

# CHAPTER 1

## Control problems in marine vehicles: Some experiences in stabilization and tracking control

J. ARANDA<sup>1</sup>, J.M. DE LA CRUZ<sup>2</sup>, R. MUÑOZ-MANSILLA<sup>1</sup>, D. CHAOS<sup>1</sup>, J.M. DIAZ<sup>1</sup>, S. DORMIDO-CANTO<sup>1</sup> and J.M. RIOLA<sup>3</sup>

<sup>1</sup> Departamento de Informática y Automática, UNED, Madrid.

<sup>2</sup> Departamento de Arquitectura de Computadores y Automática. Universidad Complutense de Madrid.

<sup>3</sup> Escuela Técnica Superior de Ingenieros Navales. U. Politécnica de Madrid. jaranda@dia.uned.es

Control problems of underactuated marine systems motivate the development of new control design methodology. Control design of tracking, point stabilization, path following for marine vehicles, or Dynamic Positioning for offshore systems is example of these types of problems. In this chapter, an overview about different problems studied in our laboratory are showed.

### 1 Introduction

In marine vehicles, we have discerning between guidance and control. The guidance term correspond to the action of determining the course, attitude and speed of the vehicle, relative to some reference frame, usually the earth, to be followed by the vehicle. The control term correspond to the development and application to a vehicle appropriate forces and moments for operating point control, tracking and stabilization. This involves designing the feedforward and feedback control laws.

Furthermore, there are a lot of marine vehicles kinds that are underactuated, i.e., systems with a smaller number of control inputs than the number of independent generalized coordinates.

One of the difficulties encountered in the stabilization and tracking of underactuated vehicles is that classical nonlinear techniques in nonlinear

control theory like feedback linearization are not applicable because these systems are not fully feedback linearizable and exhibit nonholonomic constraints. Therefore new design methodologies should be explored.

Thus, nowadays such control problems of underactuated marine vehicles motivate the development of new nonlinear control design methodologies. Control designs of tracking, point stabilization, path following for some kind of marine vehicles, or dynamic positioning (DP) for offshore systems are examples of these types of problems.

Dynamic positioning (DP) is required in many offshore oil field operations, such as drilling, pipe-laying, tanking between ships, and diving support. Critical for the success of a dynamically positioned ship is its capability for accurate and reliable control, subject to environmental disturbances as well as to configuration related changes, such as a reduction in the number of available actuators. Furthermore, robustness criteria must be considered (Muñoz et al. 2006).

The problems of motion control for marine vehicles addressed in the literature (Aguiar and Hespanha 2003) can be roughly classified in three groups:

- Point stabilization, where the goal is to stabilize a vehicle at a given point, with a desired orientation.
- Trajectory tracking deals with the case where a vehicle must track a time-parameterized reference.
- Path following refers to the problem of making a vehicle converge to and follow a given path, without any temporal specifications.

The degree of difficulty involved in solving these problems is highly dependent on the configuration of the vehicle.

Point stabilization presents a true challenge to control system designers when the vehicle has nonholonomic constraints since, as pointed out in Brocket et al. (1983), there is no smooth (or even continuous) constant state-feedback control law that will do the job

For fully actuated systems, the trajectory tracking problem is now reasonably well understood and satisfactory solutions can be found in the standard non linear control textbooks.

For underactuated vehicles trajectory tracking is still an active research topic (Aguiar and Hespanha, 2003). Actuated systems are usually costly and often not even practical (due to weight, reliability, complexity, and efficiency considerations) and for this reason the interest in the study of this kind of problems. An interesting benchmark problem is described in (Aranda et al. 2006a), where control specifications for a hovercraft model

are given, and a possible solution with a simulation environment for testing is presented in (Aranda et al. 2006b).

Path following control has received relatively less attention than the other two problems. See for example Samson (1995) and references. Path following systems for marine vehicles have been reported in Encarna o and Pascoal (2001) with a path following mode. Here the vehicle forward speed does not need to be controlled accurately, since just orientating the vehicle drives it to the path. Typically, smoother convergence to a path is achieved in this case when compared with the performance obtained with trajectory tracking controllers, and the control signals are less likely to be pushed to saturation.

