A multiobjective optimization issue: genetic control planning for AUV trajectories.

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Abstract: - Part of a research project on cooperative marine robotics is the scenario of a submarine rendez-vous. This paper considers this case, where a high-manoeuvrability AUV (autonomous underwater vehicle) should meet a submarine platform for energy, samples and data service. Since the AUV is equipped with a set of thrusters, the problem of an adequate command of the thrusters appears. Given initial and final points for the AUV underwater trajectory, the question is to determine the set of forces and times to be exerted by the thrusters to get an adequate trajectory. Several constraints and simultaneous objectives to be optimized must be considered. Given the complexity of the multi-objective optimisation problem, it seems opportune to use Genetic Algorithms. The paper describes the problem to be solved, then explains how the GA were applied, and presents results for a set of cases considered, including obstacle avoidance.

Key-Words: AUV control. Genetic Algorithms. Multi-objective optimization.

1 Introduction

An interesting case of cooperation between marine crafts is a rendez-vous between a submarine platform, which can be in charge of biomonitoring, and a service AUV. A high-manoeuvrability AUV is considered by our research. This AUV has no flaps, no rudder, but a set of thrusters for surge, pitch, yaw, sway and heave motions. The AUV must depart from an initial point, near the surface, and reach the submerged platform following a certain trajectory to be determined. Likewise, the control action of the thrusters must be determined to cause that trajectory. Several considerations and criteria appear concerning what should be an adequate trajectory. Consequently, there is a multi-objective optimisation problem. In this problem, motions are coupled and thrusters have limited authority.

Along several optimisation problems that have been found by the research of our team, it has been useful to apply Genetic Algorithms (De Andres, et al., 2000a; Esteban, et al., 2002). After some years applying GA, a MATLAB toolbox was developed: EVOCOM (De Andres, et al., 2000b). This is a multipurpose evolutionary algorithm toolbox. It has been successfully applied to the AUV control problem. The representation of this problem in terms of chromosomes and fitting function is a relevant aspect covered in this paper.

The scientific literature provides a good mathematical and modelling background for the AUV dynamics and control (Fossen, 2002). However, most of the papers and textbooks consider submergible vehicles with fins and rudders, which is not our case. With respect to the application of Genetic Algorithms to the AUV context, there are contributions considering trajectories planning. For instance (Alvarez, et al., 2004) deals with 3D scenarios, with sea currents and underwater mountains. There are some other papers in a similar vein (Kwiesielewicz, et al., 2000; Tan, et al., 2004). These contributions focus on trajectories, this paper focus instead on control planning (using thrusters).

Cooperative marine robotics is a new field that is beginning to consider different problems, such the scenarios of (Kyrkjebo, et al., 2004) on ship rendezvous operations, (Stilwell, et al., 2003) with platoons of AUVs, or (Soetanto, et al., 2003) with the coordinated control of marine robots. This belongs to the spirit of multi-agent robotic systems (Liu and Wu, 2001; Weiss, 1999; Billard, 2004), with elements of formation control (Tanner, et al., 2004). The order in this paper is the following. First, an explanation of the problem and its mathematical procedures, then a GA treatment of the problem in order to apply the method to several cases with different obstacle avoidance situations, and finally some conclusions according with the results obtained.

2 Problem Formulation

Let us describe the rendez-vous scenario, the mathematical modelling and the specific problem to be solved.

