Artificial Neural Network Based Automatic Ship Berthing Combining PD Controlled Side Thrusters

- A Combined Controller for Final approaching to Berth -

Yaseen Adnan AHMED and Kazuhiko HASEGAWA
Department of Naval Architecture & Ocean Engineering
Osaka University
Osaka, Japan
ahmed@naoe.eng.osaka-u.ac.jp, hase@naoe.eng.osaka-u.ac.jp

***Abstract*—Manoeuvring ship during berthing has always required vast experience, skill and knowledge to provide desired necessary actions. Presence of environmental disturbances as well as decreased manoeuvrability in low speed often makes the whole procedure so sophisticated that even slight mistake may results catastrophic disaster. By knowing the fact that Artificial Neural Network (ANN) has the ability to replicate human brains and good enough for controlling such multi-input multi-out nonlinear system, at the beginning of this research, consistent teaching data are created using Non Linear Programing (NPL) method and a new concept named 'virtual window' is introduced. Later on, considering gust wind disturbances, two separate multilayer feed forward networks are trained using back propagation technique for command rudder and propeller revolution output. After being successful in simulation works, real time berthing experiments are carried out for Esso Osaka 3-m model where the ship is planned to successfully stop within a distance of 1.5L from actual pier to ensure safety. Finally, as a current status, PD controlled side thrusters are included in order to shake hand with current controller to align the ship with pier considering wind up to 1.5 m/s for model ship.**

***Keywords*—ship berthing, artificial neural network, PD controller, nonlinear programming language, side thruster**

I. INTRODUCTION

Berthing requires precise and gentle control and such control is demonstrated everyday by ship handlers in ports all over the world. Although most of the time ships dock safety but the outcome of such sophisticated manoeuvring is not always successful especially in presence of environmental disturbances. Ships can and do run aground, demolish jetties, hit the berth and collide with other ships at an alarming frequency, giving rise to loss of life, environmental pollution and property damage. Therefore, bringing automation in ship berthing sector would be a great relief in terms of safety assessment. Researches on automatic berthing had been started long time ago where different controlling aspects like feedback control, fuzzy theory, optimal control theory, expert system etc. were tried to cope with such situation. But the success was not up to the expecting limit. Later on, first success came when ANN was proposed by Yamato et al. [1] for automatic ship berthing. The effectiveness of ANN as a controller was further confirmed by Fujii and Ura [2] by using both supervised and non-supervised learning system for AUVs. Since then Hasegawa and Kitera [3], Im and Hasegawa [4] [5] and many others have continued such research for berthing purpose. But very few of these researches have concentrated on including environmental disturbances like wind to judge the controller's robustness. Moreover, none of them define a proper rule to create more consistent teaching data for better learning by ANN. To take account such untreated parts, in this research the whole berthing plan is divided into three basic elementary manoeuvres. First is course changing and then it is followed by step deceleration and reversing to stop the ship at a safe distance form actual pier. Finally, tug or side thrusters will assist her to reach the pier by executing crabbing motion. For course changing, Mizuno's et al. [6] proposed minimum time ship manoeuvring method using non-linear programming is used for the first time and a new concept named 'virtual window' is introduced to ensure the consistency in teaching data by Ahmed and Hasegawa [7] as an initial stage of this research. Using this concept, as inspired by aircraft landing, ship will make course change first from any possible heading angle to merge with so called imaginary line which will act as a runway for the ship for further decent. Following the imaginary line, ship will drop propeller revolution according to speed response equation and stop at the end of it. Since, the barking force of a ship is usually small compared to its huge mass and the rudder is especially designed for full navigational speed which worsens manoeuvrability remarkably when speed is decreased, therefore, a more sophisticated PD controller is used in this research while step deceleration for treating wind disturbances. Such controller can correct not only ship's heading but also minimise the distance between ship's CG and imaginary line.

