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Application Of Fuzzy-Logic In Ship Manoeuvring In Confined Waters

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ARTICLE INFO	ABSTRACT
	A ship manoeuvring problem is solved using an algorithm built on fuzzy logic. The manoeuvring model for a design ship is coded in C++ and the results are presented here. A bulk carrier is assumed as design ship for a newly setting up harbor along the east coast of India. The harbor mouth is 25 km away from the deep water zone. The approach channel is straight along the 22 km length. Laterally restricted and shallow waters are considered and their influences on hydrodynamic derivatives are discussed. Some sample problems are solved. Trajectories, ship heading, rudder angle, velocities and accelerations, of the moving vessel, are calculated and presented for clarity. The developed code is robust in the sense that any designer or user can easily interact with various input parameters to verify the outputs and their suitability for the design ship meant for a particular water front location. The results are validated using another algorithm built on PID which is discussed in brief.

1. Introduction

Along the east coast of India a few marine infrastructure related projects are coming up at present and they are in various stages of completion. New ports and harbours, container terminal etc. are badly needed for the infrastructure starved country for its economic growth. Detailed study on environmental effects and bathymetry surveys is needed to locate a port facility preferably not very far from the deep sea. Internet is become a blessing for fast downloading of maps and topography of any geographical locations. Availability of numerical models save plenty of time for designers to fix the basic parameters and the design ship-waterway compatibility is assured by such numerical models. This paper deals with a ship manoeuvring model in C++ environment which is easy to handle.

Ship manoeuvring deals with the motion of the ship controlled by the ship's operator by activating control surfaces. The helmsman takes measures to reduce the deviation of the actual path of the ship from the required one. In the open sea, the ship's captain has plenty of time and space to monitor and control the direction and speed of the ship. There are control loops for both path or direction and speed. But in restricted waters like approach channels and canals, decisions must be made fast to maintain the clearances within the tolerance from stationary or moving bodies around. The master needs to take steps for collision avoidance ensuring safety. Such a requirement

necessitates automation and integration of both the control loops. Path keeping, path changing and speed changing is achieved using the above mentioned control loops.

2. Problem Definition

During the design stage, the Naval Architect or the designer can influence the response of the ship with the rudder deflection. The design is done based on deep water performance of the vessel. The hydrodynamic derivatives of the vessel are calculated (Lewis, 1989) and controllability parameters are established. The principal particulars of the vessel and sectional details are relied upon to get such hydrodynamic derivatives. Models are available for both linear and non-linear manoeuvring [1] of surface ships. Similar governing equations were incorporated in the paper on steering characteristics of ships in calm water and waves [2]. Maneuvering criteria of hull using linear theory and correction scheme for the shallow waters were also proposed[3]. Calculation method of ship manoeuvring characteristics at the design stage[4] is also found relevant. A more powerful resource is on models of marine vehicle kinematics and dynamics in 6 degrees of freedom [5]. Mathematical models [6] can be relied upon to solve ship motion and manoeuvring problems to get faster results. Added mass of the moving body in confined waters is an essential component in the governing equations and a procedure is available for computing reasonably accurate values [7].

The application of fuzzy logic, on ship motion and manoeuvring, already becomes an accepted practice among the researchers. Fuzzy logic controller to govern the motions of fins in order to reduce the roll motions of ships was proposed [8] in the past. Comparisons of algorithm on ship manoeuvring and harbor entry were successfully shown [9] for a standard ship of academic interest [5] .A handbook of marine craft and hydrodynamics and motion control, which deal with hydrodynamics modeling and control system [10] is an authentic resource for designers and analysts. An optimized path is preferred to in the approach channel leading to a new port and harbor project [11]. Different international standard and recommendations (Thoresen, 2003) for various design and construction is guidelines towards the minimum clearances around the moving hulls in approach channels.

For a newly planned port and harbor, the length of approach channel, its orientation and other parameters are based on a detailed bathymetry survey for a single design ship or more occupying the berths in the harbor at any point of time [12]. The infrastructure is developed for biggest size vessel. Stopping distance has a bearing on the harbor dimensions, since the ship enters at a low

speed and takes a turn nearing its berth [13]. Two loading conditions of the vessel are to be considered. One is for fully loaded arrival or departure and the other for ballast condition. The harbor entrance width is also optimized to minimize the environmental effects inside the harbor. But that requires additional attention and effort of the captain to take the ship through the harbor mouth amidst the possible cross flow of environmental disturbance, especially during monsoon. A breakwater sometimes serves as a multi-purpose platform. Concrete structures like breakwaters extend their foundation into the harbor space thus creating more confinement. As per the continuity equation of fluid dynamics, the reduced area creates more velocity of the particles for the same discharge or mass flow. Analyst of ship manoeuvring should take into account the space reduction due to various protrusions of foundations of marine structures and structure like pillars, plies etc.

2.1 Design Ship and Approach Channel

A hypothetical harbor is considered here with an approach channel, a length of 22 km and remaining length start from a curvature along the approach channel and ends up in the harbor entrance. It is presumed that some bathymetry study done by a responsible agency, is available for the project. The design vessel dimensions are given in Table 1.

Table 1. Design ship dimensions

Type of vessel	LOA(m)	LBP(m)	Beam(m)	Draft(m)
Bulk Carrier (Coal/Iron Ore)	250	240	43.4	15.0

In this particular case, the approach channel is given as 25 km away from the harbour entry. A cross section of the approach channel is shown in Figure 1 which shows a single lane channel.

