Ship Steering Control System Optimisation Using Genetic Algorithms

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Abstract: The optimisation of non-linear control systems by Genetic Algorithm (GA) is studied in this paper. It involves the performance of two systems for regulating the motion of a ship model. These systems allow course changing and track keeping through the implementation of a Sliding Mode (SM) controller. The GA is used to optimise the performance of the complete system under various operating conditions by optimising the parameters of the SM controller. The type of vessel considered is an oil tanker.

Keywords: Ship Control, Sliding-mode Control, Genetic Algorithms, Optimisation Problems

1. Introduction

The use of petroleum related products has increased considerably in recent decades and, naturally, this has caused the petroleum industry to grow along with the demand. In order for the industry to meet this demand the transport of crude oil has increased and the size of the super tankers used for this has also changed. The use of very large tankers has not come without problems and many relate to navigational control safety issues.

Improving the navigational efficiency of these vessels is not an easy task due to the manoeuvrability difficulties caused by their bulk [van Berlekom and Goddard (1972), Crane (1973)]. This is mainly due to the restricted size of the rudder which needs a large deflection to change the vessel's course significantly [van Berlekom and Goddard (1972), Crane (1973), Norrbin (1970), Astrom and Kallstrom (1976), Fossen (1994)].

The diminished controllability of these vessels may be rectified by using an automatic control system [Fossen (1994), Kallstrom et al (1979), Dove and Wright (1991), Slotine and Li (1991)]. Such control systems are able to alter the course of the vessel in a desired manner by regulating the rudder. This is clearly illustrated in the book by Fossen [Fossen (1994)] which covers the current thinking in the marine control field. In this paper two such control system configurations are presented for tanker control applications.

The first is a *Course Changing* control system which manipulates the motion of the vessel in accordance with commanded courses changes given by the pilot/helmsman [Crane (1973), Fossen (1994), Kallstrom et al (1979), Dove and Wright (1991)]. The second is a *Track Keeping* control system. This type of system is fully autonomous in that it does not need an operator to provide commands during operation. Instead it follows a predetermined course provided by an autopilot [Fossen (1994), Healey and Lienard (1993)].
Both these types of systems share a common component in the fundamental control law upon which they are based. In this study the non-linear *Sliding Mode* (SM) control law is used [Fossen (1994), Slotine and Li (1991), Healey and Lienard (1993)]. Sliding mode control laws are known to provide good performance robustness which is the main reason that they are investigated here. However, there is a considerable problem in trying to obtain optimal performance by tuning the key design parameters within such non-linear controllers. This process can be very time consuming and tedious, particularly if the designer has limited experience in using this form of control law. Hence this study also presents a well established automated method for optimising controller parameters. This technique is based on *Genetic Algorithms* (GAs) and develops solutions by mimicking the evolutionary process of natural species [Goldberg (1989), McGookin et al (1996), Li et al (1995), Li et al (1996), Ng et al (1995), Renders and Flasse (1996), Brooks et al (1996)].

In order to test the control law and the solutions provided by the GA the control systems are optimised under various simulated tanker operating conditions. Such variations as water depth, loading conditions and commanded manoeuvres are considered [van Berlekom and Goddard (1972), Crane (1973), Norrbin (1970), Astrom and Kallstrom (1976), Fossen (1994)].

The study described in this paper is structured as follows. Section 2 describes the non-linear model used to represent the tanker studied here. Particular attention is paid to the reason for the limited controllability of the rudder actuator. The next section outlines the two control systems and Section 4 describes how the various operating conditions are implemented. Section 5 provides an insight into the SM control law used in both and Section 6 outlines the GA optimisation technique used to find the best set of controller parameters for each of the operating conditions considered. The penultimate section displays the results obtained from this study and the final section discusses the conclusions drawn from this investigation.

2. Tanker Model

2.1 Tanker Dynamics

The model used in this study represents the heading and propulsion dynamics of a 304.8 m long, 190,000 dwt oil tanker as defined in van Berlekom and Goddard (1972) and Fossen (1994). Due to the coupling of the motions within the actual vessel the resulting dynamics are represented mathematically by a non-linear model of the following general state space form [van Berlekom and Goddard (1972), Crane (1973), Norrbin (1970), Astrom and Kallstrom (1976), Fossen (1994)]

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}) \tag{1}$$

As with conventional notation, **x** is the state vector and **u** represents the inputs to the tanker. The states of this model are divided into the kinetic states (defined along the body-fixed axes) and the kinematic states of the system (defined along the earth-fixed inertial reference frame) (see Figure 1)[Fossen (1994)]. The kinetic states are the velocities of the surge, sway and the yaw motions (*u*, *v*, *r* respectively). The kinematic components are the yaw (or heading) angle ψ and the earth-fixed x and y co-ordinates of the tanker (x_p and y_p). As well as having controllable inputs (i.e. rudder deflection (δ) and propeller angular velocity (*n* (rpm))) this model is dependent on the depth of the water (*h*) [van Berlekom and Goddard (1972), Norrbin (1970)]. Therefore it is directly influenced by its external environment. In this study the value for *n'* remains constant at 80 rpm (full speed) which results in a nominal surge velocity of 8 ms^{-1}.

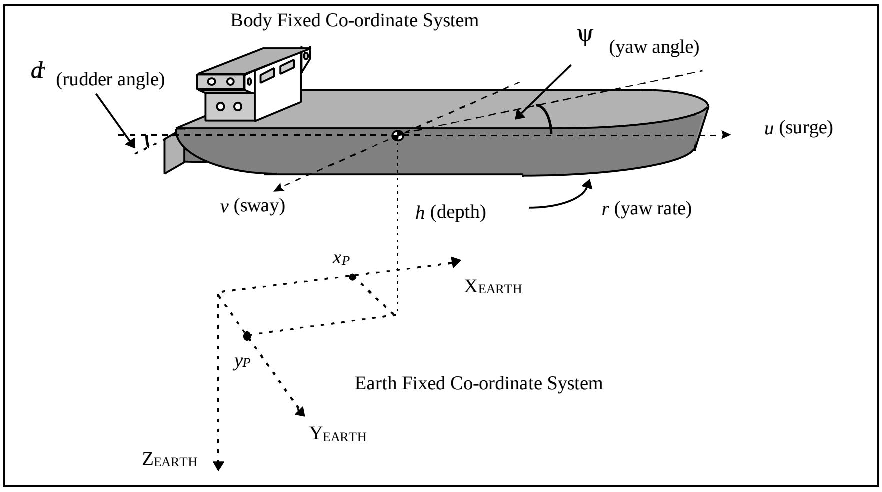


Figure 1: Tanker Co-ordinate Systems

2.2 Input Actuator Dynamics

As well as modelling the rigid body dynamics of the vessel, this model includes the mechanics of the rudder and propeller. The rudder model incorporates both maximum deflection amplitude and rate limits. The rate limit is taken as 2.33 degrees/second and the maximum rudder deflection is 30 degrees [Fossen (1994)]. The commanded rudder angle from a control system or the helmsman may be outside this operating envelope. Therefore a distinction must be made between the commanded rudder angle (δ_{com}) and the tanker's actual rudder angle (δ) [van Berlekom and Goddard (1972), Crane (1973), Norrbin (1970), Fossen (1994)].

