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DEVELOPMENT OF AN UNDERWATER REMOTELY OPERATED VEHICLE (ROV) FOR SURVEILLANCE AND INSPECTION OF PORT FACILITIES

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ABSTRACT

This work addresses the development of an underwater remotely operated vehicle (ROV), required to obtain reliable visual information, used for surveillance and maintenance of ship shells and underwater structures of Colombian port facilities and oceanographic research. The most relevant design constraints were evaluated considering environmental conditions, dimensional restrictions, hydrostatics, hydrodynamics, degrees of freedom and the availability of instrumentation and control hardware. The mechanical/naval design was performed through an iterative process by using computational tools CAD/CAE/CFD. The hardware architecture was divided in three layers: instrumentation, communications and control. The software was developed using ANSI C with Embedded Linux operating system. The guidance and navigation system used the Kalman filter to estimate the state of the vehicle. The vehicle can operate in manual and semi-automatic modes. In the semi-automatic, the position of a joystick is converted into the velocity set-points that are integrated to get the yaw and depth commands for the PID controllers. The rigorous design and a consistent construction processes allowed the development of a robust and reliable robotic system that constitutes an innovative product in Colombia.

INTRODUCTION

Because of some security-related events that have occurred in the world during the last ten years, the International Maritime Organization stated new policies in The International Ship and Port Facility Security Code (ISPS Code), [1], in order to enhance the maritime security in trade ports.

Since 95% of the world trade is made through maritime ways [2], it is necessary to develop an underwater inspection system to get reliable visual information of ship shells and underwater structures, in order to guarantee the appropriate security levels and the corresponding security measures in the trading ports of Colombia. The visual inspections include the identification of failures such as cracks, dents, deformations, incrustations and sedimentation among others.

There are different options to perform the inspections: divers, Human Operated Vehicles (HOVs) and Unmanned Underwater Vehicles (UUVs) [3–5]. The most feasible and reliable alternative is the construction of an UUV which is denominated as a Remotely Operated Vehicle (ROV) which performs underwater inspections through a real-time video transmission of the underwater environment. The robot is operated from a surface station through a tether cable, reducing the danger for humans and the operational costs.

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The ROVs have been used for surveillance and maintenance tasks in different fields such as: port industry, military industry, oceanographic research, aquaculture, marine biology, etc., with wide development in industrialized countries. These vehicles can be classified in three main groups: heavy work, observation and micro/mini ROVs [6]. Although there are commercial prototypes of the three classes of ROVs, they are expensive and represent significant economic burden for developing countries such as Colombia.

The research group in Automatic and Design (A+D) from the Universidad Pontificia Bolivariana (Medellin-Colombia) developed two previous prototypes of ROVs: VISOR I [7] and VISOR II [8, 9], which represent an important experience in the development of unmanned underwater vehicles. More recently, the A+D group has been developing the VISOR 3 which constitutes an innovative, modern and robust robot to perform underwater inspections in the Colombian ports of Cartagena, Santa Marta, Barranquilla and Buenaventura and several underwater structures [10, 11].

This work presents the complete development of the remotely operated vehicle VISOR 3, required to obtain reliable visual information, used for surveillance and maintenance of ship shells and underwater structures of Colombian port facilities, and oceanographic research tasks.

MECHANICAL/NAVAL DESIGN

The mechanical/naval design process was methodologically driven using elements from the classical machine design methodology [12] and the design spiral methodology [3, 13]. The first one proposes to divide the whole system in subsystems, finding adequate solutions for each subsystem and integrating the solutions in a unique design. This methodology was used mainly in the last design stages. The second proposes to design the subsystems systematically and sequentially until it converges into a unique solution. This one was used mainly in the first design stages.

In this study, the whole development was divided into six stages: concept design, basic design, detailed design, construction, test and final tuning, and project closing. In the concept design or preliminary design, a set of design constraints or design objectives were defined in order to get a list of desired specifications. In this first stage the design concept of the vehicle was selected from a collection of sketches made by the design team. In the basic design stage, the ROV system was divided into subsystems; then, for each subsystem different feasible alternatives were considered and evaluated in order to choose the best one. Finally, in the detailed design stage, appropriate calculations were made to ensure the reliable operation of the system. Finally, the construction and assembly drawings, and final technical specifications were made.

Design constraints and specifications

Several design constrains were taken into account when designing the vehicle, [10]. The ROV was intended to operate in Colombia's main ports, this imposed some enviromental constraints such as density, temperature, salinity, working depth, operating speed, among others. The depths of those ports are shown in Table 1.