Combining the course changing and step deceleration followed by reversing part considering wind disturbances, a whole set of consistent teaching data is created and used for training two separate multi-layered feed forward neural networks for command rudder and propeller revolution output respectively. After successful training, several simulations are done by Ahmed and Hasegawa [7], which have confirmed the effectiveness of controllers in most extent considering wind up to 1.5 m/s for 3-m Esso Osaka model ship. Later on, such consistently trained networks are implemented for real time model ship berthing experiment using the virtual window concept. Some of such experiment results are also published by Ahmed and Hasegawa [8].

Finally, since the goal point for berthing is set at a distance of 1.5L from the actual pier as proposed by Kose and Hashizume [9], therefore the controllers stop the ship within the assumed successful zone around the set goal point. After stopping, since Esso Osaka is equipped with single propeller and singe rudder, therefore, for executing the crabbing motion to approach the berth, it often needs assistance from tugs. But, in presence of wind even using tugs, the pivot point successively changes depending on wind direction and water resistance which results difficulties in control. Therefore, as current status of this research two side and one longitudinal automated thruster are developed using sophisticated PD controllers and are programmed to shake hand with the existing controller to complete the whole berthing manoeuvre.

II. MATHEMATICAL MODEL FOR SUBJECT SHIP

A 3-m Esso Osaka model which is scaled as 1:108.33 is chosen as subject ship in this research. In order to describe its hydrodynamic behaviour in three degree of freedoms, a famous modified version of mathematical model based on MMG [10] is used. This MMG model can predict both forward and astern motion for any particular propeller revolution and rudder angle. The coordinate system used to formulate the equations of motions together with assumptions during berthing is given in the following figure.

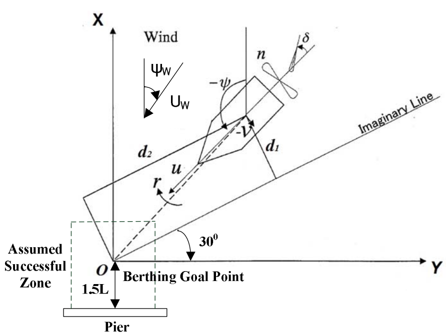

Figure 1. Coordinate system for berthing.

The equations of motion as well as measured hydrodynamic forces are considered at CG (centre of gravity) of the ship. To calculate the wind force and moment action on hull, Fujiwara wind model [11] is used. The corresponding equations of motions are expressed in the following form:

$$\begin{aligned}(m+m_x)\dot{u}-(m+m_y)vr &= X_H+X_P+X_R+X_W+X_{tug}\\(m+m_y)\dot{v}+(m+m_x)ur &= Y_H+Y_P+Y_R+Y_W+Y_{tug}\\(I_{ZZ}+J_{ZZ})\dot{r} &= N_H+N_P+N_R+N_W+N_{tug}\end{aligned} \tag{1}$$

where, m is the mass of ship, m_x and m_y are the added mass in x and y direction, I_{zz} is moment of inertia, J_{zz} is polar moment of inertia, u is surge velocity, v is sway velocity, r is yaw rate and the right side includes the hydrodynamic forces and moment term due to hull, propeller, rudder, wind disturbances and tug assistance respectively.

III. BERTHING PLAN TO ENSURE CONSISTENCY

Ship berthing manoeuvre is usually a combination of course keeping and course changing. Moreover, sequential speed drop is also one of the key factors in whole berthing process. Since, the success of ANN as a controller largely depends on how well it is trained, therefore, some similarities in teaching data often assist ANN for better learning and vice versa. That's why mixing course changing and keeping manoeuvre while creating teaching data or following different rules in propeller revolution determination should be strictly avoided. Knowing all such facts which may result confusion for ANN, in this research the whole berthing manoeuvre is divided into three basic element manoeuvres as inspired by aircraft landing. First is course changing to merge with so called imaginary line which will act a run way. Then course keeping along with it followed by step deceleration. And at last, when the ship finally stops at a safe distance from actual pier, tug assistance are allowed to execute the crabbing motion and align it with pier.