For the propeller, a maximum limit of 80 rpm is applied in a similar way as in the rudder case. However, the rate limit for the propeller is not given since the derivative of this speed is governed by a time constant T_n [Fossen (1994)] i.e.

$$\dot{n}' = \frac{1}{T_n}\left(n - n_c\right).60 \tag{2}$$

where T_n = 50 and the values of *n* and n_c are in revolutions per second (hence the scaling value of 60 to make the units become revolutions per minute (rpm)). In this particular application the value of *n* is kept constant (at a value of 80 rpm) and is not affected by this rate limit. Therefore equation (2) is presented here only for completeness.

Both these sets of dynamic limits restrict the motion of these actuators and hence constrain the motion of the vessel itself.

2.3 Rudder Effectiveness

The above limitations on the performance of the rudder are the main reason for the tanker's limited controllability. From the model and standard fluid dynamics, the amount of turning moment generated by the rudder is dependant on the flow over the rudder, c [Fossen (1994)]. This in turn depends on the surge velocity and the speed of the propeller (in revolutions per second) [van Berlekom and Goddard (1972), Fossen (1994)] as shown below.

$$c = \sqrt{c_{un} u n + c_{nn} n^2} \quad (3)$$

Both these quantities are relatively small due to the size of the vessel and as a result the flow over the rudder and the turning moment it can generate are also relatively small. Therefore it can be concluded that in order to make the tanker turn quickly or to a large heading angle, the commanded rudder deflection may be large and will meet or exceed the above limits. When the rudder has saturated like this there is very little that the controller or helmsman can do and the tanker becomes practically uncontrollable. Therefore it is very important to make sure that the rudder operates well within its operational envelope (particularly the maximum magnitude limit), thus ensuring that there is additional deflection available if more control effort is required.

Therefore any automatic control system must be able to execute a commanded turn accurately while keeping the rudder deflection within its operational limits. Hence the trade off between accuracy and actuator saturation is the major problem that needs to be addressed in this application and thus provides a design criterion for the controller to satisfy.

3. Tanker Control Systems

As mentioned previously, this study will consider two different control system configurations i.e. course changing and track keeping. Both these control systems are described below.

3.1 Tanker Course Changing

Course changing control is concerned with the change of heading of the tanker as it responds to step commands from a helmsman/pilot (see Figure 2). These commands are usually step changes in the heading reference which are then used by the controller to change the course/heading of the tanker by manipulation of the vessel's rudder deflection angle [Fossen (1994), Kallstrom et al (1979), Dove and Wright (1991)]. The amount that the heading angle changes is determined by the amplitude of the step command, y_{ref}. This produces the desired heading and yaw rate response for the SM controller to track. These responses are the components of the desired state vector, $\mathbf{x}_d$, which are compared with the actual heading subsystem's state vector, $\mathbf{x}_h$. The figure also shows that the semi-controllable water depth input[1] , h, is represented as a disturbance and can therefore be varied independently.

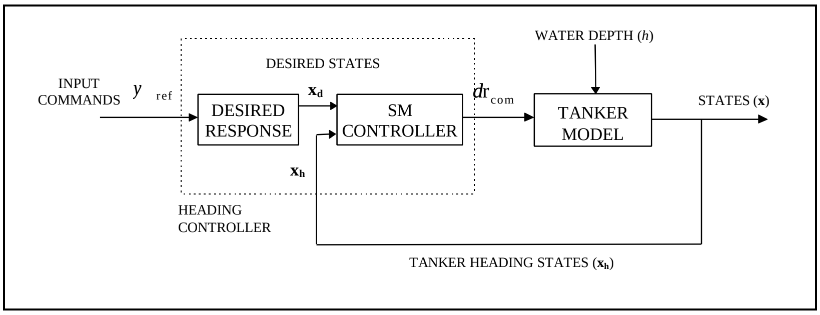


Figure 2: Tanker and Course Changing Controller

It is apparent that this controller configuration does not regulate the position of the vessel which is govern by the judgement of the operator alone.

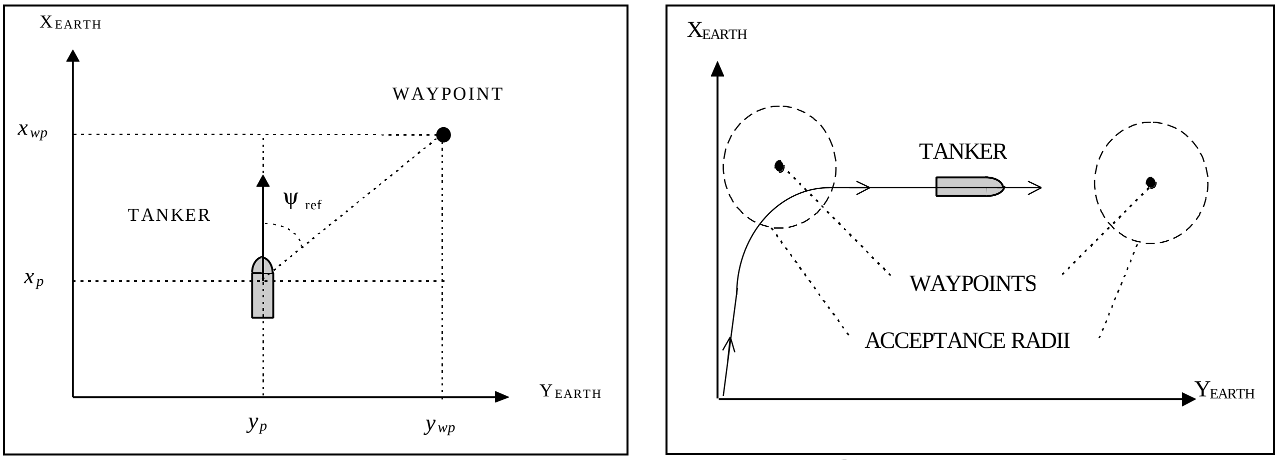
3.2 Tanker Track Keeping

Track Keeping is different from course changing in that the tanker follows the commands of an autopilot rather than the step commands of a pilot. In this context an autopilot is a system which automatically determines the heading that a vessel should follow in order to stay on course. It does this by taking vehicle position information and using this to calculate heading corrections so that the vessel follows a predetermined course set out prior to autopilot activation. The particular autopilot studied here is called a Line Of Sight (LOS) autopilot [Fossen (1994), Healey and Lienard (1993)].

Simple LOS Autopilot

[1] The depth is semi-controllable since the pilot can guide the tanker into regions of desirable water depths.

This kind of autopilot directs the tanker along a course made up of *waypoints* [Fossen (1994), Healey and Lienard (1993)]. These are used to calculate the reference heading angle between the tanker's present position and the current waypoint position (see Figure 3(a)).



(a) Waypoint diagram (b) Waypoint Acceptance

Figure 3: Autopilot Illustrations

This heading angle y_{ref} is obtained from equation (4) which follows the sign convention that positive angles ($0^O < y_{ref} \leq 180^O$) are to starboard and negative angles ($-180^O < y_{ref} < 0^O$) are to port.

$$y_{ref} = \tan^{-1}\left(\frac{y_{wp} - y_p}{x_{wp} - x_p}\right) \tag{4}$$

In this equation (x_p, y_p) are the current position co-ordinates of the tanker obtained from a Global Positioning System (GPS) and (x_{wp}, y_{wp}) are the waypoint co-ordinates [Fossen (1994), Healey and Lienard (1993)]. The reference heading is then used to obtain the desired states, $\mathbf{x}_d$, for the controller to track (see Figure 2).

The autopilot follows the course by guiding the tanker from waypoint to waypoint. Once the tanker comes within a specified distance of the current waypoint, the autopilot acquires the next waypoint position and the tanker heads towards it (see Figure 3(b)). This distance is called the *acceptance radius* and is typically between one and three boat lengths. The acquisition process is repeated until the tanker reaches its final destination.

