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Rapid prototyping for enhanced dynamic positioning systems.

Silvia DONNARUMMA [a,1], Camilla FRUZZETTI [a], Michele MARTELLI [a],
Roberto CHITI [b], Andrea PECORARO [b] and Luca SEBASTIANI [b]
[a] *DITEN, University of Genoa, Italy*
[b] *Seastema SpA, Italy*

Abstract. The paper aims to show the design procedure for a Class-2 dynamic positioning system, from initial conceptualisation upon factory assessment test. The approach involves the use of simulation–based design combined with hardware–in–the–loop testing. This kind of approach involves a detailed knowledge of the investigated ship but gives significant well-known advantages. A custom simulation platform has been developed to have realistic feedbacks of the case-study ship. The dynamic positioning controller structure, including regulator, force and thrust allocation; have been conceptualised, and then, after the porting procedure, the dynamic positioning software has been downloaded in the real programmable logic controller. Several hardware–in–the–loop tests have been carried out to fine-tune the controller parameters. The results show, under different environmental conditions, the respect of the design criteria.

Keywords. dynamic positioning, model–based design, hardware–in–the–loop

1. Introduction

Simulation-based design has now become the state of the art for dynamic positioning systems. In addition to the efficiency of the technology in terms of design time, the development of this methodology has been enhanced, over the years, by the interest of classification societies in simulation results for certifying such systems, [1]. This kind of approach involves a deep knowledge of the investigated unit, but also significant well-known advantages, [2]. These advantages concern more reliable predictability of station keeping performance (even in adverse weather conditions) and the possibility of testing different control logics and fault management.

In this study, the results of the proposed approach are reported. Indeed, systematic testing of dynamic positioning (DP) system is increasingly important as the software and hardware complexity of DP system installations grows. Hardware–in–the–loop (HIL) simulation testing is widely used in industries to test the hardware and software of computer–based control units. A DP–HIL vessel simulator is a Real–Time (RT) simulator that interfaces directly with a DP controller. In this paper results of the integration of the simulation platform implemented for a platform supply vessel equipped with

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[1] Corresponding Author: DITEN, University of Genoa, Italy, E-mail: silvia.donnarumma@unige.it

a dynamic positioning system of Class 2 with the physical controller are presented and critically discussed. In [3], [4], [5], and [6] the concept of HIL testing is described, and the experiences and findings statistics are reported from HIL testing of DP computer systems, power management systems and steering, propulsion and thruster control systems on drilling vessels, offshore service and construction vessels, patrol vessels, and shuttle tankers.

2. SIL and HIL frameworks

In a real system, the whole control system has to work in RT and the automation designer has to be sure that the performance foreseen by simulation will also be maintained in a real environment. To this end, it is necessary to limit, as soon as possible, most of the differences between the two worlds. This could be made possible by the adoption of the RT–HIL method. Several CPUs are usually used to control different components of the propulsion system, trying to limit the loss of functionalities in case of failure of one of them (even if each CPU is used in a redundant configuration). Unfortunately, the behaviour of the real hardware on board could be quite different from that one simulated during the preliminary design phase. The main differences could be due to the cyclic time of the CPUs, the time delay in exchanging data among controllers and the native functions that can be implemented; further differences could be represented by the presence of many functionalities usually not implemented in the ship numerical model (but that interact with the propulsion control) and the thousands of signals that the automation has to monitor on the real system.

In Figure 1 a general sketch of the proposed methodology is shown, in details, the Software–In–the–Loop (SIL) is the black workflow while the HIL is the dashed purple one. The first step of the procedure deals with developing a simulation platform, the MODEL block (pink). The mathematical model implemented in the software platform allows the study of the vessel behaviour during transient conditions as well as the analysis of the mutual interaction between all the elements involved.

The second step concerns the development of the DP controller in a virtual environment, the CONTROLLER SOFTWARE block (teal) in Figure 1. This is the kernel of the simulator because it contains both the regulator and the forces and thrusts allocation logics. Indeed, the control laws are implemented and tested through an iterative series of SIL simulations to achieve all the calculated data in a faster time (that means a test of 60 seconds, for example, is simulated by PC in less than 60 seconds).