After fixing a water depth with sufficient under keel clearance, lateral clearance for the length of the approach channel, a study on various operating conditions of the vessel is taken up. For the approach channel the clearance in the bottom is 20% of the fully loaded draft and that of the inside harbor is 10%. Figures 1 and 2 can be taken as based on a thumb rule for dimensions of the design ship and the approach channel. The width across the curved path is increased by 20% of the normal width of the channel. Normal width of the channel is expressed as a function of the breadth of the vessel. In the above discussions, the requirement of dredging and minimizing the same is very important since the expense of dredging consumes the maximum amount of a new project. The project is planned resulting in least dredging and the expense on the annual maintenance dredging is also is to be minimized. Please also note that transportation and dumping of dredged material is another liability. Minimizing

the use of cutter suction dredger in rocky areas should be born in mind. Use of cutter suction dredger in rocky area is very expensive compared to soft sand cutting. Figure 1 shows the available water depth in un-dredged condition. It also shows how much is intended to be dredged. The dredged slopes are 1/3 – 1/5 and it is decided by the angle of repose of that particular soil to ensure stability of the trench. Under keel clearance is to be ensured and it is to be subjected to the maximum value of the squat. The dredging tolerance is not shown, but a suitable value is to be provided there too. Tide levels are shown in Figure 1 and siltation buffer, allowance for survey inaccuracy etc. are avoided to make the figure look simple and clear.

Along the radius, the width is to be increased as per PI-ANC (Permanent International Association of Navigation Congress) or similar codes. The outer, mean curvature line and inner radius are to be provided and they are given as R1, R2 and R3 respectively. Relevant radii are shown in Figure 2. Actual figures can be arrived at based on standard manuals of PIANC, US Navy publication, BS Codes (Code 6349-4, 1994), Indian standards etc. The width is increased as per a suitable slope along the stretch of the length. The additional width is 40 meters at the middle of the curvature or turn and this higher width is as per norms of international bodies.
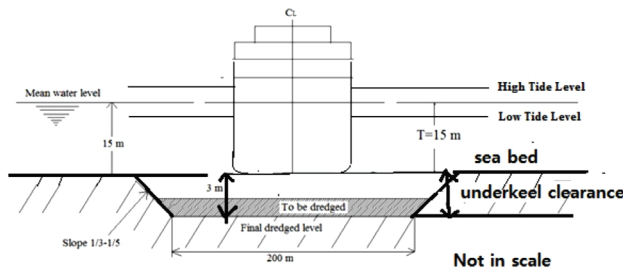

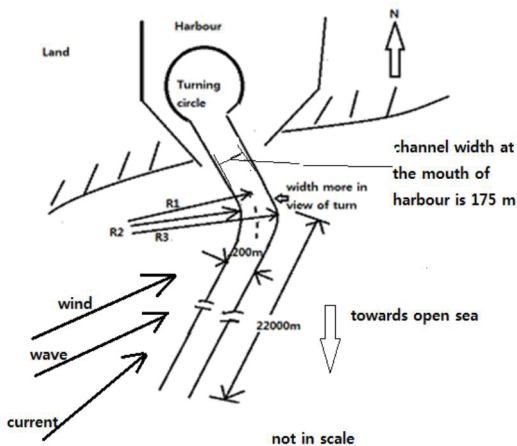**Figure 1.** One lane channel as per IS - 4651 part (v)

Figure 2. Port layout showing curvature and its wider part

The vessel response, if any, to a disturbance in a low speed entry in the approach channel is to be investigated. There are many critical situations in a wavy and windy environmental condition. At the entry point of the harbour, where the width is just 175 m. The ship can sway or yaw or move in a combined mode during cross flows in monsoons and rough weather. In many Indian harbours the entrance width becomes critical during rough seasons. Port of Mangalore and Kandla are examples. The surge, sway and yaw motions are determined using a manoeuvring model developed in connection with this work. The latter two are interlinked or coupled.

3. Manoeuvring Model

Two different axes are required to completely specify the motion of a ship. The position of the centre of gravity of the ship is determined in reference to an earth fixed co-ordinate system. The other is the body fixed axis which is fixed on the ship. The x-direction of the body fixed system coincides with the centerline of the vessel and is positive forward. The y-axis runs across the ship in the transverse direction. The z-axis is directed vertically downwards. The angle made by the earth made by the body fixed x-axis with the earth fixed x- axis is called the yaw angle. The resultant velocity vector could make an angle with the body fixed angle and is called drift angle which is non-zero normally. Figure 3 shows the details.
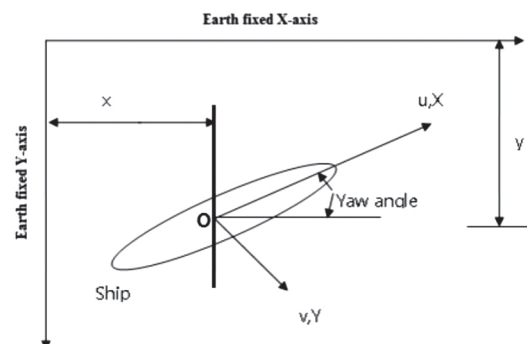

Figure 3. Earth fixed axis and body fixed axis system coordinates

As per Figure 3 the forces and moments based on the global earth fixed axes system can be written for the surface ship as follows.

$$X_0 = m\ddot{x}_0 \tag{1a}$$
$$Y_0 = m(\ddot{y}_0) \tag{1b}$$
$$N = I_z\ddot{\psi} \tag{1c}$$