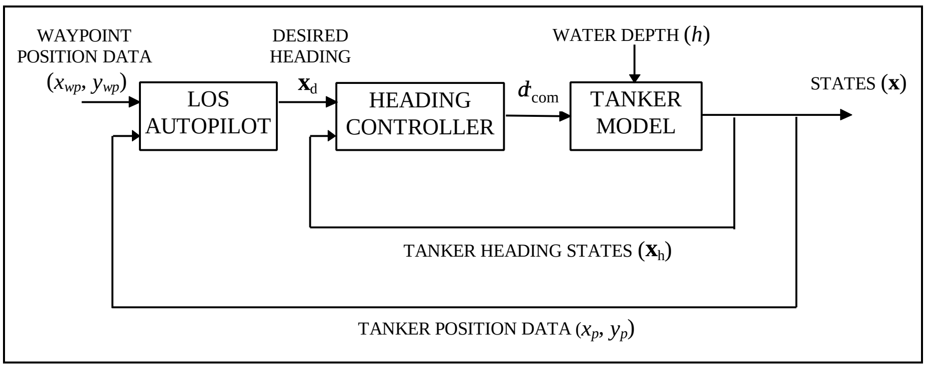


Figure 4: Tanker and Track keeping Controller

The autopilot is integrated into the controller/tanker system, as shown in Figure 4, where it adds an outer feedback loop which stabilises the tanker position. This shows that the addition of an autopilot enables the tanker to be manoeuvred accurately with regard to position, which is of particular use in coastal or hazardous waters[2]. If the situation arose where the autopilot signals need to be countermanded by subsequent helmsman commands, the signal from the operator can be prioritised thus ensuring that manual control can be restored in an emergency.

4. Operating Conditions

[2] Hazards such as shallow water regions where the tanker could run aground

The three operating conditions used to test these methods involve changes of desired course, changes of water depth and loading conditions. The first two are control system specific while the third is common to both course changing and keeping since the same vessel is used. Hence in this section the performance for course and depth changes are described separately for both types of control system while the effect of loading is considered separately.

4.1 Course Changing Operating Conditions

Course

Since this controller is designed to make the ship follow step commands it is logical to choose a test sequence which involves step changes (i.e. 45^{o} followed by a return to 0^{o}). Corresponding desired states involve critically damped second order response to steps which in turn are used to obtain desired heading, yaw rate and yaw acceleration for feedback to the controller. The critically damped steps are used since any overshoot would be damped out by the mass and inertia of the vessel. Also it is conventional to use such a second order response as a reference for control systems [Fossen (1994), Healey and Lienard (1993), M[c]Gookin et al (1996)] Both the step commands and desired heading responses are given in Figure 5.

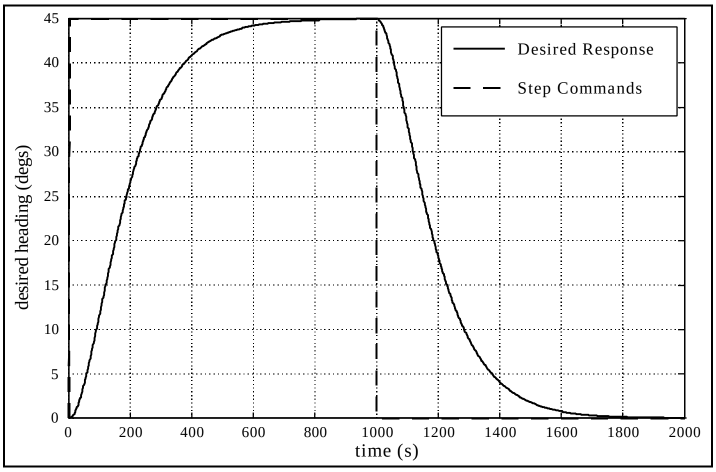


Figure 5: Course Changing Helmsman Step Commands and Resulting Second Order Desired Heading Response

The large rise time used here is mainly due to the limited manoeuvrability discussed earlier. However this should be a sufficient test of how this controller handles large turns. The differing directions of the turn will highlight any noticeable asymmetry within the model.

Water Depth

In the evaluation of course changing performance it is also necessary to consider the effect of changes of water depth. This involves the consideration of how the water depth (*h*) [van Berlekom and Goddard (1972), Crane (1973), Norrbin (1970), Fossen (1994)] interacts with the other dynamics. From the model a parameter ζ is used to relate the depth of water under the vessel and its draft to design waterline (*T*) in the following equation [Fossen (1994)]

$$z = \frac{T}{h-T} \tag{5}$$

This gives the graphical representation of ζ against *h* shown in Figure 6. On this graph the draft is represented by a dashed line which is the depth that the vessel occupies in the water. Also shown is a transition point where the hydrodynamic coefficient Y_{uvz} changes value. It obeys the following conditional operation [van Berlekom and Goddard (1972), Fossen (1994)].

$$Y_{uvz} = \begin{cases} 0 & z < 0.8 \\ -0.85\left(1 - 0.8/z\right) & z \geq 0.8 \end{cases} \tag{6}$$

The result of this transition changes the dynamics of the sway equation by increasing the surge/sway coupling by an amount related to depth ratio ζ.

It can be clearly seen from Figure 6 that this relationship does not vary considerably for depths greater than 100m. Therefore, there are two distinct operating regions and a suitable choice would involve tests in both regions.

However, it is normal practice for tankers to operate in water depths that are three times their draft which in this case is 55.38m.Although this operating restriction applies in practical situations, it is disregarded for the purpose of this investigation and two step depth changes from 200m to 25m and 25m to 200m are considered for the course changing study of this vessel. This should allow the effect of the change in dynamics due to depth to be analysed in the context of controller performance.

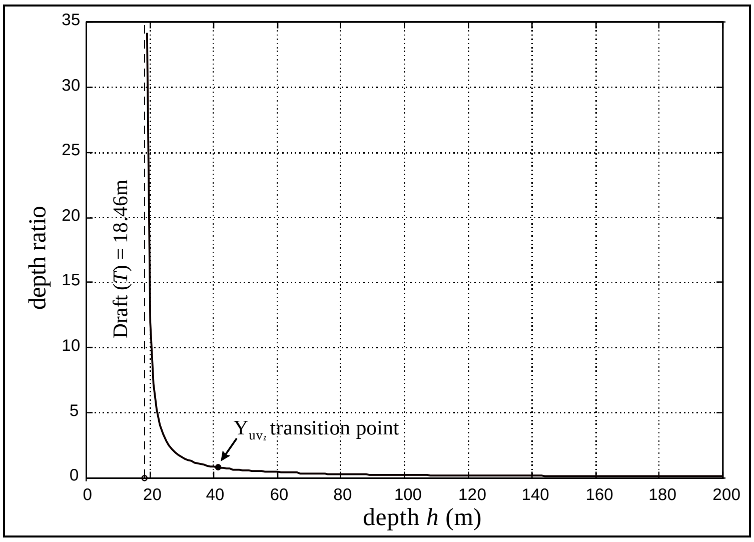


Figure 6: Depth Relationship

4.2 Track Keeping Operating Conditions

Course

Unlike the course followed by the course changing controller, some consideration must be given to the positional aspects of the course that the track keeping controller attempts to follow. Since the autopilot follows waypoint positions then a suitable waypoint course has to be defined for this investigation (see Figure 7).