The third step is the application of the RT–HIL technique. By using RT–HIL simulation, the physical availability of the ship is not required; thus, the controller testing can be done even before the ship is built. This approach allows reducing the need for time-consuming and expensive sea trials. The control logics development in the virtual environment are implemented in real Programmable Logic Controller (PLC), the HARWDWARE block (purple) in Figure 1. The controller is the AC500 CPU family produced by ABB©. The CPU model used for HIL test is the PM591 with the following processor module characteristics related to cycle time for 1 instruction: (i) Binary min. $0.002 \mu s$; (ii) Word min. $0.004 \mu s$; (iii) Floating point $0.004 \mu s$. A RT application executes the ship model; an Open Platform Communications (OPC) client reads the command parameters on the controllers through OPC servers and returns the feedback. OPC servers and the application reside on the same PC and each OPC Server exchanges data with the controllers through Ethernet LAN.

The HIL simulator of the dynamic positioning system is composed of following elements: (i) model of the ship and external environment implemented in Matlab©Simulink environment on Personal Computer (PC); (ii) control logics of the dynamic positioning system implemented in PLC language and run on the same PLC; (iii)hardware for the control of the dynamic positioning system consisting of electronic components and PLC Controller. With the above described HIL simulator several tests have been carried out and the results are shown in the following.

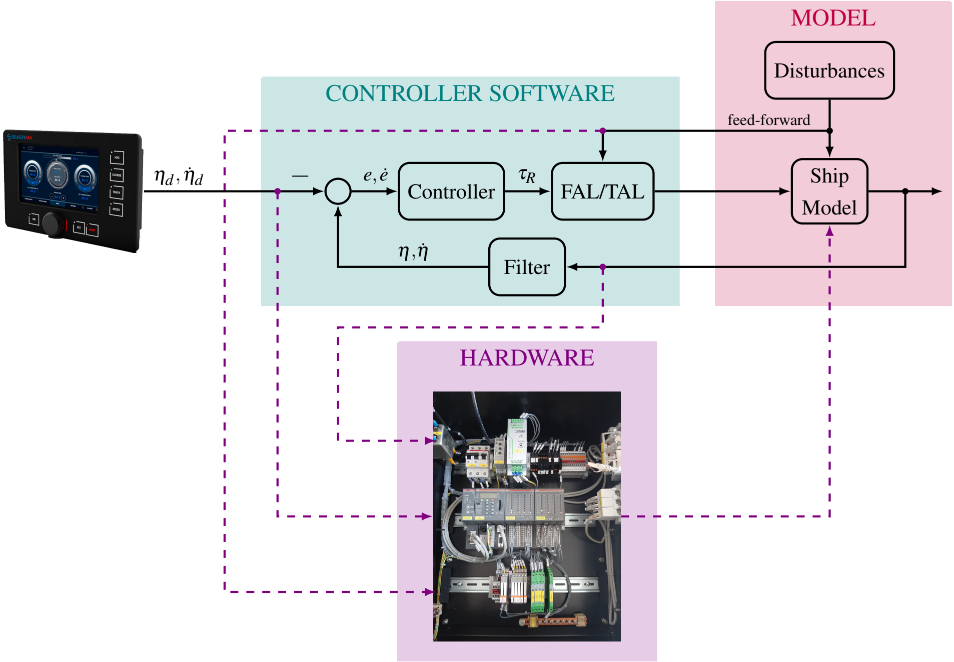

Figure 1. DP Layout

Generally, the test of the real controller is made onboard, partially during the delivery period and completely during ship full–scale trials. These trials are time–consuming and very expensive, as they require the ship availability. By using RT–HIL simulation, the physical availability of the ship is not required, thus the controller testing can be done even before the ship is built. In order to increase the simulation realism, some functionalities, not implemented in the ship model, are simulated by codes inside the controllers.

3. Silmulation Platform

The motion of a ship (speed and direction) depends on the interaction of the forces acting on the system (ship) and their variation over time, [7]. In this regard, the vessel dynamics can be defined as the set of complex effects due to the action of such forces together with their mutual interactions. In this whole process, a tangled web of differential equations determines the evolution of each variable giving its contribution to the ship dynamics. This is sketched by the pink rectangle in Figure 1. In particular, the vessel simulator contains: (*i*) hull hydrodynamic forces; (*ii*) environmental forces, such as wind, waves and current; (*iii*) propulsion line with electric motor, shaft line, gearbox, azimuth thruster, bow–thusters; (*iv*) the power generation system together with diesel generators, main electrical bus and distribution line.

