CONTAINER SHIP OPTIMAL CONTROL SYSTEM USING GENETIC ALGORITHMS

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ABSTRACT

This paper presents the design of a course-changing manoeuvre controller for a container ship. A non-linear ship model with four degrees of freedom is used to tune the controller. It has also been used to verify the performance of the complete system for different course-changing manoeuvres. Genetic algorithms have been used to solve the problem optimisation to the calculation of several classic controller parameters. The simulation of the non-linear ship model, using a second order network as the controller, provides a perfect monitoring of the desired trajectory with several changes in course.

KEYWORDS

Ship control, autopilots, marine systems, control systems, ship model, course-changing control, genetic algorithms.

INTRODUCTION

PID controllers have been widely used in the control of ship steering. The main problem in using these systems is that if the mathematical model used in the design of the controller is not precise, or if there are external disturbances, it is extremely difficult to tune the controller so as to procure a good behaviour in all situations. This is why adaptive or robust control techniques are usually used in the design of the controller.

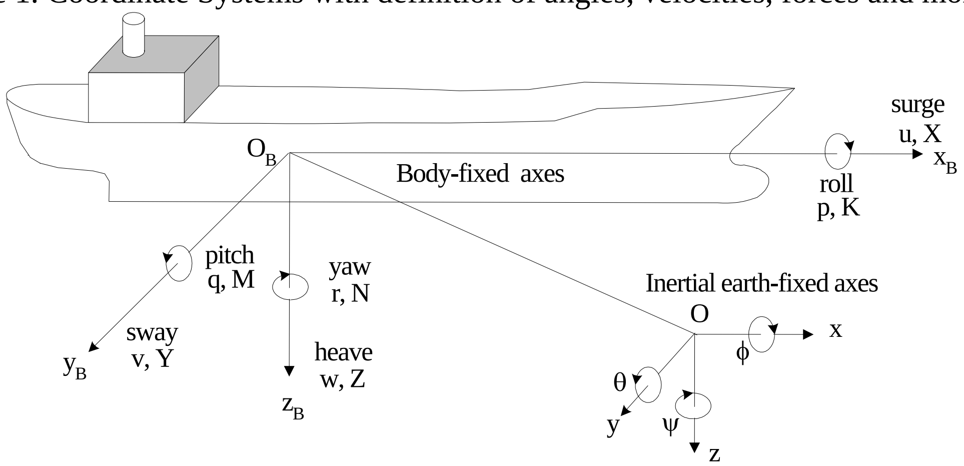
This paper describes the design of various classical controllers for governing the course of a container ship using a non-linear mathematical model with four degrees of freedom. The model uses cross coupling movement equations of surge, sway, roll and yaw to take into account the effects of rolling during the changes of heading which these ships usually undergo due to their low metacentric height. Both for the design of the controller and for the simulation, a non-linear model [1] has been used, in which the effects of rudder saturation have also been included.

The optimisation by means of genetic algorithms (GAs) [2] [3] [4] of the controller parameters provides completely satisfactory results for the behaviour of the simulation of the non-linear model of the ship for different situations of change of course.

CONTAINER SHIP MATHEMATICAL MODEL

The movement of the ship, considered as a rigid solid, has six degrees of freedom so that six independent coordinates are required to determine its position and orientation. The first three coordinates and their derivates are used to define the position and the translation movements on the axes x_B, y_B and z_B, while the other three coordinates and their derivates are used to describe the orientation around these three axes.

Figure 1. Coordinate Systems with definition of angles, velocities, forces and moments



For marine vehicles, the six different motion components are defined as surge, sway and heave for the translation movements in the three directions and roll, pitch and yaw for the rotation movements around the three axes (see fig.1). The origin O_B of the ship's coordinates system is normally situated at the intersection of the symmetry planes

Table 1 shows the nomenclature used to describe the ship's movement, forces and moments. This is the Standard notation recommended in [5] for use in applications of manoeuvre and control of ships.