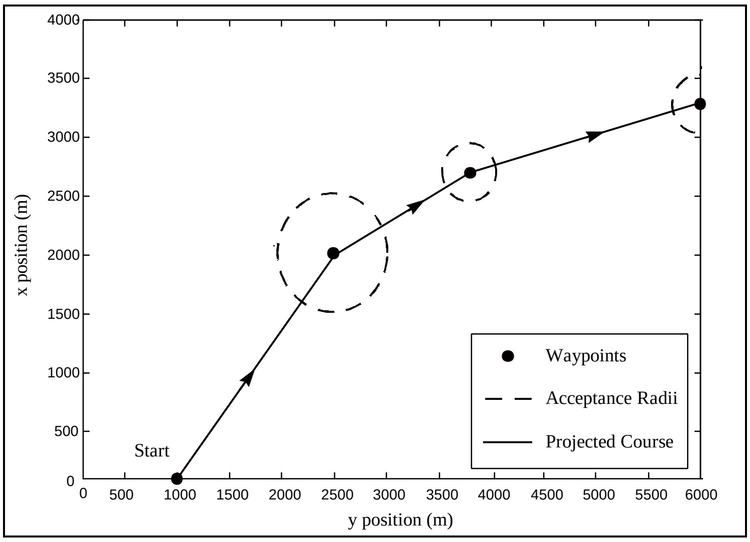


Figure 7: Waypoint Course

As this figure shows the course considered here consists of three waypoints. The acceptance radii and projected course are also given in this figure. It should be noted that the radii of the last two waypoints are only one boat length whereas the first is taken as two boat lengths [Fossen (1994)]. The smaller radii are used in confined shallow water areas of the depth configuration used in this part of the study (see below). This confined waterway calls for greater acquisition accuracy in the autopilot since manoeuvrability is constrained. The initial waypoint is positioned in deeper water which does not present a problem since there is more room to move.

Water Depth

The track keeping depth used in this study allows full advantage to be taken of the tanker model dynamics as described above. However the positional aspects of the controller performance have to be taken into consideration. Hence the depth configuration used is the three dimensional bathymetry map shown in Figure 8.

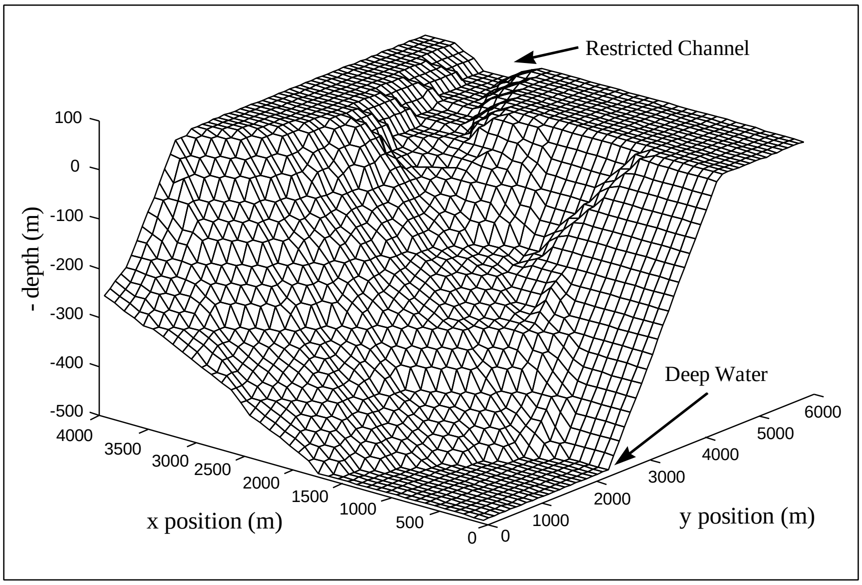


Figure 8: Water Depth Configuration

This configuration is created to represent a change in depth from deep water (500m) to shallow (25m) which covers the operating range of the depth component. Again shallowest point is less than the recommended operating depth of about three times the draft [van Berlekom and Goddard (1972), Crane (1973), Fossen (1994)], but this is used to investigate the controllability of the vessel in shallow waters. The shallow waters are restricted by the banks of the channel which are used to limit the manoeuvrability of the tanker in this area. Unfortunately the effects caused by the banks encountered in such a narrow water channel are not incorporated into the model and could not be investigated here [van Berlekom and Goddard (1972), Norrbin (1970)]. It should be noted that the x-y positions on this configuration match those for the waypoint course in Figure 7.

4.3 Loading Conditions

The model used here is a representation of a fully loaded oil tanker. One appropriate change is to also consider the dynamics of the same tanker under empty conditions.
From the relative dimensions of the oil tanker under consideration (see Figure 9) it can be estimated that on a fully loaded tanker the percentage volumes of oil and steel are 75 % and 25 % respectively. By taking the densities of these materials as r_{oil} = 900 kgm^{-3} and r_{steel} = 7850 kgm^{-3} then 25.6 % of the total mass will be oil. Therefore the mass of the vessel will be reduced to 74.4 % when it is empty. Hence all the mass components within the surge, sway forces and yaw moment will be reduced accordingly. This does not take account of water ballast taken on board when empty.

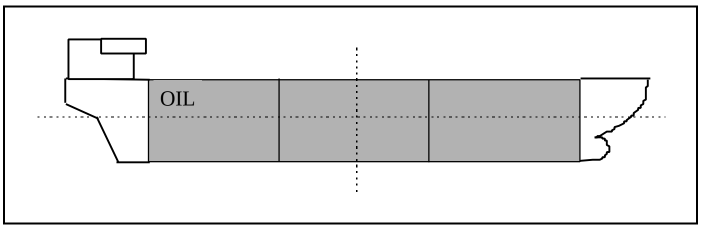


Figure 9: Tanker Loading Divisions

In addition to the mass reduction, the draft of the vessel is also decreased in an empty vessel. By Archimede's Principle the buoyancy force (*B*) of a floating vessel is equal to the weight of the water it displaces (*W*) i.e.

$$B = W \tag{7}$$

where

$$W = rVg \tag{8}$$

where r is the density of water, V is the volume of the water (and subsequently the volume of the vessel) and g is the acceleration due to gravity. This indicates that the weight is directly proportional to the volume of the vessel. Since the block coefficient for large tankers is approximately equal to 1 then the shape can be taken as a regular rectangular cubiod. Hence any variation in the volume of the vessel beneath the waterline shall only affect the draft of the ship.

Therefore, as the mass of the vessel reduces the draft shall be reduced proportionally. Hence the draft must also be reduced by 25.6 %.

The case for fully loaded and empty conditions must be applied to each of the other conditions for both control systems. For each combination of conditions the GA optimises key parameters of a Sliding Mode controller.

5. Sliding Mode Controller

As mention previously, the controller used in both the course changing and track keeping control systems is obtained from a Sliding Mode (SM) control law. The purpose of the controller in both situations is to change the heading of the vessel by manipulation of the rudder. Effectively it will provide the δ_{com} signal for the tanker model. The only thing that changes in the two instances is the way in which the desired heading change is commanded.