The above equation follows the Newton's law stating that force is equal to the product of mass and acceleration. The subscript 'o' indicates that the values are with respect to the global earth fixed axis. However, the equations are more conveniently expressed when written with respect to

the body fixed axis as follows.

$$X = X_0 \cos\Psi + Y_0 \sin\Psi \tag{2a}$$

$$Y = Y_0 \cos\psi + X_0 \sin\psi \tag{2b}$$

Similarly the velocity components can be written as

$$(\dot{x}_0) = u\cos\psi - v\sin\psi \tag{3a}$$

$$(\dot{y}_0) = u\sin\psi + v\cos\psi \tag{3b}$$

The acceleration terms can be written by differentiating the above equations.

$$(\ddot{x}_0) = \dot{u}\cos\psi - \dot{v}\sin\psi - (u\sin\psi + v\cos\psi)\,\dot{\psi} \tag{4a}$$

$$(\ddot{y}_0) = \dot{u}\cos\psi + \dot{v}\cos\psi + (u\cos\psi - v\sin\psi)\,\dot{\psi} \tag{4b}$$

Substituting Eq. (4) in Eq. (1) the governing equations of motions for horizontal plane can be achieved.

$$X = m(\dot{u} - v\psi) \tag{5a}$$

$$Y = m(\dot{v} - u\psi) \tag{5b}$$

$$N = I_z\,\ddot{\psi} \tag{5c}$$

While deriving the above equations it is assumed that origin O of the body fixed coordinate system is at the centre of gravity G of the vessel. Simplifications are possible if the origin O were chosen at the axis of symmetry. If the newly chosen O is now located at a vector R_G from G, then the above equations become as shown below.

$$X = m(\dot{u} - \dot{\psi}\,v - y_G\,\ddot{\psi} - x_G\,\dot{\psi}^2) \tag{6a}$$

$$Y = m(\dot{u} - \dot{\psi}\,v - y_G\,\ddot{\psi} - x_G\,\dot{\psi}^2) \tag{6b}$$

$$N = I_z\,\ddot{\psi} + m\{x_G\,(\dot{v} + u\dot{\psi})\} \tag{6c}$$

If the ship is symmetric with respect to the centerline y_G can be neglected, ie. when y_G is equal to zero the above equations become as follows.

$$X = m(\dot{u} - \dot{\psi}v - x_G\dot{\psi}^2) \tag{7a}$$

$$Y = m(\dot{v} + u\Psi + x_G\Psi^2) \tag{7b}$$

$$N = I_z\ddot{\psi} + mx_G(\dot{v} + u\dot{\psi}) \tag{7c}$$

The Eq. (7) show coupling between surge and sway velocities and yaw rate. These equations lead to a simpler set of equations for linear case as follows.

$$X = m\dot{u} \tag{8a}$$

$$Y = m(\dot{v} + u\dot{\psi} + x_G\ddot{\psi}) \tag{8b}$$

$$N = I_z\ddot{\psi} + mx_G(\dot{v} + u\dot{\psi}) \tag{8c}$$

Eq. (8 a) is called the linear speed equation and Eq. (8 b) and (8 c) are called the steering equations. Eq. (8 a) is independent and the other two are mutually coupled. A good numerical approach is sufficient for the solution of these equations. It can be assumed that X, Y and N are functions of various velocities and accelerations in connection with the motion of the hull. Therefore, X, Y and N can be written as follows.

$$X = F_x(u, v, r, \dot{u}, \dot{v}, \dot{r}) \tag{9a}$$

$$Y = F_y(u, v, r, \dot{u}, \dot{v}, \dot{r}) \tag{9b}$$

$$N = F_\psi(u, v, r, \dot{u}, \dot{v}, \dot{r}) \tag{9c}$$

Assuming an equilibrium condition and applying Taylor's series expansion the non-dimensional form of the steering equations as per the practices in maneuvering studies is reduced to the following equations.

$$-Y_v'\,v' + (m' - Y_{\dot{v}}')\dot{v}' - (Y_r' - m'x_G)\dot{r}' = Y_\delta'\,\delta \tag{10a}$$

$$-N_v'\,v' + (N_{\dot{v}}' - m'x_G')\dot{v}' - (N_r' - m'x_G')r'$$
$$-(I_z - N_{\dot{r}}')\dot{r}' = N_\delta'\,\delta \tag{10b}$$

In the above Eq. (10) there are two new terms. The non-dimensional force from the $Y'_\delta\delta$ and $N'_\delta\delta$, the non-dimensional force and moment due to the rudder action. Representation of non-dimensional forces and moments are as per the standard book of Naval Architecture (Lewis, 1989). Eq. (10) are highly relied upon to manipulate heading and transverse position mainly using rudder and other control surfaces if applicable. All the notations and terms non-dimensionalised wherever necessary are as per (Lewis, 1989) Section 3 with title 'Motion stability and Linear equations', in Vol. III.

In non-linear theory Eq. (9) are modified as follows

$$X = X(\Delta u, v, r, \dot{u}, \dot{v}, \dot{r}, \delta) \tag{11a}$$

$$Y = Y(\Delta u, v, r, \dot{u}, \dot{v}, \dot{r}, \delta) \tag{11b}$$

$$N = N(\Delta u, v, r, \dot{u}, \dot{v}, \dot{r}, \delta) \tag{11c}$$

where $\Delta u = u - u_1$

3.1 Problems in Restricted and Laterally Confined Waters

Ship squat in open, depth restricted and confined waters has been discussed [14]. There will be loss or propeller rpm and speed. The sluggish behavior of ship in confined waters is to be considered while designing approach channels. If the bottom is rocky more clearances are to be provided. As already mentioned, additional expense will be incurred in dredging a rocky sea bottom for more depth. Squat is dependent on the block coefficient and speed of the moving vessel. A variable known as blockage factor also influences the squat value. Rough estimates of stopping time and stopping distance can also be calculated using empirical formulas.