Table 1. Nomenclature used to describe ship's movement

Translation	**Forces**	**Linear velocity**	**Position**
Surge	X	u	x
Sway	Y	v	y
Heave	Z	w	z
Rotations	**Moments**	**Angular velocity**	**Angles**
Roll	K	p	ϕ
Pitch	M	q	θ
Yaw	N	r	ψ

For the container ship contemplated in this study we will consider course keeping or course changing and roll dampening, while the pitch and heave movements can be ignored due to their low values in comparison with other movements. Thus, the mathematical model of the ship is considered in surge, sway, yaw and roll motions and the movement of the ship can be represented using Newton equations with four degrees of freedom [6], by the following equations:

$$\begin{aligned}
\text{surge:}\quad & m(\dot{u} - vr - x_G r^2 + z_G pr \cos\phi = X \\
\text{sway:}\quad & m(\dot{v} - ur - z_G \dot{p} \cos\phi + x_G \dot{r}) = Y \\
\text{yaw:}\quad & I_{zz}\dot{r} + m\, x_G (ur + \dot{v}) = N \\
\text{roll:}\quad & I_{xx}\dot{p} - m z_G (ur + \dot{v}) \cos\phi = K - \rho g \nabla G_z(\phi)
\end{aligned} \qquad (1)$$

where ∇ indicates the ship displacement, g the gravity constant, ρ the water density, I_{XX} and I_{ZZ} are the inertial moments of the ship about x_B and z_B axes respectively, m is the mass of the ship and the centre of gravity is assumed to be in the position (x_G, 0, z_G). The linear surge and sway velocities are represented by u and v, the angular yaw and roll ones by r and p, and the corresponding yaw and roll angles are ψ and ϕ measured in the inertial frame. The righting arm function $G_z(\phi)$ can be approximated using [7]:

$$G_z(\phi) = (GM + \tfrac{1}{2}\, BM \tan^2\phi)\sin\phi \qquad (2)$$

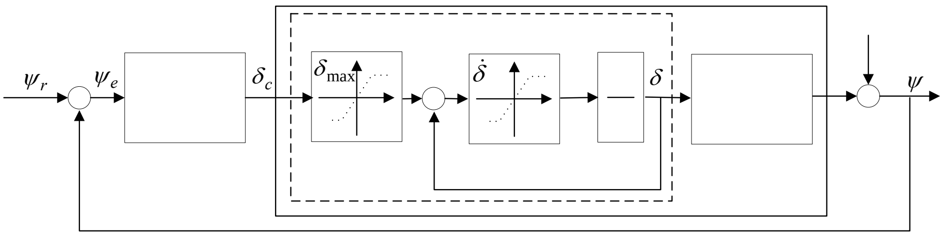
where GM is the nominal ship metacentric height and BM is the distance from the centre of buoyancy to the metacentre. For small roll angles, equation (2) is usually approximated by $GM \sin\phi$ or simply $GM\ \phi$.

The terms X, Y, N and K denote the hydrodynamic forces acting along the axes x_B and y_B, and the hydrodynamic moments around the z_B and y_B axes respectively. These quantities take into account the hydrodynamic effects of the movements of the hull, the forces and moments exercised on the ship by the propeller and the rudder and the influence of the wind, waves and currents.

In [1], a detailed presentation is made of the container-ship model used in this paper. As well as the ship's hydrodynamics, the saturations in the rudder mechanics have also been included. This is easily achieved by limiting the maximum amplitude and velocity of the rudder movement [8]. The rate limit is taken as 4.6 degrees/second and the maximum rudder deflection is 30 degrees [6]. These limitations on the rudder performance contribute to the diminished controllability of the ship.

Figure 2 shows the block diagram of the ship steering system. The command applied is ψ_r, which represents the desired heading and ψ_e is the heading error. The control signal of the controller which acts as a command to the steering gear is δ_c and represents the rudder angle required to correct the deviation from the heading. The actual value of the rudder angle is δ and ψ is the ship's heading angle.

