CONTROL OF SHIP MOTION IN MANOEUVRING SITUATIONS
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SUMMARY: The paper presents a regulator controlling ship motion in manoeuvring situations. The control system makes use of three fuzzy logic controllers, the task of which is to keep the ship at a given point, bearing the name of the reference point, with simultaneous stabilisation of the set course. The ship motion is controlled by tracing and following coordinates of the reference point, which changes according to the assumed ship motion trajectory and speed. By this way the ship can be steered along an arbitrary-shape trajectory with an arbitrary manoeuvring speed and arbitrarily selected course. Ship motion is controlled using three propellers: the bow thruster, the stern thruster and the main propeller of the ship. The control signals (thrusts powers) have the form of pulses with relevant amplitude and time duration. The pulsatory nature of the control signals was obtained by proper selection of the shape of the member functions in Mamdani-type controllers and the use of the bisector defuzzification method. The control system has worked out 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. They are very useful for manoeuvring in narrow places, but controlling many thrusters at the same time is a challenge for the helmsman. Therefore, a regulator which controls the entire propulsion system to perform the tasks in manoeuvring situation is extremely desirable. This problem has been examined by various researchers using different methods, for different ship’s propulsion kinds, and as a consequence, obtaining different results [1, 4].

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 pumpthrusters 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 Fig. 1, while the main characteristic data are given in Table 1.

Table 1 Main characteristic data of the model [3]

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Length over all LOA</td>
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<tr>
<td>Beam B</td>
<td>2.38[m]</td>
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<tr>
<td>Draft (average)-load condition Ti</td>
<td>0.86[m]</td>
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<tr>
<td>Displacement - load condition D</td>
<td>22.83[T]</td>
</tr>
<tr>
<td>Speed</td>
<td>3.10[kn]</td>
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3. REFERENCE FRAMES AND DEFINITIONS
Two reference frames are used in control. They are the Earth fixed reference frame (x_n,y_n) and the Body reference frame (Fig. 2).

Fig. 1 Arrangement of the model “Blue Lady”

Fig. 2 Reference frames
R – reference point, required position of the ship
dx – position deviation in x-axis of b-frame
dy – position deviation in y-axis of b-frame
ψ_s – set heading
dψ – course deviation

Earth Fixed Reference Frame (x_n,y_n or n-frame): The coordinate system x_n,y_n is defined with respect to the Earth reference ellipsoid. In this coordinate system the x-axis points towards true North, and the y-axis points towards East [2].

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

The position of the ship is fixed by GPS in the
$n$-frame while the control signals (deviations) are
measured in the $b$-frame. The coordinate and velocity
transfer functions between these reference frames are the
following:

\[
[x_b \ y_b \ \psi_b]^T = R^n_b [x_n - x_{ob} \ y_n - y_{ob} \ 0]^T
\]

where the rotation matrix is equal to:

\[
R^n_b = \begin{bmatrix}
\cos \psi & -\sin \psi & 0 \\
\sin \psi & \cos \psi & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

Reference point $R$: This is a point, coordinates of which
define the required position of the hull geometric centre.
Ship motion is controlled by relevant changes of
coordinates of this point.

4. ALGORITHM OF CONTROL

Control signals and controller characteristic

The control signals from the controller have the form of
pulses. The magnitude of the signal is changed in steps
and plays the role of rough control while its duration is
adjusted continuously and plays the role of fine control.
When making use of such characteristics of the control
signals, a relatively simple and effective control
algorithm is obtained. In action this algorithm is similar
to „safe” and „cautious” steering executed by the
operator (helmsman). It is relatively resistant to ship
dynamics changes and external disturbances. The
parameters of the control signals can be defined in the
following way:

\[
\Delta t = f_{\Delta t}(\epsilon_{\eta}, \nu)
\]

\[
\vec{F} = f_{\vec{F}}(\epsilon_{\eta}, \nu)
\]

\[
\dot{\epsilon}_{\eta} = f_{\text{dynamic}}(m, \epsilon_{\eta}, \tau, \vec{F})
\]

\[
\nu = \dot{\epsilon}_{\eta}
\]

where

- $\Delta t$ – acting time of control signals
- $\vec{F}$ – magnitude of control signals, chosen from
  fuzzy values $\vec{F} = \{0, \pm \text{small}, \pm \text{medium}, \pm \text{big}\}$
- $\epsilon_{\eta}$ – errors; $\epsilon_{\eta} = [dx, dy, d\psi]$
- $\nu$ – speed variation error; $\nu = [u, v, r]$
- $m$ – mass of controlled object
- $\tau$ – external disturbance forces
- $f_{\Delta t}$ – function defined by the fuzzy variables of a
  controller
- $f_{\vec{F}}$ – function defined by the fuzzy variables of a
  controller