Each of the previous systems interacts with each other, contributing to the whole ships dynamic. Indeed, whenever dealing with manoeuvring problems, it is common to introduce two reference frames, according to [8] and [9]: the Earth-fixed reference frame $\{\Omega,\underline{n}_1,\underline{n}_2,\underline{n}_3\}$ and the body-fixed frame $\{O,\underline{b}_1,\underline{b}_2,\underline{b}_3\}$. The origin O is located on the mean water-free surface at midship, then

$$\begin{cases} \Delta(\dot{u}-x_G r^2-uv)) & = X \\ \Delta(\dot{v}-x_G\dot{r}+ur)) & = Y \\ I_z\dot{r}+mx_G(\dot{v}+ur) & = N \end{cases} \tag{1}$$

where $v_O = u\underline{b}_1 + v\underline{b}_2$ denotes the linear velocity of O expressed in the body-fixed basis and $\omega = r\underline{b}_3$ is the angular velocity, x_G is the longitudinal coordinate of gravity center w.r.t. $\{O,\underline{b}_1,\underline{b}_2,\underline{b}_3\}$, Δ is the vessel mass, I_z is the moment of inertia about $\underline{b}$-axis, $\underline{R} = X\underline{b}_1 + Y\underline{b}_2$ and $\underline{M} = N\underline{b}_3$ are the force and the moment expressed in the $\underline{b}$-basis, respectively. In addition, $X = X_H + X_P + X_E$, $Y = Y_H + Y_P + Y_E$, $N = N_H + N_P + N_E$, and subscripts H, P, and E refer to hull, propellers, and environmental forces and moments, respectively. A proper selection of the single sub-models has made it possible to develop a simulator capable of simulating the dynamics of the ship and its components in fast time, or in RT. The main challenging is to merge in the same simulation platform two dynamics very different in terms of time constant, which means that the system of stiff ordinary differential equations should be integrated with the smaller time step. To do this, some simplifications have been made, which after some tests, have led to the affirmation that they do not affect the goodness of the final result, as shown in Section 5. The proposed simulation model has a wider validity than the representation of the single ship, as it has been created in a parametric and modular format.

4. Dynamic Positioning Regulator

Generally, the DP–regulator is divided into two macro-systems: the controller and the allocation, which in turn comprises the force allocation and the thrust allocation. The combination of these systems must ensure that the vessel is able to control its position and heading with a certain tolerance.

4.1. Controller

The input of the controller are: (*i*) filtered position and velocity components in the inertial fixed frame $\{\underline{n}_i\}$, i.e. $\eta = [x, y, \psi]^T$ and $\dot{\eta} = [\dot{x}, \dot{y}, \dot{\psi}]^T$, respectively; (*ii*) η_d and $\dot{\eta}_d$ are the desired position and velocities; (*iii*) relative wind speed, v_{aw}, and relative wind incoming direction, γ_{aw}.

The controller is modelled as in [6] and consists of three independent Proportional–Derivative (PD) algorithms, one for each axis. The integrative term has been replaced with the estimation of the environmental forces to be compensated. In particular, the current and the wave are estimated by a means of an average of the forces and moment required by the PD controller in a previously fixed time interval $\overline{\tau}_{PD}$, while the wind action τ_W is feed-forwarded through a wind force model thanks to the on-board anemometer measurements. The control law τ_R gives as output the required forces and moment in the $\underline{b}_i$–basis and can be written as in Eq. (2).

$$\tau_R = R(\psi)[K_P\, e + K_D\, \dot{e}] + \overline{\tau}_{PD} + \tau_W \tag{2}$$

where $e = \eta - \eta_d$ and $\dot{e} = \dot{\eta} - \dot{\eta}_d$ are the position and velocity errors, respctively; $\tau_R = [X_R, Y_R, N_R]^\top$ is the array containing forces and moment required by the controller; $R(\psi)$ is the rotation matrix between the basis $\{\underline{b}_i\}$ and $\{\underline{n}_i\}$; K_P and K_D are the diagonal gain matrices corresponding to the proportional and derivative action, respectively.

4.2. *Allocation*

The forces and moment required by the controller need to be allocated to the actuators and a set–point for each one is required. The allocation algorithm can be dived into two parts: the *Force Allocation Logic* (FAL), which takes as input the array τ_R and gives the required thrust for each actuator, and the *Thrust Allocation Logic* (TAL), that takes as input the thrust and generates the set–points to be sent at each actuator.