Figure 2. Block Diagram of the ship steering system



THE CONTROL PROBLEM

An autopilot must fulfil two objectives: course keeping and course changing. In the first case, the control objective is to maintain the ship's heading following the desired course ($\psi(t)$ = constant). In the second case, the purpose of the control system is to alter the course of the ship by changing the heading angle ψ through manipulation of the rudder. The aim is to implement the course change without oscillations and in the shortest time possible. In both situations, the operability of the system must be independent of the disturbances produced by the wind, the waves and the currents. The course followed by a vessel can be specified by means of a second order reference model [9]:

$$\ddot{\psi}(t)+2\zeta\omega_n\dot{\psi}(t)+\omega_n^2\psi(t)=\omega_n^2\psi_r \tag{3}$$

where ω_n is the natural frequency and ζ ($0,8 \le \zeta \le 1$) is the desired damping coefficient of the closed loop system.

The aim of the design of this work is that the ship should make a fast course change following, without oscillations, the course determined by the values $\zeta = 0.9$ and $\omega_n = 0.06$ rad/sec.

The ship data and the hydrodynamic coefficients used in the mathematical model [1], correspond to a container ship from the late nineteen-seventies whose main characteristics are outlined in Table 2.

Due to the non-linearity of the model and to the fact that its behaviour in response to a course change shows substantial variations, the non-linear model is used to perform an optimal tuning of the controller parameters using GAs.

Table 2: Main data for the container ship

Quantity	**Symbol**	**Measure**	**Unit**
Length between perpendiculars	L_{pp}	230	m
Beam	B	32	m
Draft	D	10.7	m
Displacement	∇	46,000	m^3
Nominal speed	U_0	12.7	m/s
Rudder speed	$\dot{\delta}_{\max}$	4.6	deg/sec
Nominal X_B coordinate of GC	x_G	-0.5	m
Nominal Z_B coordinate of GC	z_G	-3.5	m
Nominal metacentric heigth	GM	55 - 90	cm

This paper uses the most widely used classical control structures: PID controllers with approximate derivative action in its standard and series forms, a first order controller and a second order controller.

TUNING THE CONTROLLERS

GAs have been used for the optimal tuning of the controllers [3]. These are based on the theory of evolution, according to which nature tends to favour the survival of the fittest members of a population to the detriment of the weakest. This optimisation method acts on a population of defined individuals through a chromosome formed by binary genes.

The GAs act on the chromosomes using selection, crossover and mutation operators for a specific number of generations. In order to quantify the fitness of the individuals, an objective function is minimised Φ. The starting point is an initial population *P(0)*, formed by *p* individuals. Some genetic operators are applied to this population to modify it probabilistically to create a new population *P(1)*. The process is repeated over a given number of generations *T*, the successive generations, *P(t)* being obtained. The solution is obtained among individuals of the last generation *P(T)*. The cost function selected was:

$$J(\theta) = \sum_{i=1}^{n} \left| \Delta\psi_i + \lambda\delta_i \right| \tag{4}$$

where θ is the vector of the controller parameters, *n* is the total number of iterations in the control system simulations, $\Delta\psi_i$ the *i*th heading angle error between the desired and obtained heading, λ is a scaling factor (λ= 0,05 in this case) and δ_i. the *i*th rudder angle deflection. The term δ_i has been included in order to take into account also the minimisation of the control effort. A simulation time of 200 sec. has been used.

A population of 25 individuals over 300 generations has been used, with a probability of crossover of 60% and of mutation of 10%. The genetic algorithm evaluates the cost function (4) in each iteration after performing the simulation of the model with the corresponding controller. The growth rate and mutation values affect the method's convergence characteristics, depending on the problem and the algorithm in question. The mutation is introduced in order to attempt to guarantee that any point in the search space can be reached and to prevent the GA from being blocked in a local optimum.

Table 3 shows a summary of the results obtained with the controllers studied. The values indicated in the table represent for each case the cost function and the heading error obtained with the optimal values of the controller parameters for each course-change manoeuvre.

