Experimental Framework for Autonomous Fast Ships's Control Design

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Abstract: - The research on seakeeping control of fast ships requires difficult experiments for modeling and control design. To alleviate the ship motion certain active appendages are added, such moving flaps, T-foil and fins. The motion of appendages must be optimized to counteract each encountered wave. During our first research steps, a scaled down ship, with scaled appendages, has been used in a towing tank facility. The scaled ship is towed at fixed speeds of experimental interest, for instance at the equivalent to 40 knots. The wavemaker in the towing tank is used to generate specified waves. Along the experiments it was noticed that the towing of the replica spoils certain expected phenomena. A more appropriate way of doing experiments to observe all ship motions, is to use an autonomous self-propelled scaled ship. In this paper a new autonomous scaled ship is presented. It contains an on-board control system, so the ship is self-governed. Complex maneuvering can be programmed for certain study interests. Our autonomous ship is linked via radio with an external monitoring system. The ship and the off-shore monitoring system constitute an experimental framework for advanced studies about fast ship control.

Key-Words: - Autonomous ships, Naval experimental systems, Seakeeping control, Navigation control, Fast ships.

1 Introduction

From years ago our research deals with seakeeping control of fast ships [1] and [2]. In the beginning, only head seas were considered, and a towed scaled ship was used to alleviate, by using moving flaps and T-foil, the vertical accelerations. Figure 1 shows a photograph of the towed scaled ship. The experiments took place in a towing tank facility of the Spanish Navy (El Canal de Experiencias Hidrodinamicas de El Pardo, CEHIPAR, Madrid). The ship moves in a 150m x 30m basin, with a wavemaker able to make several types of sea states. It was noticed that towing the ship, certain expected phenomena were not observed, since the ship is attached to a towing mechanism, allowing for only two degrees of freedom of the ship motions (pitch and heave).

In a recent phase of the research, all six degrees of freedom of the ship motions are considered. Not only head seas, but other headings must be studied. Roll motions should appear, so lateral fins should be added. It was decided not to tow the experimental ship. Consequently our problem was to develop a new autonomous self-propelled 1/40 scaled ship with an on-board control system making the ship self-governed.

Fig. 1: A towed scaled replica at CEHIPAR

A main challenge for the development of the new ship is that the fast ferry under study is aluminum made. It means that the scaled down weight is 29 Kg. Scaled waterjets are included in the scaled ship. The waterjets need sometimes 30 amps. To reach fast speeds. Poweful batteries are needed, and this implies weight. All on-board electronics and actuators must be very light.

To highlight the real interest of a new autonomous ship, let us show an interesting experimental result just obtained with this scaled autonomous ship. Figure 2 shows the speed response of the ship to a shut off of the waterjets. The speed is not relaxing as a conventional exponential curve; in the figure it is clear that a brisk downwards change appears. It corresponds to the ship transitioning from surface effect navigation to conventional drag. This interesting phenomenon, which is most important, in the reverse sense, to reach high speeds can be observed in the autonomous ship, and not in the towed one.

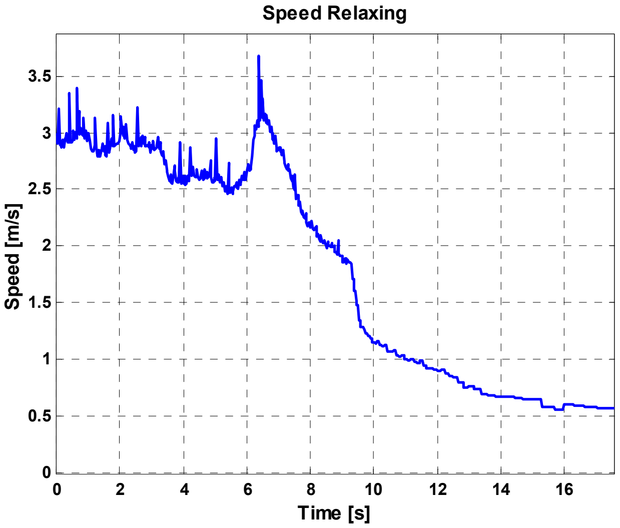

Fig. 2. Surface Effect at 2 m/s

The purposes of the research are the following:

- To implement a hardware and software technology to govern autonomous fast ships. A CANbus is used, allowing for the application of the same control system to real ships.
- To design and tune the navigation control system to describe trajectories in the wave tank to test the models for several heading, speed and sea conditions.
- To design and tune the control of the autonomous ship to improve its seakeeping. The 6dof seakeeping problem is difficult because the coupling between actuators and ship motions is complex.