4.2.1. *Force allocation logic*

The propulsion configuration of the vessel is shown in Figure 2(a). Two azimuthal thruster and two bow thrusters are present. Each thruster has modelled by means of a thrust vector applied in its center, $\underline{T}_i = X_i\underline{b}_1 + Y_i\underline{b}_2$, where the module $T_i \in [0, T_{i_{max}}]$. The allocation algorithm envisages guaranteeing, at each time, the static equilibrium, by means of Eq. (3), between the forces and moments required by the controller and the thrusts provided by each thruster.

$$\begin{cases} \sum_i X_R + X_i & = 0 \\ \sum_i Y_R + Y_i & = 0 \\ \sum_i N_R + (P_i - O) \wedge \underline{T}_i & = 0 \end{cases} \tag{3}$$

where $(\underline{P}_i - \underline{O}) = x_i\, \underline{b}_1 + y_i\, \underline{b}_2$ are the application points of the i_{th}–thruster.

Over-actuating propulsion systems is a common practice for DP systems, which is unavoidable when certain station-keeping performances are required under degraded conditions, such as in the case study. Unfortunately, this makes the allocation a problem whose constituent parts can be identified by means constrained optimization problems, [10] and [11]. Approaching the problem in this way is often not compatible with RT applications, since the performances of industrial PLCs are limited. Indeed, solving the FAL means find solutions for Eq. (4).

$$T_{ALL} = A^{-1}\,\tau_R \tag{4}$$

where $A \in \mathbb{R}^{3\times n}$ is a time-varying matrix that depends on the system inputs, called *allocation matrix* and $T_{ALL} \in \mathbb{R}^n$ is the unknown vector containing thrust component of each actuator.

There are several strategies to solve this problem, starting from reducing the order of the problem up to operation research techniques, Figure 2(a). In this paper, the choice is of reducing the order of the problem working on constant azimuthal angles and considering the two bow thrusters as an one with an equivalent thrust $\underline{T}_{BT_{eq}} = Y_{BT_{eq}}\,\underline{b}_2$ and position $P_{BT_{eq}} = x_{BT_{eq}}\,\underline{b}_1$. Then, allocation matrix is reduced to $A = [t_{PT}, t_{SB}, t_{BT_{eq}}]$.

$$t_{PT} = \underbrace{\begin{bmatrix} -1 & 0 \\ 0 & -1 \\ y_{PT} & -x_{PT} \end{bmatrix}}_{\text{portside}}, \quad t_{SB} = \underbrace{\begin{bmatrix} -1 & 0 \\ 0 & -1 \\ y_{SB} & -x_{SB} \end{bmatrix}}_{\text{starboard}}, \quad t_{BT_{eq}} = \underbrace{\begin{bmatrix} 0 \\ -1 \\ -x_{BT_{eq}} \end{bmatrix}}_{\text{bow thruster}} \tag{5}$$

where the corresponding unknown vector is defined as $T_{ALL} = [X_{PT}, Y_{PT}, X_{SB}, Y_{SB}, T_{BT_{eq}}]^\top$. The second step involves the definition of time dependence of A. The selected relationship is $A := A(\tau_R)$ is governed by Eqs. (6). The main idea is to assign two states at each time step by nullifying one of the two components of the thrust force of each main propeller. In this way, the allocation matrix is always n-by-n invertible and the reduced order allocation problem is pointwise solvable. In practice, three main configurations have been identified following the sketch presented in Figure 2 (b-d). Such configurations are toggled depending on the prevailing components of the forces and moments required by the controller. In particular three main cases are identified: (i) bow or stern seas, Figure 2 (b), where $Y_{PT} := Y_{SB} := 0$; (ii) portside seas, Figure 2 (c), where $Y_{PT} := X_{SB} := 0$; (iii) starboard seas, Figure 2 (d), where $X_{PT} := Y_{SB} := 0$.

$$t_{PT} = \begin{bmatrix} -1 \\ 0 \\ y_{PT} \end{bmatrix} \text{ and } t_{SB} = \begin{bmatrix} 0 \\ -1 \\ -x_{SB} \end{bmatrix} \quad \text{if} \begin{cases} |y_{PT}\,X_R| \le |x_{BT_{eq}}\,Y_R - N_R| \\ x_{BT_{eq}}\,Y_R - N_R < -a \end{cases} \tag{6a}$$

$$t_{PT} = \begin{bmatrix} 0 \\ -1 \\ -x_{PT} \end{bmatrix} \text{ and } t_{SB} = \begin{bmatrix} -1 \\ 0 \\ y_{SB} \end{bmatrix} \quad \text{if} \begin{cases} |y_{PT}\,X_R| \le |x_{BT_{eq}}\,Y_R - N_R| \\ x_{BT_{eq}}\,Y_R - N_R \ge a \end{cases} \tag{6b}$$