SM control law is a well documented non-linear methodology which is characterised by its switching action [Fossen (1994), Slotine and Li (1991), Healey and Lienard (1993)]. This switching provides this type of controller with an inherent robustness to internal and external changes in the environment which is the main reason for using it here. Another benefit of this switching is that it helps track the actual heading to the desired response accurately, thus enabling the tanker to reject the disturbances caused by external factors (e.g. waves) or a change in the operating point of the ship itself [Fossen (1994)]. This is particularly useful in the tanker system when meeting the control objective and minimising the rudder usage are both of critical importance.
Most SM controllers are derived from the non-linear state space representation of the system. Since in this case there is only one input being controlled[3], a control law based on a single input single output linear representation of the dynamics to be controlled is used [Fossen (1994),), Healey and Lienard (1993)]. In order to apply this, the yaw rate (r) and the heading angle (y) dynamics are decoupled from the entire system (equation (1)) and linearised into the following single input state space equation [Fossen (1994), Healey and Lienard (1993)].

$$\dot{\mathbf{x}}_{\mathrm{h}} = \mathbf{A}_{\mathrm{h}}\mathbf{x}_{\mathrm{h}} + \mathbf{b}_{\mathrm{h}}\,\delta_{\mathrm{com}} \tag{9}$$

The controller is designed for this linearised subsystem but for all subsequent simulation investigations the control input is applied to the non-linear model. In this linearised subsystem $\mathbf{x}_{\mathrm{h}}$ is the state vector, $\mathbf{A}_{\mathrm{h}}$ is the corresponding system matrix, $\mathbf{b}_{\mathrm{h}}$ the input matrix and δ_{com} the input vector (i.e. the rudder input after limitations are applied).

Using the derivation given by Fossen (1994) and Slotine and Li (1991) the following SM controller equation is obtained for the commanded rudder input.

$$\delta_{\mathrm{com}} = -\mathbf{k}^{\mathrm{T}}\mathbf{x}_{\mathrm{h}} + (\mathbf{h}^{\mathrm{T}}\mathbf{b}_{\mathrm{h}})^{-1}\left[\mathbf{h}^{\mathrm{T}}\dot{\mathbf{x}}_{\mathrm{hd}} - h_{\mathrm{h}}\tanh\left(\frac{s_{\mathrm{h}}}{f_{\mathrm{h}}}\right)\right] \tag{10}$$

In this equation $\mathbf{k}$ is the feedback gain vector for the subsystem, $\mathbf{h}$ is the right eigenvector of the desired closed loop system matrix and $\mathbf{x}_{\mathrm{hd}}$ is the desired heading state vector [McGookin et al (1996)]. The tanh term provides the switching action which characterises SM controllers. The magnitude of this switching action is determined by the switching gain h_{h} and its activity is governed by the sliding surface s_{h} which is represented as.

$$s_{\mathrm{h}}(\hat{\mathbf{x}}_{\mathrm{h}}) = \mathbf{h}^{\mathbf{T}}\hat{\mathbf{x}}_{\mathrm{h}} = \mathbf{h}^{\mathbf{T}}(\mathbf{x}_{\mathrm{h}} - \mathbf{x}_{\mathrm{hd}}) \tag{11}$$

In order to smooth the switching action so that no oscillatory chattering occurs a boundary layer thickness f_{h} is incorporated [Fossen (1994), Slotine and Li (1991), Healey and Lienard (1993), McGookin et al (1996)]. The switching action determines how robust the system will be to such things as model uncertainties and external disturbances (e.g. waves). If the switching gain is made sufficiently large to counteract these disturbances the controller is able to compensate for them. In this application the simulation of such disturbances would make the overall investigation impracticably time consuming and are therefore not included.

For this particular application the controlled output is the heading angle, y, which follows the desired heading response in a type of model reference control system. This desired response is the reference generated from step commands given by the pilot/helmsman in course changing and by the autopilot in track keeping.

Table 1: Parameters to be optimised

Heading Parameters	
1st Heading Closed loop pole	p_{h1}
2nd Heading Closed loop pole	p_{h2}
Heading switching gain	h_{h}

[3] The propeller input obeys simple step commands and does not require a complex controller to regulate its rotational speed.

Heading Boundary Layer Thickness f_h

As mentioned previously, these controllers contain specific parameters which determine how well the system will perform. For this particular application the controller has four optimisable parameters which are shown in Table 1. Parameters p_{h1} and p_{h2} are two poles of the closed loop heading system which has another pole at the origin [Fossen (1994), M^c^Gookin et al (1996)]. These pole values are used to calculate the required feedback gain **k** and subsequently the right eigenvector **h** in equation (10) [Fossen (1994)]. The last two parameters are the controller's switching gain and boundary layer thickness as described above. In applying the optimisation techniques all these parameters are manipulated and a measure of the cost is calculated using the simulation results obtained from the complete tanker system.

6. Genetic Algorithm Theory

Genetic Algorithms (GAs) provide a basis for a optimisation method which is thought to be one of the most powerful available at present [Goldberg (1989), McGookin et al (1996), Li et al (1995), Li et al (1996), Ng et al (1995), Renders and Flasse (1996), Brooks et al (1996)] and their use has increased dramatically in the last few years due to favourable publicity. They are based on the natural selection process which was outlined in the Darwinian theory of *survival of the fittest.* This theory stated that species evolve through their fittest genetic variation. In this context, fittest means the strongest, healthiest and most intelligent genus. Therefore, in order for a species to survive it must adapt to its surroundings by utilising and improving its abilities. As time goes on, the strongest become stronger and the weakest fade out until the species reaches its evolutionary optimum. As well as following this process, the GA approach also uses nomenclature from natural genetics to define its component parts and operations [Goldberg (1989), M^c^Gookin et al (1996), Li et al (1995), Li et al (1996), Ng et al (1995)].

6.1 The Genetic Algorithm

A GA explores the problem search space by using strings of integers as a representation of the parameters to be optimised. These strings are called *chromosomes* and their individual integer components are called *genes* (which have a value range from 0 to 9 in this work). A number of these chromosomes are initially generated at random and are called the *population* and the number of chromosomes is the *population size*. The initial population is the first *generation* and is evaluated by the following stages (see Figure 10) [M^c^Gookin et al (1996)].

Firstly, the chromosome is decoded from its integer representation into the form used in the optimisation problem (usually real numbers). Then the decoded form is applied to the problem in question (i.e. tanker control in this case) which is then simulated. The simulation data are then used to evaluate the chromosome by obtaining a value of the *cost*. This cost value is used to determine how well the present solution and corresponding chromosome is performing in terms of a predetermined set of guidelines. In this study the smaller the cost value is, the better the response. This evaluation process is carried out for every chromosome in the population. After all the cost values are obtained they are subjected to a selection process which arranges the chromosomes into descending cost order. Then the operations of *Reproduction*, *Crossover* and *Mutation* are executed in order to change the chromosomes and search in different areas of the search space.

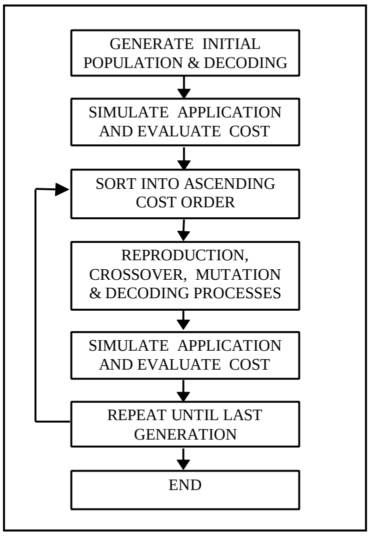


Figure 10: GA Flow Diagram

Reproduction is where the best chromosomes of the present population (typically the top 10 - 20%) are kept for the next population. The remainder are replaced by new chromosomes which are formed through the crossover and mutation of the present population. This reproduction is called *rank based selection*. Since only the elite chromosomes remain this type of optimisation technique is called an *Elite Genetic Algorithm* [Brooks et al (1996)].