Other kinds of control problems is concerning to the attenuation of non desirable movement in fast ships, attenuation of the vertical and lateral motions. The study of this problem is in relation with one of the most unpleasant aspects of sea transport that is the motion sickness suffered by both passengers and crew. This is a result of the accelerations associated with the induced roll, heave and pitch motions. (de la Cruz, et al. 2004). A solution to vertical stabilization of a fast ferry based in a multivariable QFT design is given in Aranda et al. (2005a), the extension to couple of lateral and vertical dynamic is done in Aranda et al (2005b). A methodology to identification of multivariable models based in genetic algorithm and non linear optimization procedure, with application to a high speed craft, is presented in Aranda et al (2004a). Extension and revision of this methodology is done in Aranda et al (2005c). A control oriented model for a high speed craft is obtained in Esteban et al. (2004).

In this chapter, we show some problems concerning to tracking and stabilization. In section 2, the benchmark problem for a RC-hovercraft is described. In section 3, robust control for a moored platform model is studied, and in section 4 the attenuation of non desirable movements are considered for a fast ferry.

## 2 Control of an Underactuated Vehicle

The task of designing controllers for underactuated marine vehicles is very challenging and has received increasing attention in the past few years. These vehicles exhibit complex hydrodynamic effects that must be taken into account during the control design. It should be highlighted that many marine vehicle models exhibit a drift vector field that is not in the span of the input vector fields and because of this, input transformations are not used to bring them to driftless form.

The past few decades have witnessed an increased research effort in the area of trajectory tracking control for underactuated autonomous vehicles. Trajectory tracking problems are concerned with the design of control laws that force a vehicle to reach and follow a time parameterized reference (i.e., a geometric path with an associated timing law).

Hovercrafts are a type of vehicle with a structure model similar to marine vehicles. A model for a nonlinear underactuated hovercraft was obtained from the ship model in (Fossen 1994). In this model, the hovercraft is equipped with two propellers that provide the thrust to move the vehicle forward (and backward) and to make it turn. The main difference with respect to a two-wheel mobile robot is that a hovercraft can move freely sideways even though this degree of freedom is not actuated.

Numerous control algorithms for controlling underactuated vessels have been examined and analysed in the specialized literature. For example, Fantoni et al. (2000) presents two control laws. The first one controls the velocity of the hovercraft. The other one proposes strategies for positioning the hovercraft at the origin.

Pettersen and Egelan (1996) developed a stability result involving continuous time-varying feedback laws that exponentially stabilize both the position and orientation of a surface vessel having only two control inputs.

In Fossen et al. (1998) it is considered a nonlinear ship model including the hydrodynamics effects due to time-varying speed. A backstepping technique for tracking control design is employed.

Bullo and Leonardo (1998) develop high-level motion procedures which solve point-to-point reconfiguration, local exponential stabilization and static interpolation problems for underactuated vehicles.

Strand et.al. (1998) propose a stabilizing controller by a locally asymptotically convergent algorithm based on  $H^\infty$ -optimal control.

Berge et al. (1998) develop a tracking controller for the underactuated ship using practical feedback linearization. The control law makes the position and velocities converge exponentially to the reference trajectory, while the course is not controlled.

Aguiar and Hespanha (2003) develop a nonlinear Lyapunov-based tracking controller and prove to exponentially stabilize the position tracking error to a neighbourhood of the origin that can be made arbitrarily small.

The problem of point stabilization of marine vehicles like hovercrafts that exhibit non-holonomic restrictions is so challenging, because as Brocket et al. (1983) showed, there is no smooth (or even continuous) constant state-feedback control law that stabilizes the system in a desired point in the state space.

The main problem for stabilization of underactuated hovercrafts is that any linearization of the system around an equilibrium point generates an uncontrollable system. This is due to the fact that there are no forces that allow controlling the drift velocity. This problem is related in Fantoni et al. (2000) that shows that the linear system is only controllable for a non-zero angular velocity. They also propose a controller that uses yaw angle velocity as a virtual input to obtain a discontinuous control law for stabilization.

Another approach to the stabilization problem uses smooth time-varying control laws. An example of this technique is showed in Pettersen and Nijmeijes (2001) that uses a continuous periodic time varying feedback law.