2.1 Rendez-vous scenario

The research considers a high-manoeuvrability AUV that departs from an initial point near the surface, and that should meet a submerged platform. The final rendez-vous must be with the AUV in horizontal attitude and zero speed. An adequate trajectory (not much energy invested, not much time) must be determined together with the action of the thrusters causing the trajectory. In the next figure we can see a perspective view of the designed AUV

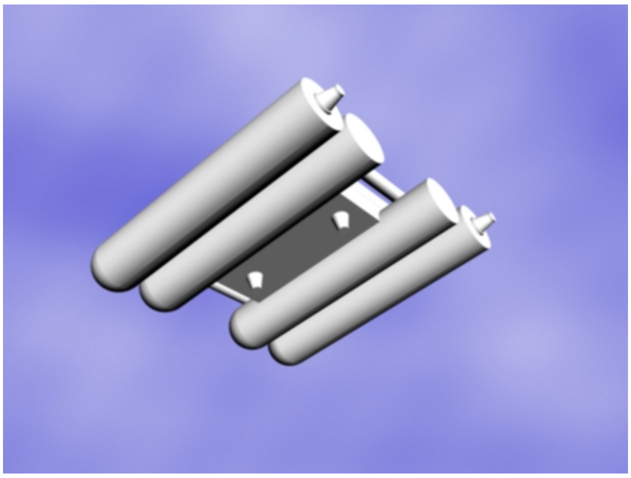

Fig. 1. View of the AUV and its thrusters.

2.2. Mathematical models.

The general motion of the AUV is expressed by the following vectors (SNAME 1950):

$$\eta_1 = [x, y, z]^T ; \quad \eta_2 = [\phi, \theta, \psi]^T ;$$

$$\upsilon_1 = [u, v, w]^T ; \quad \upsilon_2 = [p, q, r]^T ;$$

$$\tau_1 = [X, Y, Z]^T ; \quad \tau_2 = [K, M, N]^T$$

where η_1 and η_2 denote the position and orientation respect to the earth-fixed and body-fixed coordinates, υ_1 and υ_2 the speed in the same reference and τ_1 and τ_2 the forces and moments vectors applied.

The following coordinates transforms relate translational and rotational velocities between body-fixed and earth-fixed reference systems

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = J_1(\eta_2) \cdot \begin{bmatrix} u \\ v \\ w \end{bmatrix} , \quad \begin{bmatrix} \phi' \\ \theta' \\ \psi' \end{bmatrix} = J_2(\eta_2) \cdot \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

where

$$J_2(\eta_2) = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} , \quad J_2(\eta_2) = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix}$$

$$\begin{aligned}
a_{11} &= \cos\psi \cdot \cos\theta & b_{11} &= 1 \\
a_{12} &= -\sin\psi \cdot \cos\phi + \cos\psi \cdot \sin\theta \cdot \sin\phi & b_{12} &= \sin\phi \cdot \tan\theta \\
a_{13} &= \sin\psi \cdot \sin\phi + \cos\psi \cdot \sin\theta \cdot \cos\phi & b_{13} &= \cos\theta \cdot \tan\theta \\
a_{21} &= \sin\psi \cdot \cos\theta & b_{21} &= 0 \\
a_{22} &= \cos\psi \cdot \cos\phi + \sin\phi \cdot \sin\theta \cdot \sin\psi & b_{22} &= \cos\phi \\
a_{23} &= -\cos\psi \cdot \sin\phi + \sin\psi \cdot \sin\theta \cdot \cos\phi & b_{23} &= -\sin\phi \\
a_{31} &= -\sin\theta & b_{31} &= 0 \\
a_{32} &= \cos\theta \cdot \sin\phi & b_{32} &= \sin\phi / \cos\theta \\
a_{33} &= \cos\theta \cdot \cos\phi & b_{33} &= \cos\phi / \cos\theta
\end{aligned}$$

Note that the last matrix is not defined in $\theta = \pm 90^o$, but the vehicle motion does not ordinarily approach this singularity (see figures about pitch angle evolution).

