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UNDERWATER ROBOTIC VEHICLE FOR SHIP HULL INSPECTION: CONTROL SYSTEM ARCHITECTURE

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Abstract. *The inspection of underwater structure thickness has emerged as an unique and challenging application of robotics. Underwater robots with adherence system are required to precisely determine the position of cracks in these structures. This technological problem has motivated to a group of researchers of the Federal University of ABC for the development of a Hybrid Remotely Operated Vehicle (HROV) having ultrasonic transducers to check the thickness and possible cracks in ship hulls. The HROV consist of a mechanical structure made of polypropylene plates, a pressure vessel for control electronics, a set of sensors, six thrusters, two motorized tracks, an acoustic positioning system and an umbilical cable. This vehicle is classified as a hybrid robot due two operation modes: free-flying and crawler. While in the first mode the vehicle uses thrusters at the second one use the motorized tracks for its locomotion on the surface of the ship hull. The adherence to the ship hull is guaranteed by applying a force normal to the hull surface from vertical thrusters. This work describes the hardware and software architecture developed for controlling the motion of the HROV. The HROV control architecture is based on the VxWorks Real-Time Operating System running on a PC/104 single board computer.*

Keywords: *Underwater robotic vehicle, control architecture, real time system.*

1. INTRODUCTION

On the last years, Petrobras have increased the number of the floating unity of oil production in deep and ultra-deep water and has plans for installing other soon, becoming the first company in number of these kind of unities. From all kind of floating unities, the platform-ships or FPSOs (Floating Production, Storing and Offloading) are the most important for their technical and economic characteristics. FPSOs produce, store and transfer oil and are built from the conversion of the hull of a tank-ship or from a new hull project. In face of this demand of use of FPSOs in Brazil, there is the needing of guarantee the structural integrity of these ships hull. Structural failures in FPSOs are devastating, causing the loss of human lives, pollution on the sea and economic losses.

The purpose of the underwater inspection of ship hulls is to verify the structural integrity of the floater and ensure the safety of personnel and production equipment. It is required by internal rules and by international maritime conventions applicable to floating units. Hull inspections, typically, check the state of the coating and the remaining thickness of plates.

Traditionally, the FPSO hull structural integrity evaluation is performed in a dry dock or in high seas by divers. These methods of inspection have the following disadvantages: the first provokes economic losses due to the oil production cycle stop while the second one is not so reliable (due to human errors possibility). At this scenario, a robotic system which is able to perform the inspection of a FPSO hull in high sea seems to be an economic and reliable solution.

A group of researchers of the Federal University of ABC motivated by this technological challenge are developing a Hybrid ROV (Remotely Operated Vehicle), in this work is named HROV, able to perform the inspection of a FPSO hull in high seas. This vehicle poses ultrasonic transducers to check the thickness of the hull and possible cracks.

The HROV is a concept of underwater inspection robotic system. This is classified as a hybrid robot due its two operation modes: free-flying and crawler. While in the first mode the vehicle uses thrusters at the second one use the

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motorized tracks for its locomotion on the surface of the ship hull. The free-flying mode enables the operator to freely inspect the ship hull until a region or object of interest is located. A characteristic of the HROV is that its adherence to the ship hull is guaranteed by applying a force normal to the hull surface from the thrusters, avoiding, thus, the use of complex electromagnetic devices, magnetic wheel and suction vortex generator.

In recent years many researches have been published on this area, between them, could be cited the work from the MIT (Massachusetts Institute of Technology) with Bluefin Robotics Corp. On their project of an HAUV (Hybrid AUV) used to ship hull inspection with a Dual Frequency Identification Sonar (DIDSON). On this project the HAUV is maintained at least one meter from the ship hull in a free-fly movement normal to the vessel, and the DIDSON is used to inspect the plate and profiles. The possibility to inspect the hull without need to contact the vessel is an important development of this project, due to this it is not necessary to prepare the hull (Vaganay, Elkins, et al., 2007). As an autonomous system the HAUV has a map of the structure to be inspected, during the inspection the vehicle navigates above the ship in a stand-alone operation using sparse features on the hull caused by protruding objects such as anodes and welding lines for correct the actual position of the vehicle (Kaess, Johhansson, et al, 2010).

The LAURS developed at USP (University of São Paulo) was developed to recovery transponders used to help the positioning of ships. LAURS has a similar configuration of sensors (on exception of DIDSON) and actuators comparing with MIT's HAUV, but has a real-time embedded system devoted to sensor data logging, guidance and motion control. The real-time operational system (RTOS) was the VxWorks, software of WindRiver (Avila, 2008). Among the advantages of its use are the guarantee of timely response to external and internal events (Wang, Ngolah, et al., 2010) and the multitasking. Another project with uses a VxWorks as a RTOS is the SY-2, ROV that also uses the same set of sensors and actuators as LAURS, but was projected to inspect ship hull, maintaining offshore drilling platform and underwater steel structure of Nuclear Power Plant (Li, Pang, et al., 2009). SY-2 was developed by Harbin Engineering University.

