Modeling and Simulation of AUV using Hardware In The Loop

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Abstract
This document shows the methodology of simulation based on the technique Hardware-In-the-loop for the design and testing of a dynamic system that represents a robot aquatic type AUV controlled by an embedded system. The stages for the development and implementation of the project involve the mathematical model of the system, the analysis of the natural response of the system compared to external forces, the design parameters of the controller and the HIL simulation HIL. Performing this type of simulations by means of the hardware in the loop allows the detection of errors and problems in the design of the robot, which allows you to adjust the mechanical structure and the electronics embedded. In addition, the technique allows to validate that the embedded system has right implemented response times for the best robot model when in reality it is a simulated model in real time, thus enables the verification of the sensors with responses consistent with the actual model.

Keywords: Autonomous Vehicles, Hardware-In-The-Loop Simulation, Control, Robotics.

Introduction
At present, areas of research in mobile robotics are evolving due to advances in electronic and computer systems. These have allowed the exploration of new areas of interest focused on autonomous vehicles whether by land, air or water, in order to equip them with reasoning skills intelligent so they can interact with the environment in which they are [1] [2]. According to Siegwart [3], to consider a robot an autonomous vehicle it must have a system that enables you to move regarding on the variables that are in the application environment. However, to automate a particular vehicle (land, air or water), the risk that the control systems, path planning and perception may fail is high, thereby generating the interest of having a method of simulation in which they can validate these systems a priori, thus implying for example the use of Hardware In the Loop (HIL) simulation.

The HIL simulation technique is usually used in a project level where the implementation of the mathematical modeling of the system with some degree of accuracy and fidelity is possible. The dynamics of the plant often is simulated in real time, either because the physical prototype is not available or because experiments with real parties in certain phases of the project involve a high cost due to the time required for its implementation [4], [5], [6]. In addition to being, in many cases, a way to avoid unnecessary risks in projects that could compromise somehow human life, such as nuclear power plants, projects launch of space vehicles, among others [7], [8]. Accordingly, to implement this technique seeks to reduce dependence on the prototypes, especially in the preliminary practices of the project and, besides this, reduce time and effort. It allows to check in advance the complete virtual prototype of the vehicle, so that major changes of some components are decided before starting its construction and implementation.

This article describes the mathematical model of an autonomous underwater robot platform and the implementation of the simulation using the HIL technique, detailing the control design for the interaction of the
components implemented in the software development with the real subsystems of the robot.

System description

Fig. 1 describes the system architecture. This method of simulation, analysis and validation of the behavior of the dynamic model of a system, considering its inputs and outputs are connected to an electronic card embedded, the difference between this technique and other simulations, it is because that the control system is real and generates signals that depend on the response of the implemented system [9] [10]. In other words, the HIL replaces the real plant for the embedded system control according to the signals in and out of the plant in real time [11]. The real time simulation hardware represents the dynamic behavior of the system into a virtual world model realizing missions that follow paths, avoid obstacles, among others, in which this implementation was development in Matlab®; The DSPACE-Micro Auto Box II is responsible for the signal conversion, fault simulation, update and display of state variables. Finally, the electronic control unit utilized is the embedded Fox Board G20 card. It is responsible for updating the engine voltage level at every instant of time based on the response of the control algorithms implemented to realize missions such as immersion and emersion of the robot.

This method is applied in cases where the plant cannot be safely physically tested. Basically the system been simulated has a piece of software that performs all the math model, and then generates an interaction through conversion modules ADC and DAC to the controller previously designed and embedded in the electronic control system [11]. In the end is obtained a dynamic system model similar to the real system that allows verification of performance of different designs of control as shown in (Fig. 2).

Mathematical model of the Platform

The platform used for the development of this project represents an underwater vehicle, which has six degrees of freedom, three of which regarding the movement in the plane (x, y) and depth (z) and the three remaining correspond to rotational movements. The platform is composed of four propulsion engines, two of them are in the back of the robot which is responsible for surge, and the other two in the middle of the robot which are responsible for the heave of the robot, as shown in figure 3. The parameters of the robot are a circular section radius (r) 0.1 m, length (L) 0.6 m, mass (m) 18.710 kg and volume (V) 18.83 dm³.

The model of the AUV considered in this paper is based on the standard representation of marine vehicles which is based on the following assumptions: The AUV is submerged far from any surfaces, underwater currents are not considered, the AUV is a rigid body of constant mass, added mass is constant (independent of wave frequency) and the accelerations on the surface of the earth can be neglected.

