# NON-LINEAR TANKER CONTROL SYSTEM PARAMETER OPTIMISATION USING GENETIC ALGORITHMS

Euan W. McGookin†, David J. Murray-Smith†, Yun Li† and Thor I. Fossen‡

† Centre for Systems and Control &
Dept. of Electronics and Electrical Engineering,
University of Glasgow,
UK

‡ Dept. of Engineering Cybernetics,
Norwegian University of Science and Technology,
Trondheim,
Norway

Abstract - The optimisation of a non-linear control problem by Genetic Algorithm (GA) is studied in this paper. It involves the performance of a control system for course changing manoeuvres of an oil tanker. Sliding Mode (SM) control theory is used to define the structure of this controller and the GA is used to optimise key control parameters so that satisfactory performance is obtained.

## I. INTRODUCTION

In recent decades the use of petroleum in many areas of modern life has increased significantly. As a result of this there has also been an increase in the transportation of crude oil using super tankers [1-3]. Inevitably the transportation causes problems when safety issues regarding navigational control of such vessels are considered.

This is of particular importance when the results of accidental oil spillage are observed. When such accidents occur the cost in terms of environmental damage and loss of revenue can be considerable. In recent years the main cause has been inadequate control provisions provided for the helmsman. Therefore there is a need for better ways to control these vessels safely. Unfortunately this is not easy due to the size of these ships (i.e. in excess of 200m in length). Their sheer bulk makes manoeuvring difficult since the size of the rudder is restricted [1-7] and therefore a large deflection is needed in order to change the course of the vessel significantly.

This problem of diminished controllability can be rectified by the use of an automatic control system. Such control systems are able to regulate the rudder effort so that the ship responds to input commands from the pilot/helmsman [1-7]. Although linear forms of controller have been used for ship steering systems they give an overall performance which changes significantly with the forward speed of the vessel and with other factors such as the depth of the water [1-3]. Non-linear forms of controller, such as sliding mode controller [7-11], may give benefits in terms of overall performance robustness. However there is a drawback with such control systems in terms of tuning them so that they behave in the way that is required. The selection of parameter values for a non-linear controller can be a tedious and time consuming business, particularly if the designer has limited experience with the process. Hence an automated approach to tuning these parameters is presented here in the form of Genetic Algorithms (GAs) [8-14] which carry out the optimisation by mimicking the evolutionary process of species.

A particular case study of a tanker controller design and parameter optimisation is presented in this paper as follows. Section II describes the mathematical model of the tanker used in this optimisation study and outlines the problem of controlling these vessels in general. Section III describes the control system and other aspects of the simulation used in this study. The following section outlines the GA optimisation process and the results obtained from this investigation are shown in Section V. The final section provides concluding remarks about this investigation.

## II. TANKER MODEL

The model considered here represents the propulsion and heading dynamics of a 304.8 m long, 190,000 dwt oil tanker [1-3]. This vessel is represented mathematically by a model of the following non-linear state space form [4].

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

In this representation **x** is the state vector and **u** represents the inputs to the tanker system. The states are divided into two groups, those that represent the kinetic dynamics (defined along the body-fixed axes) and those that represent the kinematic dynamics (defined along the earth-fixed inertial reference frame) (see Fig.1)[4].

The states of the kinetic dynamics are surge velocity $u$, sway velocity $v$ and the yaw rate $r$. The kinematic components are the yaw (or heading) angle $\psi$ and the earth-fixed x and y co-ordinates of the tanker ($x_p$ and $y_p$). This model also has 3 inputs which are the commanded propeller angular velocity ($n_{com}$), commanded rudder deflection ($\delta r_{com}$) and the depth of the water ($h$) that the vessel is travelling through [1,4]. Therefore it is directly influenced by its external environment. In this study the nominal value for $n_{com}$ is 80 rpm (full speed) which gives a surge velocity of 8 ms$^{-1}$.