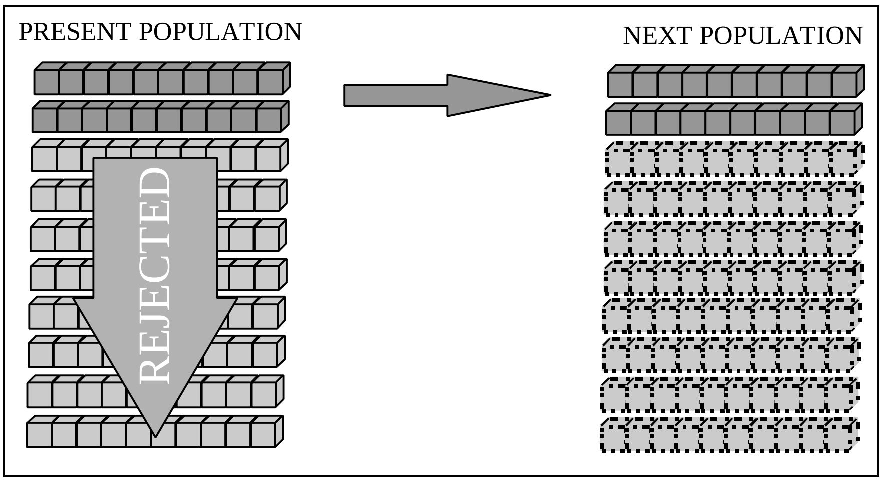


Figure 11: Genetic Algorithm Reproduction

Crossover takes any two chromosomes from the present generation (these are called the *parents*), selects a number of one of the parents genes and swaps them with the same number of genes in the same position in the other parent chromosome (see Figure 12)[McGookin et al (1996)]. This forms two new chromosomes called the *children*. This is repeated until there are enough children to replace the 80 - 90 % of the present population which have the poorest cost values.

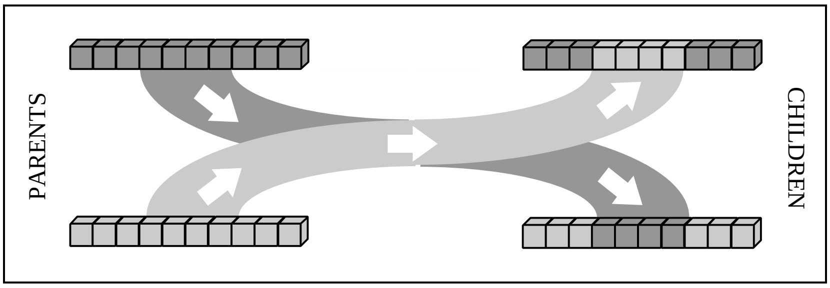


Figure 12: Genetic Algorithm Crossover

Mutation is simply the random selection of a percentage of the new population's genes and the random change of these genes values (i.e. random change of genes in the range between 0 and 9) (see Figure 13) [Goldberg (1989), McGookin et al (1996), Ng et al (1995)]. The elite chromosomes are unaffected by this operation.

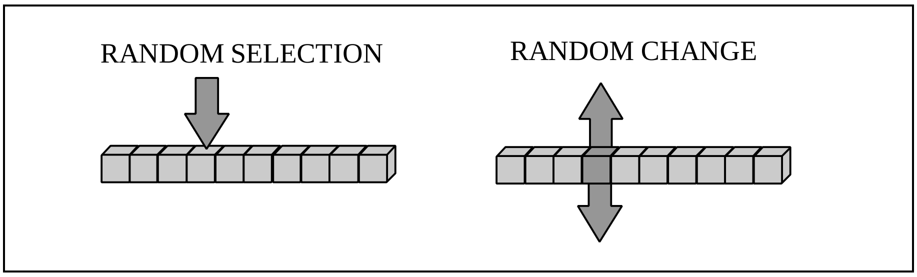


Figure 13: Genetic Algorithm Mutation

After the chromosomes have been altered to form the new population, they are evaluated in the same way as the first population (see above). Then the processes of cost evaluation, ranking, reproduction, crossover and mutation are repeated for a set number of iterations. This number is called the *generation size* and when it is reached, the GA should have reached the optimum. Usually the final population will have a number of similar chromosomes which add validity to the optimal region and give more confidence in the final result.

6.2 Cost Functions

Course Changing Cost Function

The cost function used as the design criterion in the course changing sections of this investigation is defined by equation (12) [Dove and Wright (1991)]. This function is fundamentally a discrete version of the integral least squares criterion.

$$C_{PER} = \sum_{i=0}^{m} \left[l(\Delta y_{i})^2 + (d_i)^2 \right] \tag{12}$$

Here m is the total number of iterations in the control system simulations, l is a scaling factor ($l = 10$ in this case), Δy_{i} is the ith heading angle error between the desired and obtained heading, d_i is the ith rudder deflection [Dove and Wright (1991), McGookin et al (1996)]. Since the GA is trying to minimise the value of this function it is easy to see that both Δy and d will be minimised too. The reasoning behind this selection of elements for the cost function is as follows. The quantity Δy gives an indication of how close the actual heading is to the desired heading, therefore showing how well the controller is operating. The component d is used to keep the magnitude of the rudder actuator deflection to a minimum which is very important for the reasons discussed in Section 2.3. This in turn reduces the movement of the actuator since changes in the amplitude are also reduced. This ensures that the actuator operates well within the actuator's operating limits which is of particular importance with SM controllers which have a tendency to chatter if the switching gain and boundary layer values are not chosen properly. Another advantage of minimising the rudder deflection is the resulting savings in terms of fuel consumption since the resistance to the forward motion is minimised [Dove and Wright (1991)]. Thus as the rudder deflection is minimised, the rudder/hull produces less drag and hence more of the forward force goes to producing a larger surge velocity.

Track Keeping Cost Function

The cost function for the Tanker's track keeping manoeuvre has an additional component compared to the course changing cost function in equation (12). As well as the heading and rudder performance provided by equation (12) it also counts the number of waypoints (n_{wp}) acquired by the autopilot. It is believed that in the time interval of the simulation only three waypoints should be acquired and therefore the following cost penalty function is used to calculate an addition cost value [Goldberg (1989)].

$$C_{PEN} = k\left|n_{wp} - 3\right| \tag{13}$$

Here κ is a large value used to penalise the cost and is taken as a value of 10000 in this study. The sum of this cost and the performance costs from equation (12) gives the following cost equation for track keeping.

$$\begin{aligned} C_{TOTAL} &= C_{PER} + C_{PEN} \\ &= \left[\sum_{i=0}^{m} \left(l\left(\Delta y_{i}\right)^2 + d_i^{\,2} \right) \right] + \left[k\left|n_{wp} - 3\right| \right] \end{aligned} \tag{14}$$

This total cost is used as the optimisation measure for track keeping in the same way as equation (12) is used for the course changing optimisations.

7. Results

Parameter solutions for the SM controller structure defined in equation (10) are obtained from the GA optimisation process. These involved numerous optimisations for each of the operating conditions. The plots and optimal costs for particular solutions for each control system configuration are given below.

7.1 Course Changing Plots and Cost Values

One case for the course changing manoeuvre optimisation for the 200m - 25m depth change is shown in Figure 14. This is a typical plot for this type of manoeuvre and response for loaded and unloaded conditions are shown.