It is a well known fact that wherever there is a finite water depth, the manoeuvring model is to be altered. The hydrodynamic derivatives for deep waters are to be corrected in the maneuvering equations already mentioned [15]. The following are the correction factors.

$$\frac{Y_{\dot{v}}'}{Y_{\dot{v}_\alpha}'} = K_0 + \frac{2}{3}K_1\frac{B}{T} + \frac{8}{15}K_2\left(\frac{B}{T}\right)^2 \tag{12}$$

Where B and T are the breadth and draft of the vessel.

$$\frac{N_{\dot{r}}'}{N_{\dot{r}_\alpha}'} = K_0 + \frac{2}{5}K_1\frac{B}{T} + \frac{24}{105}K_2\left(\frac{B}{T}\right)^2 \tag{13}$$

$$\frac{Y_v'}{Y_{v_\alpha}'} = K_0 + K_1\frac{B}{T} + K_2\left(\frac{B}{T}\right)^2 \tag{14}$$

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$$\frac{Y_r{}'}{Y_{r_\alpha}} = K_0 + \frac{2}{3}K_1\frac{B}{T} + \frac{8}{15}K_2\left(\frac{B}{T}\right)^2 \tag{15}$$

$$\frac{N_v{}'}{N_{v\alpha}} = K_0 + \frac{2}{3}K_1\frac{B}{T} + \frac{8}{15}K_2\left(\frac{B}{T}\right)^2 \tag{16}$$

$$\frac{N_r{}'}{N_{r\alpha}} = K_0 + \frac{1}{2}K_1\frac{B}{T} + \frac{1}{3}K_2\left(\frac{B}{T}\right)^2 \tag{17}$$

where

$$K_0 = 1 + \frac{0.0775}{F^2} - \frac{0.0110}{F^3} \tag{18}$$

$$K_1 = -\frac{0.0643}{F} + \frac{0.0775}{F^2} - \frac{0.0110}{F^3} \tag{19}$$

$$K_2 = \frac{0.0342}{F} \tag{20}$$

and

$$F = \left(\frac{H}{T}\right) - 1 \tag{21}$$

where, H is the depth of water, T is the ship draft and B is the breadth of the ship.

In equations (12)-(21) the numerator is the non-dimensional hydrodynamic derivative for shallow water and denominator is that for deep water depth. It is found that all the values are not very useful for various restrictions of water around the hull. There is scope to improve the values of the shallow water hydrodynamic derivatives discussed already.

3.2 Control System Onboard

The rudder, other control surfaces and devices like bow thrusters are important features in achieving controllability goals. The rudder action is the most important component in achieving desired course either by changing or keeping the rudder at a deflected condition. Figure 4 shows the components of a control system.
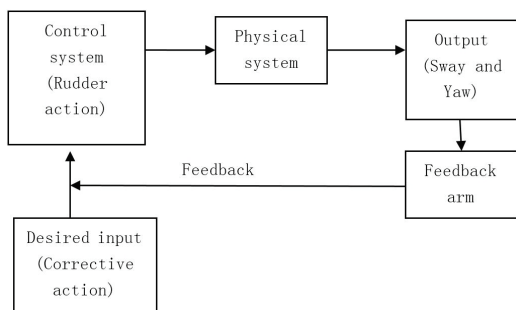
Figure 4. Components of control system

The rudder position in fact becomes the input and its turning rate can be improved by using high power hydraulic pump in the steering gear system. Basic difference be-

tween a massive rudder and a fin is that the inertia for the former is very large and that of the fins are usually small. Large power rating is required for ship rudders.

In electro-hydraulic systems used to control actuators, two factors are to be addressed separately. They are the sensitivity of the system and economy in operating the vessel. The former refers to modulation of the system. That is for a small deviation of heading from the steady state the opposing force and moment by at the turn of rudder should be of suitable magnitude. That means it should not be very high all of a sudden. If it is very high, the ship also will react unusually with a zero phase lag. In such a voyage the distance travelled will be more for a movement from port A to port B. It will tax unduly on the machinery causing more wear and tear with more consumption of lubricants and oils. Moreover, repeated and expeditious action by the crew is likely to lead to errors due to fatigue. Hence, a suitable controller like fuzzy logic can be recommended.

4. Application of Fuzzy Logic

After introduction[16] fuzzy logic has been widely used for many industrial applications. The Japanese used fuzzy logic extensively in many domestic and later in industrial products. A fuzzy- logic controller associates various sets of input data into a system with the desired control actions. Crisp or quantitative input data is converted into appropriate fuzzy or qualitative data. These are processed logically so as to produce a desired output. This output is to be brought back to a crisp form again. It is done by a de-fuzzification technique. Logical processes are simulated by rules, which associate different input data with a desired output. 'If – then' rules are applied for a sample case as follows.

a) If the heading is low and positive

b) If the shift in position is small and positive

-then the rudder angle is small and negative

The rate of position change and heading change can also be included in the conditions. All can be suitably clubbed to form decision tables. There are standard literature is available on this topic. The implementation of fuzzy logic was introduced decades ago in robots, machineries etc.