The company SeaBotix Inc built a ROV called LBV-5 to inspect ship hulls and marine structures, the difference from the previous works is the presence of wheels to crawl across the structure during the inspection, reducing the level of control from the operator, and the number of degrees of freedom, working in a two dimensional environment instead of a three with the direction normally to the vessel been considered. With the contact it is possible to considerate an odometer on the wheels to facilitate the navigation control and the positioning of the LBV-5. To attach directly onto the ship's physical hull the LBV-5 uses the attractive force of an Vortex Generator (Newsome, Rodocker, 2009).

Another similar vehicle to HROV was developed and is sold by company Eca Hytec, this product is called Roving BAT (information available on the website: http://www.eca-robotics.com/ftp/ecatalogue/216/Roving-Bat.pdf) and have the same hybrid concept with a crawler and free-flying mode. The set of sensors and features of the equipment has the same approach but the HROV has an open frame that will promote many researches on control, navigation and studies related with underwater vehicles.

An inspection vehicle with magnetic wheels for its adherence to the hull and a vehicle moved with traction cable are reported in Carvalho et al., 2009. The LUMA ROV developed in the COPPE-UFRJ (Carvalho et al., 2009) equipped with a camera for inspection.

This work has as focus report the development of the control architecture of the HROV.

2. MECHANICAL DESIGN

The HROV (Figure 1) consist of a mechanical structure made of polypropylene plates and is divided for convenience into two parts: upper and bottom. The upper part of the vehicle contains a floatation box made of polypropylene, an acoustic positioning system compose by two transponders, a pressure vessel for the control electronics and sensors, and four vertical thrusters. The bottom part of the vehicle consists of two horizontal thrusters and two motorized tracks. The thrusters and motorized tracks are actuated by DC brushless electric motors. Some navigation sensors are fixed on the structure of the vehicle. An umbilical cable is used for electric power supply and data transmission, and is connected to an isolated 4,5 kW DC power supply. Modular structural components allow HROV to be easily reconfigured in agreement with specific tasks.

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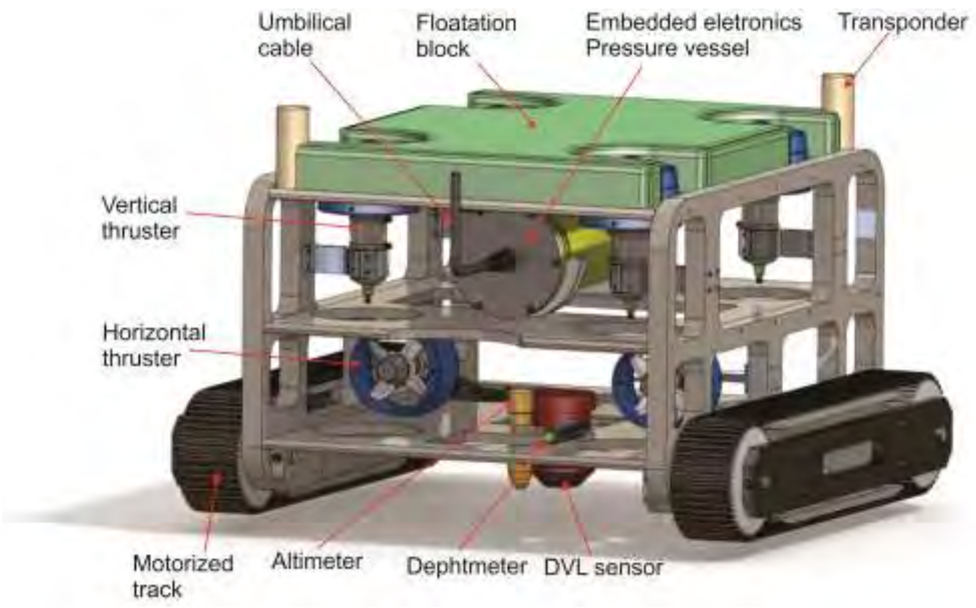

Figure 1. The HROV underwater robotic system.

The HROV was designed for operate in offshore ambient and possess an interchangeable modular design. The overall structure of the vehicle can be approximate as being symmetric at longitudinal and transversal planes. The main dimensions of the vehicle are shown in Figure 2. Its mass is approximately 125 kg and the weight-buoyancy force is positive 25 N. The positions of the mass and buoyancy centers are separated by a distance of 111 mm providing to the vehicle intrinsic stability in roll and pitch.

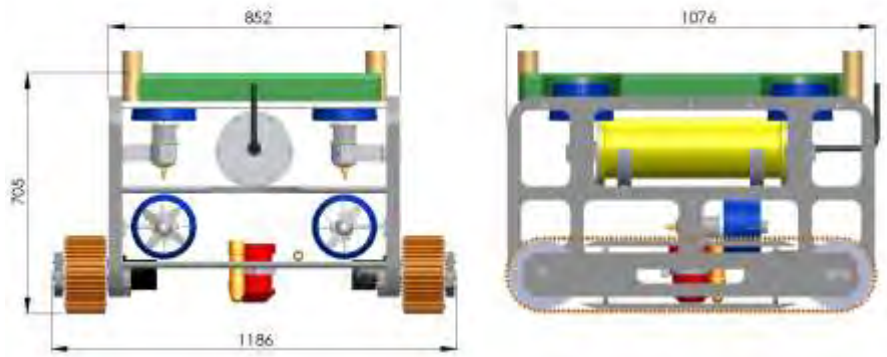

Figure 2. Projection views of the HROV. Dimensions in mm.

