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Problem of Stopping Vessel at the Waypoint for Full-Mission Control Autopilot

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ABSTRACT: The paper presents a controlling method to control vessel of a full mission autopilot at the transitional phase when vessel reduce speed from navigation speed down to manoeuvring speed while she accesses to the manoeuvring waypoint, where the vessel is started control in manoeuvring mode. The vessel is controlled by three propellers: the bow thruster, the stern thruster and the main propeller. The autopilot is designed with 5 fuzzy logic controllers. It works in Matlab-Simulink and tested on a scaled physical model of a tanker in the lake environment.

1 INTRODUCTION

Nowadays, many ships are equipped with thrusters to support manoeuvring activities. By using these thrusters, the full mission autopilot can control vessel fully automatic from a quay to other quay.

During a voyage, the controlling vessel can be divided into 3 phases: sailing phase (when vessel runs at open sea); manoeuvring phase (when vessel runs in narrow and resisted water); transitional phase (when vessel changes from sailing mode to manoeuvring mode).

In the transitional phase, the vessel is reduced speed from sailing speed (at which, the vessel can be controlled just by the rudder) to the manoeuvring speed (at which, the rudder's effect is too small and vessel mainly control by thrusters and main propeller). The autopilot's task in this phase is to reduce the vessel speed to the required speed (manoeuvring speed) during approaching to the waypoint and also keep the vessel moving on the set path with the set heading.

This paper presents the algorithm and the experiences results by using simulator and scaled model of the autopilot, which is designed and researched by the authors (Leszek et al. 2008).

2 THE OBJECT OF CONTROL

The training ship "Blue Lady" is the floating, autonomous scale model of the VLCC tanker. It is used by the Foundation for Safety of Navigation and Environment Protection at the Silm Lake near Ilawa in Poland for training navigators. The ship is built of the epoxies resin laminate in 1:24 scale. It is equipped with battery-fed electric drives and the control steering post at the stern. The model is equipped with the main propeller, a rudder, two tunnel thrusters, and two azimuth pump thrusters which can be rotated within limited angle ranges. The controller presented in the paper just controls two tunnel thrusters and the main propeller for manoeuvring tasks. The arrangement of the model is shown in Figure 1, while the main characteristic data are given in the Table 1.

Table 1. The main characteristic data of the model

Length over all LOA	13.78[m]
Beam B	2.38[m]
Draft (average) - load condition Tl	0.86[m]
Displacement - load condition D	22.83[T]
Speed	3.10[kn]

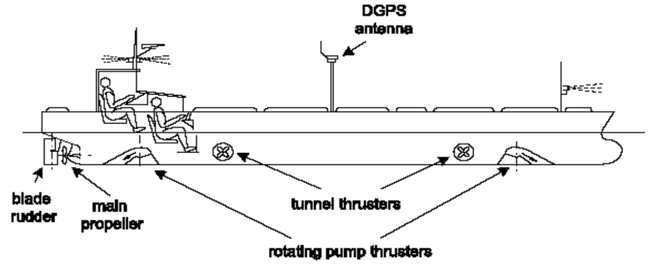


Figure 1. The arrangement of the model "Blue Lady"

3 THE REFERENCE FRAMES AND THE DEFINITIONS

There are two reference frames used in control. They are Geographic reference frame ($x_n y_n$) and Body reference frame (Fig. 2).

Geographic Reference Frame ($x_n y_n$ or n-frame): The coordinate system $x_n y_n$ is defined relative to the Earth reference ellipsoid (World Geodetic System 1984). In this coordinate system the x-axis points towards true North, while the y-axis points towards East (Fosen 2002).

Body Reference Frame ($x_b y_b$ or b-frame): This is moving coordinate frame which is fixed to the vessel. The origin O_b of the coordinate system is chosen to coincide with the center of gravity (CG) when CG is in the principal plane of symmetry. The axes are defined as x - longitudinal axis, directed from aft to fore and y- transversal axis, directed to starboard (see Fig. 2) (Fosen 2002)

