Towards Teleoperation and Automatic Control Features of an Unmanned Surface Vessel-ROV System: Preliminary Results

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Keywords: Unmanned Surface Vessels (USV), ROV, USV-ROV System and Auto Tuned PID.

Abstract: This paper presents the design, construction and control of an Unmanned Surface Vessel (USV) along with a ROV (Remotely Operated Vehicle) system, called USV-ROV system. These systems are mainly used for underwater inspection of shallow water structures, such as: ports, bridges bases and platforms. The USV-ROV, developed at CIDESI-Mexico, has been designed for academic purposes. This paper describes the Surface Control Unit (SCU), the ROV and the USV, including: electronics architecture, data managing, sensors, actuators and mechanical design considerations. USV and ROV control strategies preliminary results are presented. Real time experiments are shown for: USV heading control, and ROV depth and heading control. The goal of this paper is to present preliminary results of a coordinated USV-ROV system, desgined for the development of inspection and surveillance techniques accroding to the marine and submarine application; however, these techniques are not commercially available and have to be developed with an open architecture system like the presented here.

1 INTRODUCTION

Unmanned Surface Vessels (USV) and Remotely Operated underwater Vehicles (ROV) are widely used by academic laboratories, corporations and governments. Some examples of USV and applications are mentioned in (Manley, 2008), (V. Bertram, 2005). The USV-ROV systems are the improvement of the USVs, motivated by the applications, such as inspection of ports, bridge bases and platforms, etc. (Vladimir, 2010), (Healey, 2007). Some examples of commercial USV-ROV systems are: (1), (2) and (3).

In this paper an academic USV-ROV System designed at CIDESI-Mexico is described. The section II details: the Surface Control Unit (SCU), the ROV (Remotely Operated Vehicle) and the Unmanned Surface Vessels (USV), including: electronic architecture, data managing, sensors, actuators and mechanical considerations. Section III explains the control techniques used to control the USV - ROV system. Real time experiments are presented to show: the heading control for the vessel, and depth and heading control for the ROV. Finally, the section IV discloses conclusions and future work.

2 USV-ROV SYSTEM DESCRIPTION

This paper describes the development of a small-sized underwater vehicle ROV deployed by an instrumented USV. Some real applications of the USV-ROV system are: marine survey and USV-ROV collaborative work. The general architecture, shown in Figure 1, consists of three main parts: The Surface Control Unit (SCU), a tele-operated Vessel and a ROV. These systems, including their mechanical design considerations are described in this section.

Nava-Balanzar, L., Sanchez-Gaytán, J., Fonseca-Navarro, F., Salgado-Jiménez, T., Reyna-Alonso, M., Garcia-Valdovinos, L., Rubio-Lopez, O., Gómez-Espinosa, A. and Ramirez-Martinez, A.
Towards Teleoperation and Automatic Control Features of an Unmanned Surface Vessel-ROV System: Preliminary Results.
DOI: 10.5220/0006414302920299
In *Proceedings of the 14th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2017) - Volume 2*, pages 292-299
ISBN: Not Available

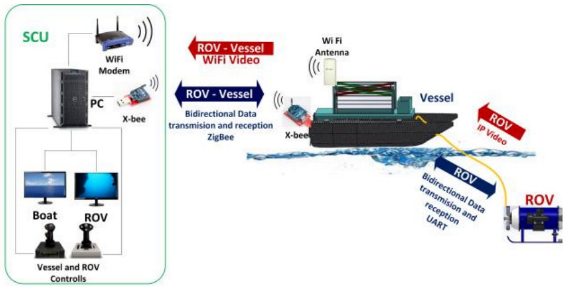


Figure 1: USV – ROV system.

2.1 Surface Control Unit

The SCU is the conjunction of the hardware (WiFi modem, PC, XBee, Joysticks, Keyboard, etc) and the software like the IP camera viewer and the Human Machine Interface (HMI) that generates the commands to perform a specific task. Additionally, the SCU receives the status of the vehicles in real time. The SCU is based on a computer that hosts the HMI which is programmed in LabVIEW software, where the data, status and images of both vehicles are displayed. All the data and commands generated from and to the vehicles are received and sent in real time by a RF Xbee radio transmitter/receiver which uses Zigbee protocol.