TABLE 1. COLOMBIAN PORTS DEPTH

Port	Maximum depth (m)
Barranquilla	12.0
Buenaventura	13.7
Cartagena	13.7
Santa Marta	18.3

The vehicle had to be neutrally or slightly buoyant, so the propulsion system had to control depth; hence, the wet volume and weight were related by the medium (water) density. Since the vehicle was intended to be carried manually by a maximum of four people, the volume and weight had to be as small as possible. The propulsion system had to control four degrees of freedom: surge, sway, heave, and yaw. The pitch and roll degrees of freedom were made naturally stable by locating the center of mass below the center of buoyancy [3, 14]. Because as depth increases the total electromagnetic radiation decreases considerably, an illumination system and a tether cable were necessary components of the vehicle. The specifications defined in the first design stage are shown in Table 2, [10].

Design concept

In the concept design of the ROV several options were studied, from complex avant-garde to simple rudimentary geometries, Fig. 1.

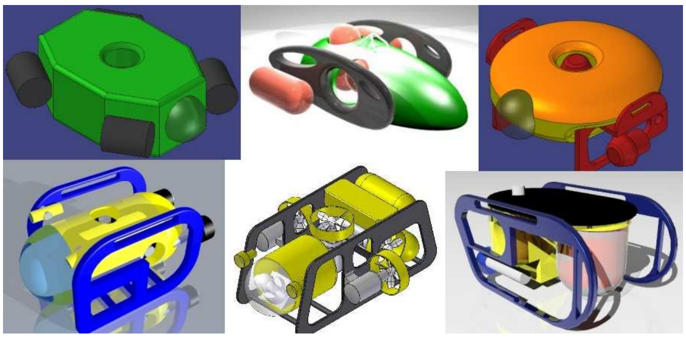

FIGURE 1. SKETCHES

TABLE 2. DESIGN SPECIFICATIONS

Characteristic	**Value**
Vehicle type	Observation range
Environment	Port salt-water
Density	1024 kg/m^3
Operation depth	100 m
Design depth	165 m
Temperature range	0–40°C
Mobility	Four degrees of freedom:
	surge, sway, heave, yaw
Speed	1.5 m/s
Buoyancy	neutral or slightly positive
Maximum weight	100 kg
Communications technology	Fiber optic
Navigation instruments	Inertial measurement unit (IMU)
	Depth meter
	Magnetometer
Auxiliary systems	Illumination
	Communication
	Instruments for analysis

In this first stage, several options were proposed and the best option was chosen using the guidelines of the design constraints. The sketches explore several geometries considering mono-hull and multi-hull options, different thruster configurations, different camera locations, plane and curved surfaces, aesthetics, among other considerations. The design concept that was chosen, after evaluating the alternatives, and the concept we used in the following stages is shown in Fig. 2.

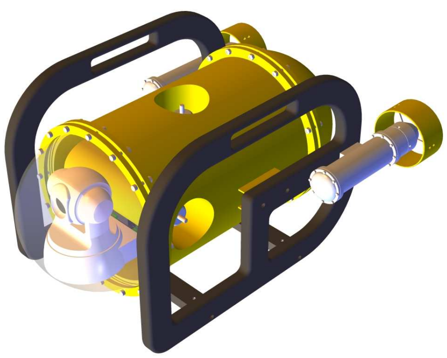

FIGURE 2. DESIGN CONCEPT SELECTED

This design uses a unique cylindrical hull with two hemispheres and a protective external frame. The thrusters were fixed with two of them external to the hull and the other two across the hull. The front hemisphere was made translucent to allow the camera image visualization.

Basic design

The ROV system was divided into three main subsystems: the vehicle, the surface control station and the communication system between them. The surface station contained remotely control devices such as: surface computer with man/machine interface, a joystick used to control vehicle's movement and an electric power plant. The communication system has a tether cable with communication and power lines. The vehicle, as a system, was divided into four subsystems: the structure, the propulsion system, the electric/electronic devices and the illumination system.

The basic design evolved as the team sequentially worked in every subsystem until it converged into a unique prototype. Fig. 3 shows the main design revisions involved in the process, starting from the design concept and finishing in the detailed final version.