Taking a general model for the six DOF which involves the influence of added mass, Coriolis effects, hydrodynamic forces, wind and currents perturbations, gravitational and control forces (Fossen, 2002):

$$M \cdot \upsilon' + C(\upsilon) \cdot \upsilon + D(\upsilon) \cdot \upsilon + g(\eta) = \tau + \omega$$

and considering a two-dimensional scenario with only three relevant control actions (surge and heave forces, pitch moment), neglecting Coriolis forces (short distances) and wind/currents effects, and taking into account only the linear damping terms, the following equations of motion are obtained:

$$\begin{bmatrix} m - Xu' & -Xw' & m \cdot z_g - Xq' \\ -Xw' & m - Zw' & -m \cdot x_g - Zq' \\ m \cdot z_g - Xq' & -m \cdot x_g - Zq' & Iyy - Mq' \end{bmatrix} \cdot \begin{bmatrix} u' \\ w' \\ q' \end{bmatrix} + \begin{bmatrix} -Xu & -Xw & -Xq \\ -Zu & -Zw & -Zq \\ -Mu & -Mw & -Mq \end{bmatrix} \cdot \begin{bmatrix} u \\ w \\ q \end{bmatrix} +$$

$$+ \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -(m - Xu') \cdot u \\ 0 & (Zw' - Xu') \cdot u & m \cdot x_g \cdot u \end{bmatrix} \cdot \begin{bmatrix} u \\ w \\ q \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ W \cdot \overline{BG}_Z \cdot \sin\theta \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix}$$

In order to implement a SIMULINK model, accelerations in each DOF can be expressed as

$$u' = \left(\frac{F_1 + Xu \cdot u + Xw \cdot w + Xq \cdot q - (m \cdot z_g - Xq') \cdot q' + Xw' \cdot w'}{m - Xu'} \right)$$

$$w' = \left(\frac{F_3 + (m - Xu') \cdot u \cdot q + Zw \cdot w + Zu \cdot u + (m \cdot x_g + Zq') \cdot q' + Xw' \cdot u'}{m - Zw'} \right)$$

$$q' = \left(\frac{F_5 - W \cdot z_g \cdot \sin q - (m \cdot x_g \cdot u - Mq) \cdot q - [(Zw' - Xu') \cdot u - Mw] \cdot w}{I_{yy} - Mq'} \right) +$$

$$+ \left(\frac{Mu \cdot u + (m \cdot x_g + Zq') \cdot w' - (m \cdot z_g - Xq') \cdot u'}{I_{yy} - Mq'} \right)$$

that are three coupled equations for the AUV trajectory. The numerical values of the constants are showed in the table below (table 1):

Table 1. Numerical values for non-dimensional derivatives in equations of AUV motion

Constant	Numerical value
Xu'	-7.6*10exp(-3)
Xw'	1.7*10exp(-1)
Xq'	2.5*10exp(-2)
Xu	5.0*10exp(-3)
Xw	2.0*10exp(-1)
Xq	7.0*10exp(-2)
Zw'	-2.4*10exp(-1)
Zq'	-6.8*10exp(-3)
Zu	-6.5*10exp(-3)
Zw	-3.0*10exp(-1)
Zq	-1.4*10exp(-1)
Mq'	-1.7*10exp(-2)
Mu	-1.0*10exp(-1)
Mw	-3.5*10exp(-2)
Mq	-1.7*10exp(-1)

The mass value is equal to *40 kg*, and it can be assumed that *W=B= 400 N* in the simulation. The center of mass and the center of buoyancy (origin of the body fixed coordinate system) are not coincident ($x_g=0.1$ *m*, $y_g=0$ *m*, $z_g=0.02$ *m*).

3 Problem Formulation

3.1. The problem

The problem is to predict the proper AUV thruster's actions for a good rendez-vous with an underwater platform, starting from an initial point near the surface. An important aspect of the solution is the multi-objective scheme proposed (explained in the section below).

3.2. Establishing a genetic planning method

The key issues for the successful application of GA are to define a good codification in terms of chromosomes, and to establish an adequate fitting function. It is important to take advantage of the open opportunities offered by GA to include "a priori" knowledge about the problem (in the case of this research, this knowledge leads to a specific semantics of the chromosomes and to define constraints and criteria to be optimized).