The SCU has two joysticks to command the vehicles, one for the Surface Vessel and another one for the ROV. The video transmission of the cameras (one at the vessel and one at the ROV) is performed by a dedicated WiFi communication channel. Figure 2 shows the Human Machine Interface (HMI).

Figure 2: Human Machine Interface.

- **Data Managing:** Both vehicles have a main processing data board, which will be described later in the sections ROV description and Vessel description, these boards are responsible for managing the data sent from the SCU to each vehicle. The way that the data is sent is simple: data frames are generated by the LabVIEW program. Those frames contain values like: thruster speed (for each thruster), thrust direction (for each thruster) and others digital functions, separated by commas. It's important to know that both vehicles have their own data frame that is sent from the SCU by a serial port. When the frames are received by the appropriate vehicle each main board separates every data, assigning it a value that generates a specific output signal for each actuator. Backwards, sensors data frames are generated by the main boards of the vehicles, and sent via serial port to the SCU, where they are classified and separated to be displayed in their correct position.

2.2 ROV Description

The underwater vehicle is a small-sized ROV, named Nu'ukul Ha (which in Mexican Mayan language means "water instrument"). Its dimensions are: 50 cm long, 30 cm wide and 30 cm height; as shown in Figure 3. It has a cylindrical pressure chamber of 15 cm in diameter, where the major part of the electronic architecture is placed. The total weight of the ROV is 10 kg. The electronic architecture of the ROV (shown in Figure 3) was placed in a plastic 3D printed rack. This architecture is divided into three groups: instrumentation, signal and data acquisition, and actuators. The instrumentation involves: pressure sensor, leakage sensors, IMU (Inertial Measurement Unit), voltage and electric current sensors.

The electronic architecture is managed by a microcontroller (main board). Finally, the actuators consist of four thrusters used to provide direction and

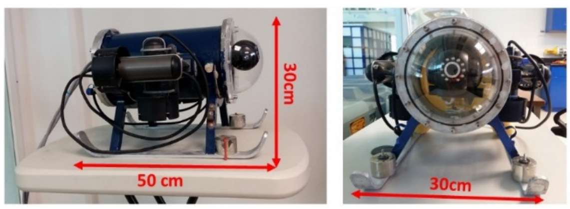


Figure 3: ROV Nu' ukul Ja ("water instrument" in Mexican Mayan language). This ROV is connected to the boat by a tether, which has twelve wires: eight are used to receive video from the IP camera, two for the power connections (24V and Ground) and four for the data UART transmission (TX)/reception (RX).

displacement to the ROV, and an IP camera for inspection missions.

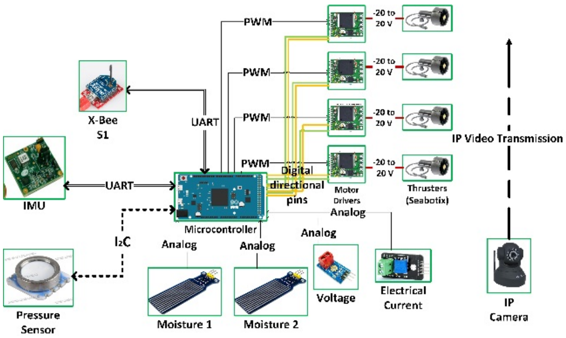
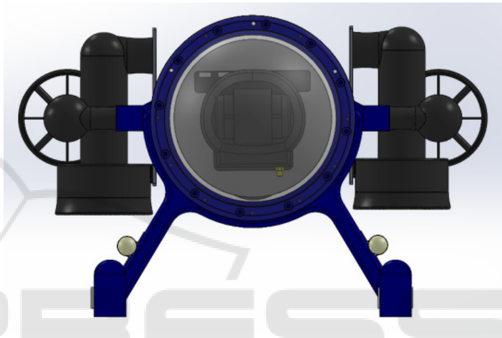


Figure 4: ROV's electronic architecture Diagram.