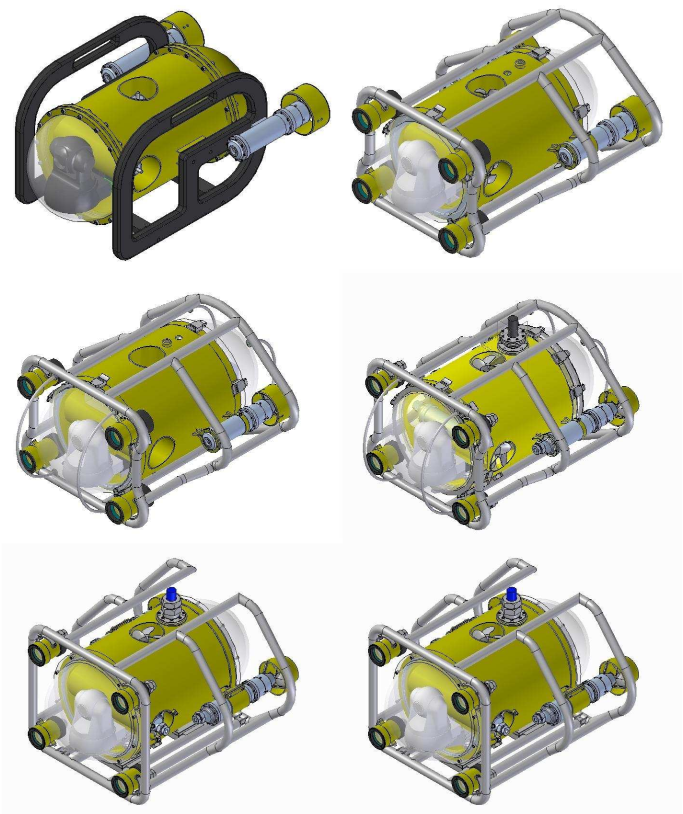

FIGURE 3. BASIC DESIGN EVOLUTION

The initial revisions showed dramatic changes in the protective frame, the hull size, the domes assembly and the tether cable assembly. The final revisions showed small changes.

Structure

The vehicle's structure, that contained all the hardware components, is composed of a cylindrical hull with two hemispheric-translucent domes, Fig. 4.

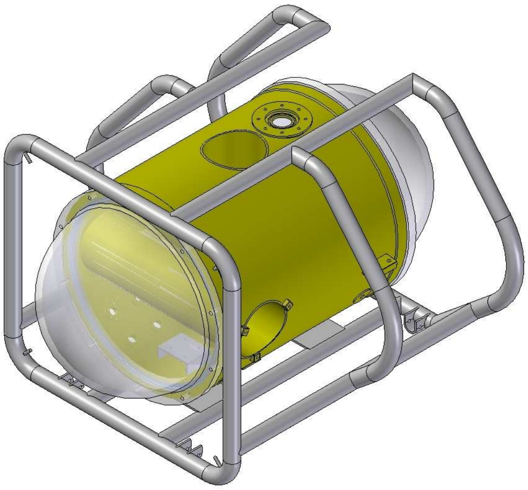

FIGURE 4. STRUCTURE: HULL AND FRAME

The hull was obtained from a rolled and welded alluminum sheet with two welded vertical/horizontal 4-in pipes, to allow thruster installation; two welded mechanized-rings in both ends of the cylinder, to allow the domes assembly and sealing; and several welded inside/outside mounting plates. Externally, the hull surface was covered with marine-grade protective yellow paint. The hemispheric translucent domes were obtained from thermoformed 0.5-in acrylic-glass sheets. Then, the domes were mechanized to obtain the required assembly and seal surfaces. The cylinder-dome assembly was fixed usign a screw-flanged union, and sealed using 11.5-in diameter O-rings and foam-polymer plane seals. Externally, the ROV was protected with a stainless-steel frame obtained from bended and welded pipes. This frame was also used to hold lighting and dead-weight mass. Besides protection, the frame was intended to facilitate the ROV manipulation.

Propulsion system

The propulsion system used four thrusters distributed as shown in Fig. 5. Two lateral thrusters were used in forward/reverse advance (surge displacement) and heading control (yaw rotation); one vertical thruster was used in depth control (heave displacement); and one last thruster used in lateral advance (sway displacement). All thrusters used 3.5-in diameter and 4 or 5 blade screwed propellers; and a MAXON EC45 brushless motor with a MAXON GP42C 3.5-ratio planetary gearhead. The thruster configuration system aimed to meet the following requirements, [10]:

- The line of action of the depth control (heave) thruster had to cross the center of mass, in order to avoid roll and pitch movements.
- The forward/reverse-heading (surge/yaw) thrusters had to be parallel and their lines of action have to be horizontal at the same height of the center of mass in order to avoid pitch movements.
- The lateral (sway) direction thruster had to be in the same height as the surge/yaw case. Since it is impossible that this thruster's line of action crosses the center of mass, it generates an undesired yaw movement which had to be compensated by the surge/yaw thrusters.

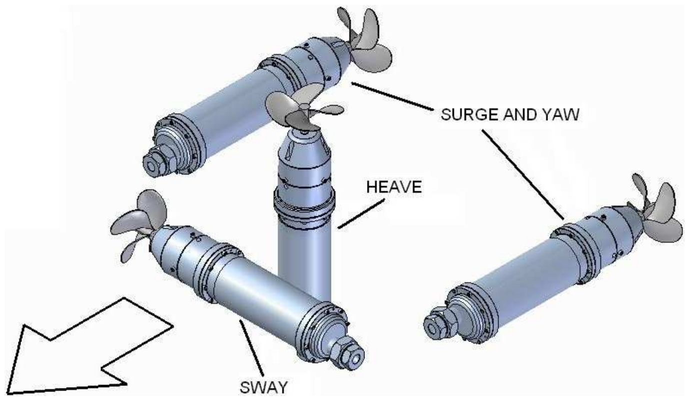

FIGURE 5. THRUSTER CONFIGURATION (THE ARROW SHOWS THE FORWARD DIRECTION)

To avoid leakages through the power shaft, each thruster used a dynamic sealing system shown in Fig. 6.