3. CONTROL ARCHITECTURE

The control architecture of the HROV (Figure 3) has been designed for providing fast development of data acquisition, control systems and, navigation and state estimation systems. The control architecture of the vehicle is modular in sense that this allows the addition of new interface boards and sensors as well as its removal without affecting the control software performance.

The control architecture (Fig. 3) of the HROV consists of two main modules: the surface computer system and the sub-sea computer system. The surface computer system consists of a laptop computer running the Windows XP operating system. It is responsible for the task-level control commands and it is connected to the sub-sea computer via the Ethernet TCP/IP protocol using a 4–26 AWG cable. A particular metaprogramming language has been designed for task level definition. Required maneuvers are defined in script files using this metaprogramming language. The file is then send to the sub-sea computer where an interpreter translates the high level task commands into low level control commands. The sub-sea computer system is responsible for the sensorial system processing (sensor raw data acquisition, position and velocity estimation) and the low-level control system (position and/or velocity control feedback loops). It consists of five PC-104 boards (see Fig. 4): CPU board on 500 MHz AMD Geode LX800 processor

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running the VxWorks real-time operating system of Windriver Inc., Analog-to-Digital converter board, D/A board, multi-serial and power supply boards. The last board not is shown at Fig. 4. The embedded programs are developed in the surface computer, using the Tornado software development kit, and then uploaded to the sub-sea computer system. In order to visualize in real time the motion of the vehicle, sensor data is send from sub-sea computer to the surface computer.

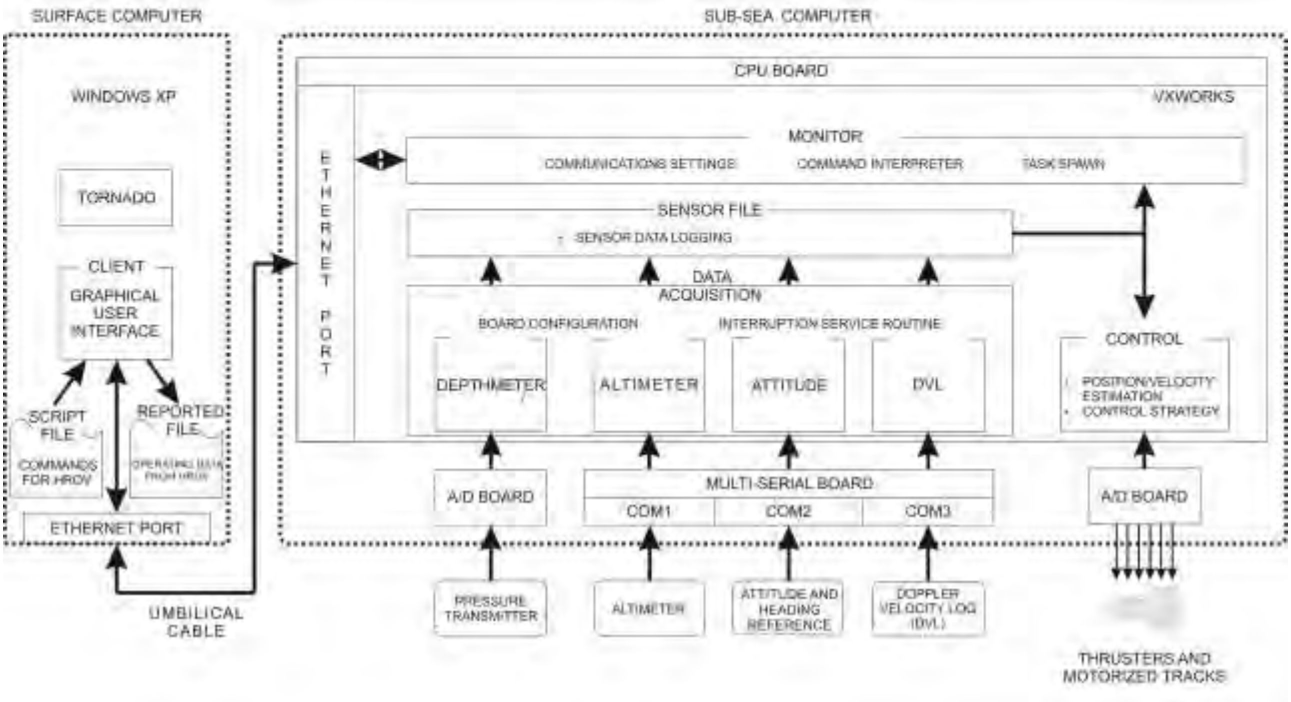

Figure 3. Schematic diagram of the control architecture.