Table 3. Cost functions and heading errors

Heading angle (deg)	Standard PID	Series PID	1st. order controller	2nd. order controller
		Cost function (rad)		
10	1.494878	1.537111	1.180951	0.832180
20	1.767833	1.791547	1.700806	0.925994
30	2.155522	2.158248	2.145421	1.949617
		Heading error (rad)		
10	1.073519	1.112889	0.819301	0.421504
20	1.033627	1.048331	0.995293	0.296864
30	0.912204	0.913328	0.905311	0.761659

It can be appreciated that the best results are achieved with the second order controller. Satisfactory results are also obtained with the first order controller and with the two PID controllers, being the standard slightly better than series one.

With the results obtained, a set of specific controllers can be implemented for each of the situations studied (course changes of 10, 20 and 30 degrees), whith an scheduling control. Moreover, the set of controllers could be extended to take in course changes of 0 to30 degrees with a lower interval.

The option presented in this paper consists in determining a single controller with which the best behaviour is achieved for all of the cases studied. The results are shown in Table 4.

Table 4. Controller parameters.

Controller	Gain (k)	Zeros		Poles	
		z_1	z_2	p_1	p_2
2nd. Order Controller	108.4685	- 0.05825 + 0.02834j	- 0.05825 - 0.02834j	- 0.6197	- 0.1137
1st. Order Controller	147.411	-0.0481	0	-1.0484	0
PIDMixto	67.6173	- 0.04934	- 0.00001	- 0.5429	0

SIMULATIONS

All of the simulations have been carried out using the SIMULINK *Matlab Toolbox.*
Figure 3 shows the course-change manoeuvres of 10, 20 and 30 degrees with the controllers from Table 4.

Figure 4 shows the heading angle errors between the desired and obtained heading responses. It can be observed that the second order controller obtains a good performance for the three course change manoeuvres studied. The first order controller produces also a good behaviour with errors below 2 degrees for all cases. With the PID controllers, the errors are greater especially for course changes of 10 degrees

Figure 5 shows the results of the simulation of several course changes with the second order system. It can be observed that the desired course is followed accurately.