The dynamic seals were SEALCO MG-1 12-mm commercial units. They have a stationary element and a rotating element with tungsten-carbide specular-finished surfaces that prevent leaking. Additionally, an O-Ring based backup seal is used.

Illumination system

The illumination system used four lights in the front part of the ROV. Each light had an AC halogen 110-Volt 50-Watt bulb inside a Stainless-Steel hull, Fig. 7.

The light case sealing was obtained using a two-O-ring based seal in the front side and a NPT thread in the back cap.

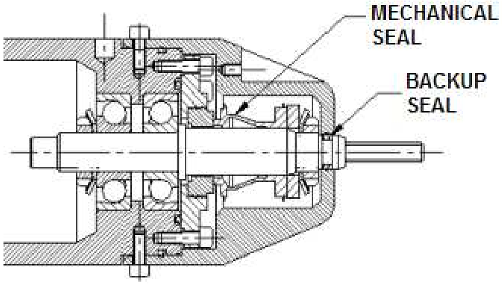

FIGURE 6. SHAFT SEALING SYSTEM

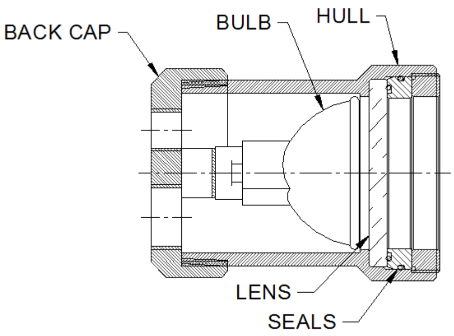

FIGURE 7. LIGHT CONFIGURATION

The front lens were made from 10-mm regular glass. The back cap had two connections for the electrical connection and for a gas presurizing valve.

Hardware distribution

It was decided that most of the hardware must be kept in a single box, Fig. 8. This box contained all the hardware except the camera, *i.e.* contained processor, ethernet/fiber-optic transceiver, power sources, lighting relays, Ethernet switch, motor drivers, instrumentation, connectors, etc. The box was custom-made, as an assembly of 1.6-mm bended alluminum sheets, to fit inside the hull.

Surface control station

The surface control station, Fig. 9, had a device to manually handle the tether cable, and power and fiber-optic connections. It also had a suitcase with a laptop and joystick to remotely control the ROV. The tether cable was arranged in a roll that rotates with respect to a free shaft. The electrical connection between the power plant and the rotating cable-roll was made with conventional brushes. The fiber optic was converted into ethernet and connected to the laptop through WiFi.

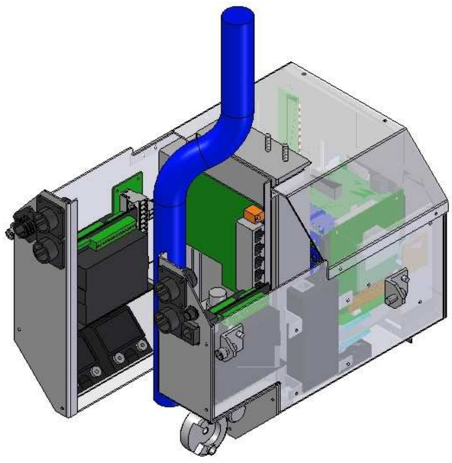

FIGURE 8. HARDWARE BOX

FIGURE 9. SURFACE CONTROL STATION

Subsystems integration

Mechanically, the design was conceived to be easily assembled and most of the unions are screw-type. The hadware box was a single unit that was assembled into the hull using screws. The lateral thrusters were fastened using clamp-type assemblies. The inner thrusters used spider-type assembly plates. The domes used flange-type screwed unions. The main difficulty in the assembly process was sealing the pass-through holes made for the cables. Figure 10 shows a Compuer Aided Design (CAD) version of the ROV with all the subsystems assembled.

MODELING AND SIMULATION

During the design process, the hydrodynamic and structural behavior of the ROV was studied. The forces and moments involved in the interaction between the vehicle and the medium, particularly the thrust force in the propeller, the drag forces in the hull and frame, and the structural analysis of the dome were modeled and simulated using Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) tools.