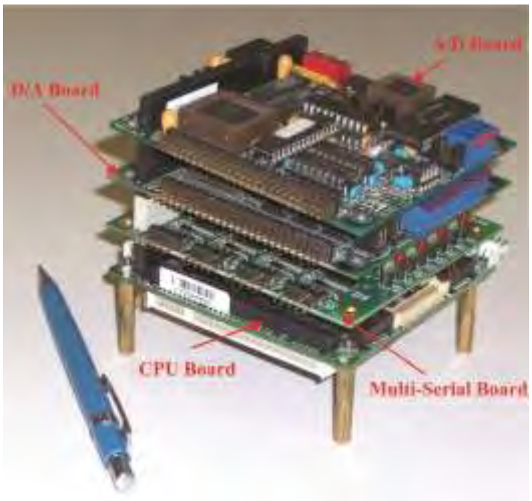

Figure 4. Embedded computational system.

3.1 Sensors

The HROV poses a set of sensors which allow measure the motion of the vehicle in six degrees of freedom. The sensor system has been specified for providing the position and orientation of the vehicle with respect to an earth-fixed reference frame. We summarize overall sensor of the vehicle in Table 1. The ultrasonic altimeter measures the distance between vehicle and the ship hull. The DVL-Doppler Velocity Log sonar provides the velocity of the vehicle in the surge, sway and heave directions, see Figure 6 for the degrees of freedom, and also the height of seabed. The vehicle poses a navigation instrument that contains attitude sensors to measure the roll and pitch angles and a compass to provide the heading of the vehicle. This instrument also provide the linear acceleration of the vehicle in surge, sway and heave directions, information that will be used at conjunction with DVL data to precisely estimate the position of the vehicle. A pressure transmitter is used to measure the depth. Figure 5 shows sensors of the HROV.

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The data of all sensors except the pressure transmitter is acquired through RS-232 serial ports, see Fig. 3. The analog signal of the pressure transmitter is acquired using the A/D board.

The navigation of the vehicle in the hull surface is based on information provides by a camera, map of the hull and two transponders. These last are the base of the acoustic positioning system of the vehicle. The transponders and camera not were specified in Table 1 (these even not were acquired).

The main task of the sensor system is to provide information for robust estimation of position and velocity while combining information from different sensors using a stochastic sensor fusion algorithm like, the Kalman Filter, for example. The HROV sensor system provides redundant information. This is due our current research project on sensor fusion algorithms. Different algorithms with different sensors are being designed in order to understand which sensors might provide the best estimation of position and velocity.

Table 1. Technical specification of navigation sensors.

Variable	**Sensor (Manufacturer)**	**Precision, update rate**	**Output**
Forward distance	Altimeter, PA500/6-PS (*Tritech Inc.*)	1 mm, 10 Hz	Digital
XYZ linear velocity; height	DVL - Doppler Velocity Log, NavQuest 600 Micro (*LinkQuest Inc.*)	1% ± 1 mm/s, 5 Hz	Digital
XYZ angular velocity; roll and pitch angles; heading	Attitude and Heading Reference System, AHRS-S305, (*Watson Inc.*)	2 %, 0.025°/s resolution ± 0.5°, 0.02° resolution ± 1°, 0.02° resolution 71 Hz	Digital
Depth	Pressure transmitter, TW-PI (*IOPE Ltda.*)	5 mm, 20 Hz	Analog

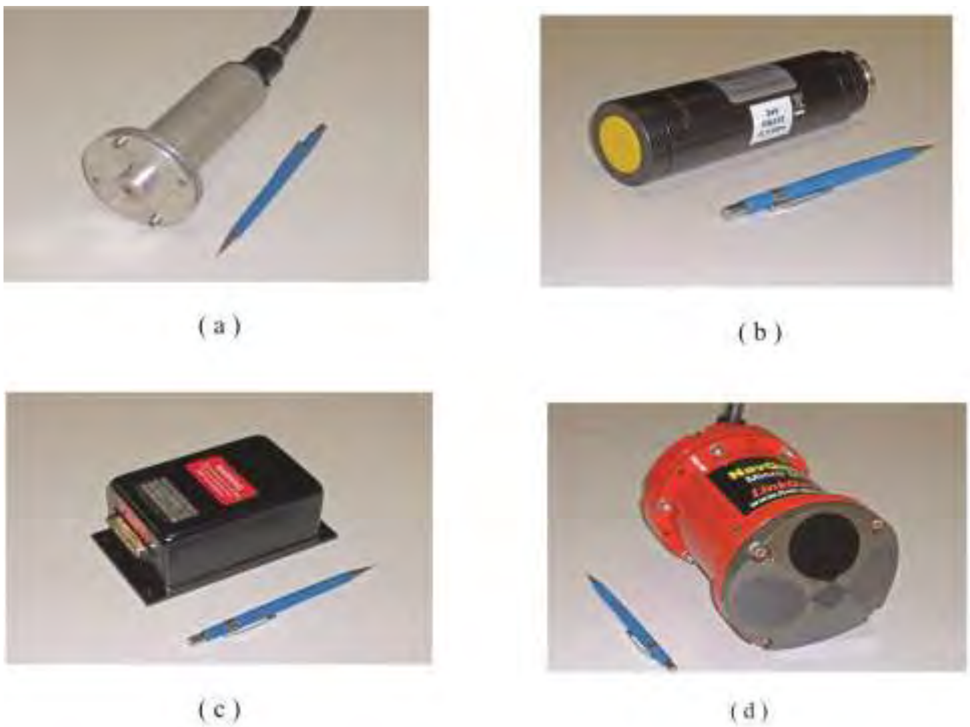

Figure 5. The sensor system: a) Depth meter, b) altimeter, c) attitude and heading system, d) DVL sonar.