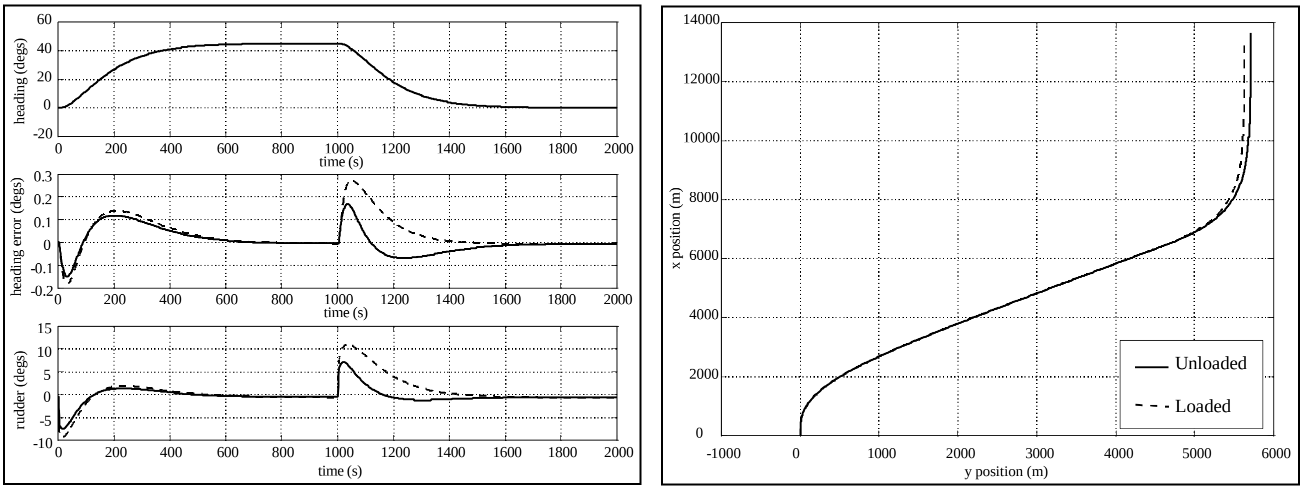


Figure 14: Course Changing Responses (200m -25m Depth Change at time = 900s)

The loaded responses are the solid lines and the dashed represent the unloaded responses. These plots are time histories of the heading, heading error and rudder deflection. Both sets of results are considered to have met the design criteria set out for this controller application. As the error indicates, the deviation of the actual heading from the desired heading is minimal for both cases. Also the rudder deflection is well within the operating envelope of this actuator. However it should be noted that the peak rudder deflection is higher in shallow water than in deep. This indicates that slightly more control effort is needed in restricted depths of water. When the two sets of responses are compared graphically the variation is very slight. However it can be seen that the vessel in the unloaded condition is more manoeuvrable than when carrying a cargo since the error and rudder are smaller.

Also shown in Figure 14 is the course in the x-y plane. It can be seen that the course held by the vessel when unloaded differs from the loaded case. This indicates that the course can vary depending on the vessel's operating condition and would be more pronounced in the presence of adverse external disturbances (e.g. waves). Therefore this suggests that a course changing control system is good at altering course heading but may fall short when used to track a position course. Hence it should not be recommended for manoeuvres where position accuracy is paramount.

For the opposite depth change (i.e. 25m - 200m) the optimised responses shown in Figure 15 are obtained for the two loading conditions. Again these are the heading, heading error and rudder deflection for this controller.

These responses also satisfy the design criteria set out for course changing. Therefore the GA has obtained an optimal solution for this condition too. It should be noted that increased control effort is also required when the tanker is initially in shallow water. Therefore the assumption that additional control effort is required for shallow waters is verified and is not due to an asymmetric aspect of this model. This is particularly the case when the vessel is loaded.

Again the positional plot is given to illustrate the actual course taken by the vessel. This time the variation appears to be reversed in that the loaded course is longer. However comparison of both x-y plots in Figures 14 and 15 suggests that the unloaded course has shortened with the decrease in depth and is therefore more sensitive to depth configuration changes than the loaded case. These plots show that although the heading is changed accurately the course position is not governed well by this type of control system.

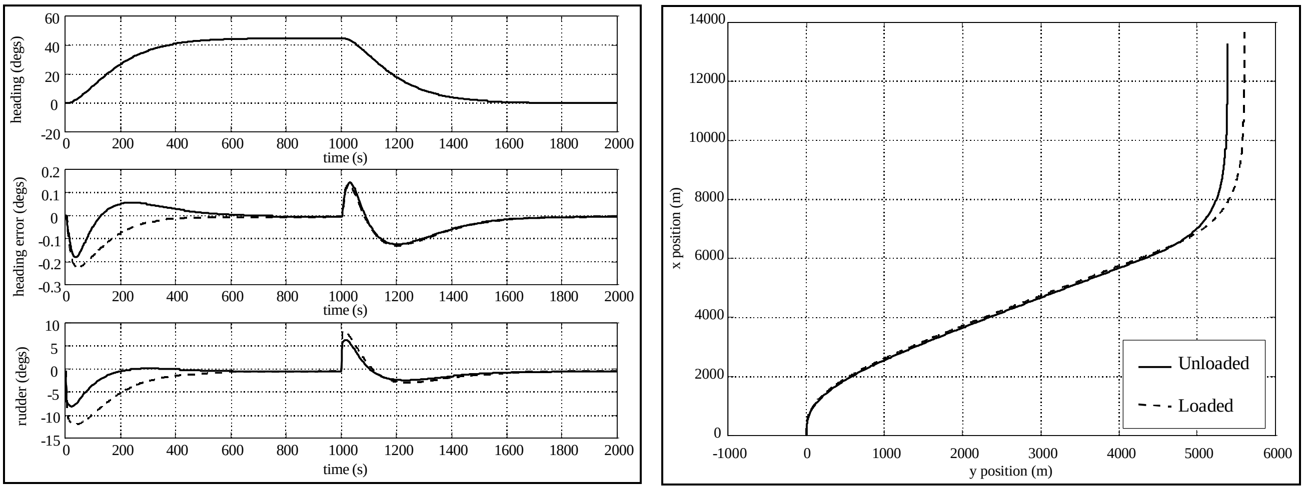


Figure 15: Course Changing Responses (25m -200m Depth Change at time = 900s)

The unloaded and loaded cases show similar results for this set of operating conditions in terms of the time history of the heading angle. This marginal change in the responses is reflected in the cost values for both course and loading solutions. These are shown in Table 2.

Table 2: Course Changing Cost Values

Costs	
Course Changing (200m - 25m, loaded)	19845.3
Course Changing (200m - 25m, unloaded)	6593.2
Course Changing (25m - 200m, loaded)	25188.1
Course Changing (25m - 200m, unloaded)	7904.7

It should be noted that the optimum costs for the loaded conditions are very much higher than when the vessel is unloaded. This indicates that more control effort is needed for manoeuvring when the tanker is full which is quite logical. However the graphical results also show that additional effort is needed for a full vessel in shallow water. This is also logical since the draft of the fully loaded case is greater.

7.2 Track keeping Plots and Cost Values

Since there is only one depth configuration the optimisation process only yields one set of results for each loading condition. Typical plots to the ones shown in Figure 16 are obtained when the track keeping control system is optimised.

Both loaded and unloaded responses are given here. The unloaded responses are the solid lines and the dashed lines represent the loaded responses. As well as the time histories of the heading, heading error and rudder deflection an additional plot is given. This shows how well the optimised controllers track the course provided by the waypoints. It can be seen that both sets of results have met the performance and waypoint design criteria set out for this control system. The error indicates that this control system also tracks the heading very well and the deviation of the actual heading from the desired heading is also very small. Although the rudder deflections used are more than in course changing, they still remains well within the operating envelope.