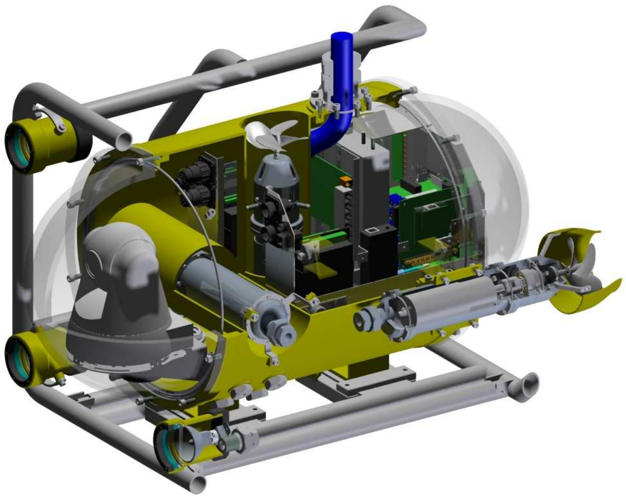

FIGURE 10. ROV INTEGRATION ASSEMBLY

The simulation results allowed to evaluate several performance scenarios of the vehicle, that were used as feedback to modify the geometry in the detailed design process before manufacturing the ROV prototype.

Propeller forces

The calculation of the thrust force in the propeller consisted first in selecting a commercial propeller considering the following parameters, [15]: material, direction of rotation, diameter, number of blades, angular speed, pitch, slip, blade area, developed area, shape of blade and skew angle. The next stage consisted in evaluating the performance of the propeller using CFD. Some of the simplifications that were taken are:

- The fluid was considered incompressible and Newtonian.
- The $k-e$ turbulent model was used.
- The angular speed of the propeller's shaft was considered constant.
- The speed of the ROV was considered constant.
- The roughness of the blade surface was considered zero (ideally smooth).
- An average of the blade thickness was considered.

Two domains were defined: a stationary domain that covered the open flow, the propeller's kort nozzle and the motor area; and a domain that covers the area were the propeller rotates. The propeller's 3D CAD model was generated by a reverse engineering process. The mesh of the propeller was refined in order to study the flow's behavior in the root, surface and edge of the blade. The independence of the meshes was considered. The mathematical model was based on the Reynolds-Averaged Navier-Stokes (RANS) equations, [16] and is addressed in [11].

The first simulation was made in steady state, and the results were used in the transient state as initial conditions. The solution in *ANSYS-CFX* used a high resolution scheme with 50 iterations. In the post-processing stage, the behavior of pressures, pathlines, speed vectors, among others were studied. Fig. 11 shows the propeller's frontal plane pressure distribution.

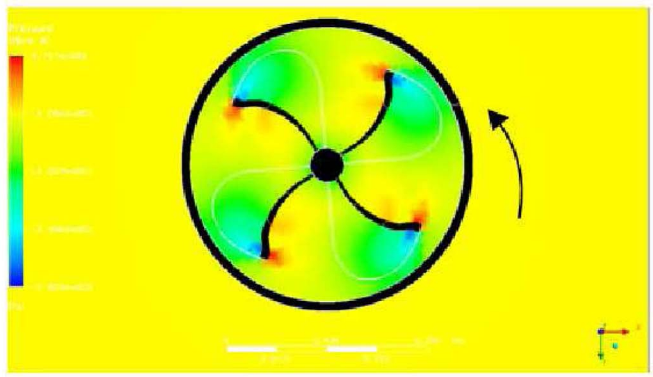

FIGURE 11. PROPELLER'S FRONTAL PLANE PRESSURE DISTRIBUTION.

Drag forces

The calculation of the drag forces of the hull and frame was performed by simulating the fluid movement around the vehicle using CFD. In the design of the ROV, the effects of drag by friction are insignificant compared to the drag by pressure, [15]. Reducing the drag force in the submergible implies that it requires less thrust to move and therefore the energetic consumption is reduced.

The drag coefficient (C_D) and the Reynolds number were considered in the study. Bodies with C_D values below 0.75 are considered low drag bodies, values over unity are considered high drag bodies. Moreover, the streamlines behavior was considered in the design process to improve the ROV geometry and decrease the drag.

Several scenarios were analyzed using *COSMOS/FLOW* and *ANSYS-CFX* considering different flow directions and movements of the vehicle, Fig. 12. With the purpose of reducing the calculation time, symmetry in the model was considered.

The computational results were validated using wind tunnel tests and with bibliographical references, [17]. Geometric, kinematic and dynamic similarities were considered in the model to guarantee similitude with the real model. A FUTEK LCM300 load cell with a nominal capacity of 25-lbf gauged with the standard guide NTC ISO 7500-1 was used to measure forces.