3.2.1. Algorithm specifications.

The standard GA algorithm is described in (Goldberg, 1989; Michalewicz, 1999). The algorithm specifications are according to the EVOCOM toolbox methodology (B. Andres-Toro, et al., 2000).

In the AUV optimisation problem, the population includes 40 individuals, with a elitist selection method and tree points for crossing operations. The crossing probability used is 0.8 and the mutation probability is 0.008.

3.2.2. Fitting function.

The optimization criteria are explained in the following list, and are implemented like a multi-objective function:

- Trajectories avoiding obstacles.
- AUV trajectories without points over the sea surface or under the sea bottom.
- Good arrival at the submarine platform, with zero final speed and zero final pitch angle.
- Short trajectory length, with not much time involved.
- Low energy requirements.

The objectives are grouped into two sets. The first set includes primary objectives; and the second one the secondary objectives. A Pareto front is determined for the first set (but the second set is considered: between two individuals with equal fitting function value, the individual with better value in the second set is preferred). When the Pareto front has been determined for the first set, another Pareto front is determined for the second set (considering values in the first set). This is repeated, till results converge.

3.2.3. Individual Structure. Chromosomes.

The total trajectory from the starting point to the final point is divided in a different number of intervals. In each of these intervals a set of forces and moments F_{surge}, F_{heave} and F_{pitch} are applied during a time "t". This is, during the first t_1 seconds, the $F_{1,1}$ surge force, the $F_{1,3}$ heave force and the $F_{1,5}$ pitch moment are applied. During the second interval, along t_2 seconds, increments $\Delta F_{2,1}$, $\Delta F_{2,3}$ and $\Delta F_{2,5}$ are added to the surge force, the heave force and the pitch moment respectively. This is repeated in the rest of intervals (with increments $\Delta F_{j,1}$, $\Delta F_{j,3}$ and $\Delta F_{j,5}$).

With this codification, in the "jth" interval the forces and moments applied during a time T= $t_j + t_{j-1}$ are

$$F_{j,surge} = \Delta F_{j,1} + \Delta F_{j-1,1}$$
$$F_{j,heave} = \Delta F_{j,3} + \Delta F_{j-1,3}$$
$$F_{j,pitch} = \Delta F_{j,5} + \Delta F_{j-1,5}$$

3 Problem Solution

The most interesting application of the explained above is the avoidance of obstacles. Next figure shows a general scenario:

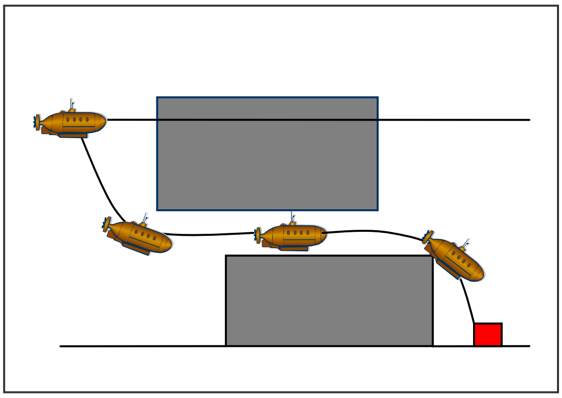

Fig.2. Schematic scenario

Next figures show the solution for a floating body (for example, a ship) and for an obstacle located at sea bottom (like an underwater hill), and table 2 resumes the numerical results:

