Bilateral teleoperation of a commercial small-sized underwater vehicle for academic purposes

Mariela Serna, Luis G. Garcia-Valdovinos, Tomas Salgado-Jimenez, and Manuel Bandala-Sanchez
Energy Division, Center for Engineering and Industrial Development (CIDESI)
Santiago de Quertaro, Qro. Mexico
Email: mserna@cidesi.edu.mx, ggarcia@cidesi.edu.mx, tsalgado@cidesi.edu.mx, mbandala@cidesi.edu.mx

***Abstract*—This paper describes the platform for a bilateral teleoperation where the master is a haptic device and the slave is a commercial small-sized underwater vehicle. The submarine will be instrumented, so that the electronics architecture can be upgrade at any time. With this new architecture it will be possible to program any advanced control scheme an the embedded. Also, position and velocity commands from the haptic interface to the small-sized underwater vehicle, will be send. Such that, when the force sensor, placed in the nose of the underwater vehicle, interacts with the environment, it will measure the force at the slave site and feed back it to the master robot.**

I. INTRODUCTION

Mankind has discovered and created countless means to conduct work in the most inhospitable environments. Underwater envioronments for instance are all but impossible to work in if it weren't for technological advancements in automated underwater vehicles. Nonetheless, these vehicles alone sometimes require human intervention, either due to complexity of a task or even unanticipated emergencies. It is for this reason that tele-operation manipulation is such an important process and tool to many underwater tasks, such as offshore oil production and deep-sea exploration. It allows for a human host to take control of an underwater vehicle, thus allowing for greater intelligence and accuracy to complete tasks. However, remote control of these vehicles is usually in the form of visual feedback solely, and this can be limiting to some tasks.

Although force feedback has been proven to enhance productivity in many types of tasks, including underwater applications [1], force feedback greatly increases system complexity. The master manipulator becomes a force-controlled robot and thus requires accurate communications and control algorithms. A few previous studies have discussed the issue of force feedback in a task-related context [2, 3, 4]. Previous work, provide an integrated framework for teleoperation of underwater vehicles that provides the operator with a haptic feel for obstacles in the environment based on optic flow measured by the vehicle [5], and vibrotactile feedback [6] that improved performance in telemanipulation, particularly tasks where vibrations reveal the mechanical state of the hand-object interaction.

The bilateral teleoperation system consists of 5 blocks (Figure 1): 1) Human operator, 2) Master robot (Phantom Premium 1.0 haptic device), 3) Communication channel, 4) Slave robot (Underwater vehicle Neptune SB-1) , and 5) Remote environment (underwater environment).

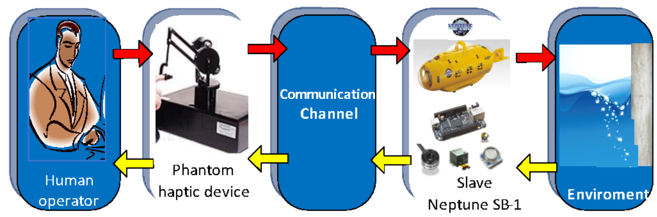

Fig. 1. Bilateral teleoperation scheme

In this paper we describe the platform for bilateral teleoperation, as shown in Figure 1, and experimental results of the force applied by the human operator vs the force obtained by the force sensor placed in the nose of the underwater vehicle. In Section II we provide the characteristics of the Neptune SB-1 platform. Section III describes the reasons why an open architecture of the submarine is required. The proposed electronics architecture is also described. The new architecture includes the integration of new sensors,a new system for signal processing and acquisition, and two vertical thrusters. Section IV discusses the five blocks of the bilateral teleoperation system. Finally in Section V, we describe the experimental implementation of these concepts.

II. NEPTUNE SB-1 SUBMARINE DESCRIPTION

The main component selected for the project is a radio controled submarine, the Neptune SB-1 by $ThunderTiger^{TM}$. The Neptumne SB-1 has a radio control unit working at 75 Mhz, that controls the up/down, left/right, forward/backward and the nose up/nose down directions [9].