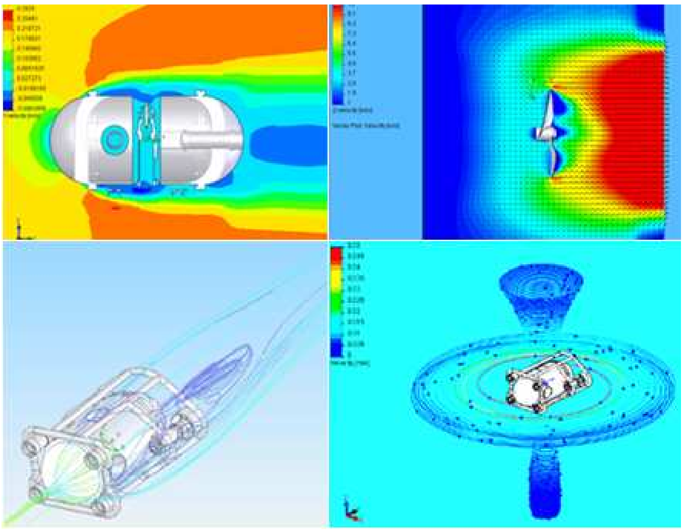

FIGURE 12. ROV CFD ANALYSIS

Structural analysis

The ROV's structure was subject to different loads: impact forces, hydrodynamic forces and hydrostatic pressure. Therefore, such load scenarios had to be considered during the detailed design of the ROV, [15]. Some considerations in the structural analysis were:

- The dynamic pressure produced by the flow was considerably smaller than the hydrostatic pressure.
- The dome (made of acrylic) was considered like a thin wall recipient and subjected to small deformations.
- The boundaries of the domain corresponded to a depth of 100 m.
- Thetrahedral elements were used in the analysis of dome with elastic-lineal material.

The computational results were validated applying the theory of vessel pressure and the membrane theory, [18]. For instance, the dome's optimal thickness was computed iteratively with *UGS/NX* considering several operating conditions, Fig 13.

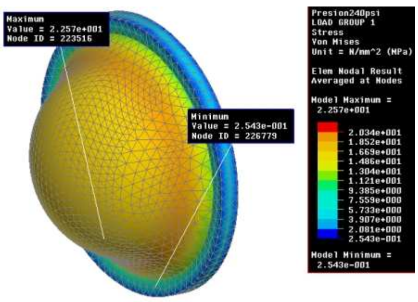

FIGURE 13. FINITE ELEMENT ANALYSIS OF THE DOME

HARDWARE

In terms of hardware, the system was divided into five subsystems: power supply, communication, propulsion, control and sensors. The hardware team objectives were to select the appropriate devices and to develop the necessary hardware (and its architecture) to assemble them to function together. A short description for each subsystem is presented below.

Power supply system The main power supply device was a portable power plant. This generator was located near the surface control station. Since the plant generates 110VAC, the energy had to be adapted to each device or subsystem depending on the specifications. For example, for the motors in the propulsion system a 600W 48VCD AC-DC converter power supply was acquired. Other vehicle's on-board devices were powered by a 5 and 12VDC AC-DC converter. In the surface station each device was powered with its own adapter.

Communication system Data from surface station to underwater vehicle traveled as follows:

- Between the surface station and the umbilical cable there is a WiFi connection. In this way, the operator does not need to be physically connected to the cable management system.
- The WiFi link becomes Ethernet before being transformed into optical fiber, which was inside the umbilical cable and provided electromagnetic noise isolation.
- When information arrives to the vehicle by optical fiber, it is converted again to Ethernet which provides flexiblity and reduces development times due to its simplicity.

Propulsion system The propulsion system comprised four thrusters. Each one had a brushless DC motor in a cylindrical waterproof hull. A driver for each motor was used to set the speed with the information coming from the control system through a voltage signal.

Control system The ROV's on-board brain was a PC104 form factor 400MHz PXA255 XScale Arcom VIPER embedded processor. This processor made calculations needed for navigation and control. It was connected with the surface station using Ethernet and with the sensors using RS-232 serial connection.

Sensors The vehicle measured the working depth, the heading and exterior temperature. A inertial measurement unit (IMU with a 3-axial gyroscope and accelerometer) also provided vehicle's attitude information. There was also a network of humidity sensors inside the ROV. A list with the sensors is presented at the end of this section.

Hardware architecture

The hardware architecture was developed following the conceptual design specifications and constrains, Fig. 14. Some of them are weight, working depth, mobility, operational speed and auxiliary systems.

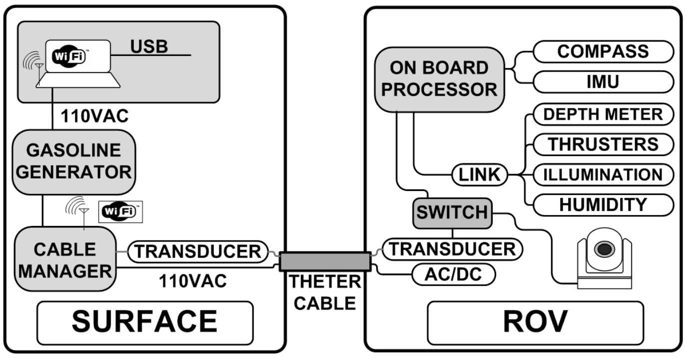

FIGURE 14. HARDWARE ARCHITECTURE

Developments

The integration of devices required aditional hardware and firmware development. The designed hardware was a board developed to read the analogic sensors' signals, such as temperature, pressure (working depth) and humidity sensors. Communication errors were detected and filtered by a firmware on the board's processor. Also this board was in charge of sending the voltage signals to control the power provided to the thrusters.