A. *Virtual Window Concept for Course Changing*

To ensure consistency in teaching data and to make the controller more robust by including all possible ship's initial heading and different rudder angle in operation, non-liner programming method for minimum time course changing is proposed and used by Ahmed and Hasegawa [7]. This programming method enables the user to set the desired equality and non-equality constraints to execute any types of manoeuvre by setting the rudder angle as optimal variable and time as objective function. Then by using the repeated optimization technique in NPL, several trajectories are created by setting the equality constraints as final heading 240° with no sway velocity and yaw rate for ship's different initial heading. This will align the ship parallel to the imaginary line. Here, it is usual that due to starting from same staring point and different angle to turn, ship's termination point will be different as seen in figure 2(a).

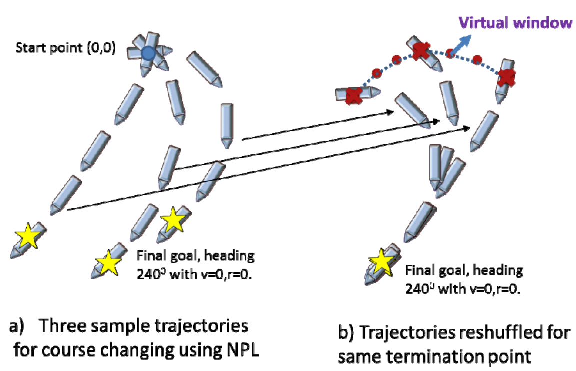

Figure 2. Creation of Virtual Window Using NPL method.

But, by reshuffling the trajectories for same termination point as seen in figure 2(b), it is possible to get several initial points from where ships may start and by taking the calculated rudder command by NPL method it can reach the same destination point which will be the starting point of imaginary line. Thus by adopting such reshuffling process, it is possible to draw a 2D window for each restricted rudder angle operation used as non-equality constraints and the authors call them as virtual windows. In this research, four different rudder angles as ±10°,

±15°, ±20° and ±25° are included in teaching data to make the controller more robust.

B. Course Keeping Along with Imaginary Line

After merging with the imaginary line with no sway velocity and yaw moment, the ship is expected to go straight without taking any rudder if there would no wind disturbances. But, in reality it never happens. Moreover, when the ship's speed drops, the effect of such wind disturbances becomes more dominant. Therefore, in this research the course keeping along with imaginary is subjected to both deciding proper telegraph order and designing a sophisticated controller in low speed of ship capable to withstand the wind disturbances.

To decide the proper timing of propeller revolution change without making any shaft damage, Tp concept from speed response equation is used as proposed by Endo and Hasegawa [12]. On the other hand, a sophisticated PD controller given in following expression is used for maintaining the path during step deceleration. This controller is tested for maximum gust of 1.5 m/s for Esso Osaka model which is 15 m/s for full scale ship from any direction.

$$\delta_{order} = C_1 * (\psi_d - \psi) - C_2 * \dot{\psi} - C_3 * d_1$$
$$\Rightarrow if \begin{cases} \delta_{order} > 0^0, \delta_{order} = 10^0 \\ \delta_{order} = 0^0, \delta_{order} = 0^0 \\ \delta_{order} < 0^0, \delta_{order} = -10^0 \end{cases} \quad (2)$$

where, ψ_d is desired heading angle, d_1 is deviation from imaginary line, C_1, C_2 and C_3 are coefficients. The first term of equation (2) provides the necessary correction for maintaining particular ship heading, second term belongs to minimizing yaw rate and the third term is for compensating ship's deviation from the pre-set imaginary line.