Another author had applied the latest control techniques to the problem of point stabilization. An example of these techniques is showed in Tanaka et al. (2001) where a switching fuzzy control is implemented achieving stabilization in an RC hovercraft. Another example is in Segudii and Ohtsuka (2002) where stabilization is achieved using a model controller predictive with receding horizon strategy. The greater advantage of the last technique is that allows including saturation restrictions in control signals during the control design.

In our laboratory, control algorithm for tracking and point stabilization are analysed using a radio control hovercraft. Previous to the laboratory experimental validation with the radio controlled vehicle, simulations are carried out using Matlab and Easy Java Simulations (Aranda et al. 2006a) with the goal of comparing different control strategies and test diverse conditions. As a first approach, benchmark problems have been developed (Aranda et al. 2006b), a non linear control for both, tracking and point stabilization problems, was designed; also an assessment is designed as verification of the robust and performance criteria. Now, in our laboratory, techniques based in a non-linear multivariable QFT methodology are studied for this problem.

In the next subsections, the model of the hovercraft and the benchmark problem are described.

## 2.1 Hovercraft Model

The model system is a radio control hovercraft equipped with two longitudinal thrusters to control speed and turning as shown in Figure 1. The impulse of both motors is asymmetric and is greater when the hovercraft moves forwards than backwards.



Fig. 1. R.C. Hovercraft.

Figure 2 shows a schematic model: X and Y are the fixed inertial reference system axes,  $X_B$  and  $Y_B$  the body reference system axes,  $\bar{u}$  and  $\bar{v}$  the surge and sway velocities,  $\theta$  is the orientation angle and  $\Psi$  the drift angle (Aranda et al. 2006b).

The hovercraft has three degrees of freedom, two associated with the movement in the plane of its centre of masses ( $x, y$ ), and one more associated to its orientation  $\theta$ .  $u_1$  and  $u_2$  variables are the forces of the thrusters and  $r$  is the distance between the centre of the fan and the symmetry axis that cuts to the centre of mass ( $x, y$ ).

The vehicle is underactuated because it has more degrees of freedom than control actions. This means that is not possible to control the surge velocity because of the impellers configuration.

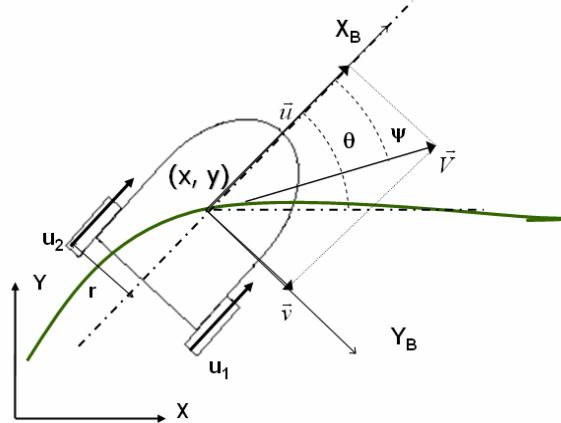


Fig. 2. Schematic model.

The dynamic equations are obtained in the fixed inertial reference system by direct application of Newton's laws.

$$m \frac{d^2x}{dt^2} = F_x = (u_1 + u_2) \cos(\theta) - \mu_T v_x \quad (1)$$

$$m \frac{d^2y}{dt^2} = F_y = (u_1 + u_2) \sin(\theta) - \mu_T v_y \quad (2)$$

$$J \frac{d^2\theta}{dt^2} = \tau = r(u_1 - u_2) - \mu_R w \quad (3)$$

Where  $m$  is the mass of the vehicle,  $J$  the moment of inertia,  $\mu_T$  and  $\mu_R$  the coefficients of viscous and rotational friction respectively. The system can be defined by the state vector  $[x, y, v_x, v_y, \theta, w]$ .

The parameters have been experimentally obtained by measurements in the real system. The mass, the force of thrusters and  $r$  have been measured directly. The friction coefficients are obtained from measurements of the maximum linear and rotational velocity. The nominal values and their uncertainties are shown in Table 1.