Equipment

The ROV's electronic hardware comprises the following equipment:

- Dell Inspiron 730m Laptop.
- Industrial C90 Joystick.
- Wireless bridge.
- TC Comm. TC3210T-03ST1-12 Fiber-optic Transceiver.
- D-LINK DES-1005D Switch.
- Arcom VIPER PC-104 Processor.
- Sony SNC-RZ50N/P IP Camera.
- PNI TCM5 Magnetometer.
- MEMSENSE μIMU IM02-0300C050A25.
- PT100 DIN Thermometer.
- Omega PX02C1 Pressure Transmitter.
- MAXON 1-Q-EC Motor Driver.
- LAMBDA NV175 Power Source.
- Tamura AAD600S Power Source.
- Hydrocable Systems Tether Cable.
- 2700W YAMAHA Powerplant.

SOFTWARE AND CONTROL

ROV control system

The ROV was controlled through four manipulated variables associated to the angular speeds of the four thrusters: right, left, lateral, and vertical. The controlled variables were four degrees of freedom of movement: x axis displacement (forward displacement or surge), y axis displacement (sideways displacement or sway), z axis displacement (upward displacement or heave), and rotation about z axis (yaw). Pitch and roll were not controlled since the ROV was designed to be stable so the tilt of the hull was kept small.

To uncouple the ROV dynamics, the angular speeds of the thrusters were calculated based on four virtual forces: force in x, y, and z axis, and torque about z axis. Hence, the control system was composed of four independent loops: x axis control loop, y axis control loop, z axis control loop, and yaw control loop. x and y controls are open loop since there are no instruments to sense position in $x-y$ plane. Both axes were controlled directly from surface control station joystick movement: if joystick is moved forward, x virtual force is changed proportionally; if joystick is moved to the right, y virtual force is changed proportionally.

There were two modes of operation for z axis control loop and yaw control loop: manual and automatic. In manual mode virtual forces for z axis and yaw are computed based on surface control station joystick position. In automatic mode PID control loops were activated for depth (z axis movement) and heading (yaw movement). The feedback signals for these control loops were generated by a navigation system which filters measurements from a depth meter, a triaxial magnetometer and accelerometer and computes depth, heading and tilt of the ROV. For this mode of operation the joystick in the surface control station set commands for velocity in z axis and angular velocity about z axis (yaw).

ROV control software implementation

ROV control system described above was implemented in ANSI C language, on a PC104 form factor 400MHz PXA255 XScale Arcom VIPER embedded processor using Embedded Linux operating system. This processor was connected directly through several interfaces to the instruments and actuators:

- RS485 interface to IMU.
- RS232 to connect to interface microcontroller managing thruster signals, lights, pressure, temperature, and humidity sensors.
- Ethernet to connect to surface control station.

The software was implemented using the Structure Manager, a software tool that allows to implement a console interface which interacts with the software at run time. This way all the software variables and parameters were accessible through the Structure Manager and different commands can be easily implemented to interact with the ROV. Moreover, the Structure Manager allows to implement scripts for simple tasks like sensor calibration, control parameter tunning, etc.

Onboard software runs in five threads of execution:

- The main thread executes navigation system, update joystick commands, and runs control system.
- Thread to read IMU measurements (accelerations, magnetic field, and angular rates).
- Thread to update actuators and other sensors data.
- Thread to manage communications with surface control station.
- Thread to manage console commands to interact with Structure Manager.

The PID controls were implemented in discrete time with variable sample time. When the control system is executed, the sample time is measured and the control signals are calculated accordingly.

Software onboard the ROV was monitored from the surface control station using an application implemented in NI/LabVIEW. This application implements a graphical user interface to manage the joystick signals, send commands to change the control mode of operation, control the lights and visualize the main variables from the ROV like depth, heading, tilt, temperature and humidity (inside the hull).

CONSTRUCTION, TEST AND FINAL TUNING

All the ROV's mechanical components were manufactured in local shops using conventional manufacturing techniques *i.e.* machining (milling, lathing, drilling, etc), welding, thermoforming, bending, painting, composite manual molding, etc.

Fig. 15 shows two of the hull's manufacturing steps, Fig. 16 shows the structure partially assembled and Fig. 17 shows the ROV finally assembled.