Figure 2 shows in detail the main parts of the submarine Neptune SB-1. The platform uses the Archimedes principle, a body immersed in fluid will be subjected to an upward buoyant force that is equal to the weight of water that the object displaced. The submarine is equipped with a roll pump with a ballast tank device in the inner hull. This allows the pump operating system to draw or drain water

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into/out of the ballast to change the weight of the submarine, allowing it to float or dive as needed. This system is called power pump with ballast tank and it is shown in block 1 of Figure 2. Likewise, the submarine had two side fins which are controlled by a servomotor, that in combination with the ballast for tank allow the system dive or floatation. Additionally, the propulsion system (block 3) is regulated by a speed motor controller (block 2). This device controls the vehicle's forward/ backward movement. It has a control system for the pump and propulsion motor (block 4), and for both servomotors that controls the left/right movement. One 12V sealed Lead-Acid battery (block 5) is included to supply the required power for all the electric equipment and power drive system.

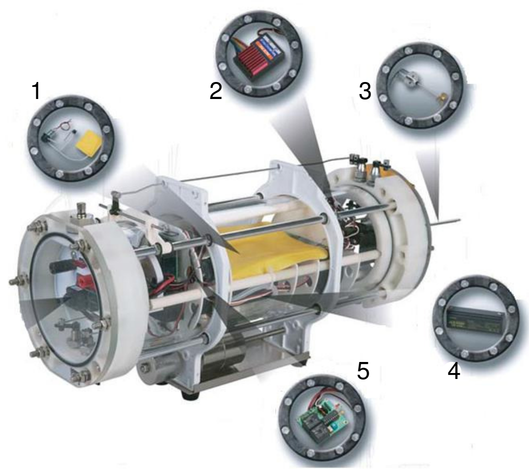

Fig. 2. Neptune SB-1

It is combined with an auto-detect protecting system on the main PCB control board, if the system detects low battery power, low transmission signal, leakage (water inside hull), then the roll pump will auto start to drain the water out of the ballast tank to make the submarine come back to the surface. At same time, a red light LED will flash [9].

The major constraint is that the pump power electronics works as an on/off controller, which limits the resolution and accuracy of the closed loop system.

III. Open architecture proposal

Figure 3 shows the proposed electronics layout for the project. Where the underwater vehicle Neptune SB-1 is the slave robot. The system can be divide into three main sections: instrumentation, which consists of the leakage sensor, depth sensor, inertial measurement unit and the force sensor. Acquisition and signal processing: a computer. Finally the actuators: the servo motors, two DC motor and the propulsion motor that the submarine has.

A. Instrumentation

The slave robot is equipped with (Figure 3): leakage sensor, miniature variometer module (MS5803-01BA), the Inertial Measurement Unit (IMU ADIS16362) and a low range precision miniature load cell.

The leakage sensor is screwed into the bottom of the submarine in order to detect humidity inside the vehicle. When it comes in contact whit water the submarine will emerge to the surface. The miniature variometer module (MS5803-01BA) is a high resolution depth sensor that is optimized for depth measurement systems with a water depth resolution of 1cm and below. The sensor's module includes a high linearity pressure sensor and ultra low power 24 bit $\Delta\Sigma$ ADC with internal factory calibrated coefficients. It provides precise pressure andtemperature values, and different operation modes that allow the user to optimize for conversion speed and current consumption. The communication protocol is I2C, without the need to programming internal registers in the device.

After obtaining the value of the hydrostatic pressure the Formula (1) is applied to determine the depth where the submarine is located. Depth is understood as a distance [11](in meters) between surface and sensor in the submarine.

$$h = \frac{P - P_0}{\rho\ g} \tag{1}$$

Where:

h = Height (m)

P = Hydrostatic pressure (Pa)

P_0 = Atmospheric pressure (Pa)

ρ = Density of water(kg/m^3)

g = Gravitational acceleration (m/s^2)

We consider the gravity acceleration as 9.81 m/s^2, the density of water is 1000 kg/m^3, the atmospheric pressure is acquired from the pressure sensor and is usualy 810 Pa. The value of hydrostatic pressure is acquired from the depth sensor and it is updated every 60 milliseconds.

The Inertial Measurement Unit (IMU ADIS16362) is a complete inertial system that includes a triaxis gyroscope and triaxis accelerometer. The IMU is an electronic device that measures and reports on a aircraft's velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes, sometimes also magnetometers. IMUs are typically used to maneuver aircraft, including unmanned aerial vehicles (UAVs), among many others, and spacecrafts, including satellites and landers.