In these equations, the values “0”, “small”, “medium”
and “big” are the amplitudes of the control signals.

The controllers used in the control system are fuzzy
logic controllers of Mamdani type. To create the control
signals as the pulse, the membership functions of the
controllers must have a narrow and not intersectional
shape. Additionally, the defuzzification procedure in the
controller must be of bisector type. A detailed description
of controllers’ characteristics is presented in Section 5.

Control of ship movement

The control system contains three fuzzy logic controllers.
They are: course keeping controller, $x$-position keeping
controller and $y$-position keeping controller. Three
controllers work independently to keep the ship hull
centre at the reference point $R$ with the set course $\psi$. The
principle of the use of particular propellers for generating
required hull movements is explained in Fig. 3. Ship
rotation around $z$-axis is executed using the bow thruster
and the stern thruster, which generate opposite thrust
(Fig. 3a). During ship motion along the $y_b$ axis both
thusters work in the same direction (Fig. 3b), while its
motion along the $x_b$ axis is generated by the main
propeller (Fig. 3c).

Fig. 3 The used force in ship control

a) Heading control
b) Side-movement control
c) Longitudinal movement control

The required ship motion along a set directory is
generated by changing coordinates of the reference point
$R$. Since the power of the propulsion system is limited,
hull movements are delayed with respect to the moving
reference point. This delay is higher when the speed of
reference point motion along the set trajectory is high.
Therefore the control algorithm includes a series of
conditions relating to reference point movement.

Let us assume that the accepted range of the course
error is $\Delta \psi_{\max}$ and the accepted range of the position
deviation is $l_{\max}$ (Fig. 4). The reference point $R$ has just
moved forwards when all above deviations are within
accepted ranges. If the course error and/or the position
deviation are larger than the accepted range, the
reference point is stopped to wait until the controllers
stabilize the ship in the accepted range. The flowchart in
Fig. 5 shows the algorithm of controlling the reference
point $R$. 

Fig. 4 Moving reference point R along the set path

![Diagram](image_url)

**Fig. 4** Moving reference point R along the set path

The set speed for the reference point R. The angle with respect to the reference point R.

$l < l_{\text{max}}$

When the ship motion is stable and the deviation is $l < l_{\text{max}}$, it means that the ship has the speed identical with that of the reference point. When $l$ is equal or slightly larger than $l_{\text{max}}$, and at the same time $\alpha < 90^\circ$, than the ship speed is lower that the reference point speed ($V < v_R$). In this case, the forward motion of the reference point is restrained. It can be imaged as the reference point R pulls the ship by a rope, the length of which is $l_{\text{max}}$ (Fig. 6a). If $\alpha > 90^\circ$ the ship speed V is higher than the speed of the reference point R ($V > v_R$). In this situation, the reference point R can move with its set speed $v_R$. The controller tries to curb the forward motion of the ship to keep the deviation position smaller than $l_{\text{max}}$. It can be imaged as the reference point R pulls the ship back to reduce the ship speed to set speed $v_R$ (Fig. 6b)