C. Side Thrusters as Final Approach to Berth

After the ship successfully stops within the surrounded area of berthing goal point as shown in figure 1, the final step in to align it with actual pier. Usually, a big ship with single rudder single propeller often needs tug assistance for executing such crabbing motion. The number of tugs involves in such operation depends on size of ship as well as existing environmental disturbances. In this research, to develop a controller for side thrusts first ANN has been tried as by Tran and Im [13]. But considering wind which is mostly unpredictable, there is no other easy way to maintain consistency in teaching data which is very important to ensure effective ANN controller. As a result, PD controller has been given preference over ANN in such cases. Moreover to control the forward motion especially in wind, longitudinal trust is also involved for better control in longitudinal direction. The methodologies considered while designing the PD controllers are heading angle correction, surge and sway velocity control, ship's position control and reverse thrust when almost reaching destination i.e. making sway velocity minimum as possible. The following expressions describe the PD controllers used for automated thrust generation in lateral and longitudinal direction.

if $\Psi < 270^0$ and dis_fore>dis_rev

$$\begin{aligned} T_{fore} &= C_1 * (Y_{fore} - 1.5 - Y_{fore}) + C_2 * \text{sway} \\ T_{aft} &= C_1 * (Y_{fore} - 1.5 - Y_{fore}) + C_2 * \text{sway} + C_3 * \text{diff} \end{aligned} \quad (3)$$

if $\Psi > 270^0$ and dis_aft>dis_rev

$$\begin{aligned} T_{fore} &= C_1 * (Y_{aft} - 1.5 - Y_{aft}) + C_2 * \text{sway} + C_3 * \text{diff} \\ T_{aft} &= C_1 * (Y_{aft} - 1.5 - Y_{aft}) + C_2 * \text{sway} \end{aligned} \quad (4)$$

if $\Psi < 270^0$ and dis_fore<dis_rev

$$\begin{aligned} T_{fore} &= C_1 * (-1.5 - Y_{fore}) + C_2 * \text{sway} \\ T_{aft} &= C_1 * (-1.5 - Y_{fore}) + C_2 * \text{sway} + C_3 * \text{diff} \end{aligned} \quad (5)$$

if $\Psi > 270^0$ and dis_aft<dis_rev

$$\begin{aligned} T_{fore} &= C_1 * (-1.5 - Y_{aft}) + C_2 * \text{sway} + C_3 * \text{diff} \\ T_{aft} &= C_1 * (-1.5 - Y_{aft}) + C_2 * \text{sway} \end{aligned} \quad (6)$$

Longitudinal thrust

$$X_{tug} = C_4 * surge + C_5 * \text{Xpos} + C_6 * \text{distance} \quad (7)$$

where, Ψ is ship's heading, Y_{fore} and Y_{aft} are y coordinate of ship's fore and aft peak respectively in earth fixed coordinate, *diff* is $abs(Y_{fore}\text{-}Y_{aft})$, *distance* is perpendicular distance of ship's CG from the actual pier, *dis_fore* and *dis_aft* are perpendicular distance of ship's fore and aft peak respectively from the actual pier, *dis_rev* is perpendicular distance from the actual pier to start reverse thrust, *Xpos* is the x coordinate of ship's CG in earth fixed coordinate, C_1, C_2, C_3, C_4, C_5 and C_6 are coefficients. Considering equation (3) and (4) for providing side thrusts, first part belongs to a constant value irrespective of ship's position to withstand the wind force up to 1.5 m/s. Second part is for controlling sway velocity and third part activates if correction for ship's heading is needed. On the other hand, if ship reaches the zone to provide reverse side thrusts as given in equation (5) and (6), first part is no longer constant rather increases the thrust value gradually with the decrement of *distance* value so as to minimize sway velocity upon reaching the pier. Other parts are remained same. Here, the value of *dis_rev* depends on the steady sway velocity while approaching to the pier using side thrusters in presence of wind disturbances form different direction. Considering equation (7), first part is for controlling forward velocity, second part is for controlling ship's position in longitudinal direction and third part is for controlling thrust value with respect to ship's distance from actual pier.