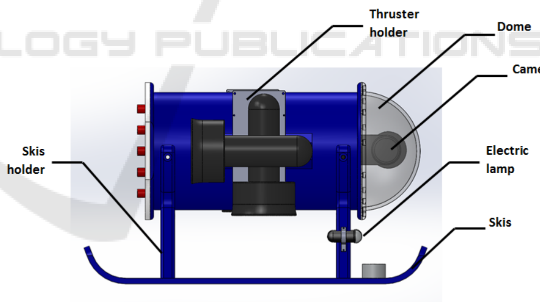
- **Instrumentation:** This ROV has a MS5837-30BA pressure sensor which is placed outside the pressure chamber of the submarine. This sensor is a high resolution barometer which obtains data of the surrounding hydrostatic pressure. Once the hydrostatic pressure is obtained the depth level is calculated by: $h = \frac{P-P_o}{\rho g}$, where $h =$ depth [m], $P =$ hydrostatic pressure [mbar], $P_0 =$ atmospheric pressure [mbar], $\rho =$ water density $\left[\frac{kg}{m^3}\right]$ and $g =$ acceleration of gravity $\left[\frac{m}{s^2}\right]$.

In order to measure 3 DOF (degrees of freedom) of the ROV (pitch, yaw and roll), a TCM-MB IMU is used. The TCM sends hexadecimal serial packages with a frequency up to 30 Hz. To prevent malfunction of the electronics due to water presence, leakage sensors are used. Besides, a voltage sensor (5 to 1 Vdc divider) offers analog signal of voltage of the batteries. A Hall effect current sensor (Pololu AC715) measures the current consumption of the vehicle, while the current sensors embedded in the motor driver (Pololu VNH5019) allows to monitor the operation of the thrusters.

- **Signal and Data Acquisition:** Inside the pressure chamber of the submarine is located a SAM3X8E ARM Cortex embedded in the Arduino Due board. It has 54 general purpose inputs and outputs, 12 of them PWMs, 12 analog inputs, 4 UART ports and one I2C bus. This board is used to manage communication between the user and the small-sized ROV.
- **Actuators:** As mentioned previously, to control the submarine in the horizontal plane, two brushed SeaBotix BTD150 thrusters are placed horizontally on each side of the underwater robot. Two more BTD150 thrusters are placed vertically on each side of the ROV to sink the vehicle at will (Robert D, 2014), (see Figure 5). The BTD150 thrusters are powered by 20 VDC@ 4 A.
- **ROV Mechanical Considerations:** The mechanical considerations for the ROV design were: small-sized remotely operated vehicle (50 cm long, 30 cm wide and 30 cm height), maximum working depth 10 m. Additionally, the ROV has a convenient shape to be launched and recovered by the remotely controlled vessel by using a LARS (Launch and Recovery System). The Figure 5 shows some CAD views. By using CAD the center of gravity and center of buoyancy were calculated, and a structural analysis was performed.



(5.a)



(5.b)

Figure 5: ROV's frontal view (5.a) and lateral view (5.b).

2.3 Unmanned Surface Vessel (USV)

The instrumented vessel was developed at CIDESI. Its dimensions are: 204 cm long, 137.5 cm wide, and 92 cm height (Figure 6). It has two floats: one has the rack with the electronic architecture and the second the batteries. Both floats have humidity sensors for leak detection. The electronic architecture is shown in figure 7, it is divided into three groups: instrumentation, signals and data acquisition, and actuators. The instrumentation includes the following devices:

current, voltage and humidity sensors, IMU and GPS. A BeagleBone Black computer is used to manage the signal and data acquisition. Finally, the actuators consist of four thrusters to provide direction and displacement to the vehicle, and an IP camera is used for surface inspections.

Figure 6: USV developed at CIDESI, mounted in a carriage for ground transportation.

The communication SCU - Vessel is wireless (Xbee cards) by using the UART peripheral, while the wired communication Vessel - ROV uses another UART peripheral. The vessel power supply is 24 Vdc.