When determining the position and the orientation of the AUV it is useful to define two coordinate frames, one fixed on the earth Ro (x, y, z), assumed as an inertial frame, and the other one is fixed into the body of the vehicle Rb(xb, yb, zb). The general motion of the vehicle can be described by the following variables:

\[ \eta = [\eta_1^T, \eta_2^T]^T, \eta_1 = [x, y, z]^T, \eta_2 = [\phi, \theta, \psi]^T \]
\[ \nu = [v_1^T, v_2^T]^T, v_1 = [u, v, w]^T, v_2 = [p, q, r]^T \]
\[ \tau = [\tau_1^T, \tau_2^T]^T, \tau_1 = [X, Y, Z]^T, \tau_2 = [K, M, N]^T \]

(1)

Where \( \eta_1 \) represent the position of the body-fixed frame relative to the earth-fixed frame, \( \eta_2 \) represent the orientation and are Euler angles (roll, pitch and yaw), \( v_1 \) and \( v_2 \) represent
the linear and angular velocities, respectively, given in the
body-fixed frame, and \( \tau_1 \) and \( \tau_2 \) are forces and moments acting
on the vehicle, respectively, given in the body-fixed frame. It
should be noticed that \( \tau_1 \) and \( \tau_2 \) are assumed as the state
vectors of the AUV.

The nonlinear dynamic equations, derived using Newtonian
mechanics under the assumptions formerly stated, can be
written as [12] [13]:

\[
M \dot{v} + C(v) \dot{v} + D(v) \dot{v} + G(v) = \tau
\]

(2)

Where \( M \) denotes the inertia matrix (including added mass), \( C \)
denotes the Coriolis and centripetal effects matrix (including
added mass), \( D \) denotes the hydrodynamic damping effects
matrix and \( G \) denotes the vector of hydrostatic forces and
moments (gravitational and buoyancy). The right hand side
term represents external forces and moments actuating on the
AUV, and can be decomposed as:

\[
\tau = \tau_d + \tau_u = \tau_d + Bu
\]

(3)

Where \( \tau_d \) is a vector of nonlinear disturbances (model
parameter variation, current, waves, etc.) and \( \tau_u \) is the vector
representing the controlled input forces generated by the
actuators \( u \) arranged on the vehicle according to the matrix \( B \).

The numerical values of the vehicle parameters used in this
paper to perform the simulations were obtained from [14] and
here are the calculated matrices:

\[
M = \text{diag}(16.85, 16.83, 16.83, 0.09, 0.55, 0.55)
\]

\[
The \quad D = \text{diag}(12.54, 71.85, 71.85, 0.038, 3.885, 0.189)
\]

(4)

Where diag(\( * \)) stands for diagonal matrix with the \( * \) elements
on its diagonal.

Design of Controller

One of the mechanisms of control more widely used in
various applications such as automation, robotics, domotics,
among others, it is the PID controller (proportional-integral-
derivative). To take advantage of all the benefits that provides
this control it should be used in a configuration with negative
feedback to calculate the deviation or error between a
reference value and the current state [14].

There are various methods of setting the parameters of PID
controllers but when applied in this case none of them ensures
the resulted controlled system it is stable. So the most used
method remains the method of trial and error, checking the
output behavior by varying these parameters. The PID
Controller is expressed mathematically as follows [15].

\[
F_t = k_p * e + k_i * \int_{t_0}^{t} (e) \, dt + k_d * (d(e)/dt) + k_0
\]

(4)

Where \( F_t \) is the resulting of the PID action, \( e \) is the error
between the desired position and the real, \( k_p \) is the
proportional gain, \( k_i \) is the integral gain and \( k_d \) is the
derivative gain. Finally you have \( k_0 \) which is the minimum
value of the force that must be imposed to the engines to keep
submerges the robot within a margin of 4 m.

The gains proportional, integral and derivative were
established as: \( k_p = 12, \, k_i = 1, \, k_d = 0.5 \) and \( k_0 = 2.8 \).

These values are obtained from an experimental setup (trial and
error) with the HIL simulation in execution, which is
considered in this case to be the best way to find these values,
since the dynamic system that describes the behavior of the
robot is a non-linear system. On the other hand, these
parameters that you want to obtain should also avoid the
overshoot response and stationary error.

Results

The first simulation experiment have been carried out using a
helical reference trajectory with a radius of 3 m on the XY
plane, linear velocity of 0.3 m/s and a simulation time of 50s.

The results can be seen in the Figure 3 and again it allows to see that the vehicle achieved tracking.

\[
\text{Figure 3}
\]

\[
\text{Figure 4a}
\]
Conclusions

The proposed prototype in this work proves to be able to realize trajectory tracking missions. The simulation using the HIL technique allows to obtain the parameters of the PID controller that meet the initial requirements imposed on the dynamic response behavior of the AUV without performing trial and error experiences in the real platform. This simulation based on the method Hardware-In-the-Loop allowed to check the efficiency of the embedded system Board Fox G20 as aquatic robot controller. Finally, validates the design of the mechanical structure proposal at the beginning of this document.

For future work the current and waves will be implemented in the simulation, as well as different control strategies and estimation of unknown states of the AUV such as position and velocities.

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References