IV. ANN-PD Controller for Ship Berthing

The main objective of the controller in this research is to guide the ship from any position within the constructed virtual windows to the berthing goal point by providing adequate rudder command and propeller revolution considering wind disturbances. To attain the purpose, consistent teaching data for course changing and course keeping along with imaginary line are summed up to make a complete berthing manoeuvre. Figure 3 shows the completed teaching data for training ANN under wind disturbances.

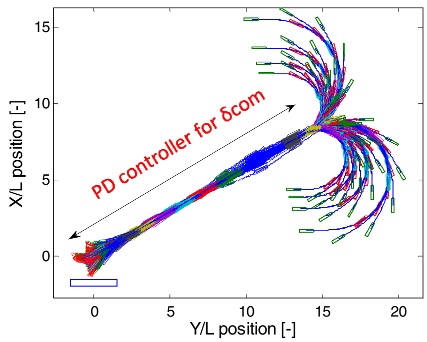

Figure 3. Teaching data for traing ANN.

Using the above mentioned teaching data, two separate multi layered feed forward neural networks are formed for command rudder and propeller revolution output considering Lavenberg-Marquardt algorithm as training function. As transfer function log sigmoid is used for hidden layers and pure linear is used for output layer. The resulting ANN can be demonstrated in the following figure.

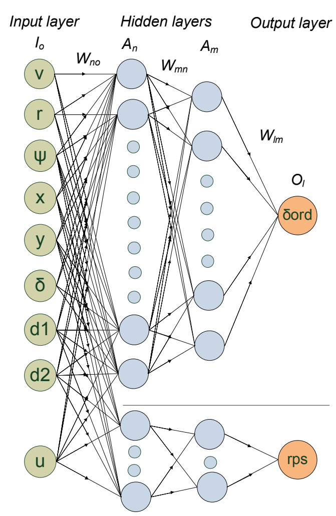

Figure 4. Constructed ANN.

where, for command rudder output, as an input parameter for the net *u* is surge velocity, *v* is sway velocity, *r* is yaw rate, *Ψ* is heading angle; *(x, y)* is ship's position, δ is actual rudder angle, *d1* is distance to imaginary line and *d2* is distance to berthing point. For propeller revolution output, as an input parameter *u* is surge velocity, ψ is heading angle, *(x, y)* is ship's position, *d1* is distance to imaginary line and *d2* is distance to berthing point. ANN controller for rudder command is used only during course changing starting from any point on virtual window and followed by PD controller for course keeping along with imaginary line. On the other hand, ANN controller for propeller revolution is used during whole berthing manoeuvre.

V. Berthing Simulations Including Side Thusters

A. *Plant to be Controlled*

A successful control system design and further description of the design problem often requires the knowledge of plant to be controlled. Without knowing the plant itself and its necessary elements, controlling its particular output is almost impossible. While controlling the ship motion, developing a proper mathematical model is the most important part for capturing the knowledge of the system. In this research, this is done by famous MMG model which is well verified by the authors [7] [8]. Adopting such precise mathematical model not only allow one to design an effective controller but also to perform numerical simulations of different scenarios and obtain a preliminary assessment of the impact that the design can have on the performances of the system. For berthing manoeuvre, the plant to be controlled is also the same as for controlling motion of ship and given in following figure.

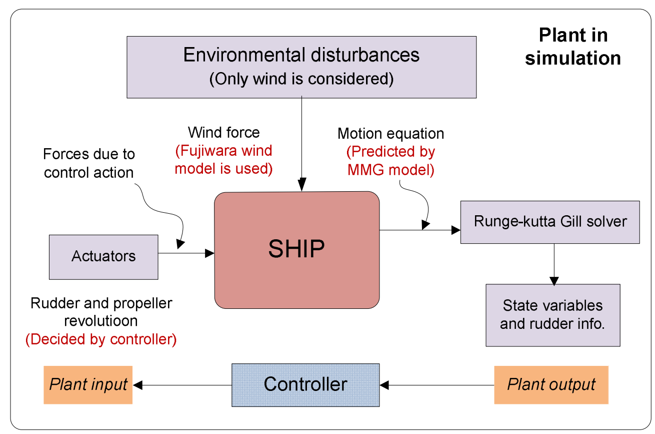

Figure 5. Plant for controlling berthing manoeuvre.