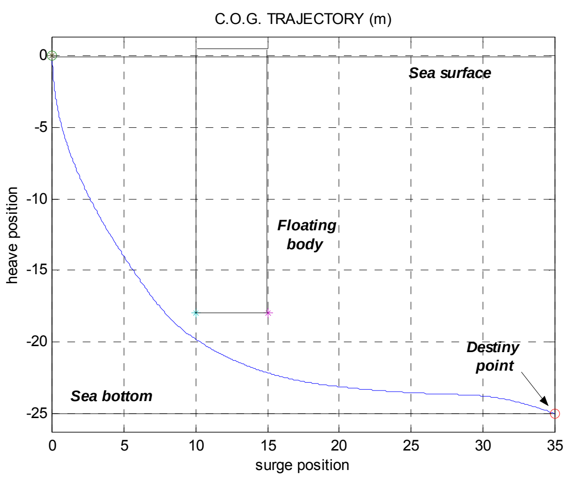

Fig. 3. C.O.G. Trajectory with a floating obstacle

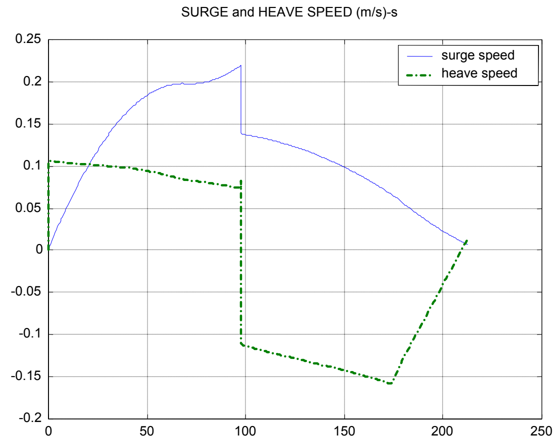

Fig.4 Speeds for the trajectory showed in fig.3

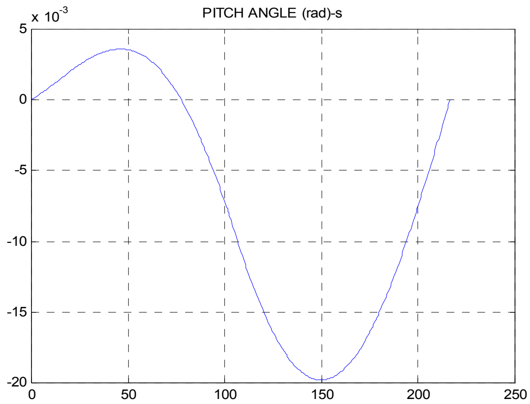

Fig.5. Pitch evolution for the trajectory showed in fig.3

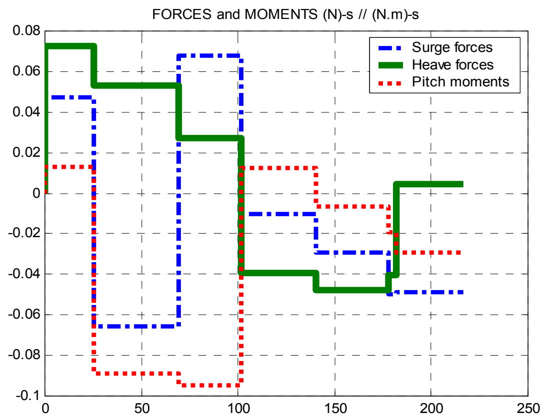

Fig.6. Control actions and times for the solution in the case of fig.3

Look at figure 3 and figure 4. The final speed in surge and heave degrees of freedom is zero. The zero final attitude is also reached.