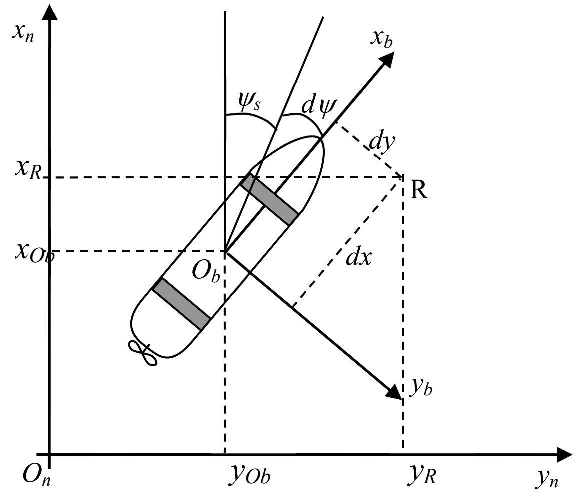


Figure 2. Reference frames

R – reference point, required position of the vessel
dx – position deviation in x-axis of b-frame
dy – position deviation in x-axis of b-frame
ψs – set heading
dψ – course deviation

The position of vessel is fixed by GPS in n-frame while the signals for control (deviations) are measured in b-frame. The transfer functions of coordinates and velocities between these frames as following:

$$
\begin{aligned}
[x_b \quad y_b \quad \psi_b]^T &= R_b^n [x_n - x_{Ob} \quad y_n - y_{Ob} \quad 0]^T \\
[u \quad v \quad r]^T &= R_b^n [\dot{x}_n \quad \dot{y}_n \quad r]^T
\end{aligned}
\tag{1}
$$

where

$$
R_b^n = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \tag{2}
$$

Reference point R: This is a point on which the vessel position has to be maintained. The vessel movement will be controlled through this point (Vinh 2007).

4 ALGORITHM OF CONTROL AND AUTOPILOT DIAGRAM

The diagram of the autopilot is shown in Figure 3. The *Positioning* regulator has task of controlling main engine and thrusters to keep vessel at the *reference point* with the set heading. The *Trajectory* regulator has task to steer the ship along a strait path segment. The *Trajectory* controls rudder and main engine of the ship. Depending on the control mode, the *Signals selector* block switches and connects the output signals of the regulators to the propulsion system.

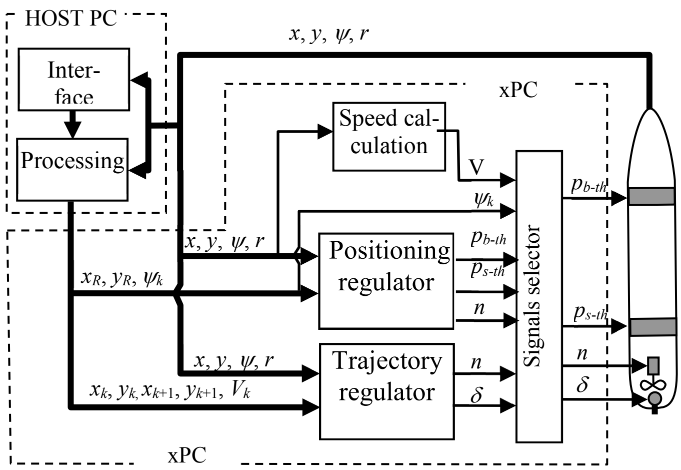


Figure 3. Regulator diagram

As mentioned in the section 1, in the transitional mode, the autopilot has to 1) keep the vessel course stable in the path segment direction and the vessel movement stable on the path segment; 2) control the braking force to obtain the speed that is within the manoeuvring speed range when the vessel arrived exactly at the waypoint.

The braking up of a vessel is carried out in 2 steps:

Step 1: Starting braking up at the braking distance $d_{braking}$. When the distance from the vessel to the waypoint is less than or equal $d_{braking}$, the auto pilot changes the control mode from trajectory mode to transitional mode.

Step 2: Adjusting the braking up force. In this step, the autopilot controls the rudder, thrusters to keep the vessel moving on the set path with the required heading and it also controls the main engine to reduce the vessel speed.

The algorithm used in each steps is presented in detail in the next subsections.