B. *Simulations for Compelte Berthing Manoeuvre*

The effectiveness of developed ANN-PD controller to stop the ship around berthing goal point have already been verified by Ahmed and Hasegawa [7] for several known and unknown situations. Depending on the ship's initial condition and the presence of wind disturbances, ship may have different termination point as well as different surge, sway velocity and yaw rate. Therefore, the compatibility of the newly developed PD controller for side thrusters should be tested for the exiting ANN-PD controller. In this research, side thrusters are allowed to take over the current controller if surge velocity is less than 0.05 m/s and as it approaches the berthing goal point. Figure 6 to 9 demonstrate the total automatic berthing process including thrusters to finally align the ship with pier.

Considering the mentioned figures, ship having different initial heading is tested from different arbitrary point within constructed virtual for maximum allowable wind disturbances. In simulation, when staring the side thrusters, the termination state of the ship is different in each case. As seen in figure 6, the following wind brings the ship much closer to the pier than in figure 7 and 8 and poses some difficulties for the controller to provide heading angle correction. Therefore, in figure 6, the ship's heading ends with 286.1° and the final sway velocity is -0.027 m/s.

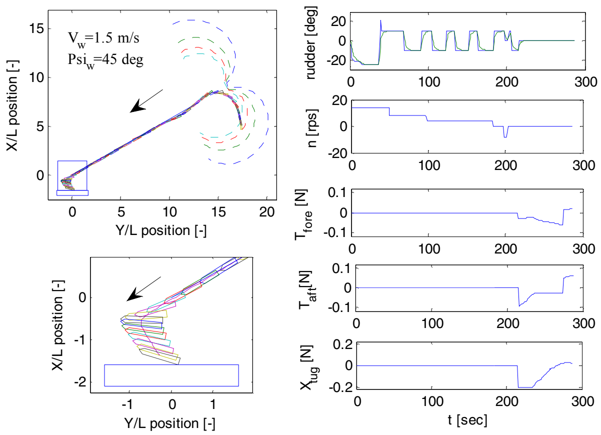

Figure 6. Ship's initial heading 350º starting from an arbitraty point.

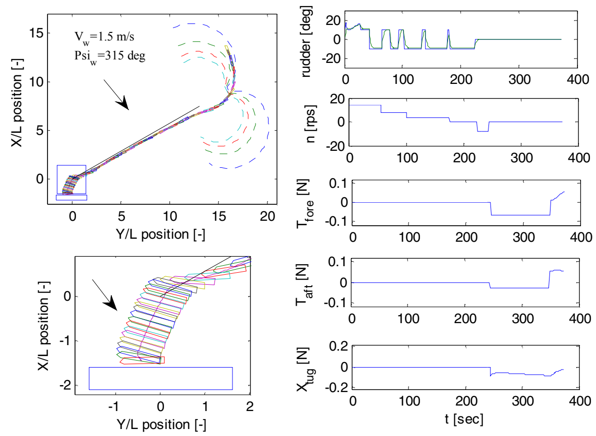

Figure 7. Ship's initial heading 160º starting from an arbitraty point.

