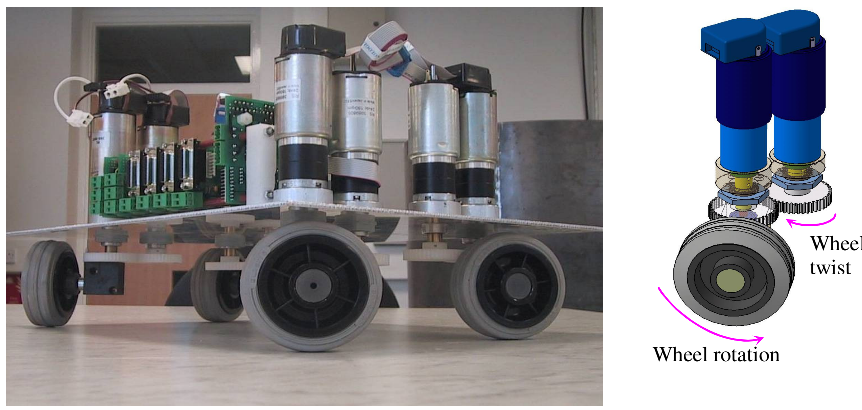

Figure 6: Rotating wheel mechanism to provide high maneuverability to the robot

The two ultrasonic range sensors on the front of the robot are used to first locate a wall plate or a stiffener plate. The robot then rotates at the same spot till it is normal to the plate (equalizing the distance on both sensors). It then moves towards the plate and stops at a given distance so that the scanner arm can move the NDT probe along the weld. The robot follows the weld along the plate, keeping a fixed distance from it, till a side wall is detected by the sensor on the side of the robot. The robot can then be rotated by 90 degrees at the same spot till it is facing the other plate. The sequence is repeated to go from wall to stiffener and to the other side of the stiffener etc.

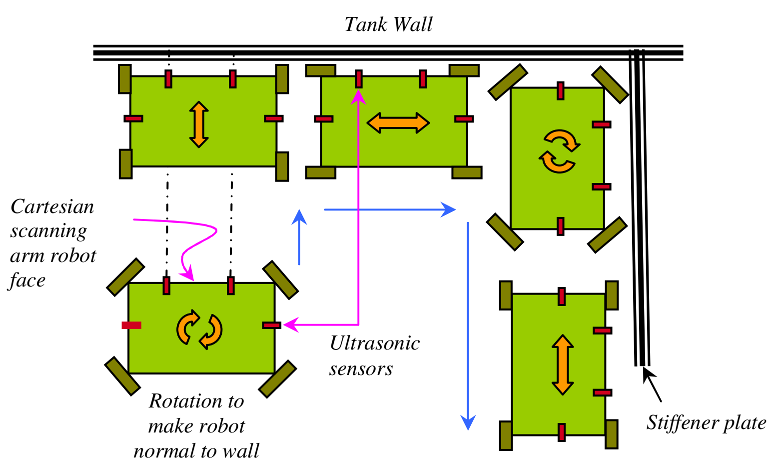

Figure 7: Use of range sensors to follow welds along wall and stiffener plates

4. Robot Swimming Performance

Figure 8 shows the robot in a 7 meters deep water diving tank. Depth regulation is effected by using buoyancy control by changing mass. Figure 8 (left) shows the robot on the surface taking on water to obtain negative buoyancy to sink the robot. The water level is adjusted to obtain neutral buoyancy to remain at a given depth (middle picture). Water is expelled, aided by air pressure, to obtain positive buoyancy to ascend to the surface (right picture).

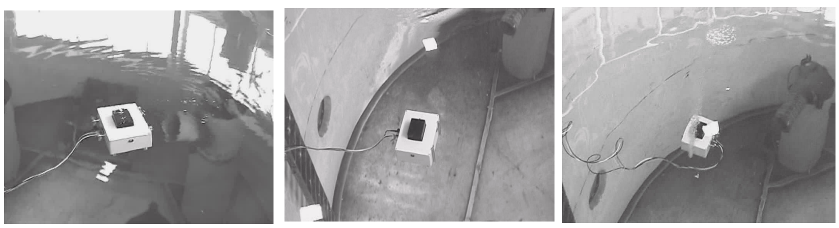

Figure 8: FPSO swimming robot in a water tank. Vertical motion by depth sensor feedback and buoyancy control.

Figure 9 shows the robot descending to the floor and moving around with wheeled motion. The floor can be inspected with the trajectories described earlier.

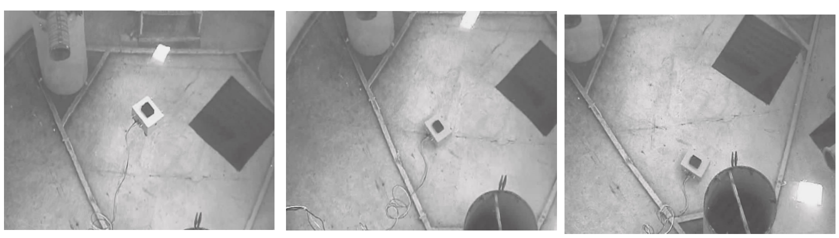

Figure 9: FPSO swimming robot in a water tank. Robot descends to the tank floor and moves on the floor to follow weld lines along stiffener plates and walls

Figure 10 shows the robot swimming horizontally to gain access to the wall surfaces of the tank. Two thrusters are used to obtain this motion.

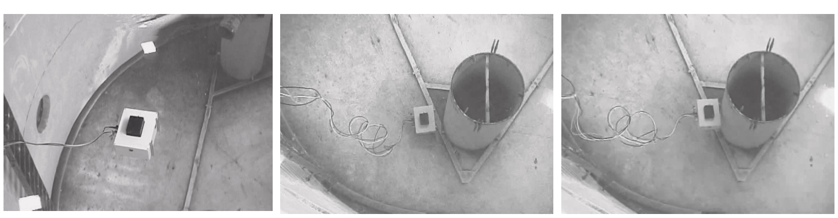

Figure 10: FPSO robot swimming horizontally to inspect wall surfaces

5. NDT Results

The NDT tests were done on the mock up of stiffener plates shown in figure 11. ACFM and Ultrasonic Plate waves methods were used.

Figure 11: FPSO amphibious robot shown performing NDT with ACFM arrays (on the right), and ultrasonic plate waves (on the left)

Acknowledgments

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References:

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