Low, medium, high etc. are converted into numerical values. Quantitative, numerical or crisp data is converted into qualitative, logical or fuzzy data. The standard practice to fuzzify input or output is to define membership functions. Membership functions associates the degree of belonging to any crisp value of some variable. Position error is shown in Figure 5 with membership functions. Membership functions are scaled from 0 to 1.0. Low value is 30 m from the reference line. Medium is 60 m and high

is 90 meters from the reference line respectively. For high with a membership value of 1.0 refers to 90 m or more than that. With a membership value of 0.5 high position error is 75 m as per the relevant figure.

Similarly the membership values are plotted for rate of position error, heading error and rate of heading error in Figure 6, Figure 7 and Figure 8 respectively.

The required rudder angle is determined using fuzzy logic for a set of position error, rate of position error, heading error and rate of heading error. This rudder angle is fed into the governing equations. The outputs obtained are heading, positions and associated velocities and accelerations.
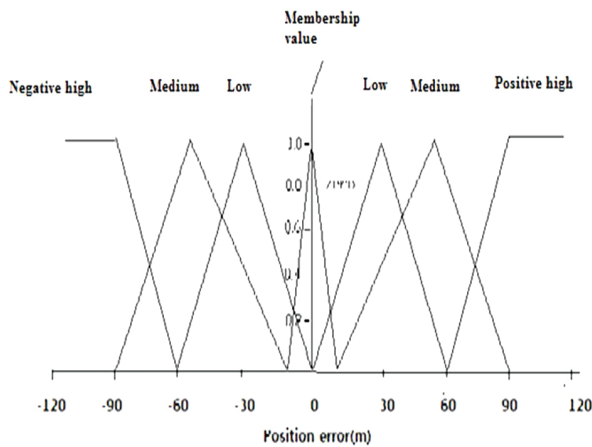
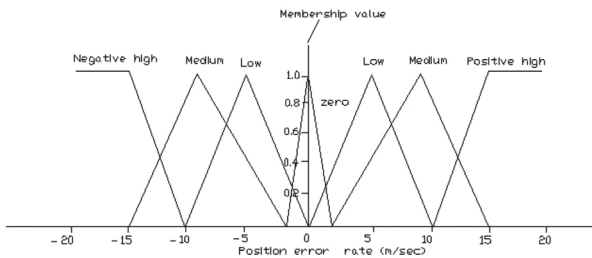**Figure 5.** Membership function of position error

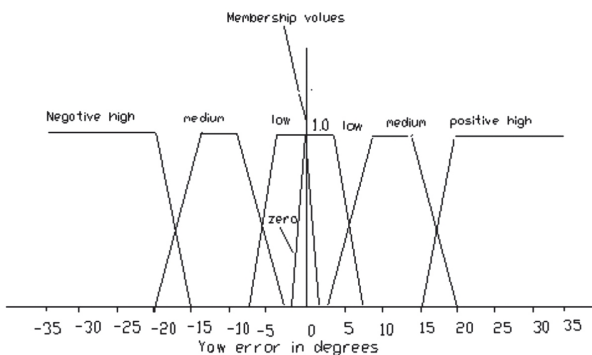**Figure 6.** Membership function of position error rate

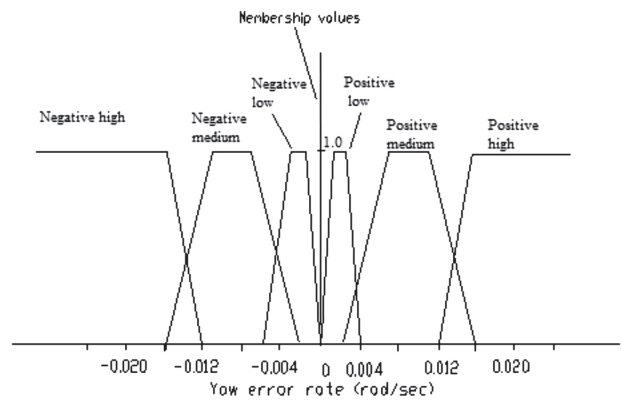**Figure 7.** Membership value of heading angle error

Figure 8. Membership function values of error rate of heading angle

4.1 De-fuzzification

For de-fuzzification, there are six most often used approaches [17] as follows.

1) The centre-of-area method which is also called the centre of gravity method.
2) Centre-of-sums de-fuzzification
3) Centre of largest area de-fuzzification
4) First of maxima de-fuzzification
5) Middle of Maxima de-fuzzification
6) Height de-fuzzification

Among these the first one is the best well-known de-fuzzification method and more accurate since it covers all the events in the fuzzy sets of membership functions. Here the angle of deflection of the rudder angle is to be determined from a membership sets plotted against the domain. The domain range is maximum and minimum rudder angle. Similarly heading angles can also be chosen from another sets of membership functions. The linguistic variables are converted into crisp values. It is to be noted that the inputs and outputs are passed through a transfer function like box, which governed all the manoeuvring theory. The membership functions of rudder angle and vessel heading are similar to the membership functions are

A linguistic variable is defined by

$$(U, £U, u, M_u) \tag{22}$$

Here U denote the symbolic name of a linguistic variable. £U is the set of linguistic values that U can take on. A linguistic value denotes a symbol for a particular property of U. Arbitrary element of £U is denoted by LU. u is the actual physical domain over which the linguistic values are meaningful. Mu is a semantic function which leads to an interpretation of a linguistic value in terms of quantitative elements of u.