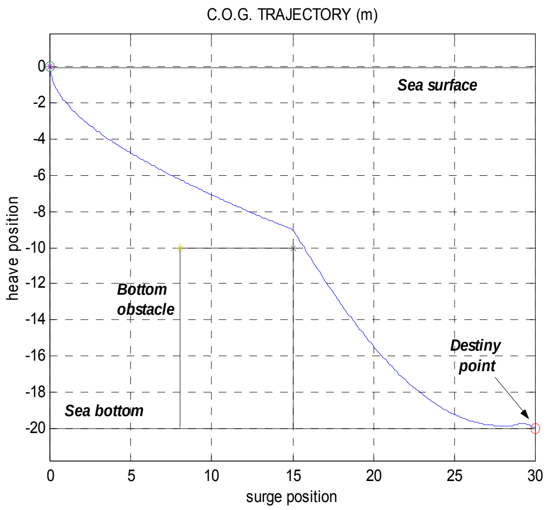

Fig.7. C.O.G. trajectory for the avoidance of an obstacle located at sea bottom

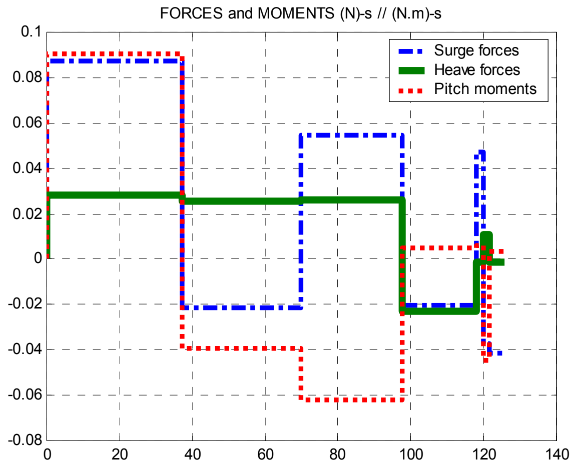

Fig.10. Control actions and times for the solution in the case of fig.7

Floating obstacle				Bottom obstacle			
T	F_{surge}	F_{heave}	F_{pitch}	T	F_{surge}	F_{heave}	F_{pitch}
25.2	0.047	0.072	0.013	37.05	0.087	0.028	0.091
69.5	-0.07	0.053	-0.088	69.7	-0.022	0.025	-0.04
101.4	0.068	0.027	-0.094	97.6	0.054	0.026	-0.062
140.4	-0.01	-0.038	0.013	117.8	-0.02	-0.023	0.005
177.6	-0.03	-0.047	-0.007	119.9	0.047	-0.001	0.006
182.1	-0.05	-0.041	-0.019	121.4	-0.037	0.011	-0.044
216.5	-0.048	0.004	-0.029	125.7	-0.041	-0.001	0.004

Table 2. Solution in terms of times and forces showed in fig.5 and fig.9

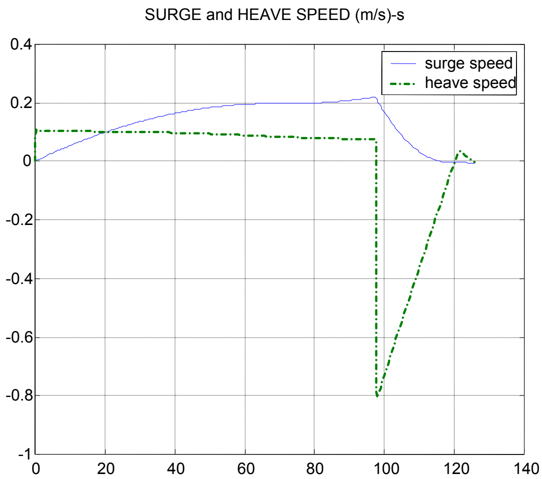

Fig.8. Speeds for the trajectory showed in fig.7

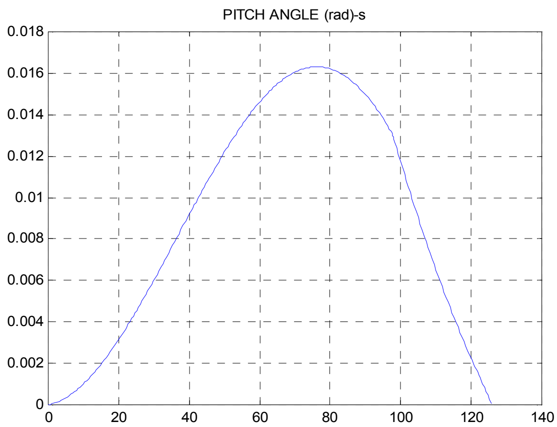

Fig.9. Pitch evolution for the trajectory showed in fig.7

Two obstacles are considered now. The next figures and table relate the same information as in previous cases