$$t_{PT} = \begin{bmatrix} -1 \\ 0 \\ y_{PT} \end{bmatrix} \text{ and } t_{SB} = \begin{bmatrix} -1 \\ 0 \\ y_{SB} \end{bmatrix} \quad \text{otherwise} \tag{6c}$$

where $a > 0$ is a coefficient introduced to avoid fast transitions when the required forces are limited in magnitude. In this way it is possible to reduce the machinery wear and prevent the bang–bang effects. Moreover, switching law described in Eqs. (6) guarantees that propellers are never flushing on other working propellers. Then, the proposed methodology avoids working in areas affected by high hydrodynamic losses and facilitates implementation on the PLCs.

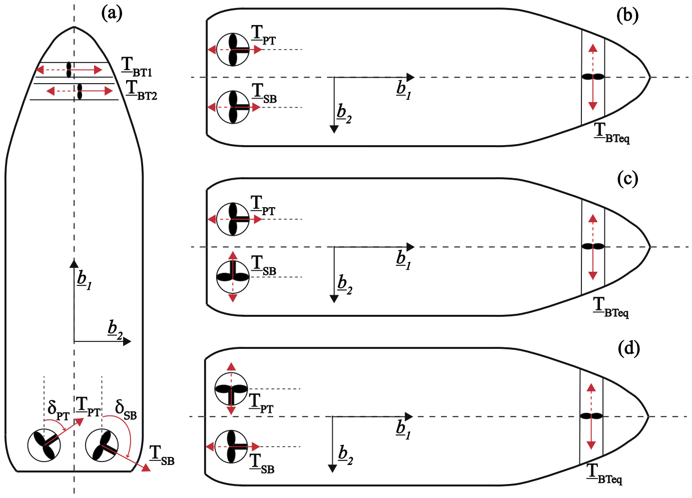

Figure 2. (a) Actuators layout (b-d) Fixed Main thruster

4.2.2. Thrust Allocation Logic

When the thrust requested at the two azimuths and the two bow thrusters, the TAL module translates them into proper set–points for the various actuators. In particular, the two bow thrusters are characterised by a single controllable propeller and are designed to operate at constant revolution speed and to change the pitch to meet various thrust requirements; while the two azimuths are characterised by propellers with fixed blades and therefore the thrust request is satisfied by changing the number of revolutions. Hence, starting from the thrust required and thanks to the combinator curves of the azimuthal and the bow thruster, it is possible to find the set–points to send at each actuator.

5. Results

The reguraltor described in Section 4 is tested through the architecture shown in Section 2 by means of simulation platform reported in Section 3. Several tests have been carried out, with SIL and HIL techinques, and hereinafter the results are reported. The controller paramenters have been modified to allow the HIL controller to converge. The environmental disturbances are aligned and coming from 90°, with a wind speed magnitude equal to $20\,kn$, a current speed equal to $1.5\,kn$, a wave height equal to $6.2\,m$, and a wave period equal to $10.4\,s$. In all the figures the orange continuous line refers to the HIL test, while the blue dotted line refers to the SIL. In Figure 3 the trajectories of the ships are reported and it is worth of notice that all the design requirements are satisfied (black dotted line equal to $L_{PP}/4$). In Figure 4 the position and heading errors are reported, the green dotted lines refers to the maximum allowed errors, these are set equal to $L_{PP}/4$ for the position errors, and equal to 15° for the heading error. The figure shows a bigger fluctuation in the case of HIL due to previously mentioned motivations.

In Figure 5, where both set–point and feedback are reported. Thanks to the fast dynamic of the electric prime mover, it is possible to note that no delays in actuation are experienced. In Figure 6 shows required bow propeller pitch time histories. It is possible