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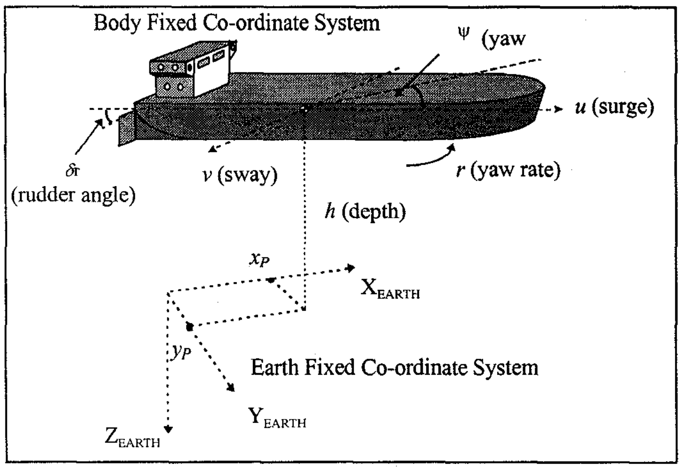

Fig.1: Tanker Co-ordinate Reference Frames

In addition to the vessel's hydrodynamics, the mechanics of the rudder are also modelled. This is easily done by applying rate and maximum amplitude limits to the deflection of the rudder. The rate limit is taken as 2.33 degrees/second and the maximum rudder deflection is 30 degrees [4]. The commanded rudder angle obtained from a control system may be outside this operating envelope. Therefore a distinction is made between the commanded rudder angle ($\delta r_{com}$) and the tanker's actual rudder angle ($\delta r$) [1-4].

These limitations on the rudder performance contribute to the diminished controllability of these ships. From the modelled fluid dynamics, the amount of turning moment generated by the rudder is dependant on the localised flow over the rudder [4] which in turn depends on the surge velocity and the speed of the propeller [1,4]. Due to the size of the vessel both these values are relatively small and so is the flow over the rudder and its resulting the turning moment. Therefore it can be concluded that in order to make the tanker turn quickly or to a large heading angle, the rudder deflection will be large and may meet or surpass these limits. When the rudder has saturated at these limits there is very little that the controller or helmsman can do to correct this and the tanker becomes practically uncontrollable. Therefore it is very important to ensure that the rudder operates well within these limits (particularly the maximum magnitude limit). This ensures that there is an adequate amount of deflection available if more control effort is required and thus provides a design criterion for the controller to satisfy. Therefore it is clear that the need is for a control system which will operate the rudder within its operation envelope and still perform the tasks required.

## III. TANKER CONTROL SYSTEM

The purpose of the control system is to alter the course of the vessel by changing the heading angle $\psi$ through manipulation of the rudder. This type of manoeuvre is called *Course Changing* and the appropriate controller would be required to provide a commanded rudder input (i.e. $\delta r_{com}$)[1-6]. As mentioned previously these controllers respond to step commands from a pilot or helmsman where the step commands correspond to the desired heading change required to alter the course (see Fig. 2).

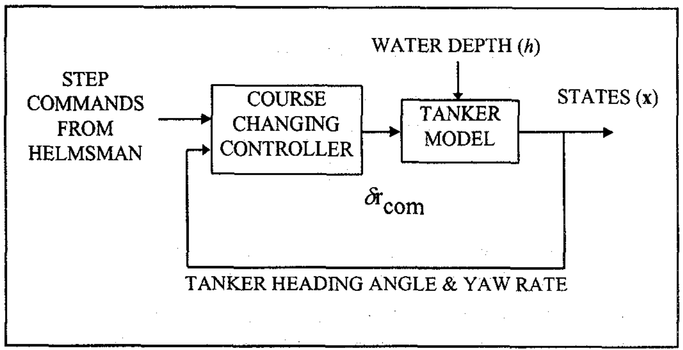

Fig.2: Control System and Tanker Model

The particular approach used here involves *Sliding Mode* (SM) control [4,8-11] which is known for its robust ability to reject changes in the systems' operating conditions. In order to test this aspect of this control law the tanker model has to be simulated in a changing environment. This is readily achieved by changing the depth of water input to the system. Both these aspects are considered below.

### A. Sliding Mode Controller

Sliding Mode Control is a well documented non-linear methodology which is characterised by its switching action [4,7-11]. The reason for using this type of controller is that it gives robustness to internal and external changes in the environment. This helps the controller to track a desired heading response accurately hence 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 [4]. This is particularly useful in the tanker system where it is critical both to meet the control objective and to minimise the rudder usage.