4.1 *Calculating a breaking distance $d_{braking}$*

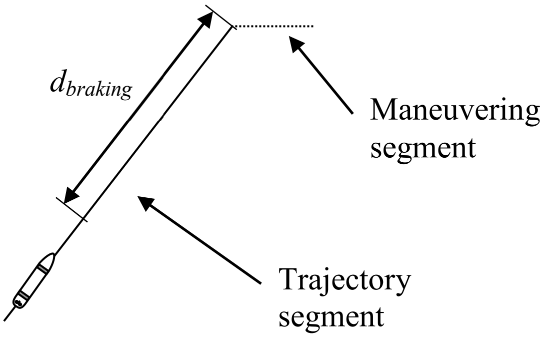


Figure 4. The braking distance $d_{braking}$ in transitional phase

The braking distance $d_{braking}$ is the distance to the first waypoint of the manoeuvring segment, at this distance the autopilot should change from the trajectory mode to the transitional mode to access the waypoint correctly (Fig. 4).

In this autopilot, the braking distance $d_{braking}$ is calculated by using the following formula

$$d_{braking} = au^4 + bu^3 + cu^2 + (d + f)u + e \tag{3}$$

In the formula (3), u is the surge of the vessel. The coefficients of equation (3) are defined from the results of the experiment. The coefficient f is the time taken to change the engine mode of the vessel. Other coefficients *a, b, c, d, e* are defined by the experiment as following: "Vessel is full loading, runs ahead at maximum speed in the wind on a straight path. At a moment, change engine to dead slow astern then record the vessel speed and the passing distance of vessel until the vessel completely stops."

The graph in Figure 5 is an example of the experiment result. On the basis of the recorded data, the coefficients of formula (1) are defined by using Horner's method.

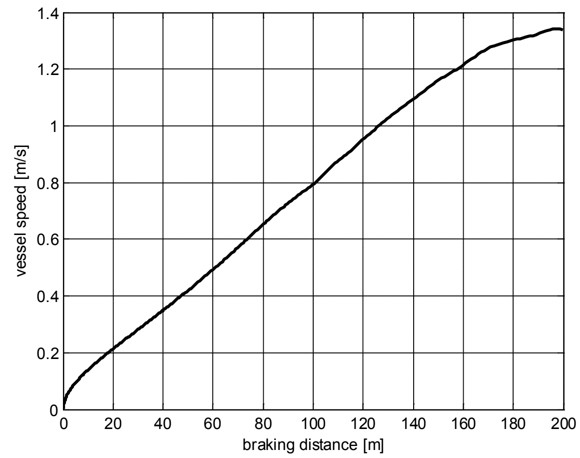


Figure 5. The relation between the braking distance $d_{braking}$ and speed of the Blue Lady model when the engine mode is set to dead slow astern

The dead slow astern engine mode was used for transitional mode after many experiments on the lake with the *Blue Lady* model. During braking up, the engine runs astern while vessel moves forward, the chaotic water flow increases and causes abnormal movement of the vessel. If a higher engine mode is used, the chaotic flow will be stronger then the thrusters and the rudder will be not strong enough to manage the vessel.

4.2 *Adjusting the braking up force*

In the transitional phase, the *Processing* block sets and controls the *reference point R* moving along the path segment; and sets the heading as same as direction of the path segment (see Fig. 6).

When the vessel speed is enough for rudder effect, the *Trajectory* regulator controls the rudders to support thrusters keeping the vessel course. When the speed is too low, the signal from *Trajectory* regulator is cut off.

The *Positioning* regulator controls the vessel heading by the thrusters and braking force by main propeller to obtain vessel speed within the manoeuvring speed range when the vessel reaches the waypoint.

As mentioned in subsection 4.1, the braking force is fixed by the engine mode dead slow astern. So, to adjust vessel speed, the autopilot just changes the engine vessel to dead slow astern, stop or dead slow ahead mode. The engine mode is selected by comparing the actual distance from vessel to the waypoint with the *expected passing distance S* of the vessel.