Table 1. Experimental parameters and uncertainties

Parameter	Value and uncertainties
$m$	$0.894 \pm 0.001$ Kg
$J$	$0.0125 \pm 0.0050$ Kgm <sup>2</sup>
$r$	$0.050 \pm 0.001$ m
$u_{\max}$	$0.615 \pm 0.008$ N
$u_{\min}$	$-0.300 \pm 0.008$ N
$\mu_T$	$0.10 \pm 0.01$ Kg/s
$\mu_R$	$0.050 \pm 0.001$ Kgm2s

## 2.2 Benchmark Problems

A benchmark problem has been defined for each of the three points indicated in the introduction (point stabilization, tracking and path following) (Aranda et al. 2006a). The evaluation criteria for each problem are organized in three groups.

### **2.2.1 Performance Criteria**

*Point stabilization:* The specifications for a displacement of a distance  $D \leq 1\text{m}$  in the set point without a change in direction are an overshoot  $M_p < 5\%$  and a setting time  $t_s \leq 20\text{s}$ , whereas for  $D > 1\text{m}$   $M_p < 20\%$ .

For a change of reference angle  $\Delta\theta = 90^\circ$  without displacement the controller must verify an overshoot  $M_p < 10\%$  and a setting time  $t_s \leq 5\text{s}$ .

*Trajectory tracking:* a specification is set for the steady-state tracking error  $TE_{ss} = \lim_{t \rightarrow \infty} \|\vec{x}(t) - \vec{x}_r(t)\|$  for each trajectories defined in Table 2.

*Path following:* For a desired speed and a predefined trajectory, the lateral deviation must be reduced to 5% in a setting time  $t_s \leq 20\text{s}$ . In addition the drift angle  $\Psi$  must be reduced.

Table 2. tracking specifications.

Trajectory	Specification
Circle, Radius=2m, V=0.2m/s	$TE_{ss} < 10\text{cm}$
Circle, Radius=2m, V=0.8m/s	$TE_{ss} < 30\text{cm}$
Straight line, V=0.2m/s	$TE_{ss} < 5\text{cm}$
Straight line, V=0.8m/s	$TE_{ss} < 10\text{cm}$

### **2.2.2 Robustness Criteria**

Stability and performance must be satisfied by the controller for all the model parameter range shown in Table 1.

### **2.2.3 Actuator Effort Criteria**

For the trajectories defined in section 3.1 the control signals must not exceed saturation limits of the actuators  $u \in [u_{\min}, u_{\max}]$ .

## **2.3 Example Controller**

The controller inputs are the system state and the references vector  $[x_r, y_r, v_{xr}, v_{yr}, \theta_r, w_r, d, l]$ . The controller outputs must be the control actions  $u_1$  and  $u_2$ .

The example controller that is implemented by defect in the model consists of two cascade controllers PD (see Figure 3). The L1 controller takes the position errors and calculates the forces that must be applied in the fixed coordinates system to follow the trajectory. These forces are the references for the L2 controller that calculates the angle of the force with the

x-axis and control the orientation to follow this angle. The outputs of L2 are the control signals  $u_1$  and  $u_2$  that must be applied to obtain to the force and the suitable direction  $\theta$ . L2 obtains the direction from the state to control the hovercraft.

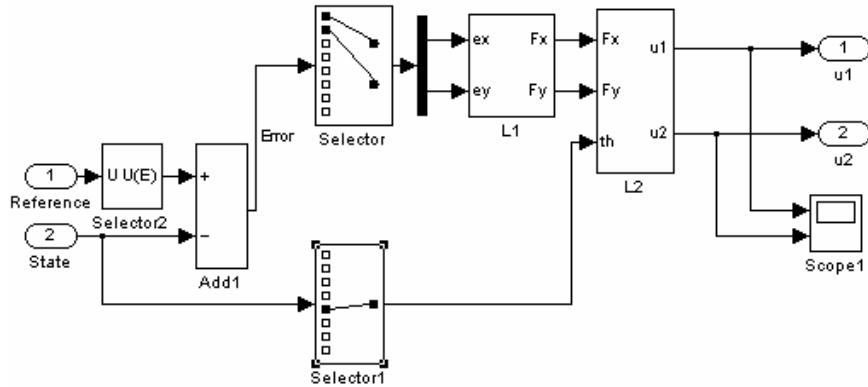


Fig. 3. Example of controller.

The parameters of the controllers are optimized for a predetermined trajectory (circle with a radius of two metres with 0.2m/s of velocity). The design and behaviour of the example controller is shown in (Aranda et al. 2006b).