Most SM control schemes are derived from the non-linear state space representation of the system to be controlled. However in this case there is only one input being controlled[1], and a control law based on a linear representation of the tanker dynamics is used [4,7,8]. In order to apply this, the yaw rate ($r$) and the heading angle ($\psi$) dynamics are decoupled from the rest of the system (equation (1)) and linearised into the following single input state space equation [4,8].

$$\dot{\mathbf{x}}_{\mathrm{H}} = \mathbf{A}_{\mathrm{H}}\mathbf{x}_{\mathrm{H}} + \mathbf{b}_{\mathrm{H}}\delta r_{\mathrm{com}} \qquad (2)$$

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

The controller is then designed for this linearised subsystem and the control input is applied to the non-linear model. In this linearised subsystem $\mathbf{x}_H$ is the state vector, $\mathbf{A}_H$ is the corresponding system matrix, $\mathbf{b}_H$ the input matrix and $\delta r_{com}$ the input vector (i.e. the rudder input before limitations are applied) [8].

Using the derivation given in references [4] and [7] the following SM controller equation is obtained for the commanded rudder input.

$$\delta r_{com} = -\mathbf{k}^T \mathbf{x}_H + (\mathbf{h}^T \mathbf{b}_H)^{-1} \left[ \mathbf{h}^T \dot{\mathbf{x}}_{HD} - \eta_H \tanh\left( \frac{\sigma_H}{\phi_H} \right) \right] \quad (3)$$

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 $\mathbf{x}_{HD}$ is the desired heading state vector [8]. The tanh term provides the switching action which characterises SM controllers. The magnitude of this switching action is determined by the switching gain $\eta_H$ and its activity is governed by the sliding surface $\sigma_H$ and the boundary layer thickness $\phi_H$ [4,8]. The sliding surface [4,7,8] is represented by the following relationship

$$\sigma = \mathbf{h}^T (\mathbf{x}_H - \mathbf{x}_{dH}) = \mathbf{h}^T \Delta \mathbf{x}_H \quad (4)$$

where $\Delta \mathbf{x}_H$ is the state error vector (i.e. the difference between the actual and desired states).

For this particular application the controlled output is the heading angle, $\psi$, which follows the desired heading response in a type of model reference control system. The desired response used in this investigation follows a combination of critically damped steps (see Fig.3).

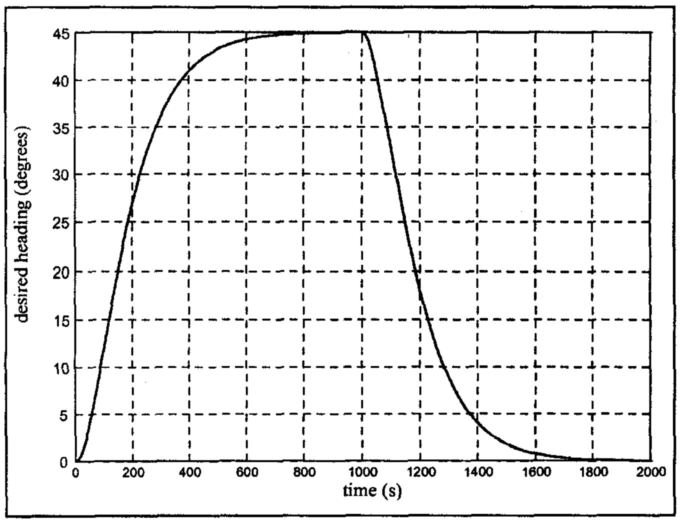

Fig.3: Desired Heading Response

This response is considered adequate for testing the course changing controller in that the amplitude of the turns is reasonably large and there are two changes in opposite directions.

B. Depth Configuration

In course changing there is no need for an elaborate bathymetry configuration but a suitable change of depth for this investigation is required. This is obtained from consideration of how the water depth (*h*) interacts with the other dynamics. From the model, a parameter $\zeta$ is used which relates the depth of water under the vessel and its draft to design waterline (*T*) in the following equation [1,4].

$$\zeta = \frac{T}{h - T} \quad (5)$$

This gives the graphical representation of depth ratio, $\zeta$, against *h* shown in Fig.4. Here the draft is represented by a dashed line and is the depth of the vessel in the water.