It is possible to write $M_u : LU \rightarrow \overline{LU}$, where $\overline{LU}$ is a

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denotation for a fuzzy set or membership function defined over u.

That is $\bar{L}\bar{U} = \sum \mu LU(u)/u$ in the case of discrete u. (23)

And $\bar{L}\bar{U} = \int_u \mu LU(u)/u$ in the case of continuous u. (24)

M_u is a function which takes a symbol as its argument and returns the strength of this symbol in terms of a fuzzy set. The centre of gravity is method is applied here as it is powerful and gives reasonable results for a problem like this.

Now the fuzzy set of a number of rules can be defined in the 'if-then' form. Here it is possible to concentrate on the heading angle and rudder angles. 49 sets of rules for are formulated in each case. Two tables of 7*7sets of membership values and plots against the respective domains are prepared. The table dimensions depend on the number of rules used. The advantage of fuzzy rule is that there is flexibility in using the number of rules and there is an optimum level for the same. The shape of membership functions are as shown for position and heading. For linear case it is of the shape of triangle and trapezium. For the inputs considered in this problem both were used and there was no appreciable result found for change in the shape membership function from all triangle to all trapeziums or vice-versa or even combination of both. Easiness in mathematical representation in the code is another factor to choose the shapes of membership function. The de-fuzzification part was incorporated in the C++ code and the output us directed into a Matlab code for plotting. The code in C++ is run for stretch of 6km length to cover the entire approach channel. The code can be used for any reasonable lengths of channel. Therefore, after making and running the code, still modifications are easily possible for the channel parameters. Fully loaded cases are discussed. In the ballast condition wind load may be higher, but it is of lesser important in other aspects.

4.1.1 Control Algorithm Based on PID in Brief

PID control defines the relationship between the input and the output variable as follows.

$i = K_p(e) + K_d(\dot{e}) + K_i \int e(t)dt$ (25)

where, i is the input variable, Kp is the proportional constant P, Kd the derivative constant D, Ki the integral constant I, e the instantaneous error and the instantaneous time derivative of error. Here, the input is the rudder angle and the output is the yaw angle and position co-ordinates and the physical system is represented by the governing equations. Figure 4 illustrates the positions of the control boxes of the system. A code is developed separately for PID control system in C++ and the problems worked out using fuzzy logic is done using the PID control algorithm.

In all cases, the results are comparable and in the next part only typical results are compared and presented to optimize the space in this paper.

The control constants Kp, Kd and Ki have various effects on the system. Kp reduces the time taken to reach the desired output but results in overshoot. If Kp alone is used neglecting the other control constants, it cannot provide convergence due to the existence of a steady error. The integral constant, Ki, may be used to eliminate a steady error but it will result in an adverse transient response. Kd improves stability of the system, reduces overshoot and improves the transient response. In some cases all these control constants are needed for a successful design. There is scope for tuning of these constants so as to achieve a reasonable and comparable result of parameters of ship navigation. The control constants can also be represented as physical parameters like mass, natural frequency in particular mode, time period etc. of the ship[11]. Such approach will provide guidelines to choose proper initial values for trial and error exercise of tuning.

### 4.2 Results and Discussion

As already discussed, a global system of fixed co-ordinates system is usually assumed for simulations. A few cases of arrival and departure in the approach channel is considered. Initial conditions of the vessel, that is heading and shift of its CG from the centerline of the channel, and intended speed are given as input to the code before running. A few cases are worked out and displayed.

A 6km distance is considered for the simulation which take 1500 secs. Less than half the full speed of ship is considered. It is 8 knots and which is considered to be suitable for the approach channel, however, it may vary port to port. A co-ordinate system is assumed to be the x direction at the centre line of the ship. Perpendicular to this is taken as the lateral direction. The ship body force is countered by the external loads.

In Figure 9, the vessel is at the centre line of the path and is turned by 10 deg. to one side. It can be assumed as a result of the environmental disturbance. However, for various ships this turn in heading may vary due to their superstructure heights, forecastle shape etc