### 3 Dynamic Positioning of a Moored Platform

Moored floating platforms are used for drilling and exploration activates and they require high degree of precise positioning to perform optimally with associated facilities. They are subjected to combined environmental loads of waves, wind and current while in service, which affects their stability in addition to positioning.

Dynamic analysis of a floating moored platform is therefore carried out to determine its response to environmental loads. This analysis could be done in the time domain or the frequency domain. A floating platform is associated with lots of non-linearities, which are linearised in the frequency domain simulations. In the time domain analysis however, the non-linearities are modelled with the intention of making more accurate analysis but this makes the computation complex and require a great deal of computer time.

In our group, a moored floating model is considered as a testing platform to analysis different robust synthesis methods for Dynamic Positioning.

The model is a single-input/multi-output (SIMO) linear time invariant (LTI) system with a single degree of freedom.

This system has been examined and analysed in the specialized literature, in which is possible to find several robust control methods. For example, (Scherer, et al., 1997) presents an overview of a linear matrix inequality (LMI) approach to the multiobjective synthesis of linear output-feedback controllers. A multiobjective  $H_2/H_\infty$  is proposed to specify the closed-loop objectives in terms of a common Lyapunov function.

In (Revilla, 2005), this system is used to validate the results obtained in the study about synthesis of reduced-order controllers based on LMI optimization. In Nakamura, et al. (2001) the problem was formulated in the framework of a multimodel-based design of the  $H_\infty$  control law with pole region constraint. Methodology based on LMI was used to solve the problem. And in (Muñoz-Mansilla et al. 2006), a multivariable robust QFT controller is used to stabilize the moored platform.

The next subsections show the control problem and a solution by QFT technique.

### **3.1 Control Problem**

The system consists of a floating platform that is anchored to the bottom of the ocean and equipped with two thrusters, as it is showed in Figure 4 (the model of a replica of this system and previous control is described in Kajiwara et al. 1995). The objective is achieving an appropriate thrusters control in order to minimize the drift  $Y$  resulting from the wave action.

The model of the system has two outputs  $\mathbf{y}$  (the horizontal drift  $Y$  and angular deviation from the vertical axis  $\phi$ ), one control input  $u$  (the force delivered by the thrusters  $F_u$ ) and two disturbance inputs  $\mathbf{d}$  ( the force  $F$  and the torque  $M$  from the wave action). Therefore a single degree of freedom (DOF) SIMO system is presented, with one single input  $F_u$  and two outputs  $(Y, \phi)$ .

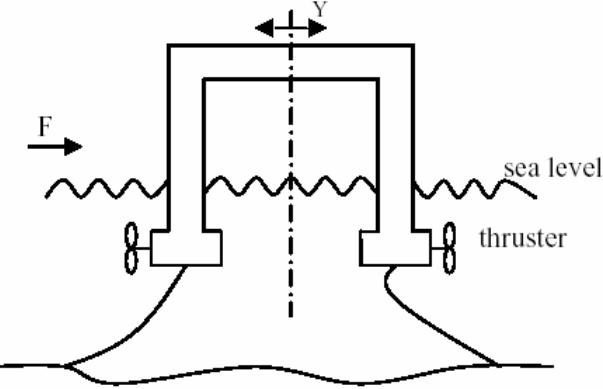


Fig.4. Moored floating platform

For design purposes, the system transfer function can be described as:

$$y = P_{\text{plant}}(s) \cdot u + P_d(s) \cdot d \quad (4)$$

$$u = -G_{\text{control}}(s) y \quad (5)$$

Where  $P_{\text{plant}}(s)$  is a transfer functions matrix (2x1) that connects the input  $u$  with the output  $y$ , and  $P_d(s)$  is a transfer functions matrix (2x2) that connects the disturbance  $d$  with the output  $y$ . The control structure is schematically displayed in Figure 5.