Additionally, the force sensor is a low range precision miniature load cell that measures: tension and compression load forces from 50 grams to 500 g. The sensor model is 31 from Honeywell^{TM}, which has the highest accuracy, stainless steel construction and is designed to eliminate or reduce at minimum the effects of off-axis loads. A modification allows this model to be completely hermetic welded for underwater

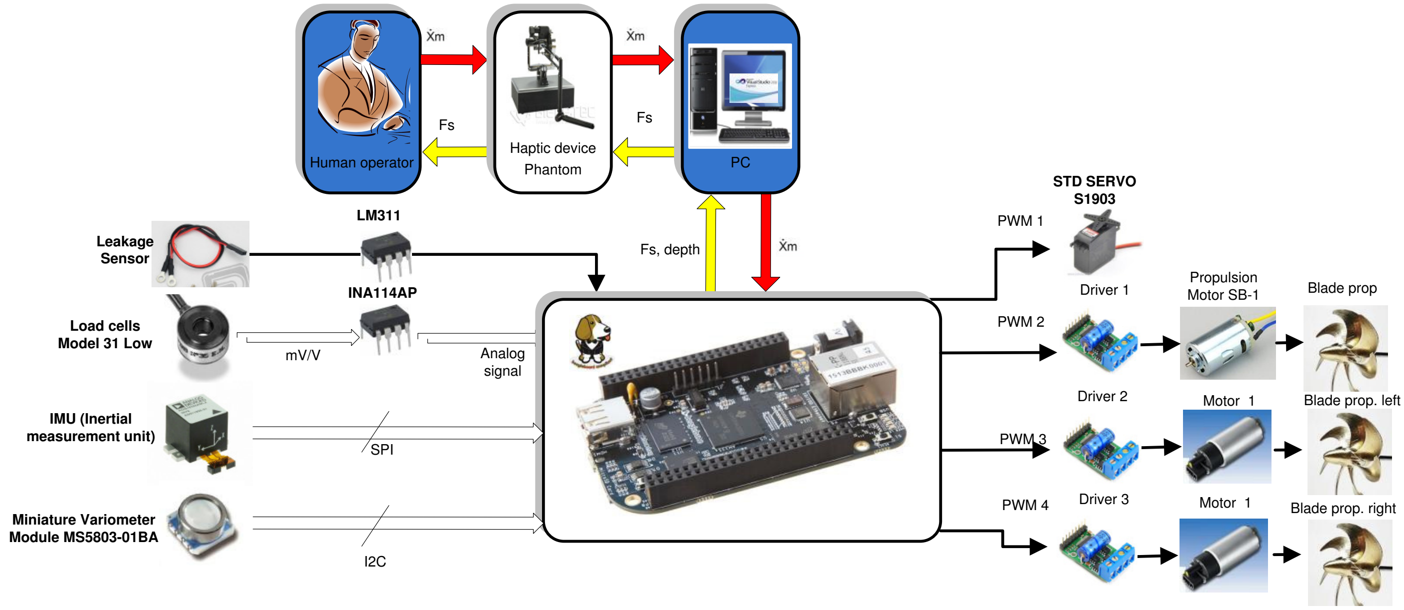

Fig. 3. Electronic architecture layout

applications. This sensor is mounted on the nose of the underwater vehicle and has a high accuracies of 0.15 % to 0.25 % at full scale.

B. Acquisition and signal processing

The data from these sensors are acquired and processed in a low cost development board with the embedded Linux system $BeagleBoneBlack^{TM}$. This system has a Sitara AM3359 ARM Cortex-A8 1 GHz processor. The board receives data and generates the control signals to control four actuators.

C. Actuators

Four actuators control the movement of the submarine. Two DC motors located on the side of the robot control the depth, as shown in Figure 4.

Fig. 4. Side DC motors

The variation to the speed of these DC motors is performed by varying the duty cycle percentage. These DC motors replace the ballast tank and the two-side fins. These system were replaced because they have slow response. The propellant system was kept. This system regulates speed and direction of rotation to move the underwater vehicle forward or backward. The servomotor is for rudder control, which provides the underwater vehicle the capability to move right and left.

To control these four actuators a PWM signal is used, this is one reason why the BeagleBone Black was selected, because this computer provides over 4 PWM by hardware, which guarantees greater precision in the signal.

IV. Bilateral teleoperation system

Figure 5 shows the master/slave system for an underwater manipulation, where $\dot{X}_s$ and $\dot{X}_m$ means the velocity of the master and slave arm respectively. Z_s and Z_m means the displacement in the Z axis and ψ_s and ψ_m means the yaw movement. f_m denotes the force that the operator applies to the master arm, and f_s denotes the force that the slave arm applies to the object. The force f_m is measured by the force sensor, which is attached at the end of underwater vehicle.