Next case of a fully loaded arrival is shown in Figure 10. The ship's initial heading is 5deg and CG is shifted by 20m from the centre line. The disturbance is bit stronger because of initial sway by 20m. The ship is under control within 1500 secs.
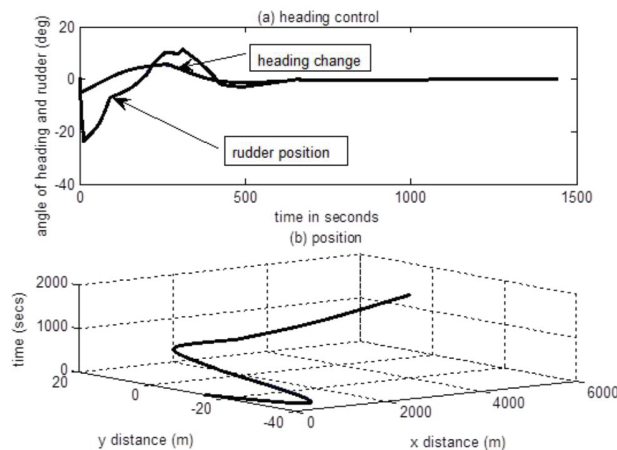
Another case is shown Figure 11 for an initial heading of -5 deg and shift of -15m, which is somewhat opposite to the previous case. The ship is seen to be under control in reasonable limits of time and space.
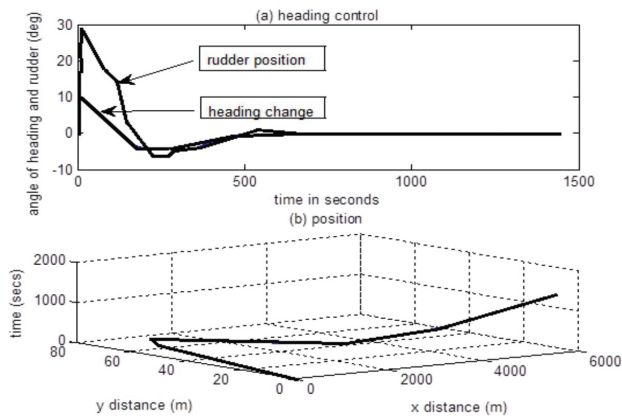
Figure 9. Fully loaded arrival, no shift from CL of path, but tilted 10 in heading
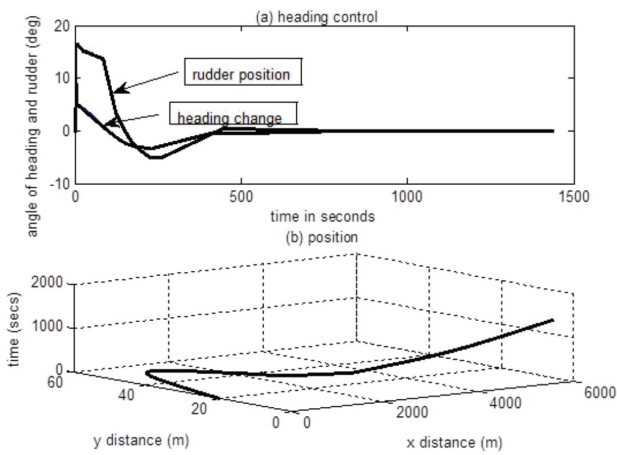
Figure 10. Fully loaded arrival with 20m shift of CG from the CL of path, heading 5 deg


Figure 11. Heading -5deg and shift from CL -15m, fully loaded arrival

A number of cases have been simulated using the code which mimics the presence of a captain onboard ship.

Ballast conditions are also simulated using the code de-

veloped. Heading angle is turned by -5 deg and the position is shifted by -20m. The vessel is brought into the desired path by activating the rudder within a desirable time and is shown in Figure 12. Another initial condition of heading change by 10 degree and the cg of the vessel is in the midline of the approach channel. In all these simulations, an analyst or designer should look at the clearances from the sides of 200m lane. The vessel clearance by from the outer limit of channel is determined from the ships frame superposed on its trajectory with the ship's centre line as a tangent at the point of interest. Thus, the tangent with the relevant heading angle will give the ship' actual positions with its frame superposed. The centre of gravity can be assumed point at which the tangent is made. The CG is plotted to avoid congestion of closely packed lines of the outer hull of hip. The timing is also a factor since controlling the vessel in shallow water is difficult. But the output of the code gives reasonable results. Sufficient lateral clearances from the outer border of approach channels are ensured in all cases. Any number of simulations can be repeated similarly.
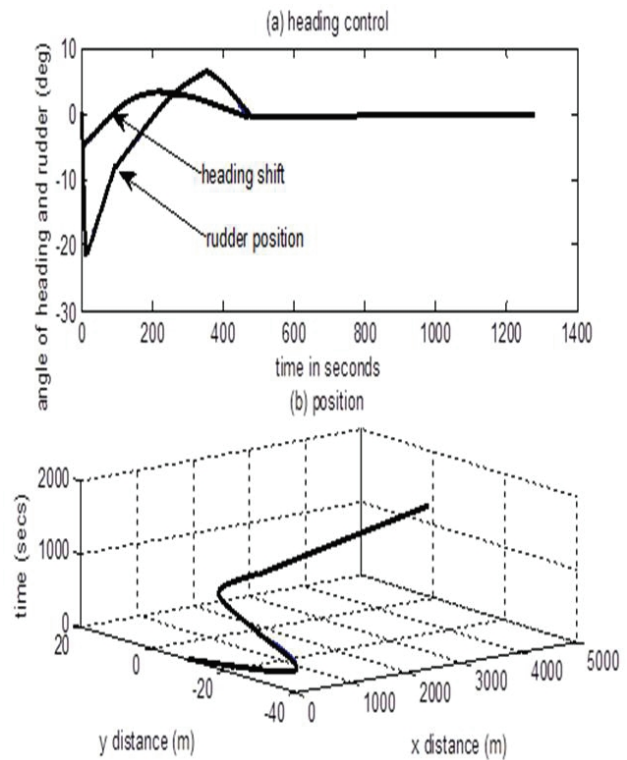
Figure 12. Ballast departure heading -5 deg and shift -20 m

The code is capable of giving velocities and accelerations. Such details are helpful to verify or to arrive at the hydrodynamic derivatives, which govern the trajectory of the ship. For a fully loaded arrival condition, the trajectory and heading angles have already been shown

in Figure 9. The same problem is worked out using PID algorithm of control. In PID maximum rudder angle is 25 degrees while that in fuzzy logic control it is nearly 30 degrees. PID is a well established procedure for control engineering of plants and in fuzzy logic the trajectory in y-direction is much more. It shows that there is scope for improving the method.
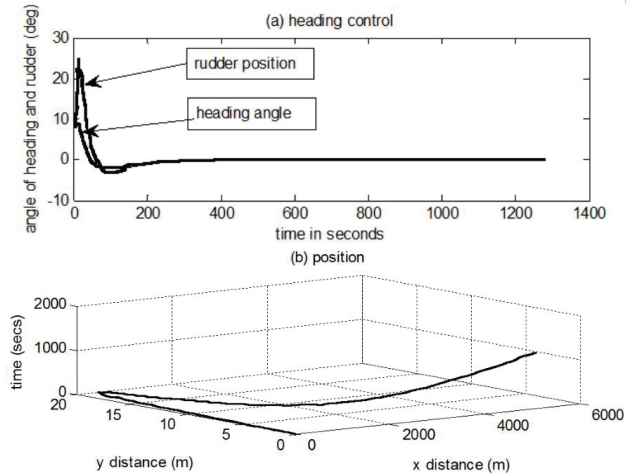