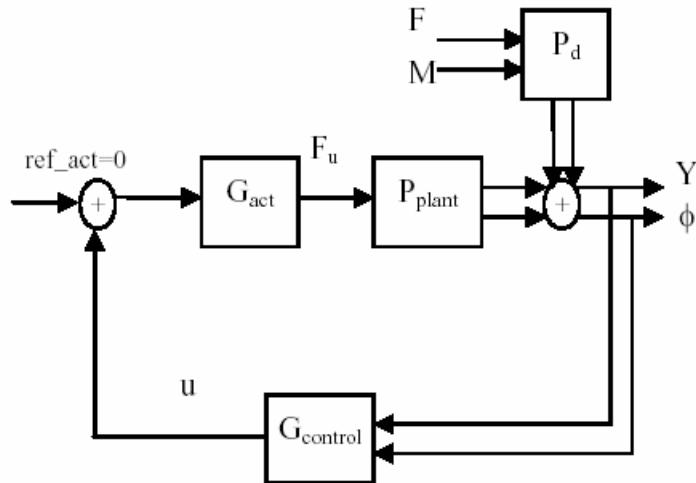


Fig.5. Single DOF SIMO system with disturbances at the plant's output

In these conditions, the problem of interest is how to design the controller  $G_{control}$ . The control objectives are:

- Reduce the drifting action  $F_2$  by using the actuators control.
- Maintain the horizontal drift  $|Y| < 0.025\text{m}$
- Maintain the angular deviation  $|\phi| < 3 \text{ degrees}$
- Keep  $|F_u| < 0.25 \text{ N}$
- Make sure that the thrusters have no response to the high-frequency component  $F_1$ .

An interesting question is added to the position control design because the plant has less degree of freedom for actuation, it is an underactuated system, and is more difficult to control.

### **3.2 A Multivariable QFT Controller for the Moored Platform**

The foundation of QFT is the fact that feedback is principally needed when the plant is uncertain and/or there are disturbances acting on the plant.

Taking into account all this; the challenge is to study the effectiveness of the QFT technique to accomplish the dynamic positioning system (Muñoz et al 2006).

The QFT design procedure involves three basic steps: *i*) computation of QFT bounds, *ii*) design of the controller (loop shaping), and *iii*) analysis of the design.

QFT converts close-loop magnitude specifications into magnitude constraints on a nominal open-loop function (QFT bounds). A nominal open-loop function is then designed to simultaneously satisfy its constraints as well as to achieve nominal closed-loop stability (loop shaping). It is defined the open-loop function  $L(j\omega)$  as the product of the controller transfer function and the plant transfer function.

In any QFT design, it is necessary to select a frequency array for computing bounds. In the case of the platform plant, the range of frequencies that belongs to the seaway spectrum will be  $\omega \in [0.1, 10]$ .

The specifications must be given in terms of frequency response. For the particular case of the design of the dynamic positioning system for the moored platform model, the specifications ( $|Y| < 0.025\text{m}$ ,  $|\phi| < 3 \text{ degrees}$ ) are given in temporal domain. Therefore, it is necessary to translate these constraints into frequency domain specifications. The QFT specifications used are: the gain and phase margins stability, the output disturbance rejection and the control effort.

The control law of the system in Figure 5 is:

$$u = -G_{control} \cdot \begin{pmatrix} Y \\ \phi \end{pmatrix} = -(k1 \quad k2) \cdot \begin{pmatrix} Y \\ \phi \end{pmatrix} \quad (6)$$

Solving (4), it yields one equation with two unknown quantities,  $k1$  and  $k2$ .

$$\begin{aligned} & (\pi_{13} + k1)Y + (\pi_{23} + k2)\phi = \\ & = (\pi_{13}p11 + \pi_{23}p21)F + (\pi_{13}p12 + \pi_{23}p22)M \end{aligned} \quad (7)$$

The control design process is based on this equation, which aids in transforming the problem into the design of two sequential SISO systems. Thus, it is solved by an iterative multi-stage sequential procedure, in such a way that the solution of  $k1$  in the first system is used in the design of  $k2$  in the second system, and vice versa. The stages repeat successively up to  $k1$  and  $k2$  meet the objectives for the SIMO system. Finally, the control design procedure has been completed in five stages.

Temporal responses of the SIMO system (Figure 5) in closed loop dynamic are shown. Figures 6 and 7 compare both the outputs  $Y$  and  $\phi$  with and without control respectively. It is shown that the control achieves the positioning system.