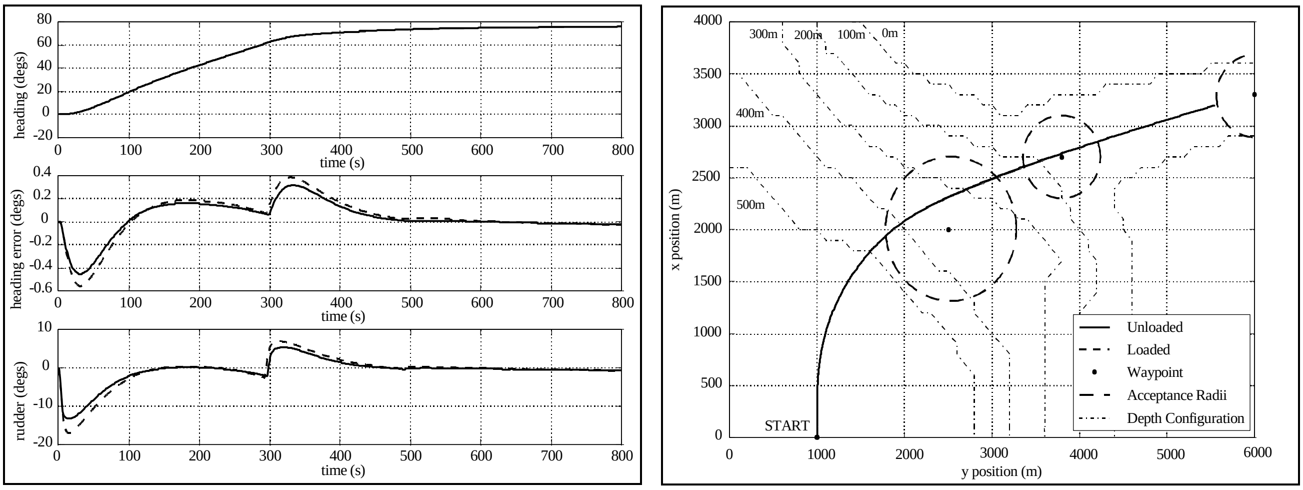


Figure 16: Track keeping Responses

Again the responses in shallow water indicate that slightly more control effort is needed in restricted depths of water. However the positional course is tracked well in both loading conditions and is more accurate than the course changing control system in this respect.

The variation in the two sets of responses when they are compared graphically is very slight. But again it can be seen that the unloaded condition is more manoeuvrable since the rudder deflection is smaller. Both the unloaded and loaded cases show the same x-y responses for the given operating conditions and therefore show that the waypoint course is tracked well by the autopilot. However the marginal change in the rudder and error responses is reflected in the cost values for both loading solutions (see Table 3).

Table 3: Track keeping Cost Values

Costs	
Track keeping (loaded)	15109.8
Track keeping (unloaded)	9494.3

Again these show a lower cost value for the unloaded case which is mostly due to the decrease in control effort.

7.3 Optimised Parameter Values

In order to obtain the above responses the GA optimises the four parameters shown in Table 1. Obviously each operating condition will yield variations in the optimal parameter solutions necessary for each specific case. The corresponding parameters that were obtained for the responses above are given in Table 4.

It can be clearly seen that there is very little variation in the pole values and typical values of -0.1 and -0.2 could be used effectively for all the operating conditions considered here. However the variation in the switching gain and boundary layer values is considerable. This is explained when the ratio of these two parameters is considered and found to be approximately one in all cases [McGookin et al (1996)]. The reason behind this that the controller operates only in the boundary layer which enables the control action to be in the sliding mode throughout the whole manoeuvre. This is fundamental in ensuring good tracking performance for this type of controller. Therefore a suitably high set of values would enable performance and robustness to be maintained. A range of values can be determined through the Lyapunov stability criterion set out in Slotine and Li (1991).

Table 4: Optimised Parameter Values

	Course Changing (Depth : 200m - 25m)		Course Changing (Depth : 25m - 200m)		Track Keeping	
Parameters	Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded
p_{h1}	-0.1000	-0.1000	-0.1572	-0.1000	-0.0874	-0.0882
p_{h2}	-0.2457	-0.2220	-0.2000	-0.2197	-0.1923	-0.1781
h_h	8.7790	0.4496	0.0226	8.8390	0.0179	6.8880
f_h	9.2560	0.3923	0.0272	7.3430	0.0205	7.1830

7.4 Performance Evaluation

Although the above parameters appear to be similar for all the different operating conditions, the performance of the resulting controllers may differ. One way to evaluate this is by calculating the cost of each set of controller parameters for each operating condition (see Table 5). This table shows the cost values for each of the optimised solutions when they are applied to the different operating conditions thus indicating any differences between their respective controllers.

Table 5: Performance Evaluation Costs

		EVALUATION OPERATING CONDITIONS					
OPTIMISED SOLUTION OPERATING CONDITIONS		Course Changing (Depth : 200m - 25m)		Course Changing (Depth : 25m - 200m)		Track keeping	
		Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded
Course Changing	Loaded	19845.3	6601.7	25227.8	7914.5	15725.2	9840.5
(Depth : 200m - 25m)	Unloaded	19856.2	6585.4	25237.4	7905.1	15662.2	9803.9
Course Changing	Loaded	19807.4	6585.4	25188.1	7897.4	16010.4	9940.2
(Depth : 25m - 200m)	Unloaded	19858.8	6593.0	25239.6	7904.7	15702.3	9829.7
Track keeping	Loaded	20003.6	6653.8	25393.3	7967.5	15109.1	9510.5
	Unloaded	20047.0	6661.8	25436.1	7975.2	15155.0	9494.3

The cost values show that all the controllers perform well no matter which operating condition is being considered. Hence the sliding mode controllers can be seen to be robust enough to govern the heading of a tanker in all conditions. It should be noted that the costs for the track keeping controllers are slightly larger for the course changing manoeuvres and smaller for the track keeping. This would indicate that they have been optimised specifically for track keeping manoeuvres. However, the response performance of the controllers does not vary noticeably from the responses shown previously and can therefore be considered near optimal.

8. Conclusions

A number of points of interest have arisen from this study. Firstly it has been shown that automatic SM control systems can be used effectively to manoeuvre an oil tanker for course changing and track keeping operations. Although both operate very well in their respective ways it has been shown that only the addition of an autopilot can ensure good course tracking irrespective of the operating conditions. However, course changing is effective for manoeuvres where the positional course is not of particular importance (e.g. in open waters). Since both operate well it can be said that automatic controllers can be considered effective alternatives to manual operation of a tanker.

Another interesting point arises from the Sliding Mode controllers being designed around a nominal linearised model of the tanker. Although they have been designed using this simplified model their performance is evaluated for the full non-linear model which can be clearly seen to be very good. Therefore this type of controller has been shown to handle any deviation from its designed operating condition that the dynamics of the tanker model may impose.

This study has also shown that the GA optimisation technique can be used to obtain design parameters for such controllers and that these perform well in simulation. This will provide a very good starting point for physical implementation and is therefore a very useful design method.

A consequence of this study is that nearly the same parameters can be applied to both the course changing and track keeping systems in all conditions, therefore indicating that a single controller can be implemented in both situations. This suggests that the SM controller structure presented here exhibits very good performance robustness and can handle a variety of operating conditions without losing the ability to track a desired course well.

Overall, this study has indicated that through utilising modern techniques for the design and implementation of automatic control systems the navigation of oil tankers could be improved. This would be beneficial to everyone affected by the petroleum industry in that it can help reduce the number of oil spillage incidents that occur and make the transportation of crude oil safer and subsequently less expensive.

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