FIGURE 15. HULL CONSTRUCTION

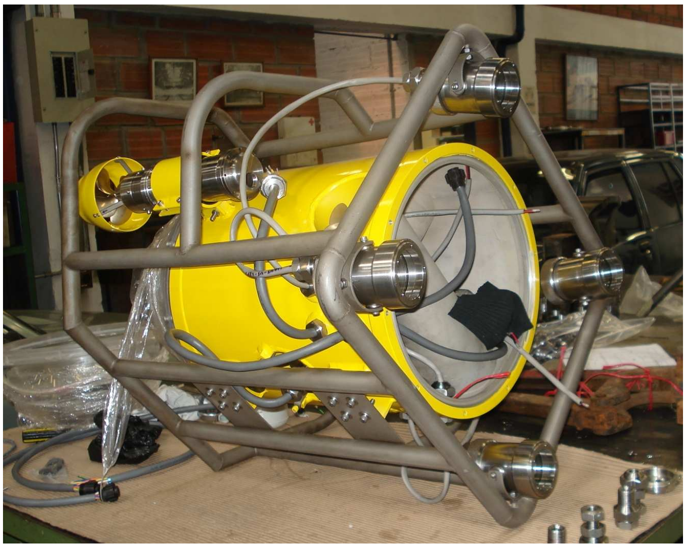

FIGURE 16. STRUCTURE PARTIAL ASSEMBLY

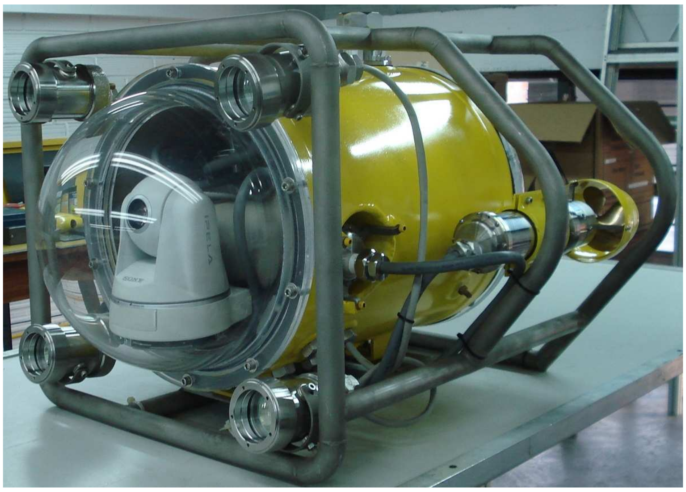

FIGURE 17. ROV FINAL ASSEMBLY

Before the final assembly, some subsystems were tested individually. All thrusters and lights endured hydrostatic pressure tests until succesful sealing was achieved. The hull was tested under internal air pressure until succesful sealing was achieved. The thrusters also endured hydrodynamic tests under pressure. All the hardware was tested before assembling it in the hull.

Finally, when all systems were integrated, the ROV's operation was tested in the University's pool, Fig. 18.

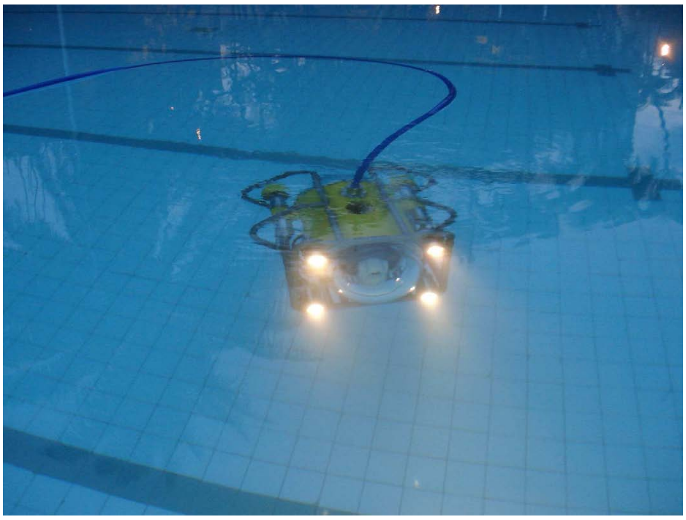

FIGURE 18. POOL TEST

CONCLUSIONS

This work discussed the development of the underwater remotely operated vehicle VISOR 3, designed to obtain reliable visual information in surveillance and maintenance of ship shells and underwater structures of Colombian port facilities and oceanographic research.

The project was executed following six stages: concept design, basic design, detailed design, construction, test and final tuning, and project closing. The design was divided into subsystems: mechanical/naval design, modelling and simulation, hardware and software and control. The design constraints were evaluated considering environmental conditions, dimensional restrictions, hydrostatics, hydrodynamics, degrees of freedom and the availability of instrumentation and control hardware.

The rigorous design process usign modern tools such as CAD/CAE/CFD/CAM, and a consistent construction processes allowed the development of a robust and reliable robotic system that constitutes an innovative product in Colombia.

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