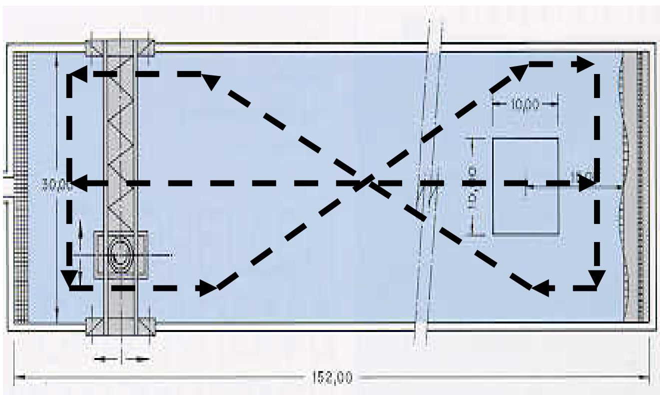

Fig. 3. Trajectories at the Towing Tank.

2 Ship Motion and Actuators

The six ship motions are the following: surge, x_1 , sway, x_2, and heave, x_3, roll, x_4, pitch, x_5, and yaw, x_6 . In [3] there is a set of simplified equations that describe the response of the ship motions to the forces and moments caused by waves. The equations are the following:

$$(m+a_{11})\ddot{x}_1 + b_{11}\dot{x}_1 = F_1\angle_1(w) \quad (1)$$

$$(m+a_{22})\ddot{x}_2 + b_{22}\dot{x}_2 + a_{24}\ddot{x}_4 + b_{24}\dot{x}_4 + a_{26}\ddot{x}_6 + b_{26}\dot{x}_6 + c_{26}x_6 = F_2\angle_2(w) \quad (2)$$

$$(m+a_{33})\ddot{x}_3 + b_{33}\dot{x}_3 + c_{33}x_3 + a_{35}\ddot{x}_5 + b_{35}\dot{x}_5 + c_{35}x_5 = F_3\angle_3(w) \quad (3)$$

$$a_{42}\ddot{x}_2 + b_{42}\dot{x}_2 + (I_{44}+a_{44})\ddot{x}_4 + b_{44}\dot{x}_4 + c_{44}x_4 + a_{46}\ddot{x}_6 + b_{46}\dot{x}_6 + c_{46}x_6 = M_4\angle_4(w) \quad (4)$$

$$a_{53}\ddot{x}_3 + b_{53}\dot{x}_3 + c_{53}x_3 + (I_{55}+a_{55})\ddot{x}_5 + b_{55}\dot{x}_5 + c_{55}x_5 = M_5\angle_5(w) \quad (5)$$

$$a_{62}\ddot{x}_2 + b_{62}\dot{x}_2 + a_{64}\ddot{x}_4 + b_{64}\dot{x}_4 + (I_{66}+a_{66})\ddot{x}_6 + b_{66}\dot{x}_6 + c_{66}x_6 = M_6\angle_6(w) \quad (6)$$

Two of the vertical plane motions, pitch and heave are coupled (surge is not coupled). Horizontal plane motions, sway, roll and yaw, are coupled. There is, however, no coupling between the vertical and lateral plane motions. The right hand part of the equations are magnitudes a phases of the external forces and moments, caused by waves.

Figure 4 shows photographs of the actuators added to the scaled ship: transom flaps, lateral fins, T-foil almost under the bow, and waterjets. Notice that the flaps are under the waterjets. The forces and moments caused by these actuators should be put also in the right hand of equations (1-6).

Fig. 4. Scaled actuators: T-Foil, Fins, Flaps and Jets.

3 Hardware Architecture

An on-board distributed monitoring and control system was developed and implemented in the physical model. Figure 5 shows a block diagram of the system.