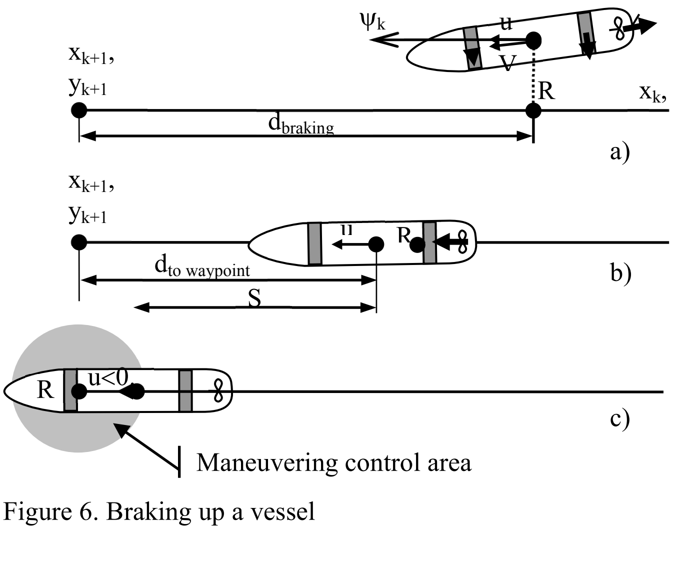


Figure 6. Braking up a vessel

The *expected passing distance S* is calculated by following formula:

$$S = \frac{u_2^2 - u_1^2}{2a} \tag{4}$$

where
u_1: actual vessel surge
u_2: the required speed (surge) at the waypoint, it should be within the manoeuvring speed range. In this autopilot, the value of u_2 is set at 0
a : average acceleration of a vessel while speed changes from u_1 to u_2
S : the distance which vessel passed while speed changes from u_1 to u_2.

As mentioned above, the engine mode for braking is fixed at dead slow astern so the braking force may be treated as a constant force. Hence, the average acceleration a can be treated as constant and it can be calculated as:

$$a = \frac{u_{t2} - u_{t1}}{t_2 - t_1} \tag{5}$$

The *Processing* block reads vessel surge every sampling period and calculates acceleration a as formula (5). From values of a, u_1 (actual surge), u_2 (required surge), the *Processing* block calculates the *expected distance S*.

5 EXPERIMENTS AND RESULTS

5.1 *Experiment using simulator*

The experiments on braking up a vessel were performed using computer simulation as well as the model in real environment. In computer simulation, a vessel was tested braking up from four different speeds with respect to four engine modes: full ahead, half ahead, slow ahead and dead slow ahead (Table 2).

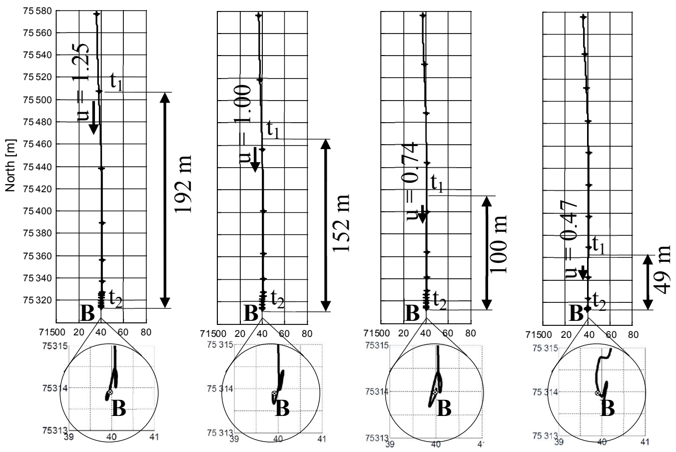
In the experiment, the vessel was running from waypoint A(75768, 71540) to waypoint B(75314, 71540) on the course of 180^o (Table 2). The autopilot's task was to stop the vessel at waypoint B. While stopping vessel, the heading had to be kept at 180^o and the vessel track had to be kept close to the path segment AB.

While the vessel was running steadily along path segment AB, the *Processing* block calculated braking distance $d_{braking}$ basing on the actual vessel speed using formula (3). Depending on the instant speed, these distances $d_{braking}$ were 192 m, 152 m, 100 m and 49 m with respect to the speed of 1.25 m/s, 1.00 m/s, 0.74 m/s and 0.47 m/s (Fig. 7).