5. THE CONTROL SYSTEM

The diagram of the control system with the used regulators is shown in Fig. 7. The database of the set path is stored in the Data of trajectory block. The set trajectory data include coordinates of the waypoints, set ship courses along successive trajectory segments, and set speeds of ship motion along those segments. Based on current position coordinates, ship course, angular speed and set values of the current trajectory segment, the master trajectory controller determines, using the above presented algorithm, coordinates of the reference point R and the set ship course. From those parameters the ship position and course errors are determined. These errors, in fact, are coordinates of the reference point R in the Body frame, $b$-frame. These coordinates, along with the angular speed ($\psi$), and estimated components of longitudinal and lateral velocity (surge, sway) are input signals for three fuzzy logic controllers, which are the course keeping controller, the $\gamma$-position keeping controller and the $x$-position keeping controller. All fuzzy logic controllers are of the same type, and their properties were given in Table 2. In the control system, the components of the hull surge and sway are estimated using a stationary Kalman filter, the construction of which is based on the signal model of changes of linear speeds and ship position coordinates in the reference frame $x_{b}y_{b}$ [6]. The velocity components $dx_{b}/dt$, $dy_{b}/dt$ are estimated first, after which the velocities $u$ and $v$ are calculated using the formula (1).

The signals controlling the bow and stern thrusters are, respectively, the sum and difference of standardised output signals leaving the course controller and the controller stabilising the $\gamma$-deviation. The output signals of these two controllers were standardised to the interval

![Diagram](image_url)
(-1, +1), the limiting values of which correspond to the maximum thrust generated by the thrusters. This way in some situations the sum or difference of the control signals can exceed the maximum thruster values. That is why the control system was equipped with the signal saturation block. Its operation is the following: when, as a result of control signal algebra, one of them exceeds the maximum value, then its action is limited to the maximum executable thrust while the action of the other thruster is reduced in the way securing the same difference as before the signals have been limited. As a result, the same rotating and hull side movement effects are obtained, but in a limited scale. A method of limitation of signals controlling the thrusters is shown in Fig. 8

![Fig. 8 Signals saturation block algorithm](image)

**Table 2** Fuzzy logic controllers’ properties

<table>
<thead>
<tr>
<th>FIS type</th>
<th>Mamdani</th>
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<tbody>
<tr>
<td># Inputs</td>
<td>2</td>
</tr>
<tr>
<td># Outputs</td>
<td>1</td>
</tr>
<tr>
<td>AND method</td>
<td>min</td>
</tr>
<tr>
<td>OR method</td>
<td>max</td>
</tr>
<tr>
<td>Defuzzification</td>
<td>bisector</td>
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<tr>
<td>Implication</td>
<td>min</td>
</tr>
<tr>
<td>Aggregation</td>
<td>max</td>
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**Course keeping controller:** This controller controls the bow thruster and the stern thruster to keep the ship heading stably at the set direction. To fulfil this task, the controller has to keep the heading error and turning rate nearing 0. Due to this, the input membership functions are established symmetrically around 0 (Fig. 9). In real control situations, course errors within the range of \( \Delta \psi = [-150^\circ +150^\circ] \) can be recorded. At the controller input they are limited to the interval \([-30^\circ +30^\circ]\). Similar limitations were applied for the other controller input, the turning rate. The interval of changes for this parameter was limited to \([-1^\circ/s +1^\circ/s]\), while the real maximum turning rates can reach as much as \(3^\circ/s\). Within the limited intervals of input signal changes the membership functions were defined.

**Fig. 9** Input membership functions of the Course keeping controller

The output membership functions and the rules of the course keeping controller are shown in Fig. 10. The levels are \(\pm s, \pm m, \pm b\) and correspond to 1/3, 2/3 and 1/1 of full thruster power. The lowest thruster power level \(\pm s\) is used during course stabilisation and compensation of disturbances. The level \(\pm b\) is used to turn the ship when the error course is, as a rule, smaller than \(\pm 15^\circ\). The level \(\pm m\) is used to accelerate the turning ship when the error course is larger than \(\pm 15^\circ\). The output signal of this controller is used to control two thrusters (bow and stern). Both control signals have the same amplitude but opposite signs (see Fig. 7) depending on the required course change direction.

**Fig. 10** Output membership functions and table of rules of the Course keeping controller

The shapes of the membership function and the rule bases were determined using computer simulation calculations, done using a heuristic method, and numerous tests performed on a real object.

**The y position keeping controller:** This controller controls side (transversal) movements of the ship. The task of the controller is to keep the ship position closest to the reference point in the \(y_b\) axis direction of the \(b\)-frame. Two inputs consisting of the deviation \(dy\) and the sway \(v\) with relevant membership functions are shown in Fig. 11, while the output membership functions and rules of this controller are shown in Fig. 12.