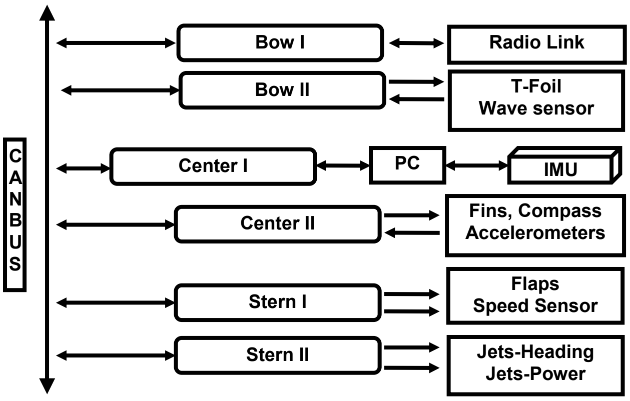

Fig. 5. Distributed Architecture.

The missions of the on-board system are the following:

- To acquire, condition and record all signals from on board sensors along experiments.
- To control the actuators of the ship.
- To transmit real-time data to the Base.
- To transmit the complete record of data, at the end of experiments, to the Base.
- To obey to orders given by the Base.

Some of the nodes include sensors for data acquisition and control. Other nodes are devoted to actuators handling. Other block is in charge of wireless communications. And finally there is a central node with a low power embedded computer, for govern, coordination and data processing. There is an Inertial Motion Unit connected directly to the PC [4].

4 Sensors and Signal Processing

Two sets of sensors were included into the on-board control of the autonomous ship. One of the sets is used for control purposes, in view of real scale future application. The other set is for scientific purposes, to study the quality of the ship control solutions. Both sets are independent, also in their functional characteristics. The CANbus based architecture of the on-board system allows for both systems to work in parallel.

4.1 Sensors for scientific purposes

A miniature inertial unit has been selected to be included in the on-board system. This unit allows for the measurement of rotational kinematics. The inertial unit includes the following sensors:

- 3-axis accelerometers with a $\pm 20ms^{-2}$ range, a 30Hz bandwidth and a noise of 0.01 rms.
- 3-axis gyroscope with a $\pm 900^{o}s^{-1}$ range, a 50Hz bandwidth and a noise of 0.7 rms.
- 3-axis magnetic flux sensor with a ±750mGauss range, a 10Hz bandwidth and a noise of 4.5 rms.

Some of the sensors are good at low frequencies, other at relatively high frequencies. This has been taken into account to deduce roll, pitch and heave from the inertial unit signals. Figure 6 shows the filtering and information fusion that has been devised after many experiments.

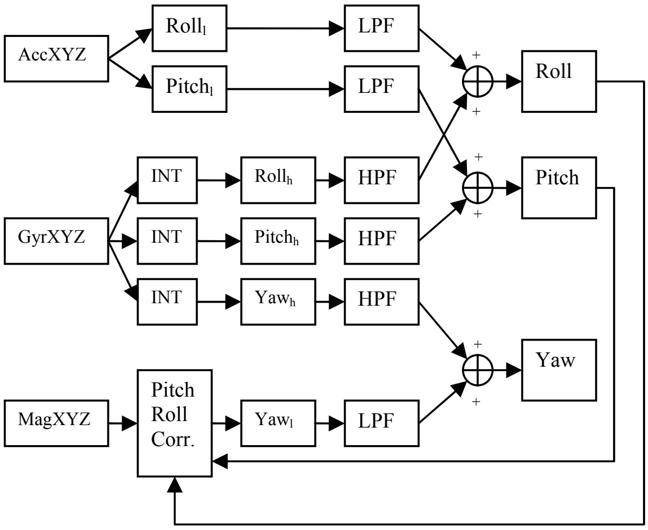

Fig. 6. Basic Control Loops.

Roll and pitch low frequency components can be obtained from low-pass filtering (LPF) of accelerometers. By integration and high-pass filtering (HPF) of the gyroscope outputs, the high frequency components of pitch, roll and yaw can be obtained. Yaw low frequencies can be derived from magnetic flux sensors, being corrected taking into account the instantaneous roll and pitch of the sensor itself.

The fusion of low and high frequencies is easy, since HPF and LPF filters are complementary (their transfer functions add to one). They are simple discrete filters, with the following transfer functions:

$$LPF(z) = \frac{0.05z}{z - 0.95} \quad (7)$$

$$HPF(z) = 1 - LPF(z) = \frac{z-1}{z-0.95} \quad (8)$$

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Figure 7 shows an experiment with the autonomous ship. The ship has to follow a rectangular trajectory. The figure shows a view from top of the ship motion and the information given by the on-board sensors. The dashed curve is the ship position evolution estimated by using the gyroscopes. The dotted curve is the position evolution estimated by using the magnetic sensors. A fusion of both sources of information has been developed, according to figure 6, which approximates well (the continuous curve in figure 7) the real trajectory of the ship.