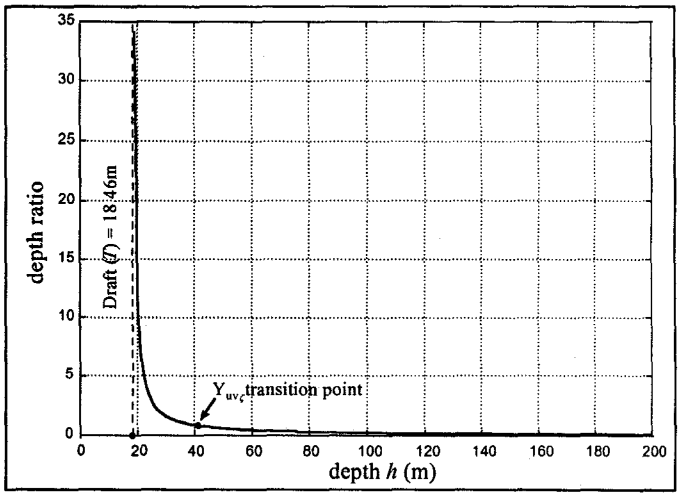

Fig.4: Depth Relationship

Also shown is a transition point where the hydrodynamic coefficient $Y_{uv\zeta}$ changes value. It obeys the following conditional operation.

$$Y_{uv\zeta} = \begin{cases} 0 & \zeta < 0.8 \\ -0.85\left(1 - {0.8}/{\zeta}\right) & \zeta \geq 0.8 \end{cases} \quad (6)$$

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

It can be seen clearly from Fig.4 that the depth ratio does not vary considerably for depths greater than 100m. Therefore, there are two distinct operating regions and a suitable choice would be to use one depth from each region. However, it is normal practice for tankers to operate in water depths that are three times their draft [2,3] which in this case is 55.38m. Although this operating restriction applies in practical situations, this will be disregarded for this investigation and a step depth change from 200m to 25m is used for the course changing study of this vessel (see Fig.5). This should allow the effect of the change in dynamics due to depth to be analysed in the context of controller performance. The timing for the change (t = 900s) is chosen so as to occur immediately prior to the change in desired heading (t = 1000s).

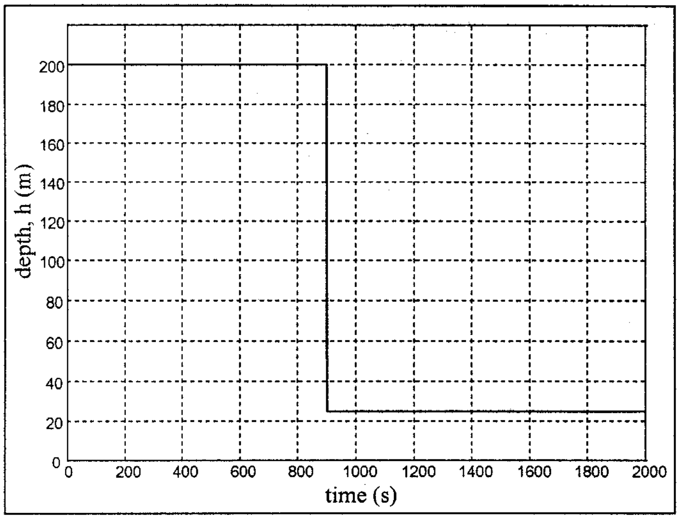

Fig.5: Depth Configuration

## IV. GA IMPLEMENTATION

Genetic algorithms (GAs) provide a basis for one of the most powerful search methods used at present for parameter optimisation [8-14]. Their use in many fields has increased dramatically in the last few years due to favourable publicity. The method itself is based on the natural selection process which was first outlined in the Darwinian principle of *survival of the fittest* which stated that species evolve through their fittest genus until the species reaches its evolutionary optimum.

Simulating this process, GA methods also use nomenclature from natural genetics to define its component parts and operations [8-12]. The GA searches the problem solution space by using strings to represent the parameters to be optimised. These strings are called *chromosomes* and their individual integer components are called *genes* (each having an integer value range from 0 to 9 in the current work [8]). A number of these chromosomes can be initially generated at random. This is called the *population* and the number of chromosomes is the *population size*. This initial population is the first in the *generation* and may be evaluated by the following steps (see Fig.6) [8,12].

Firstly, the individual chromosomes are decoded from their integer representation into the form used in the optimisation problem (usually real numbers). The decoded parameters are then applied to the optimisation problem (usually in time domain simulation) to obtain a measure of how close the simulated responses are to the desired responses. In this GA application the evaluation is achieved by using a *cost function* [8] which is minimised in order to obtain optimum results. The cost function is defined by the difference between the desired and actual responses obtained from the evaluations and the GA looks for an optimum with a low cost (low cost meaning that the actual response is close to the desired).