Figure 3: Course-change manoeuvres: heading responses

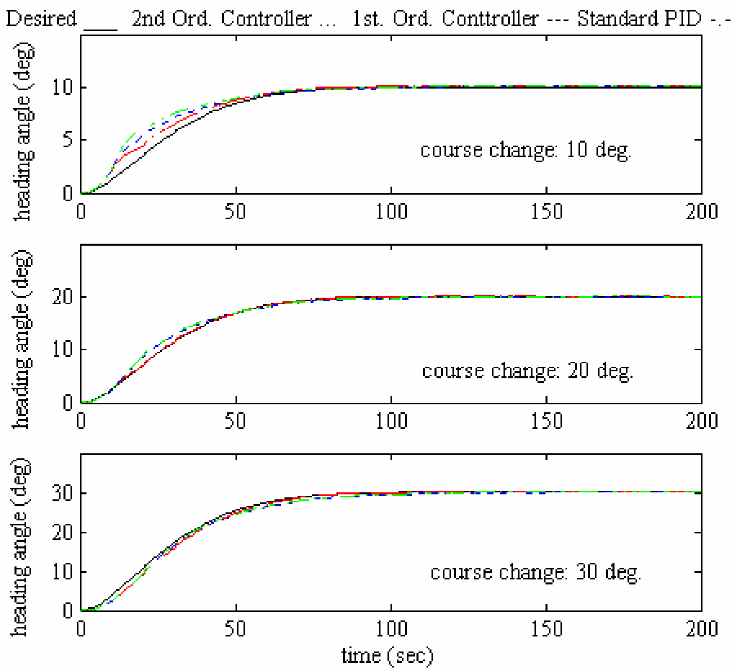


Figure 4: Course-change manoeuvres: heading error

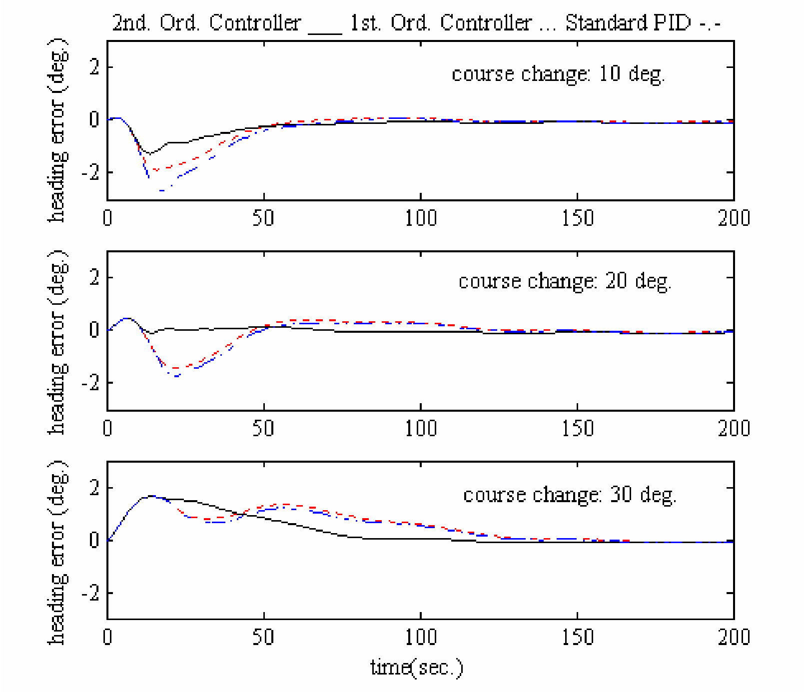
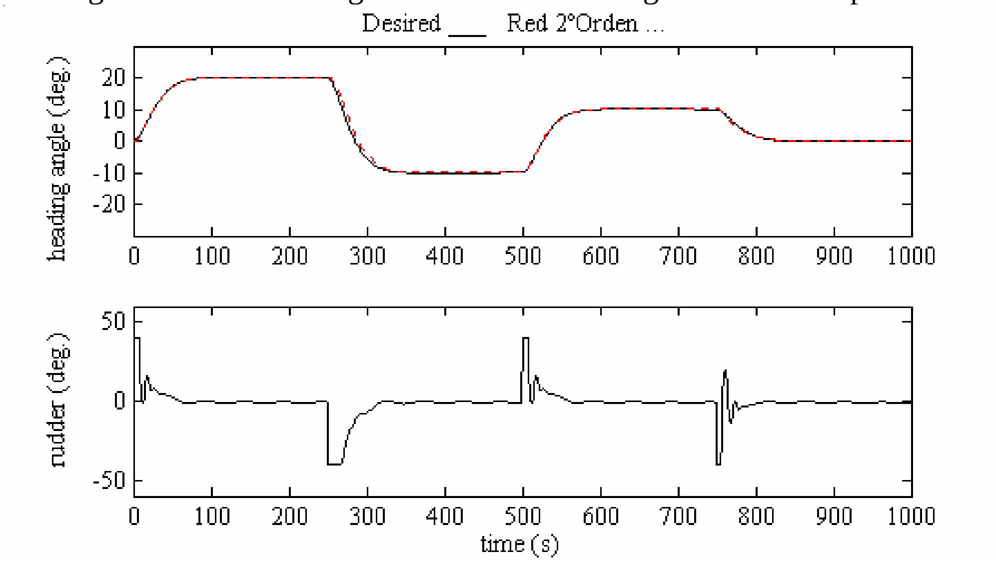


Figure 5: Course-change manoeuvres: heading and rudder responses.



CONCLUSIONS

In this paper, an application of the use of GA for the tuning of various classical control structures has been presented. The non-linear model of a container ship has been used to calculate the controller parameters and to verify its behaviour in the following of a specified trajectory with several course-changes. It has been verified that for course change manoeuvres, the second order controller can follow the desired path quite satisfactorily. By using GAs to calculate the controller parameters, values can be obtained which enable a good behaviour to be attained for various manoeuvring situations.

ACKNOWLEDGEMENTS

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