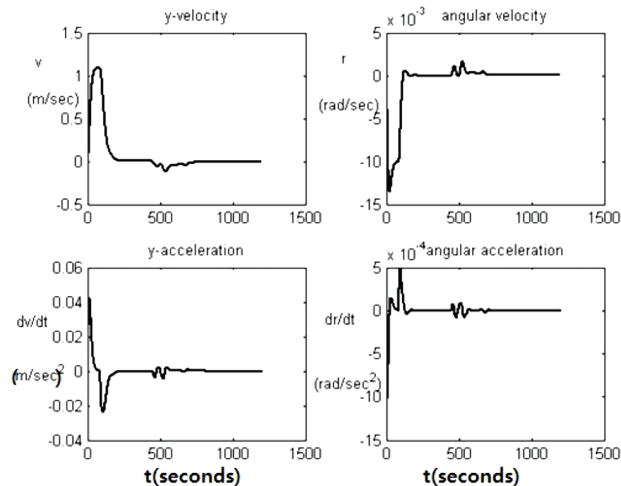**Figure 13.** Trajectory and heading under PID for comparison.

Figure 14. Ship velocities and accelerations using Fuzzy logic

Figure 14 is shown the kinematic details of the system for fully loaded arrival at 8 knots and the ship is controlled by fuzzy logic algorithm. The ship velocities and accelerations as PID system are shown in Figure 15. The velocities and accelerations are plotted after the rudder action as a result of ship's disturbance due to an external force. In fuzzy logic the lateral velocities are of more than 1.0m/sec and that of PID is 0.075m/sec. Though drastic variation is seen in transient condition but later both converge into negligible values. The initial condition of any dynamic system is unpredictable till it reaches a steady

state condition. It can be seen that the angular velocities and accuracies are also comparable for both approaches. The comparison shows that fuzzy logic can still be improved by admitting more membership functions and decision matrix in the code.
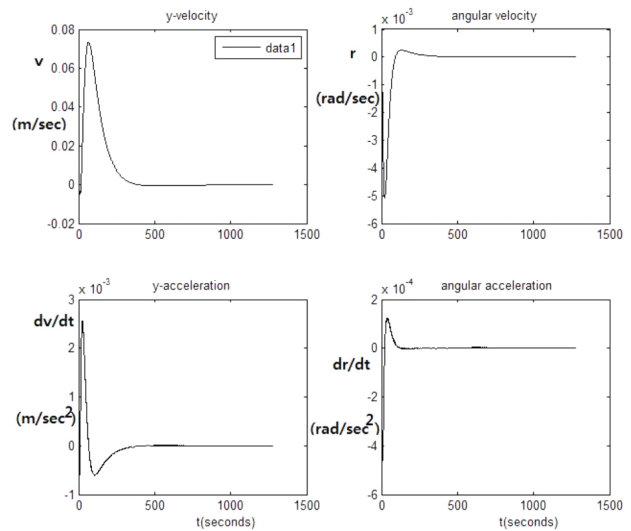

Figure 15. Ship velocities and accelerations using PID control

5. Conclusions

Initiation of setting up of a new port and harbor facility along the east coast of India is discussed for a design ship. Waterway is decided for a design ship and is based on the requirement of international bodies. A powerful algorithm based on fuzzy logic is discussed. Standard linear maneuvering equations are used in C++ code. The control system works on fuzzy logic. Shallow water and confined water effects are discussed. The most powerful de-fuzzification method is discussed and implemented.

First 22 km length of the approach channel, 4 to 6 km stretch till the entrance of harbour is analyzed using manoeuvring model. The trajectories of a fully loaded bulk carrier at 15m draft are demonstrated. The vessel trajectory in ballast condition also is demonstrated. The clearances, speed, accelerations are found to be reasonable. Such kinematic details are very much useful for analysts to arrive at added masses and other hydrodynamic derivatives. These are all very important for the designers to provide the strength of fenders, dolphins etc.

The manoeuvring clearances for single lane passage are found to be of reasonable values. The model has provisions to add on additional environmental effects. It is possible to find the trajectory in rough weather acting perpendicular to the ship while the ship is entering the main harbour mouth. There is provision for superposing the environmental forces.

A vital part of technology in the immediate future in

the automation of ship manoeuvring and control is demonstrated here with case studies.

The model is compared with the well established PID control system and is found that the trajectories, velocities and accelerations are comparable. There is room for improving the accuracy of model using fuzzy logic principle.

Fuzzy logic based model is a general one and versatile in the sense that it can be used for any other channel-ship combination with suitable changes in the hydrodynamic parameters of the ship considered.

Author contributions.

The work was done by single author and the topic was a continuos passion for the author.. Other unpublished part of the work is retained in view of optimization of space.

Conflict of interest.

There is no conflict of interest for this work.

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