When the vehicle is in operation the data of all sensors is continuously stored in RAM memory and the circular buffers created via software for each of the sensors play an important role in this process. The buffers are continuously emptied while data is stored on computer hard drive for posterior data treatment. Full data of sensors is sends in real time to the surface computer for its visualization.

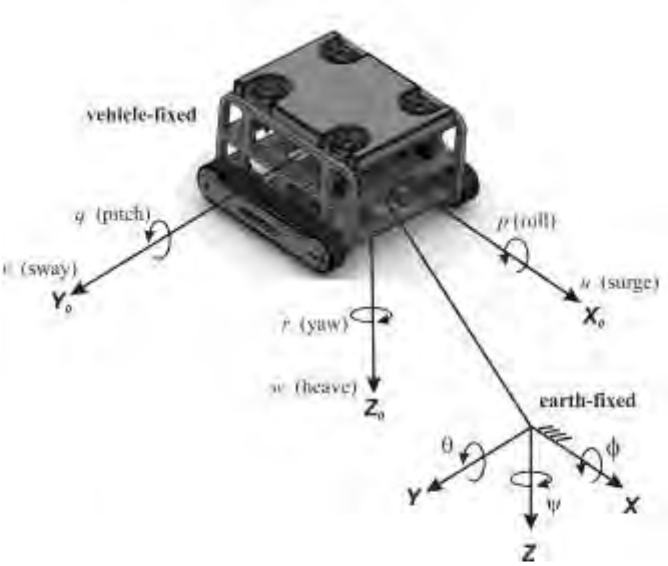

Figure 6. Reference frames and elementary motions of the vehicle.

3.2 Actuators

HROV use eight actuators (manufactured by *Tecnadyne Inc.*) for its locomotion: six 1020 model thrusters and two 40 model rotary actuators, the lasts for driving of the motorized tracks. Overall actuators are powered by 150 V DC brushless motors and controlled by analogy voltage in the range of ±5 V. The maximum forward trust of the thrusters is 250 N and in reverse is 145 N. The maximum torque of the rotary actuators is 54 Nm. Control signals are sends to overall actuators through the D/A board. The output signals of the D/A board are magnetically isolated to allow the sends of control signals without noise.

The thrusters of the HROV have been experimentally tested in a water tank in order to determine the characteristic operation curve (Avila, 2008). The experiments were performed in bollard-pull condition. Figure 7 shows the experimental setup. The Archimedes lever law is used to calculate thrust when a voltage is applied to the DC electrical motor. A load cell, which is located in the upper part of the bar, measures momentum generated in relation to the fulcrum. Figure 8 shows the results of the experiments conducted with one of the thruster.

Avila (2008) verified that the settling time of thruster step response has a time constant equal to 0.1 s. Based on this information we assumed that the control system of the HROV is not affected by the dynamics of the thruster time delays. Considering this, we used the following thruster model to calculate the axial force, *F*, produced by the propeller:

$$F = aV^2 + bV, \tag{1}$$

where *V* is the control voltage, that is applied to the thruster servo-amplifier, and *a* and *b* are the force coefficients of the thruster which should be experimentally identified. By applying a least-square fitting to the data of Fig. 8, the following force coefficients are obtained: $a = 11.53 \pm 0.1$ [N/V^2] and $b = 4.21 \pm 0.36$ [N/V] for forward thrust, and $a = 7.87 \pm 0.15$ [N/V^2] and $b = 4.68 \pm 0.55$ [N/V] for reverse thrust.

The control system of the vehicle for free-flying mode allows the control of motion at five degrees of freedom: surge, heave, roll, pitch and yaw (Fig. 6). The four thrusters mounted in the upper part of the vehicle allow the movement in heave, roll and pitch while two thrusters localized in the low part allow the motion in surge and yaw. In crawler mode the vehicle use only the four top thrusters to keep the adherence to the hull while the motorized tracks allow the locomotion on the hull. The vehicle has been designed to reach maximum surge velocity of 1 m/s in free-flying while 0,5 m/s in crawler mode.