**Fig. 11** Input membership functions of the y position keeping controller

The effect of action of the bow and stern thruster are different in side movement control. That is why the signals passed to the thrusters are set with ratio \(k\) in the gain block (Fig. 7). The coefficient \(k\) was determined in
such a way that the moment leading to the course change does not appear during the operation of the both thrusters in one direction and transversal movement of the hull.

**Fig. 12** Output membership functions and table of rules of the \textit{y} position keeping controller

The \textbf{x position keeping} controller: This controller controls longitudinal movements of the ship and stabilizes the position closest to the reference point in the \( x_b \) axis direction of the \( b \)-frame. The membership functions of the controller have nine zones. Seven of them (from \(-b\) to \(+b\)) are proportional to the membership functions of the \( y \) position keeping controller. Two other zones (\(-vb\) and \(+vb\)) are used when the speed is to be reduced from operating to manoeuvring, i.e. when the ship moves with the speed higher than that accepted for manoeuvring.

Two inputs, consisting of the deviation \( dx \) and the surge \( u \) with relevant membership functions, are shown in Fig. 13:

**Fig. 13** Input membership functions

In a manoeuvring situation, ship movements have the same priority in any direction, therefore the output signals of the \textit{x position keeping} controller in levels \( \pm b \), \( \pm m \) and \( \pm s \) must correspond to relevant levels of the signal output in the \textit{y position keeping} controller. Besides, the ship hull is designed with the priority in longitudinal motion so the resistance in this direction is the lowest. Therefore stopping the ship requires high power. The levels \(+vb/-vb\) with full engine ahead/astern are reserved for this task.

**Fig. 14** Output membership functions and table of rules of the \textit{x position keeping} controller

6. **Experiments and results**

The above presented control algorithm was an object of examination, performed on the Silm lake using a model tanker VLCC Blue Lady. A photo in Fig. 15 presents, among other details, the model tanker and part of the lake. White lines with arrows illustrate two experiments of control, the results of which are given below.

**Fig. 15** View of the Silm lake

The first experiment was carried out to test oblique movements of the ship. In this experiment, the model was controlled to move in four directions: aft-port (AB), fore-port (BC), fore-starboard (CD) and aft-starboard (DA) Fig. 16.

There is a big difference between the nature of action of the main engine and thruster on the ship. The main engine is more powerful but responds very slowly to mode changes. The main engine simulated on the Blue Lady is of turbine type. It takes tens of seconds (in the model scale) to change from the ahead engine mode to astern. At the same time the thrusters have very low power but are very quick in respond. Therefore it is very difficult to combine the action of the main engine and thrusters in oblique motion. What is more, the position accuracy in the transverse direction is also higher than in the longitudinal direction.

**Fig. 16** Track of the oblique motion experiment

\begin{verbatim}
<table>
<thead>
<tr>
<th>Power of thruster</th>
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<tbody>
<tr>
<td>(-1)</td>
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<td>(-0.5)</td>
</tr>
<tr>
<td>(0)</td>
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<tr>
<td>(0.5)</td>
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<td>(1)</td>
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<table>
<thead>
<tr>
<th>Degree of membership</th>
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<tbody>
<tr>
<td>(+vb)</td>
</tr>
<tr>
<td>(+b)</td>
</tr>
<tr>
<td>(+m)</td>
</tr>
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<td>(+s)</td>
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<td>(-m)</td>
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<table>
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<table>
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<th>Deviation</th>
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<td>(dx)</td>
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<table>
<thead>
<tr>
<th>Degree of membership</th>
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<tbody>
<tr>
<td>(+vb)</td>
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<tr>
<td>(-m)</td>
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<tr>
<td>(-b)</td>
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<tr>
<td>(-vb)</td>
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<tbody>
<tr>
<td>(-6)</td>
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</tbody>
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\end{verbatim}
After turning, the model was affected by the cross wind blowing from the starboard side. The cross wind with scale of 7-8°B is too strong for the ship thrusters to act properly. The stern thruster worked with almost maximum power against the cross but the cross deviation still existed along the entire path segment CD. The bow thruster could not work with its maximum power because if it had worked with higher power, the ship heading could have changed. The Saturation signals block is programmed in such a way that the course keeping task has higher priority than the position keeping task. In this situation, the position accuracy was sacrificed to secure keeping the heading.