- **Instrumentation:** The Surface Vessel, is a mothership vehicle that carries the ROV, which has data reception functions, a camera, while the instrumentation has the following sensors:

Current Sensor: to monitor vehicle's electrical current consumption. Pololu ACS714 is a linear sensor with a resolution of 0.066 V/A. Voltage sensor: to measure the power supply. It is B25 analog device with a resolution of 0.00489 Vdc. Two humidity sensors: to detect water leakage, the high sensitivity water sensors have an analog interface with an output voltage signal of 0~4.2 Vdc. Inertial sensor: to determine the Euler angles of the vehicle (roll, pitch and yaw), (Robert D, 2014) the AHRS DC-4EP Sparton device is used; this sends NMEA serial packages or Euler angles only with a frequency of 10 Hz. GPS 15xl-w Garmin device: for global location of the Surface Vessel, this sends NMEA serial packages with acquisition time less than 2 seconds.

The current, voltage and humidity sensors are analog devices; these are connected to a voltage divisor because the analog inputs of the BeagleBone Black are 3.3 Vdc, while the AHRS and GPS are connected to UART peripherals.

- **Signal and Data Acquisition:** A BeagleBone Black development board is used for signal and data acquisition, which has the following specifications: a Sitara ARM Cortex-A8 processor running at 1000 MHz, 512 MB of RAM, 4 UART ports, 8 PWM signals, 2 SPI ports, 2 I2C ports, 7 A/D Converters, 2 CAN bus, 4 Timers and a consumption of 210–460 mA, programmed with the software Eclipse IDE Development (version Mars 2.0).
- **Actuators:** Two brushless motors VideoRay with a Pololu's VNH5019 driver at rear for forward and reverse motion, they are powered by 12Vdc and maximum current to 17 A. Two brushless motors BlueRobotics for lateral motion, the T100 Thruster are powered by 12Vdc and maximum current to 11.5 A. One Permanent Magnet DC motor Dayton for the LARS motion, it is powered by 12Vdc and 1/8 HP.

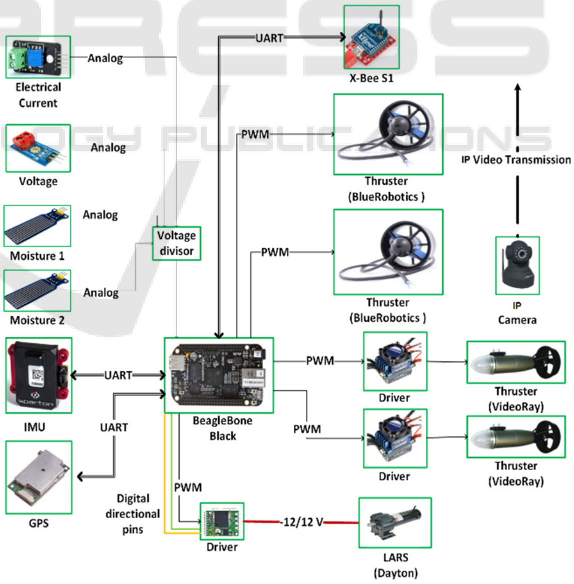


Figure 7: Vessel electronics Architecture Diagram.

- **Vessel Mechanical Design:** The mechanical considerations for the vessel design were: The boat is used for the surveillance in collaboration with a ROV. The main task of the vessel is to transport, launch and recover a small sized ROV. The Figure 8 shows some views from the CAD. A LARS is used to launch the underwater vehicle into the water and to recover it, without direct human intervention. Figure 9 shows LARS transportation position (top) and launch and recovery position (bottom).

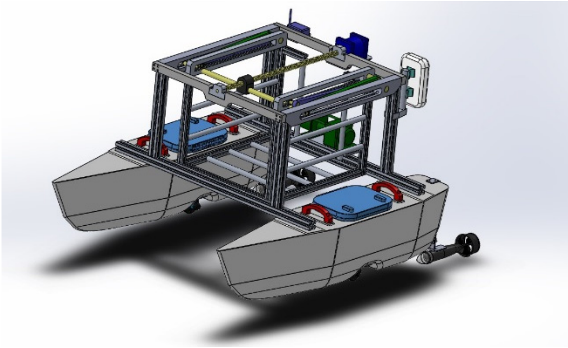


Figure 8: Vessel isometric view.