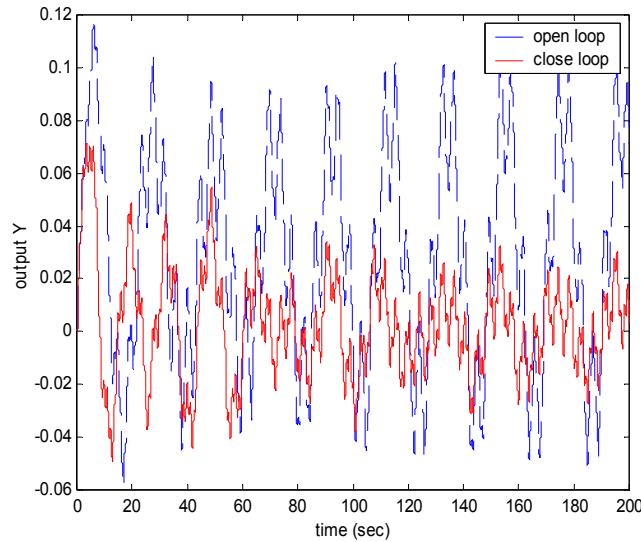


Fig. 6. Comparison of temporal responses  $Y$  (a) with and without control

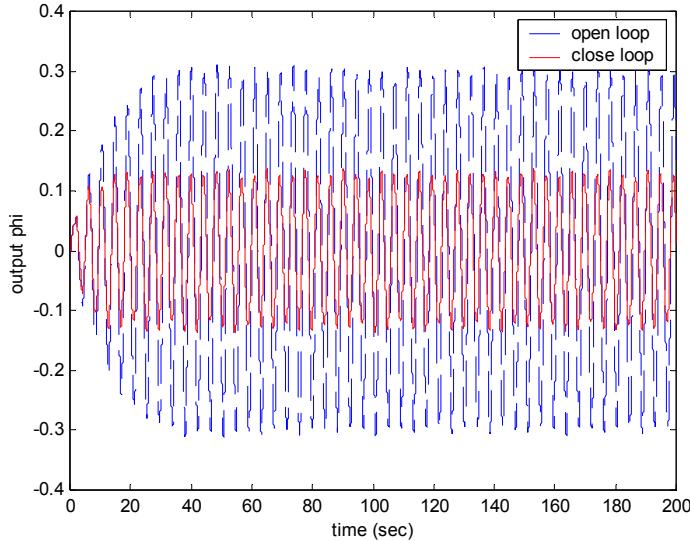


Fig. 7 Comparison of temporal responses  $\phi(b)$  with and without control

#### 4 Stabilization of Vertical and Lateral Movements in a Fast Ferry

The interest on fast ships for cargo and passenger transportation was growing during the past decade. Different designs have been considered, and a significant attention has been focused on fast monohull displacement ships (Allison, et al., 2004).

The next history is an interesting introduction to main problems in the building of fast ferries in relation with the seasickness (Laertius): Anacharsis, brother of Caduides the king of the Scythians, was a philosopher who traveled around the East Mediterranean and the Black Sea in the 6th century BC. His mother was Grecian woman and the contemporaneous Greeks said him that he exhorted moderation and good criteria in everything he did, for example saying “the vine bears three clusters of grapes: the first wine, pleasure; the second, drunkenness, the third, disgust”. As a seaman, he had to travel in different kinds of sea conditions and he had one of the best references, with the same philosophy, listened about seasickness “people may be divided into three classes; the living, the dead and the seasick”.

Therefore, the main objectives in the design and built of high speed crafts are the passenger comfort and the vehicle safety. The vertical accel-

erations associated with roll, pitch and heave motions are the principal cause of motion sickness.

The ship considered in our researches is a fast ferry with the following characteristics (de la Cruz et al. 2004): 110m. length, 1250 passengers, deep-V monohull, aluminium made, able to get 40 knots or more. Fig. 8 shows a photograph of the ship.