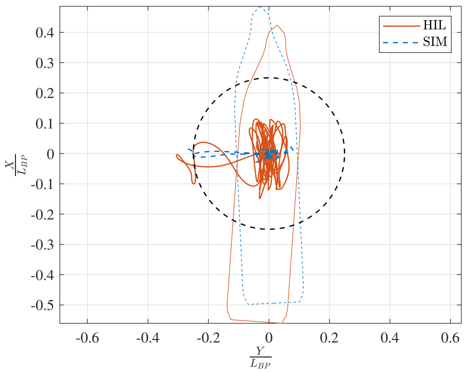

Figure 3. Trajectory

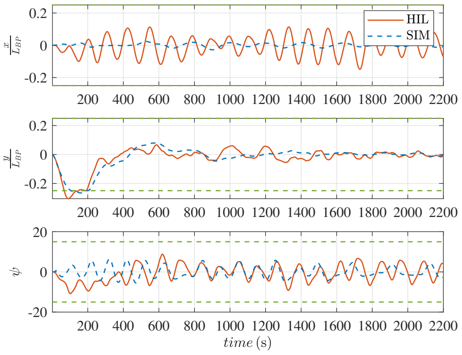

Figure 4. Position Errors

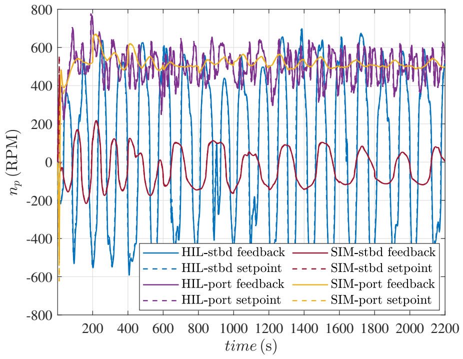

Figure 5. Azimthal RPM

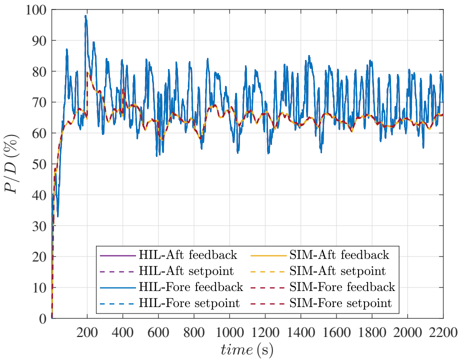

Figure 6. Bow Thruster Pitch

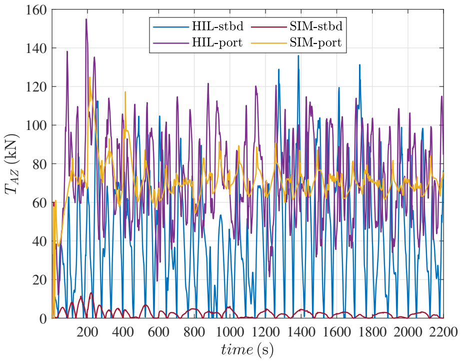

Figure 7. Azimuthal Thrust

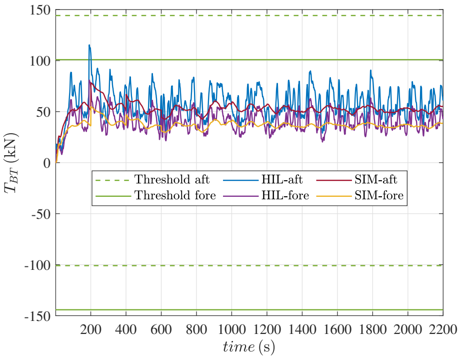

Figure 8. Bow Thruster Thrust

to notice that mean values of commands are similar for HIL and SIL results. In Figures 7 and 5 the time histories of azimuthal and tunnel thrusters are reported. In both cases the actuation strictly follows the commands, by remaining within their design limits.

6. Conclusion

The simulation platform developed, and tested thoroughly, is considered suitable to be used for the design of the dynamic positioning system DP–2. Based on literature data and the experience of the authors, the results obtained appear to be truthful. For greater reliability in terms of accuracy of the results of the simulator validation with *ad hoc* tests are necessary. Results obtained through the dynamic simulator have demonstrated two positive aspects. Firstly, the simulation platform for controller testing was robust and provided reliable results (compared to the few data available). Secondly, the controller developed allows the accomplishment of both requirements and limits in terms of maximum error allowed. The simulations carried out confirmed what has been obtained from the results of the dynamic simulator realized in SIL environment. In particular, through the HIL demonstrator, it was possible to evaluate how the delays related to OPC communication and the cycle times of the PLC affect the performance of the control system. In order to further improve the developed system, future studies will focus on introduction of an observer, e.g. Kalman filter (linear or extended), in replacement of the low–pass filter and in a future perspective in which also the other environmental disturbances (sea and current) were measured, a restructuring of the architecture of the dynamic positioning system could be considered.

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