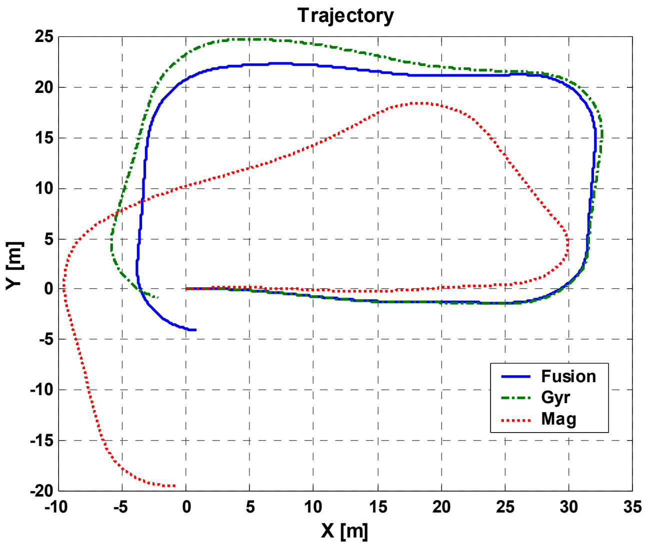

Fig. 7. Magnetic and Gyroscopic sensors fusion.

4.2 Sensors for 6 DOF motions control

A set of sensors has been deployed for ship motions control. They are not so expensive as an inertial unit, so they are more competitive for real scale application, if, of course, they prove to be sufficient for the control purposes.

The sensors selected for this application are three 2-axis accelerometers, located at the centre, a side, and near the bow (so they can measure the six accelerations of the ship), a paddlewheel for speed measurement, and a digital magnetic compass. These two last sensors are the key for heading and speed control.

The distributed architecture of the on-board system, around a CANbus, accommodates well the set of sensors, through CANbus enabled microcontrollers with A/D converters.

Based on our previous experience with seakeeping control, accelerometers are sufficient for this objective, using some filtering to avoid the typical noise of this kind of sensors. The control design must take into account the filters.

Figure 8 shows photographs of one accelerometer (a small die), the paddlewheel and the small printed board with the digital compass based on Hall effect.

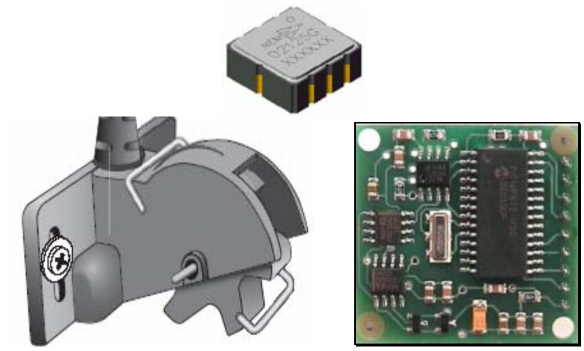

Fig. 8. Sensors for control.

A control alternative to be studied in the next future is to make from these sensors a set of smart components, embedding digital processing and local control capabilities. For instance, they can include the needed filters and local control algorithms to obtain in a simple way a distributed control system.

5 Control Loops

Before trying to conduct experiments for seakeeping control, a good heading and speed control must be ensured. An important reference for control design is [5].

Figure 9 shows a set of three block diagrams: one for heading (yaw) control, other for speed control, and the third for seakeeping control using the flaps, the lateral fins and the T-foil.