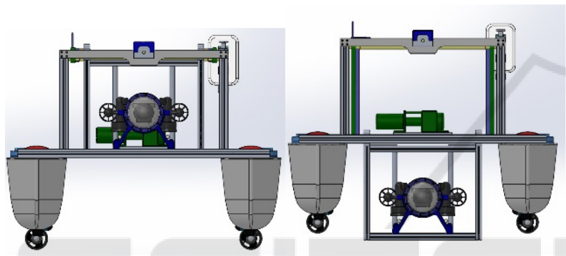


Figure 9: LARS (Launch and Recovery System). LARS transportation position (left) and launch and recovery position (right).

2.4 USV-ROV System Control

The USV-ROV system has two modes of control: teleoperation and automatic control. In this section, the implemented automatic control are explained. Two control algorithms were implemented: a conventional PID and an auto-tuned PID. The controllers were tested in a set of real time experiments.

2.4.1 PID Control

The PID controller is well known and widely used in the industry and robotics to improve the dynamic response of a system as well as to reduce or eliminate the steady state error. PID control consists of three types of control: Proportional, Integral, and Derivative control. The tuning of PID controllers depends on adjusting its gains (K_p, K_i, K_d) so that the performance of the system under control becomes robust and accurate according to the established performance criteria. In the discrete time domain, the digital PID algorithm can be expressed as follows (10):

$$\tau(n)=\tau(n-1)+K_p\,(e(n)-e(n-1))+K_i\,e(n)+K_d\,(e(n)-2e(n-1)+e(n-2)) \quad (1)$$

where $\tau(n)$ is the original control signal, $e(n)=\eta_d-\eta$ represents the position tracking error, η_d denotes the desired trajectory, K_p is the proportional gain, K_i the integral gain, K_d the derivative gain, and n-the sample time. This controller was applied to heading control (ψ) in both vehicles: ROV and Vessel.

2.4.2 Auto Tuned PID Control

In order to control the depth (z) of the ROV, an auto-tuned PID controller based on an online Neural Network (NN) was implemented. The purpose of having an auto tuned depth control, was to allow the vehicle to be modular, which means, makes the ROV capable of adding or changing tools or different kinds of instrumentation depending the mission to be performed, avoiding the necessity to re-adjust the control parameters.

A block diagram of the auto-tuning control with an artificial neural network (NN) is shown in figure 10.

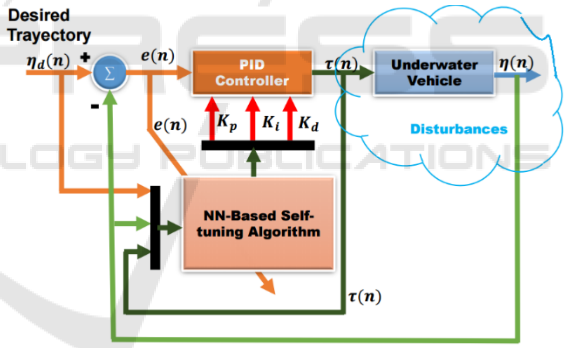


Figure 10: Auto-tuned PID control block diagram (8).

The algorithm used as auto-tuning is the backpropagation method, chosen for its ability to adapt to changing environments. The back-propagation algorithm looks for the minimum of the error function in weight space using the method of gradient descent (D. Maalouf, 2013), (Hernández, 2016). The combination of weights which minimizes the error function is considered to be a solution of the learning problem.

The NN has seven neurons in the input layer, three neurons on the hidden layer and three on the output layer. The neurons placed on the output layer correspond to the PID gains: K_p, K_i and K_d. The PID algorithm used in the automatic tuning control is the same as that presented in equation (1).