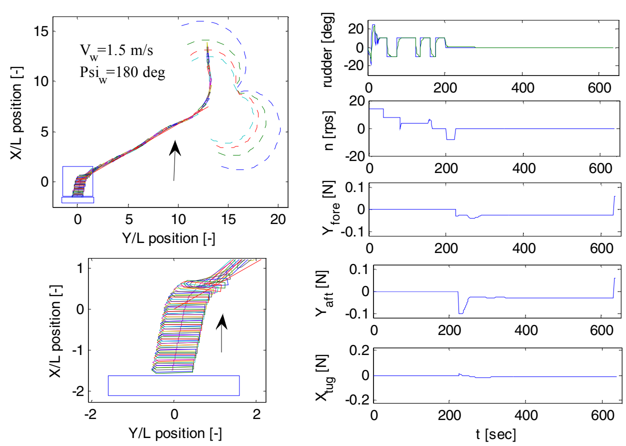

Figure 8. Ship's initial heading 180º starting from an arbitraty point.

On contradictory, in figure 7, controller for thrusters initiates quite earlier and the wind direction is also suitable enough to work effectively. Therefore, the ship perfectly aligns with the pier upon reaching with a heading of 267º and sway velocity of -0.01 m/s. For figure 8, controller also successfully manages to maintain the ship's heading against the wind during executing the crabbing motion. Although, ship takes long time to reach the pier as sway velocity is relatively low due to opposite wind direction and there is barely need for any longitudinal thruster for position alignment. Here, ship's final heading is 269º with sway velocity of almost zero.

C. *Simulations start with Experiment End Conditions*

Experiment results are often worthy and not that much of experiments had been carried out for berthing purposes. Although, the developed ANN-PD controller works effectively but simulations only never give an ANN based controller full appreciation until it is tested in real world. To do that, in this research the trained networks are implemented within the existing free running experiment system in order to perform automatic ship berthing. Ahmed and Hasegawa [8] already mentioned some of such successful and interesting experiment results considering the effect of wind and initial conditions. Upon getting several experiment results, the newly developed PD controller for thrusters is then simulated for different end conditions as found during those experiments. Figure 9 to 11 demonstrate such illustration where the first two row on right side of each figure provides the relative wind information during the experiment conducted.

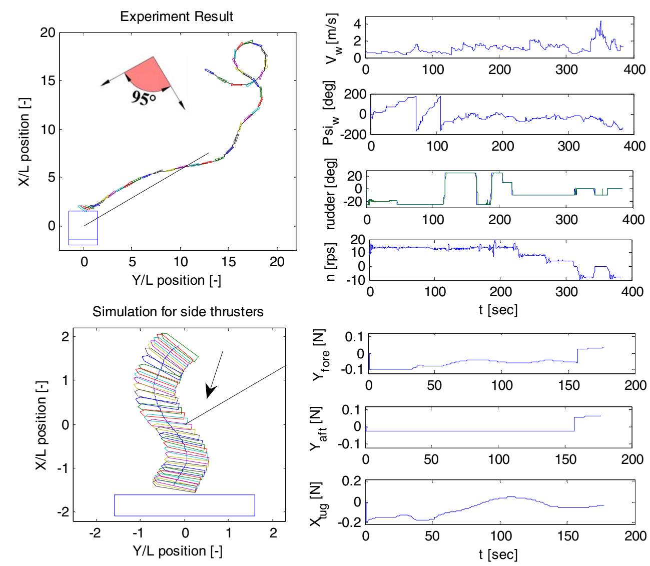

Figure 9. Ship's initial heading 124.2º starting from virtual window ±10º.

In case of figure 9, ANN first decides to make a complete turn and then goes for approaching due to having different initial conditions than used during training the net. On the other hand, ANN for propeller revolution continuously maintains half ahead speed throughout the whole course changing procedure until it reaches the imaginary line. Later on, high wind disturbances during low speed running has altered the ship's course and it stops just near to successful boundary zone. Therefore, in such case the total distance to cover by the tugs is greater than expected. However, its end conditions are tested as initial conditions to judge the effectiveness of the newly developed PD controller as shown in 2nd half of figure 9 considering wind disturbances and found satisfactory result.