Table 2. Set path of braking up experiments

Experiment No.	Waypoint A X[m]	Waypoint A Y[m]	Waypoint B X[m]	Waypoint B Y[m]	Speed[m/s] /engine mode
No. 1	75768	71540	75314	71540	1.31/full ahead
No. 2	75768	71540	75314	71540	1.00/half ahead
No. 3	75768	71540	75314	71540	0.70 /slow ahead
No. 4	75768	71540	75314	71540	0.50 /d.slow ahead

When the distance from the vessel to waypoint B was less than $d_{braking}$, the autopilot changed the control mode from the trajectory mode to the transitional mode. From this moment t_1 in Figure 7, the main engine was controlled by the *Processing* block to adjust braking force; two thrusters were controlled by the *Positioning* regulator to maintain vessel course; the rudder was controlled by the *Trajectory* regulator until the vessel speed was less than 0.1 m/s.



a) Experiment 1 b) Experiment 2 c) Experiment 3 d) Experiment 4

Figure 7. Track of the vessel in the braking up experiment using computer simulation. Position marked every 60 s; u – surge of vessel at the starting of the transitional mode.

When the vessel speed reached the manoeuvring speed range or the vessel was in manoeuvring area around waypoint B, the autopilot changed the control mode to the manoeuvring mode (t_2). In experiments 1, 2 and 3 (Fig. 7 a, b, c), the vessel speed reached manoeuvring speed at about 10m before the target waypoint B (position of t_2 in Fig. 7). From this moment t_2, the vessel was controlled using the manoeuvring mode and it took about five minutes to move to the waypoint B.

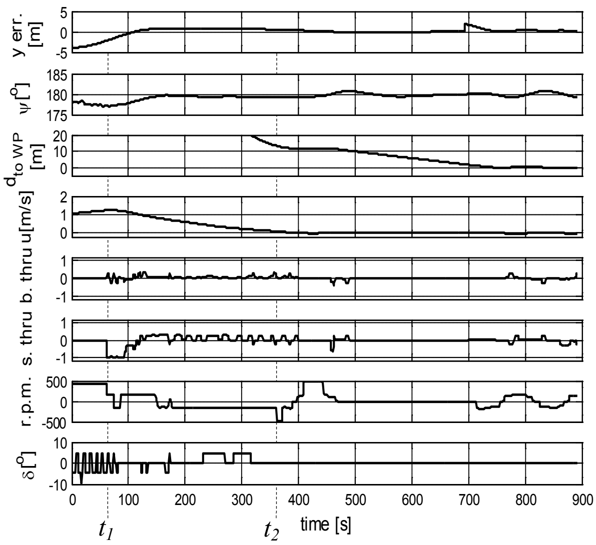


Figure 8. Recorded data of the braking up experiment 1
$d_{to\ WP}$ – the distance from the vessel to the target waypoint.

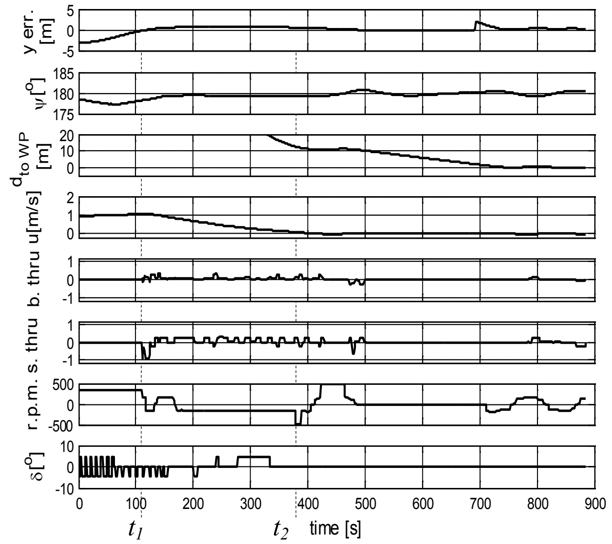


Figure 9. Recorded data of the braking up experiment 2
$d_{to\ WP}$ – the distance from the vessel to the target waypoint.

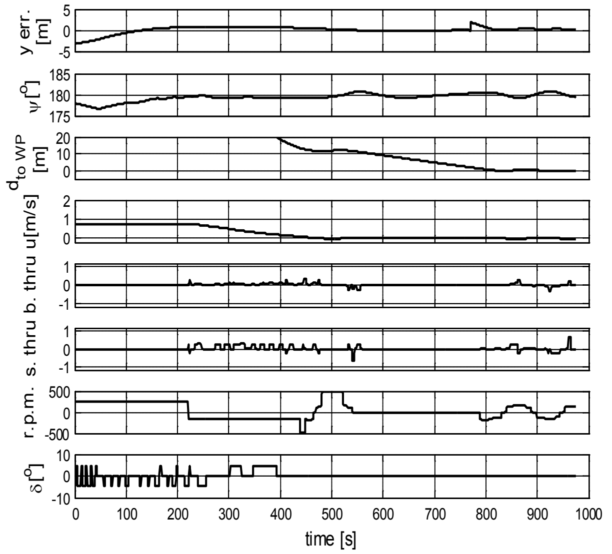


Figure 10. Recorded data of the braking up experiment 3
$d_{to\ WP}$ – the distance from the vessel to the target waypoint.