The heading errors when the model turned by 90° at the point C for 270s, could not be taken into account in the statistics of heading deviations because they returned unrealistic values. Therefore the evaluation of this experiment was split into two parts including the segment ABC from beginning to second 650th (part one) and segment CDE from second 920th to 1800th (part two). Along the segment ABC, the model had the ahead wind and along the segment CED it had the cross wind. The means and standard deviations of the cross deviation are $\mu_c = -0.4883\ m$, $\sigma_c = 0.7842\ m$ along the segment ABC and $\mu_c = -1.0765\ m$, $\sigma_c = 0.4943$ along the segment CDE. The means and standard deviations of the heading error are $\mu_\theta = 0.0184$, $\sigma_\theta = 1.9078\ m$ along the segment ABC and $\mu_\theta = -0.2346\ deg$, $\sigma_\theta = 1.0818\ deg$ along the segment CDE.

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Fig. 17 Oblique motion experiment

During experiments, the wind force changed from “Moderate breeze” to “Strong gale” in the Beaufort scale. But the result obtained in the control test is the mean of the cross deviation $\mu_y = 0.2157\ m$ and the standard deviation $\sigma_y = 0.4445\ m$; the heading of the model was always kept well within the error $\mu_\theta = 0.4544\ deg$ and standard deviation $\sigma_\theta = 2.0062\ deg$. When comparing to the dimensions of the model, these values are acceptable in practical navigation.

The second experiment was carried out to test the control of model moving along purely transverse or longitudinal directions, and model turning at a waypoint. The model Blue Lady started from the quay (Point A), performed the side movement along the segment AB. Then, it moved forward along the segment BC. At the point C, it turned by 90° and then sailed astern along the segment CD. Along the last segment DE, the model moved transversely and reached the second quay (Fig. 18).

In this experiment, the model moved in the port area under the shadow of many metal constructions so the positions fixed by GPS sometimes were not stable, see many position jumps around point C in Fig. 18. The ship speed (surge and sway) was calculated from ship position changes. As a result, when the fixed position revealed a relatively big error the calculated speed also returned unrealistic values (see Fig. 19 from second 900th to 1200th). These errors significantly affected the control quality.

The wind force during the experiment was 7-8°B. It is a strong wind for manoeuvring activities. Along the segments AB and BC, the wind blew along the model hull so its effect on the model was less pronounced than that observed along the path segments CD and DE, when the wind blew straight on the model side.

At the point C, the model performed turning by 90°. The turning was carried out in 270s (from second 650th to second 920th) with the course error of about 2° and small oscillations.

Fig. 18 Track of the transverse and longitudinal motion experiment
7. CONCLUSIONS

The results of the above reported and many other experiments reveal that the control system can be effectively used for ship maneuvring. Its characteristic may be listed as follow:

- The controller can keep the ship position under the wind up to $5^\circ$B, which are normal wind conditions for the ship entering or leaving the port quay. When the wind is stronger, the ships often need support of tugboats for safety reasons.

- The controller provides pulse forces to control ship movements. The width of the pulse force is controlled based on the speed of movement. When the ship is light, it quickly speeds up under the control force so the pulse force is short. In contrary, when the ship is heavy it needs more time to speed up so the pulse force is longer. The controller always provides strong force in pulses so it can quickly act against the effect of environment and easy adapt to different ship loads.

- The speed of the ship can be controlled by tracing the speed of the reference point. This changing speed does not affect the ability to keep the ship position. The speed can be changed from 0 to 0.1 m/s. It is suitable for the ship in maneouvring actions.

- The recorded error levels are accepted. The mean values of cross and longitudinal error was smaller than 1 m and the heading error was smaller than 2 deg during strong windy conditions (7-8$^\circ$B).

As for turning at a fixed point: the ship position little changed, as the hull rotation centre did not coincide with its geometric centre.

8. REFERENCES