Fig. 8. Fast ferry

Previous researches of the work group have studied the longitudinal and transversal dynamics separately and next the coupled of both dynamics. Firstly, it has been studied heaving and pitching motion for the case of head seas ( $\mu=180\text{deg}$ ) (Aranda, et al., 2004a), modeled actuators and designed different controllers was done, (Aranda, et al., 2002a, Aranda, et al., 2002b, Aranda et al. 2005a, Diaz et al. 2005, Esteban et al 2001, Esteban et al. 2005), in order to achieve heave and pitch damping and with successful results. And secondly, it has been analyzed the rolling response for the case of lateral waves ( $\mu=90\text{deg}$ ) (Aranda, et al., 2004b) and in the same way, it has been carried out the actuators modeling and controller designing (Aranda et al. 2005b, Aranda et al. 2004b).

#### 4.1 The Control Problem

The goal is to reduce longitudinal and transversal motions of the fast ferry system with three coupled degrees of freedom.

Three modes of the system are analyzed: the heave and pitch motions (vertical dynamics) and the roll motion (horizontal dynamics).

The actuators employed for the vertical dynamic control consisted of active stabilized surfaces, one T-Foil on the bow and two flaps on the stern. The control surfaces employed for the roll control were two fins.

The model of the system has two outputs: the roll angular velocity  $\omega_{\text{roll}}$  and the vertical acceleration  $a_{cv}$ . The input disturbances are the seaway. The control inputs are the angles of attack  $\alpha_P$  and  $\alpha_H$  of flaps and T-Foil,

and  $\alpha_R$  for the lateral fins. The coupling of the modes is considered as a consequence of the control surface action in different incidence angles of the seaway.

The mathematical models of the three modes of the craft and actuators are obtained from system identifications methods (Aranda 2004a, Aranda et al. 2005c).

Therefore, the problem of interest is how to design the controllers for these active surfaces to achieve a reduction of the Motion Sickness Incidence (MSI), given by equation (8) (de la Cruz, et al. 2004):

$$MSI = 100 \cdot \left[ 0.5 \pm \operatorname{erf} \left( \frac{\pm \log_{10}(\bar{|s_3|}/g) \mp \mu_{MSI}}{0.4} \right) \right] \quad (8)$$

This aim can be translated to different specifications, in accordance with the design methodology chosen. For example (Rocio CAMS), we can consider the following specifications:

- system stability,
- heave, pitch, roll reduction,
- no saturation on T-Foil, flaps and fins.

## 4.2 An Example Control

A control system must perform mainly three functions. The first is to assure stability, the second is to attenuate seaway-induced motions, and the third is to assure the safety of the ship and its passengers. Different solutions were given, (see for example the references Esteban et al. 2004, Aranda et al 2002a, 2004b, 2005a, 2005b, Díaz et al. 2005).

As an example, we can consider the design of a PI scheduling for each speed of the craft, in the particular case of roll reduction.

For the particular case of  $V = 40$  knots, figure 9 shows the root locus of the system with the controller PI  $G_{PI40}(s)$ . The transfer function of this controller is given by expression (9).

$$G_{PI40} = 2.2 \frac{50s + 1}{50s} \quad (9)$$

Table 1 shows the values of  $J$  and roll reduction percentage for the cases of regular wave with frequency 1 rad/s and irregular wave with SSN = 5 with this controller.

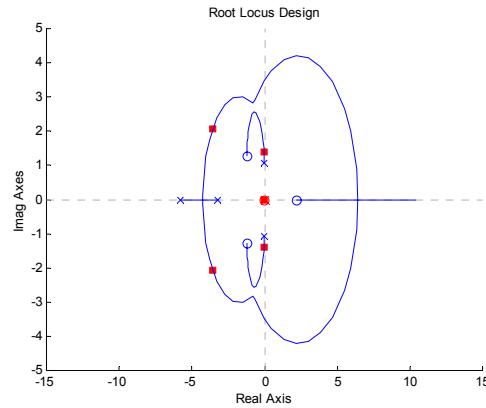


Fig. 9. Root locus of the system with  $G_{PI40}$

Table 1. Value of J and reduction for control PI.  $V=40$  knots

wave type	J	roll reduction (%)
regular $\omega = 1$ rad/s	0.29	82.69
irregular SSN=5	0.82	69.01

## 5 Conclusions

The problems of tracking and stabilization of underactuated vehicles, dynamic positioning, and control for stabilization in high speed craft are example of the problems solved in our group. For each of these problems, a description of the problem and an example of one solution is showed. There are different solutions and a complete description of each case in the references of our group.

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