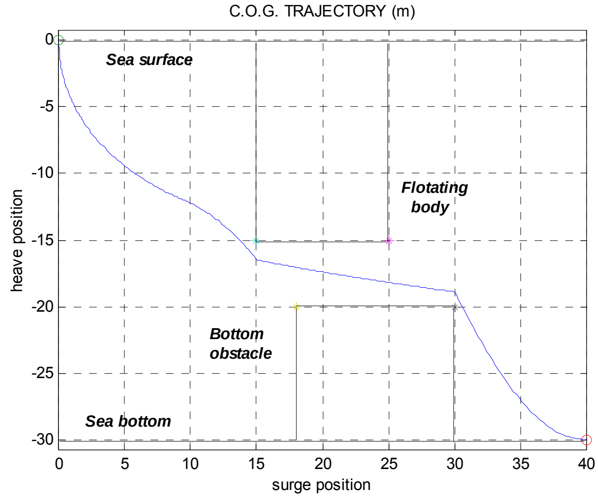

Fig.10. C.O.G. trajectory for the avoidance of two obstacles

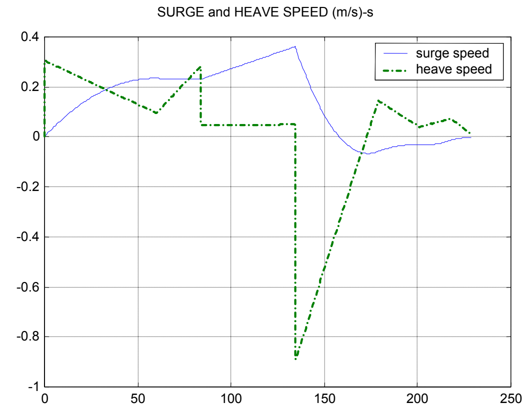

Fig.11. Speed evolution for c.o.g. trajectory of fig.10

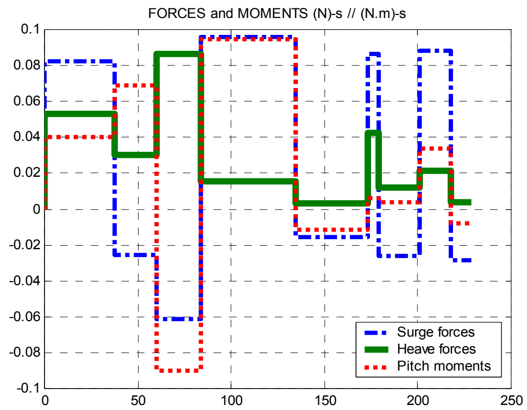

Fig.12. Control actions and times for the fig.10

Two obstacles			
t	F_{surge}	F_{heave}	F_{pitch}
37.3	0.082	0.053	0.040
60.14	-0.025	0.030	0.069
83.74	-0.06	0.086	-0.09
134.5	0.096	0.015	0.095
173.2	-0.015	0.003	-0.011
178.9	0.086	0.043	0.006
200.9	-0.026	0.012	0.004
217.6	0.088	0.021	0.034
228.7	-0.028	0.004	-0.008

Table 3. Solution of times and forces of fig.10

4 Conclusion

This is a multi-objective optimization problem with several constraints. A statement of the problem in genetic terms has been devised and satisfactory solutions have been obtained for a set of paradigmatic cases.

The procedure obtained is easy to apply, including “a priori” knowledge. Obstacle avoidance has been studied, with good results. The result obtained by the procedure is a vector of references for the thrusters, easy to transfer to the AUV before operation. The next step of our research group is to design and implement a control system for the AUV.

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