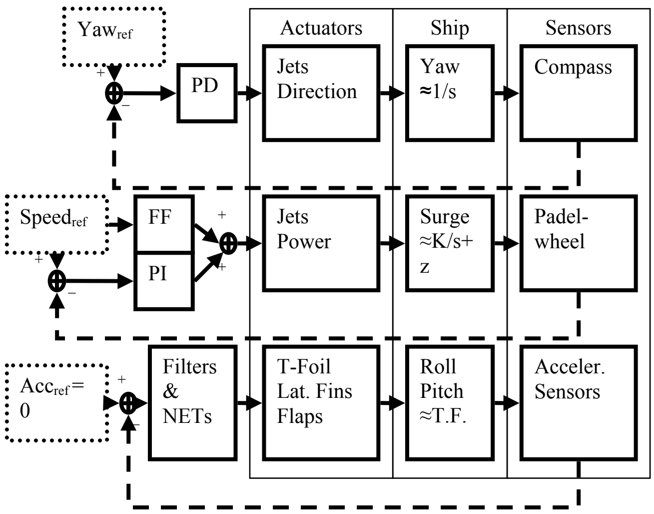

Fig. 9. Main control loops.

Notice that simplified models of the ship motions have been used for the control design. Many experiments have been done to confirm the satisfactory behaviour of the heading and speed control. It has been also experimentally confirmed that the heading and speed controls withstand well the perturbations due to the use of actuators during seakeeping control experiments.

5.1 Heading Control

The waterjets output can be oriented in a symmetrical range from left to right around the centre. In this way, we can control the ship's heading, as it is done in real scale ships with waterjets. There is no rudder. It is important for the control design to consider the time constants of the waterjets orientation feature.

A basic model of the ship's yaw dynamics is an integrator. Consequently a digital PD controller has been designed for heading control, with satisfactory experimental results. Figure 10 shows the results of one of the experiments with the scaled ship, at high speed (3 m/s, equivalent to scaled 40 knots), the ship starts from 15º yaw, and corrects her heading to reach and maintain 0º yaw.

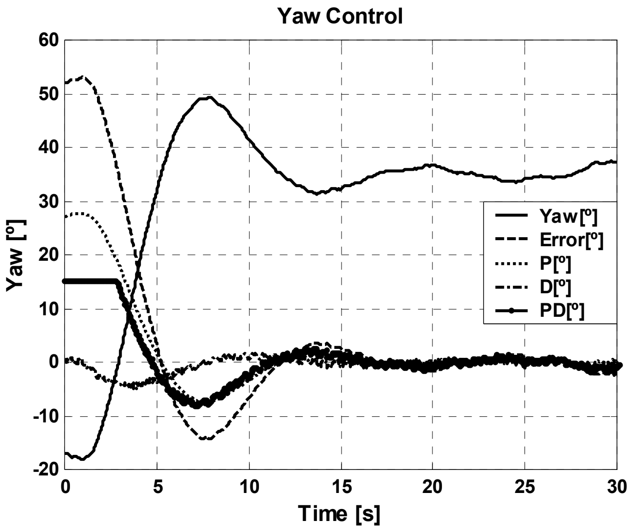

Fig. 10. Yaw control components.

5.2 Speed Control

The ship's speed is governed by the electric power given to the waterjets. A feedforward control action has been devised to keep the waterjets power in the reference, and a feedback digital PI control has been added to eliminate the speed deviations that may be caused by perturbations.

Figure 11 shows experimental results with the speed control. The ship starts a run, then, after 30 sec. stops. The target is to keep the ship's speed in 0.5. The speed measurements are normalized between 0 and 1, where 1 is maximum power (6 m/s).

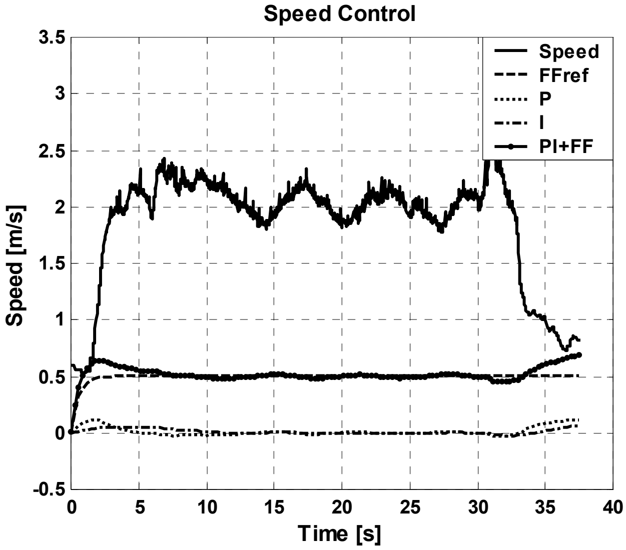

Fig. 11. Speed control components.