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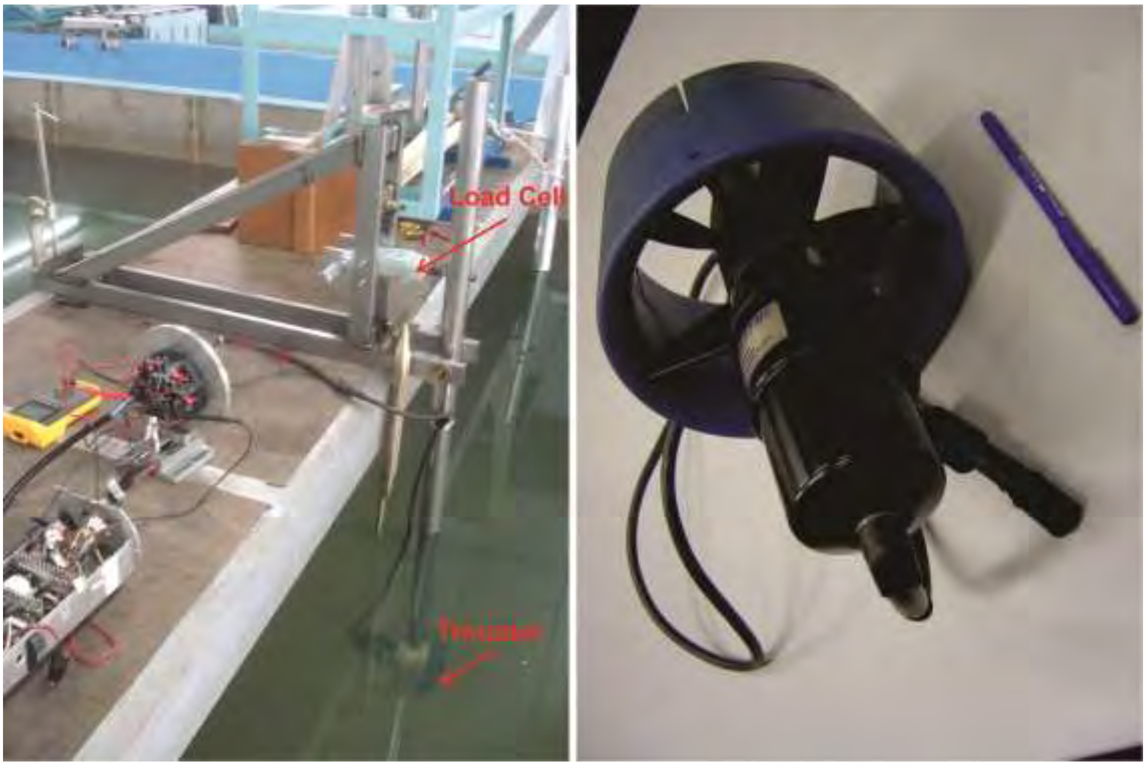

Figure 7. Thruster experimental setup. (Avila, 2008)

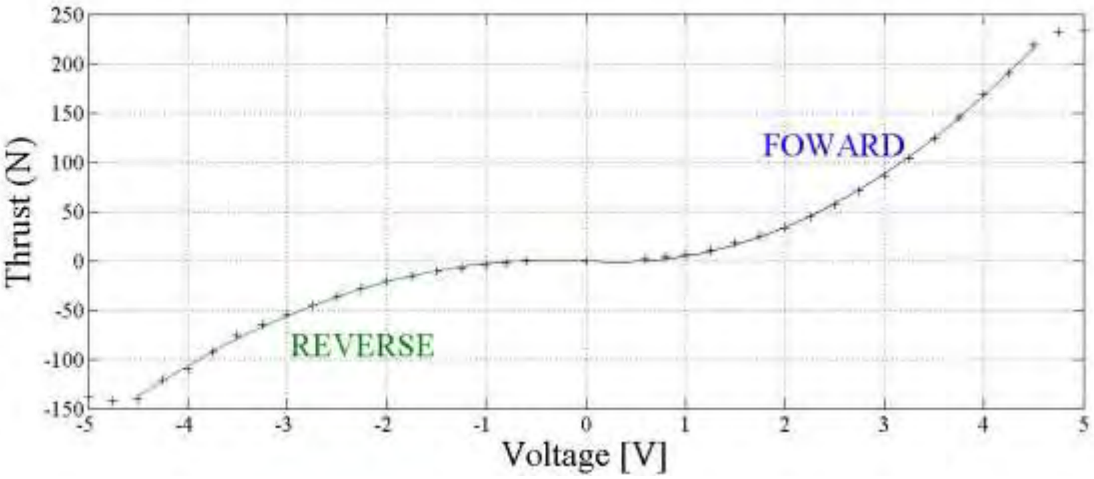

Figure 8. Thrust vs. control voltage for a thruster. (Avila, 2008)

3.3 Software

The software for the surface computer, named CLIENT, was developed in C language on Windows XP operating system. CLIENT allows the sends of commands of high level to the sub-sea computer, by example; the character “s” is used to stop a maneuver, the characters “m 5” are used for that the vehicle descend a distance of 5 m below the surface of the water, between others commands. The commands written in script files or in the prompt by the operator are sent to the sub-sea computer. The software for the sub-sea computer is being developed in language C using the Tornado program, software for cross-development environment of Wind River Inc.

The software in the sub-sea computer uses the features of real time system, standing out the guarantee of time responses facilitating the control action of the vehicle, keeping pre-set time limits for the execution of tasks. The concept of multitask has been implemented, which creates the appearance of many threads of execution in the program, running concurrently when, in fact, the kernel interleaves their executions on the basis of a scheduling policy (Wind River, 2008). Semaphores are used to prevent concurrent access to shared variables, allowing only one access at the same time.

The data acquisition of the sensors with serial output is carried-out using interrupt service routines (ISR). The sample frequency set on each sensor is maintained in the program: altimeter - 10Hz, DVL – 5Hz, attitude and heading reference – 71Hz. The depth meter which has an analog response, and therefore does not provide samples of the signal, has the data acquisition sampled by clock pulse of the A/D board that triggers the ISR in a constant frequency of 20Hz. As seen in Fig. 3, each sensor has a different program, providing a modular aspect to the software. For the control of the motors is made feedback of the sensor data.