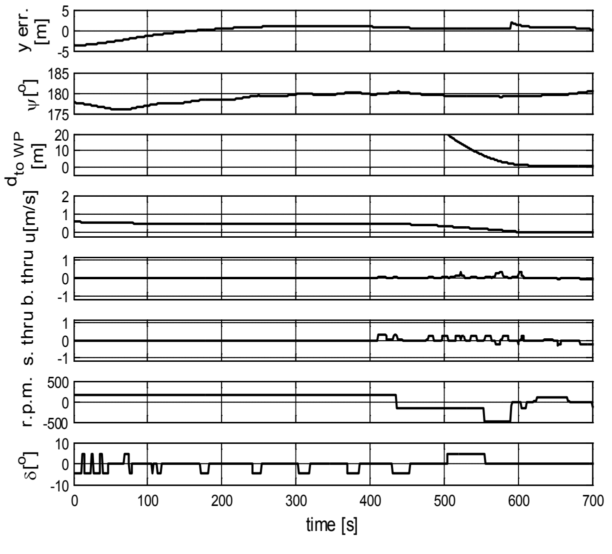


Figure 11. Recorded data of the braking up experiment 4
$d_{to\ WP}$ – the distance from the vessel to the target waypoint.

In the experiment 4, the vessel approached the maneuvering area of waypoint B but the speed was higher than the maneuvering speed. In this situation, the autopilot changed also the control mode to the manoeuvring mode. After that, the *Positioning* regulator immediately set the main engine to full astern mode to stop the vessel quickly (see Fig. 11).

The Figures 8-11 show the recorded parameters of the four experiments. The vessel was stopped at the waypoint B with position deviation less than 0.5 m and the heading drift in these slowdown manoeuvres was less than 2^o.

5.2 *Experiment using scaled model Blue Lady*

The next experiment was performed with the *Blue Lady* model on the lake. In this experiment, the vessel was running from waypoint A(75273, 71480) to waypoint B(74952, 71754) with the engine mode slow ahead (r.p.m = 240 ~ V = 0.6 m/s). The task of the autopilot was to reduce the vessel speed to the manoeuvring speed at waypoint B. At waypoint B, the vessel was turned to the heading of 150^o and then moved to waypoint C(74978, 71780).

At the speed of 0.6 m/s, the braking distance was 72 m (using formula 3). When the distance from the vessel to waypoint B was less than 72 m, the autopilot changed the control mode to the transitional mode. The *Processing* block controlled the braking force by the main engine r.p.m., while the *Positioning* regulator and *Trajectory* regulator controlled the heading by the two thrusters and the rudder.

At the moment t_2, when the model was within the manoeuvring range of the waypoint B, the autopilot changed the control mode to the manoeuvring mode. From t_3 to t_4 the vessel turned to the heading of 150^o as required in the set path.

Table 3. Set path of experiment No. 5

Way -points	X [m]	Y [m]	Set speed [m/s]	Set heading [^{o}]	Control mode
A	75273	71480			
B	74952	71754	A→B: 0.6	A→B: 130 at B: 150	Trajectory& Transitional
C	74978	71780	B→C: not set	B→C: 150	Manoeuvring

From t_4 to the end of the experiment, the vessel moved translationally to waypoint C with the heading of 150^o.