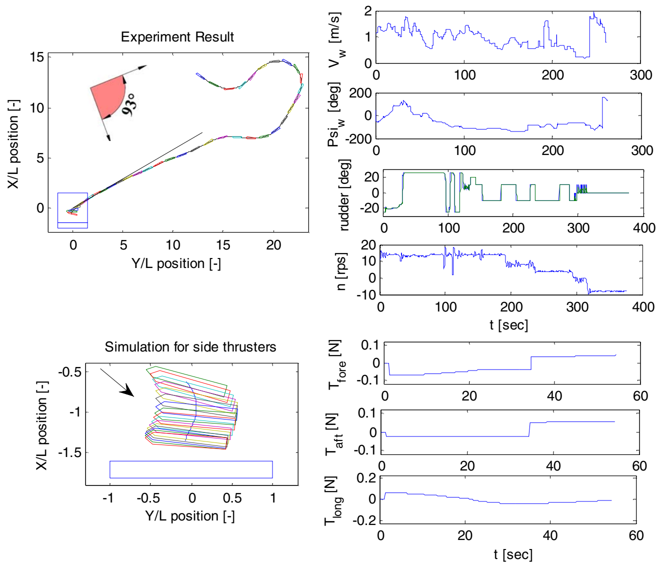

Figure 10. Ship's initial heading 122.3° starting from virtual window ±20°.

Considering figure 10, although ANN first decides to take port rudder but instead of complete port turn, it realises to take starboard rudder and then followed by some straight like path before starting its approach to merge with imaginary line. Under reasonable wind disturbances, the ANN-PD controller works effectively and the ship stops just near the berthing goal point as expected. As a result, the available distance to reach the actual pier during this experiment is relatively shorter than in figure 9 and even in such case the controller for thrusters plays an effective role considering the maximum wind disturbances and average wind direction for that experiment.

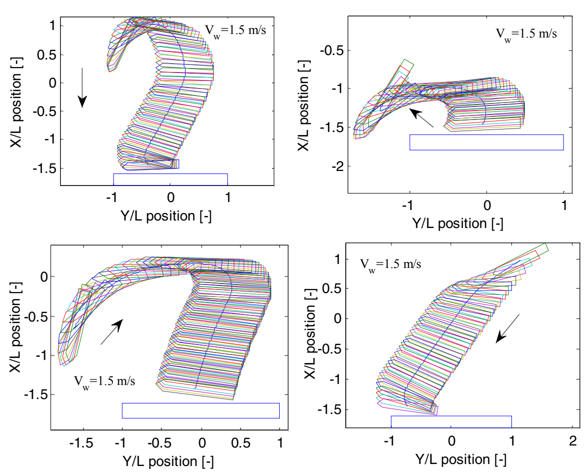

Figure 11. Simulations start with different experiment end conditions.

Figure 11, shows more simulation results tested with other experiment end conditions where, ship has different heading angle for correction as well as different end point. Irrespective of that, the PD controller seems effective enough to guide the ship successful up to the pier in each case. Only for following wind, it poses some difficulties for heading angle correction.

VI. Conclusions

This paper briefly explains the sequential stages of the current research work where 'virtual window' concept is introduced using NPL method to train ANN based controller for berthing manoeuvre. Since the existing controller is designed to stop the ship at some safe distance from actual pier, therefore this paper includes a newly developed PD controller for proving automatic side thrusts and is coupled with the current controller to finally make the ship align with the pier considering wind disturbances up to 1.5 m/s. The compatibility of these two controllers is tested for ship's different initial heading and starting from any arbitrary point within the constructed virtual windows. Several experiment results are also tested with their end conditions to judge the capability of developed controller to finally approaching and aligning the ship with actual pier.

As a future step, using air fans attached on board, experiments for the developed PD controller will be tried to execute by combining it with the exiting ANN-PD controller as a final approach to berth.

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