The main program is called MONITOR, and spawns the other programs (tasks for the VxWorks) setting the priority level' of each one. The VxWorks kernel provides 256 priority levels, numbered 0 through 255. Priority 0 is the highest and priority 255 is the lowest. Application tasks should be in the priority range of 100 to 255, driver support tasks (which are associated with an ISR) can be in the range of 51-99, to avoid lose data. Priorities lower than 50 should not be used due to the network connection could die and prevent debugging capabilities with the surface computer tools (Wind River, 2008). The configuration of TCP/IP communication is done in the MONITOR and, also, the receiving and transmitting of data for the surface computer. The MONITOR has the interpreter for the commands sent by the operator or written in the script files, these are separated in low-level tasks. During the operation, the MONITOR sends for the surface computer the real-time data of the sensors and actuators to be visualized in the operator's screen. At the end of the operation a file is created by the program SENSOR FILE to put in array: the sensor data, the voltage set in each motor and the specific time of each data. This file is also sent for the surface computer by the MONITOR, providing a feedback for the operator to analyze the information about the operation of the vehicle.

3.4 System Control

The proposal for this project is make the HROV able to perform full automation routines in free-flying operation mode. It enables the operator to program automated routines, such as pre-established trajectory or path tracking in order to position the HROV close enough of the vessel. Then, the crawling mode is activated after the vehicle is attached to the vessel surface. Therefore, two different set of controller need to be designed. One for free-flying and another for crawling operation mode. The first approach describes the control system for free-flying operation mode.

Considering the offshore environment, the control technique needs to fulfill some general requirements:

- The closed loop and the controller must be stable;
- Robust and fault-tolerant enough to absorb the disturbances in the sea like waves, currents and wind;
- Avoid errors in steady state due to assure reliable values of HROV position.

Gain scheduling controller based on PID control technique in decentralized mode between the 5 DOF can be considered as a reasonable solution for comply with HROV requirements.
The dynamic model of a HROV in free-flying operation mode can be expressed using the standard equations, as follows Fossen (1994):

$$M\dot{v} + C(v)v + D(v)v + g(n) = \tau , \tag{2}$$

Where v represents the velocity vector, M represents the mass matrix, $C(v)$ represents the Coriolis matrix, $D(v)$ represents the damping matrix, $g(v)$ represents the hydrostatic force vector, and τ represents the control vector. The equation (2) represents a Multivariable system where the matrix orders are determined by the degree-of-freedom (DOF) of the underwater vehicle motions. The HROV presented in this paper moves in 6 DOF (fig. 6). However, due the distribution of thrusters, 5 DOF are controlled, row, pitch, yaw, heave and surge.

The 1-DOF model is obtained from Eq. (2) by neglecting off-diagonal entries and coupling terms, umbilical cable dynamics, as well as assuming a constant added mass (Avila, Donha and Adamowski, 2013a). This approximation relies on the fact that:

- The off-diagonal elements of the added mass matrix of a rigid body having three symmetry planes are identically null (Newman, 1977);
- The off-diagonal elements of the positive definite matrix are much smaller than their diagonal counterparts (Fossen, 1994);
- The hydrodynamic damping coupling is negligible at low speeds. The resulting model structure is:

$$m_i\dot{x}_i + d_{L,i}x + d_{Q,i}x|x| = \tau_i, \tag{3}$$

Where, for each DOF i, x_i is the velocity at the direction of the DOF i; m_i is the effective mass; $d_{L,i}$ and $d_{Q,i}$ are the linear and quadratic drag coefficients, respectively; τ_i is the net control force.

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3.4.1 Surge Control

In order to implement a gain scheduling controller is necessary a linear parametrically varying standard model defined from the dynamic model of HROV in 1-DOF (Eq.3)(Lebret and Tanguy, 2004). The chosen parameter to define a standard varying is the velocity, not only for surge control but also for the others degrees of freedom.

The velocity of HROV in surge DOF is defined with steps of 0,2 m/s from 0,2 to 1 m/s. With a fixed value of mass m_i it's possible to calculate the others parameters for each value of velocity.

Linearization and implementing the PID control technique is needed in order to have the grid of values Kp, Ki and Kd gains. The values obtained of torques can be traducing in voltage values and handled in software procedures for control the horizontal thrusters in HROV.

The concept of this control technique is implemented also for others degrees of freedom.

3.4.2 Crawling Operation Mode

After the HROV is attached on the vessel, it's not expecting disturbances enough that motivate an implementation of complex control technique.

In the crawling operation mode, the normal force enough for keep HROV attached on the vessel can be obtained from experimental tests in order to design an on/off control for this operation mode. A simple on/off control can be design using the attitude sensor and the encoder of rotary actuators. The values of encoders can be compared in order to synchronize the motorized tracks or change the angle of trajectory. Moreover, with the values of attitude sensor is possible check the angle of movement direction of HROV on the vessel and make possible create an estimated trajectory of HROV. This trajectory compared with the vessel 3D model gives an estimated position of the HROV on the vessel.