3 USV AND ROV REAL TIME EXPERIMENTS

This sub-section describes the heading control for the vessel and the ROV. The pilot defines heading set points in degrees referenced to the magnetic North. These set points are sent to the Vessel and the ROV, the automatics controls algorithms cause the two vehicles headed to the same direction. The way that the ROV and the boat change the heading is spinning in opposite direction their lateral thrusters, generating in this way a moment of torque with respect the center of gravity of each vehicle.

3.1 Experiment Description

The procedure to perform the experiment is:

1) Locating the ROV at 1 m of depth by an auto tuned PID, a set point of 110 ° heading is sent to the ROV and the Vessel.
2) Once both vehicles are stable in the reference, the experiment starts recording samples of: actual heading, set points and output control signals every 100 ms by 2 minutes.
3) After two minutes and without stop the sampling, a reference of 45° is sent to the vehicles for another two minutes.
4) Then, the set point is changed to 80° for 2 minutes.
5) Finally, the reference is changed to 180° for the last two minutes.
6) The sampling time is 100 ms.

3.2 USV and ROV Heading Control: Experimental Results

Following the procedure mentioned above, the PID controllers for the vessel and the ROV were tested. In the figure 11, graphs of the heading behavior are show.

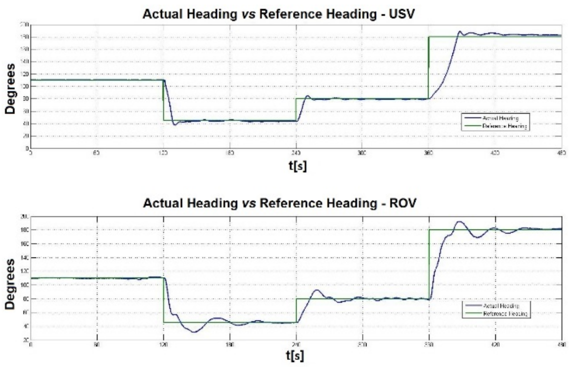


Figure 11: Heading vs time behavior for the vessel (above) and the ROV (bottom).

Figure 11 shows that the vehicles have about the same behavior when they are exposed to the same reference signal. It is important that the vehicles have an identical heading, which would be useful when they are carrying out a structural inspection. The Root of the Mean Squared value (RMS) was obtained for the experiments. The vessel has 17.787 degrees and ROV has 13.134 degrees.

3.3 ROV Depth Control

As detailed above: Throughout the heading experiments the ROV depth reference point was 1 m. The implemented controls were: PID and auto-tuned PID.

These controls were evaluated by performing a three-minute test with the following characteristics (phases):

Phase 1:

- The ROV is placed at 1 m depth.
- Not disturbance was given to the ROV during the first minute.

Phase 2:

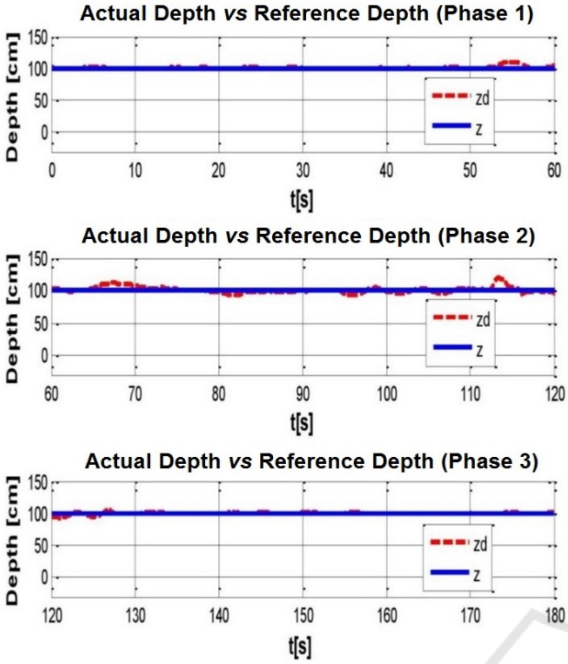
- During the second minute, a 400 g lead weight was placed on the top of the ROV.