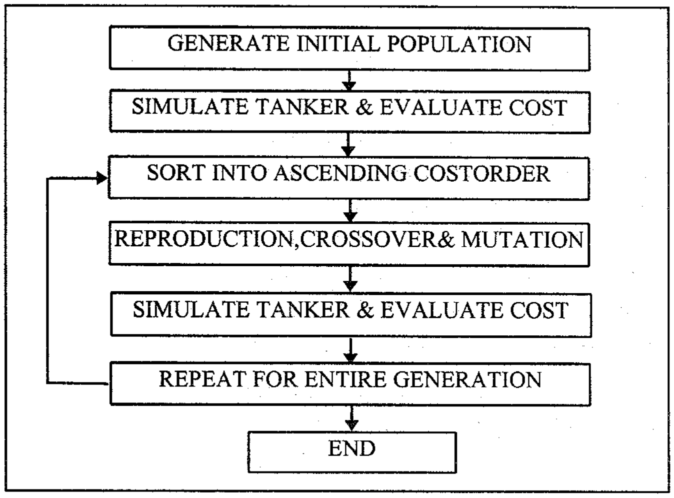

Fig.6: GA Flow Diagram

At this stage in the GA new chromosome solutions are created by the operations of *Reproduction*, *Crossover* and *Mutation* [8-14] which change the parameter values and allow the GA to search in different areas of the search space. This is achieved in the following ways.

*Reproduction* involves a process in which the fittest chromosomes of the present population 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. Since this reproduction is rank based it is generally called *elitist selection* and the corresponding algorithm is called an *elite GA* [14].

*Crossover* takes any two chromosomes from the present generation (these are called the *parents*), selects a number of the parents genes of one and swaps them with the same number and positioned genes in the other. This process forms two new chromosomes, called the *children*. This is repeated until there are enough children to replace the remainder of the present population that were not selected for reproduction .

*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. randomly change the values in the range between 0 and 9).

After the chromosomes are altered to form the new population, they are incorporated into the optimisation process and evaluated in the same way as the initial population. The whole GA process is then repeated a set number of times so that more points within the problem search space can be evaluated. This number of iterations is called the *generation size* and when it is reached, the GA has reached the optimum. Past experience has shown that this optimum is usually very close to the global optimum of the problem. This suggests that this is an appropriate search method to use on this problem.

### A. GA Optimisation

In this investigation the elite GA [14] used selects the top 20% of the population [8-14]. In order for this type of GA to avoid getting stuck in local minima its mutation rate is set at 5%. Elite GAs are used because of their speed of convergence [14] which is very important in this application since the execution time of the tanker system simulation is large (typically 26 seconds using a 166MHz Pentium PC).

Table 1: Parameters to be optimised

| Heading Controller Parameters | |
|---|---|
| 1st Heading Closed loop pole | $p_{H1}$ |
| 2nd Heading Closed loop pole | $p_{H2}$ |
| Heading switching gain | $\eta_H$ |
| Heading Boundary Layer Thickness | $\phi_H$ |

The key controller parameters that the GA tunes in this study are shown in Table 1 [8]. Parameters $p_{H1}$ and $p_{H2}$ are two poles of the desired closed loop heading system which has another pole at the origin [4,8]. The other two parameters are described above. In applying this optimisation technique all the values of these parameters are manipulated by the GA and a measure of the cost is calculated using the simulation results obtained from the complete tanker system [8-14]. The GA only accepts parameter solutions which yield smaller cost values. Therefore it is trying to minimise the cost to obtain an optimal solution [8,12].