4. CONCLUSION

An underwater robotic system for thickness measurement of ship hulls is being developed in the Federal University of ABC. The vehicle design is a new concept of inspection robotic system with control architecture robust enough to allow to operate in offshore ambient. A characteristic of design of this vehicle is its classification as a hybrid robot, because this uses thrusters for the motion in free-flying and motorized tracks for locomotion on the ship hull. The adherence system, based on the application of a force normal to the hull from vertical thrusters, allow to the vehicle guarantee its locomotion in surfaces metallic and not metallic.

The control architecture of the vehicle has been designed for providing fast development of data acquisition, control system and, state estimation and navigation systems. The on-board computational system is based on PC-104 CPU board running the VxWorks real time operating system. Experimental tests of data acquisition have been carried-out with each one of the sensors and also with all the sensors simultaneously connected. The results of the experiments verified the developed software. The software for actuator control is being developed. Actually, one-dimensional classic control algorithms are being created and tested in laboratory to control the surge, row, pitch, yaw and heave motions of the vehicle.

In summary, a software platform is being developed in order to conduct researches in dynamics and control of robotic systems for ship hull thickness inspection. This platform will allow the development of new algorithms of advanced control, hydrodynamic parameter identification, state estimation and trajectory tracking.

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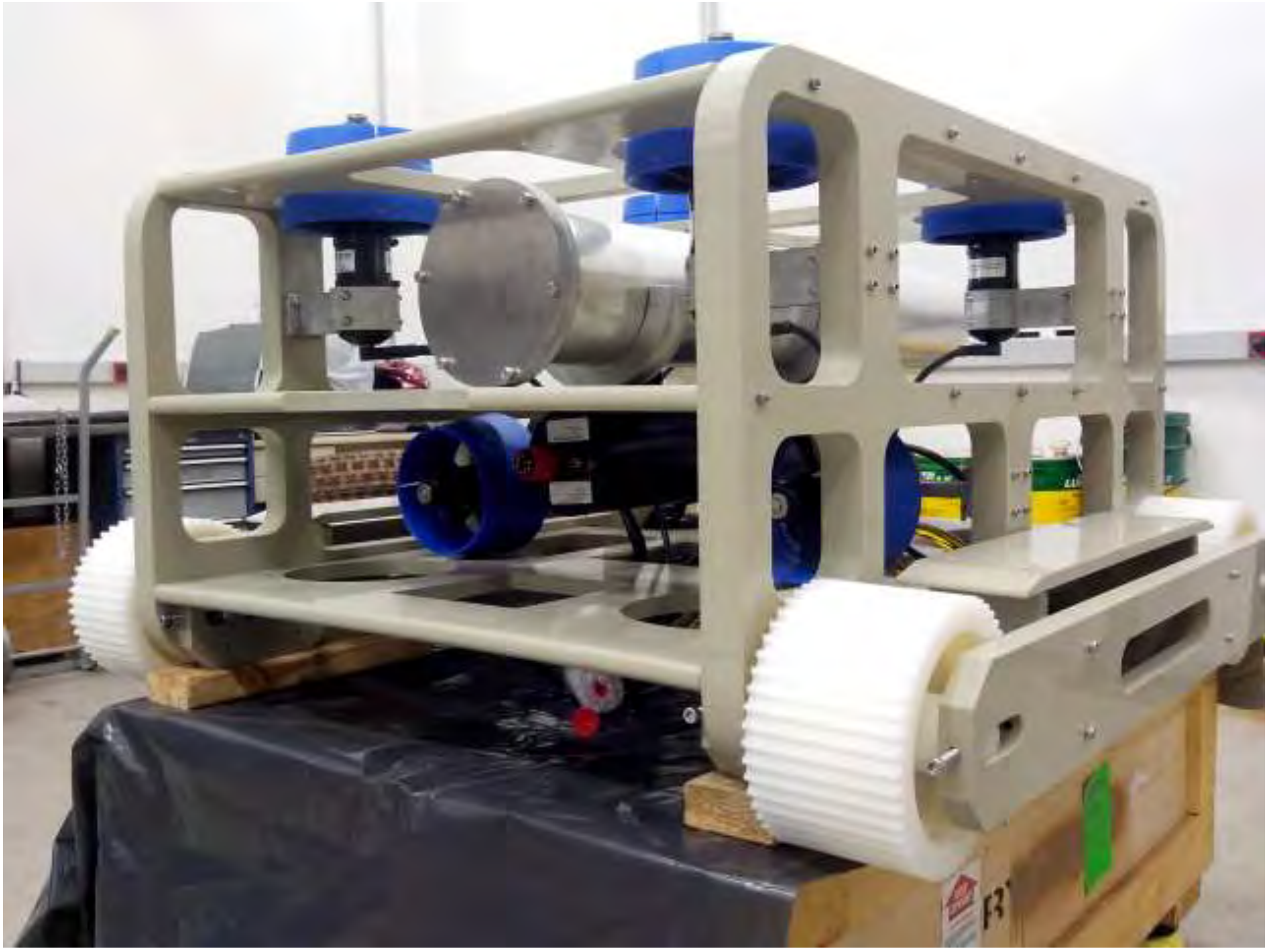

Figure 9. The actual stage of the HROV's mechanical assembly.

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