Phase 3:

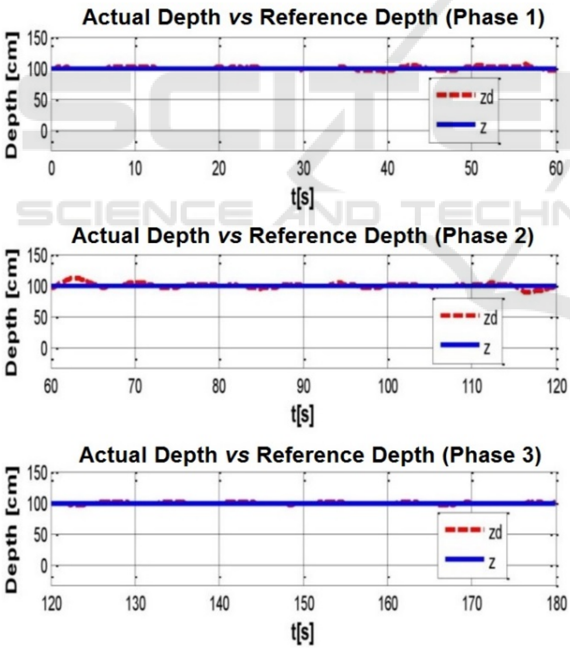
- Finally, at the third minute the weight was removed, making the parameters of the vehicle be exactly the same as when the experiment was started.

The gains of the conventional PID control were obtained by means of the NN. The ROV was requested to get the set point of 1 m depth by using the Auto-tuned PID controller. Once the ROV reached the stability and the control gains computed by the NN became stationary, these gains were programmed into the conventional PID. It is important to remark that once the conventional PID was tuned, the gains remained constant along the experiment, even when the disturbances took place.

The graphs obtained by this experiment divided by its three phases are the ones shown in the figure 12, comparing the reference (blue) and the actual depth (red) of the ROV during the experiment. Figure 12.a conventional PID control and figure 12,b auto-tuned PID control.



(12.a)



(12.b)

Figure 12: Depth control. Conventional PID Controller (12.a). Auto-tune PID (12.b).

The Root Mean Square Error (RMSE) is computed in each experiment; A 3.51 cm error is obtained for the conventional PID, while a 2.47 cm error is obtained for the self-adjusted PID.

The RMSE of three phases was obtained and it is shown in figure 13. It is important to note: the conventional PID presents the biggest error in the second phase (when the weight is added), proving the need of re-tuning the PID gains.

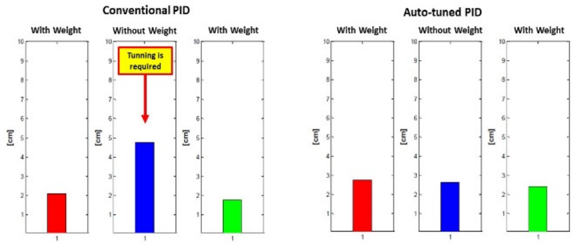


Figure 13: RMSE of both experiments (convwnbtional PID and auto-tuned PID) for each phase.

4 CONCLUSION

The development of an academic USV – ROV system was presented, including electronic, data transmission and mechanical considerations. Preliminary control results are presented, towards automatic collaborative techniques.

This USV – ROV system was designed thinking in the application of inspection and surveillance of marine and submarine structures. The main contribution of this work is the collaborative USV – ROV techniques considering a low cost - open architecture system.

Future Work:

- Improve collaborative USV - ROV control techniques.
- USV-ROV system field test.
- Suggest improvements to develop the inspection of oil platforms in Mexican waters.

ACKNOWLEDGEMENT

Research supported by CONACYT projects: PDCPN2013-01-215770.

This study is part of the project number 201441 “Implementation of oceanographic observation networks (physical, geochemical, ecological) for generating scenarios of possible contingencies related to the exploration and production of hydrocarbons in the deepwater Gulf of Mexico”, granted by SENER-CONACyT Hydrocarbons Sectorial Fund.

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