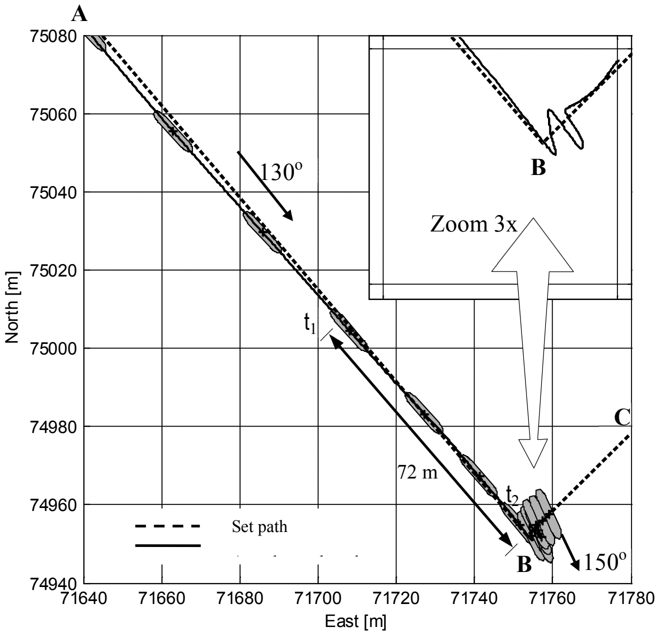


Figure 12. Experiment No. 5 from second 1000th to 1825th. The positions are marked every 60 s.

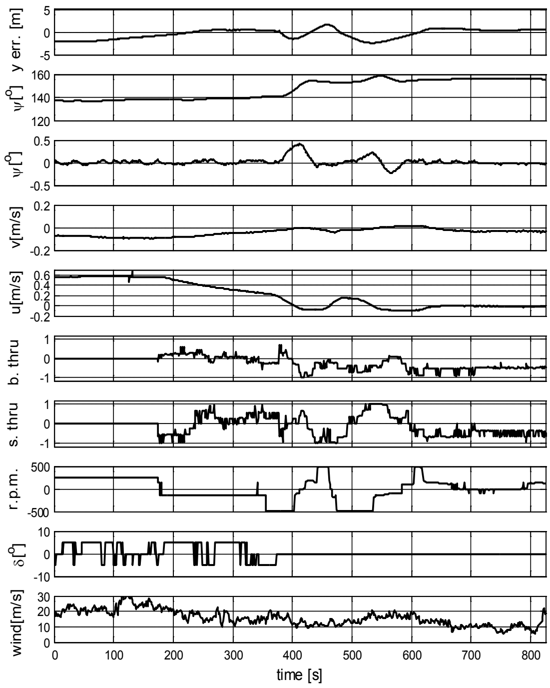


Figure 13. Recorded data of experiment No. 5 from second 1000th to 1825th.

The recorded data is shown in Figure 13. Compared to the results obtained using computer simulation, the thrusters were working harder. The reason of this is that the simulator did not simulate well the effect of a chaotic water flow. In the experiment on the lake, the chaotic water flow had a very strong effect on the model. In many experiments, the thrusters were not powerful enough to manage the model while braking up it by full astern or half astern engine. That is why the autopilot brakes up a vessel only by dead slow astern engine.

6 CONCLUSIONS

In simulation experiments, the model was stopped completely with the position deviation less than 0.5 m around the set waypoint. In the experiment on the lake in windy conditions, the final position deviation was about 2 m. Compared to the length of the model (13.75 m), the deviations are acceptable in practical manoeuvrings. The heading deviations of the model in this manoeuvre were less than 5o in all experiments.

When vessel runs at full speed, to stop it the passing distance is 192 m (about 15 lengths of the vessel). It is also can be accepted in the practice navigation.

REFERENCES

Rak A., Nguyen Cong V., Pomirski J, Morwaski L. 2005. Simulation and real-time control of scale ship model in Matlab-Simulink environment. 16th Conference HYDMAN'05, Ostroda, Poland

Fosen T.I., 2002. Marine Control Systems. Marine Cybernetics, Trondheim, Norway.

Gierusz W. 2005. Simulation model of the ship handling training boat "Blue Lady"

Morawski L., Nguyen Cong V., Rak A. 2008. Full-Mission Marine Autopilot Based on Fuzzy Logic Techniques. Gdynia. Poland

Nguyen Cong V. & Morawski L. 2006 Track keeping autopilot with fuzzy logic controller. 6th ASIA CONFERENCE. Haiphong Vietnam

Nguyen Cong V., 2007. The synthesis of trajectory regulator using fuzzy logic theory in a marine vessel autopilot. Gdynia. Poland