5.3 Seakeeping Control

Seakeeping control is the most difficult target. The main purpose of this control is to reduce as much as possible the pitch and roll accelerations. Pass-band filters must be applied to extract from the accelerometers the frequencies of interest for control. The DC components of signals must be eliminated. On the other hand, the noise of accelerometers, which are high frequencies, must be also eliminated. The filters must have a flat phase in the pass-band, to favour a simpler control design.

Figure 12 shows the good results obtained by the T-foil motions, the continuous curve with large excursions, in order to minimise the vertical accelerations at the bow (mainly pitch), the dashed curve.

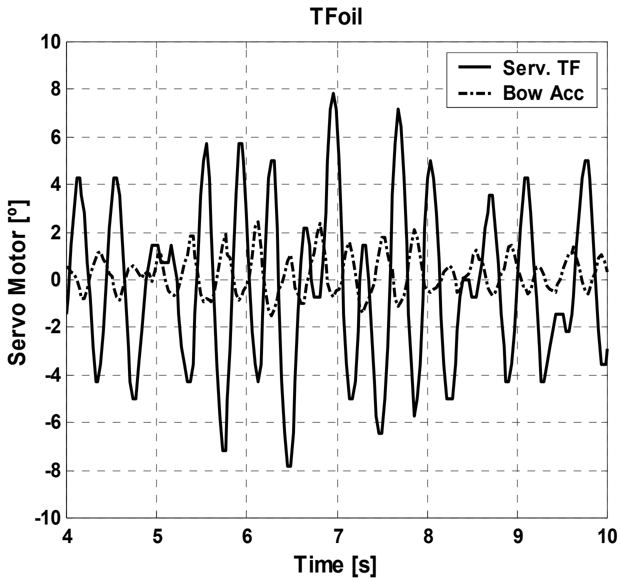

Fig. 12. T-Foil control action.

Notice in figure 12 how the T-foil opposes to the bow vertical accelerations.

Figure 13 shows the experimental results about the alleviation of roll accelerations using the lateral fins. The continuous curve with large excursions shows the fin motions. The dashed curve shows the roll accelerations.

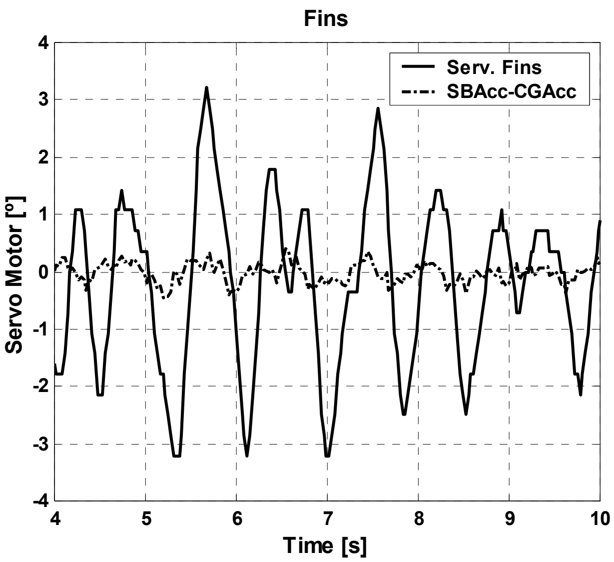

Fig. 13. Fins control action.

The *SEAcc-CGAcc* signal is obtained subtracting the signals from the accelerometer at the centre of the slip, and from the accelerometer at the side. Although this is a noisy signal, the filters applied for the control are good enough to obtain a clean motion of the fins.

6 Conclusion

An experimental framework has been developed to support the design of fast ship motions control. It consist of an autonomous self-governed scaled ship, and an external monitoring system. The new framework paves the way for several important research tasks:

- Analysis of the behaviour of the ship under several navigation conditions: ship's speed, heading and sea state.
- Test of new sensors and complementary devices, such are filters. Advancing in order to develop smart components.
- Study of new actuators showing their effects in six degrees of freedom.
- Design and test of new control strategies.

The new system is of general interest. The on-board architecture can be used in other ships, scaled or not, and can give more impulse to experimental facilities.

In the future more difficult experiments will be attempted. Open air experiments are also under way, using GPS as another sensor included in the on-board system.

Since the experimental framework is operational, new control design studies are planned, focusing on multivariable approaches.

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