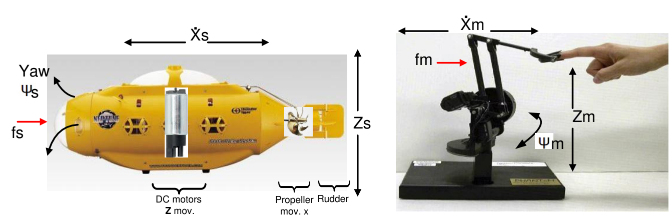

Fig. 5. Master/Salve system

In the last section we describe the Slave robot (Underwater vehicle Neptune SB-1) block. In this section we will discuss the remaining blocks of the bilateral teleoperation system (Figure 1).

A. Master robot

The master robot is the Phantom Premium 1.0 haptic device that acquires position in the ψ_m movement and Z_m displacement from human operator and sends them to control yaw and depth, respectively. Position in X_m-axis is appropriately converted into velocity ($\dot{X}_m$ -axis) commands and sent to the submarine to control the forward, backward motion. Additionally, the Phantom allows to reflect the contact force (*fs*) to the master robot so that, the human operator will be able to perceive, with some degree of accurancy, the remote environment. Even though there exist unknown external disturbances, f_m should be equal to the measured force at the slave side (f_s).

B. Communication channel

For bilateral communication between the Phantom Premium 1.0 haptic device and the PC, a parallel port is implemented. Serial UART protocol is used to send commands from the PC to the BeagleBone Black located inside the submarine, as shown in Figure 6.

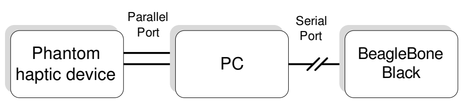

Fig. 6. Communication channel

V. Experimental results

The master force is sent to an underwater vehicle with an update rate of 1 kHz, to ensure that the system is haptic.
Figure 7 shows that the Phantom haptic force f_m is inversely proportional to the underwater vehicle force f_s. It can be seen that in the first impact force signal is greater. The increase in force close to the wall is clearly visible in the graphic, and can be perceived by the human operator. To better understand

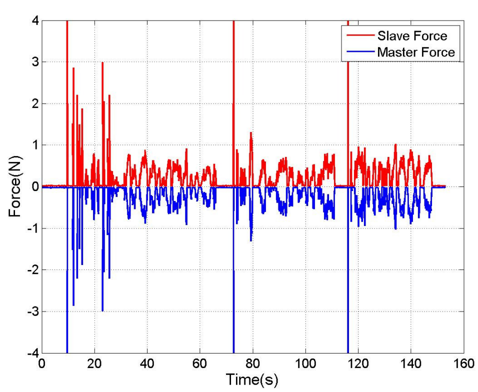

Fig. 7. Master and slave force

the Figure 8 is importatne to mention that the speed variation is performed through the variation of a some percentage of the PWM duty cycle applied to the propeller drive. When the duty cycle is equal to 7% the motor speed is zero. As the duty cycle decreases the speed motor is increasing and the motor moves forward. As the duty cycle increases the motor speed increases, in this case the vehicle goes backward. Figure 8

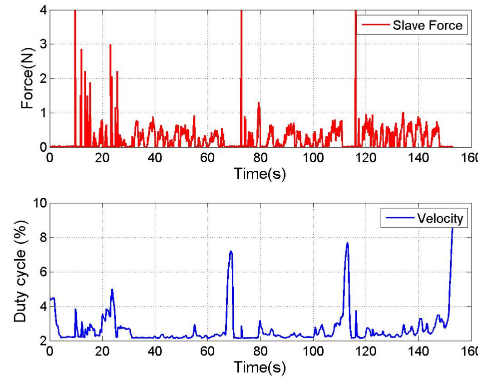

Fig. 8. Force vs Velocity

shows the behaviour of the system as the human operator increases the speed of the submarine towards a vertical wall. Due to the action of f_s the underwater vehicle slows down and and even though the master robot is commanding full forward velocity.

VI. Conclusion

The bilateral teleoperation system allows us to be able to program any advanced control law in $BeagleBoneBlack^{TM}$ and send position (in ψ and z displacement) and velocity (in x axes) commands from the Phantom haptic interface to the underwater vehicle. Additionally, the human operator receives clear haptic repelling force feedback prior to collisions with objects.
As such, this paper has demonstrated the effectiveness of implementing a force sensor. This sensor allows measuring the front force between the underwater vehicle and the environment,in order to detect sustained contact and frontal collisions. Furthermore eliminating the need to rely solely on visual teleoperations.

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