### B. Cost Function

The cost function used here is a discrete version of the integral least squares criterion [6,8] i.e.

$$C_{PER} = \sum_{i=0}^{m} \left[ \lambda(\Delta\psi_i)^2 + (\delta r_i)^2 \right] \tag{7}$$

Here $m$ is the total number of iterations, $\lambda$ is a weighting factor ( $\lambda = 10$ in this case), $\Delta\psi_i$ is the $i$th heading angle error between the desired and obtained heading, $\delta r_i$ is the $i$th rudder deflection [6,8]. The weighting factor is needed in this application because the rudder deflection is so large that it would overshadow any improvements in the heading error. This is not a problem with smaller vessels since they respond more readily to small rudder deflections. Since the GA is trying to minimise the value of this function it is easy to see that both $\Delta\psi$ and $\delta r$ will be minimised too. The reasoning behind this selection of elements for the cost function is as follows. The quantity $\Delta\psi$ gives an indication of how close the actual heading is to the desired heading, therefore showing how well the controller is operating. The component $\delta r$ is used to keep rudder actuator movement to a minimum so that it can operate well within the actuator's operating limits. This 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 [4,8]. Another advantage of minimising the rudder deflection is the savings in terms of fuel consumption since the resistance to the forward motion is minimised [6]. Since the deflection is minimised, the rudder/hull produces less drag and hence more of the forward force goes to producing a larger surge velocity. This cost is used as the measure for the GA to optimise the tanker course changing control system.

## V. RESULTS

The following typical parameter values (see Table 2) are obtained for a GA of generation size of 100.

Table 2: GA Optimised Heading Controller Parameters

| Heading Controller Parameters | |
|---|---|
| 1st Heading Closed loop pole | -0.1000 |
| 2nd Heading Closed loop pole | -0.2457 |
| Heading switching gain | 8.7790 |
| Heading Boundary Layer Thickness | 9.2560 |

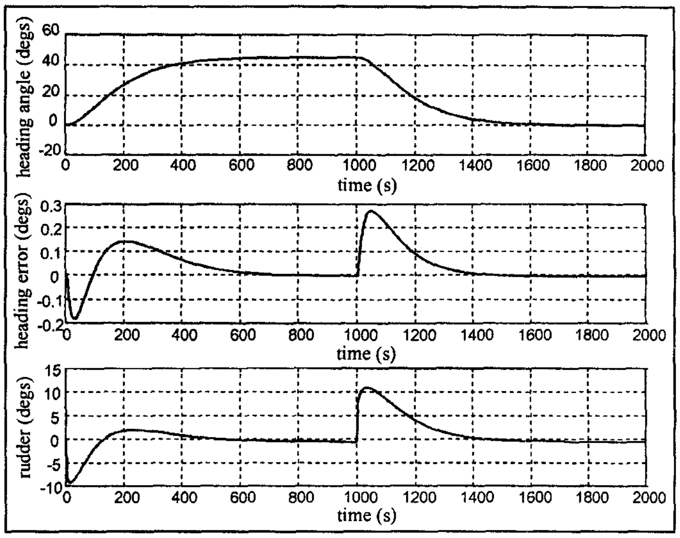

Fig.7: GA Optimised Responses

These parameters give the responses shown in Fig.7. They have been optimised successfully in that the tanker system follows the desired response shown in Fig.3 while keeping the rudder deflections well within the actuator's operational envelope. The heading error is very small thus showing that the tracking is particularly good. However, it should be noted that the peak heading error for the turn in shallow water is slightly larger than the peak in deeper water. Although there is this marginal difference, the rudder deflection is not very much larger thus indicating that the controller has handled the depth change well. Since this control system has managed to manoeuvre the tanker in the desired manner with relatively small rudder movement, it is logical to say that this is an optimal solution. Therefore the GA has managed to obtain a solution which is very close to the global optimum of the problem space defined by the optimisation criterion.

In order to verify this further, the cost value of this solution (19845) has been compared with cost values obtained from manually tuned solutions for this problem (19850). The GA cost is found to be marginally smaller and therefore very slightly more optimal. However, this optimisation method obtained these solutions with no a-priori knowledge of the optimal region and in a much shorter time.

These results show that optimisation by the GA approach provides a solution which satisfies the course tracking properties required for this control system application. Therefore, this system will automatically change the course of the tanker in response to the commands from the helmsman/pilot.

## VI. CONCLUSIONS

An application of a genetic algorithm to the optimisation of a course changing control system for an oil tanker has been described in this paper. It has been shown that for course changing manoeuvres a sliding mode controller can track a given desired response very well. This is of particular importance when the vessel's environment changes, as in this case. Also GAs have been shown to optimise the performance of simulated control systems so that the rudder motion is well within the limits of this actuator. This indicates that an optimised automatic controller of this type could improve the navigational performance of super tankers and even reduce the number of future accidents involving such vessels.

## ACKNOWLEDGEMENTS

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