Design auto trajectory of passenger ship in variation of sea condition in line Ketapang - Gilimanuk of Bali strait, Indonesia

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Abstract. The fleet of ferry ships crossing the Bali Strait between Ketapang - Gilimanuk is relatively old, where when the waves are quite large and the current is strong enough the ships cannot go directly to Ketapang or vice versa. In order for the ship to reach its destination, it needs the right trajectory based on sea conditions. An automatic control system algorithm is proposed to perform an auto trajectory system. New trajectory is created based on the sea conditions. The auto trajectory system consists of steering and speed control system. The study was done by computer simulation and using of Matlab software. Simulations were carried out for various conditions of sea current speed of 3-7 knots and waves with in height of 1-1.5 meters. The auto trajectory system used of adaptive fuzzy control system to determine the proportional - integral and - derivatives (PID) gain controller. The rules in fuzzy control use the Sugeno type. The performances of control to meet IMO standards and produced 5 trajectory models for various current and wave heights, in both of the direction from the north (Java Sea) and from the south (Australian sea). The fuzzy control can keep the ship on its trajectory with the largest error of 3.93 meters when the sea current is 7 knots from the south and the sea wave height is 1.5 meters.

Notation List:

- $\eta$ = direction orientation vector;
- $x$ = surge (m);
- $y$ = sway (m);
- $z$ = heave (m);
- $\phi$ = roll angle (deg);
- $\theta$ = pitch angle (deg);
- $\psi$ = yaw angle (deg);
- $\psi_L$ = low frequency yaw angle (deg);
- $\psi_H$ = high frequency yaw angle (deg);
- $u$ = surge speed (m/s);
- $v$ = sway speed (m/s);
- $w$ = heave speed (m/s);
- $p$ = roll speed (deg/s);
- $q$ = pitch speed (deg/s);
- $r$ = yaw speed (deg/s);
- $\dot{u}$ = surge acceleration (m/s²);
- $\dot{v}$ = sway acceleration (m/s²);
- $\dot{w}$ = heave acceleration (m/s²);
- $\dot{p}$ = roll acceleration (deg/s²);
- $\dot{q}$ = pitch acceleration (deg/s²);
- $\dot{r}$ = yaw acceleration (deg/s²).
1. Introduction

The number of ship accidents is one indication of the need for improvements in the sea transportation system, where Indonesian shipping is known to have high potential or risk related to safety. From 2006 to 2021, according to data from the Ministry of Transportation, passenger ships are at the top of the rankings for the ships accidents with the highest number of victims. According to the accident category, capsize ships are the most frequent cases of ship accidents and cause the most casualties when compared to other accidents.

Based on the final report released by the Ministry of Sea Transportation in 2021, during the period 2006-2021 weather factor had a significant contribution in causing accidents in sea transportation modes. The majority of ship accidents in Indonesian waters occurred in inter-island waters, where according to wave data, the average extreme between islands, the wave height can reach 5.8 m. Meanwhile, according to BMKG's (Badan Meteorologi, Klimatologi, dan Geofisika) 2019 significant wave height data, it is known that waves can reach 5 to 6 meters, if from this range the average value is taken to be 5.5 meters. Research conducted [1] also states the same thing. Attached to this study is the decision of the Maritime Court of the Secretariat General of the Ministry of Transportation, which was released in 2017, which stated that during the 2011-2015 period, sea transportation accidents caused by weather factor increased by 17.2%. The decision also stated that accidents due to weather factor occurred as many as 86 cases in the same period, higher than the human factor of 47 cases.

Another problem that needs to be addressed is the relatively old age of the ship. The Ketapang-Gilimanuk route is one of the important shipping lanes in Indonesia also has the same problem. On this track, 56 Ro-Ro ferry fleets are operated to serve the trajectory, where the average age of the ships is 27 years (Rachman, 2016). The maneuverability and power of the ship has been greatly reduced and is less able to deal with the strong currents that often occur in the Bali Strait. If the ship continues to sail in strong currents, it is likely that the ship will not be able to reach its destination and the worst
posibility is that an accident will occur. An alternative strategy is needed to overcome these problems.

The strategy that can be pursued is to develop a trajectory guide that is adapted to sea water conditions. The trajectory guidance created will provide additional reference trajectory options for the ship, in which the selection of the new trajectory was adjusted to the conditions of the sea waters at that time. By creating a trajectory guidance, it is hoped that the ship can sail to the destination port safely. In addition, an adaptive control algorithm for the ship's autopilot system can also be developed. The adaptive controller made is by compiling a control system that can change the value of the controlling parameter according to the water current conditions. The selection of adaptive controllers is intended so that ships can respond more responsively due to changes in water conditions.

The method of designing an automatic ship control system was pioneered by Minorsky in 1922 by using the PID controller algorithm [2]. The main advantage of the control system based on the PID controller algorithm is its ease of arrangement. However, the PID control system is more suitable for linear systems. Meanwhile, the condition of the waters as a trajectory for sailing ships is not always the same at all times. Changes in water conditions can be caused by weather factors that affect the speed of sea water currents. The performance of the PID control system under different conditions does not match the desired conditions [3]. Therefore, need an adaptive automatic ship steering system that is able to adjust to the condition of the ship when sailing to reduce disturbances such as wave height and changing sea water current speed.

2. Control System Design Method

In this research, a ship's automatic steering system is designed that controls two variables, namely the heading angle and the speed of the ship. The ship's heading angle control system is arranged using the Fuzzy-PID controller algorithm, while the ship speed control system uses Sugeno's Fuzzy Logic. The block diagram of the proposed control system can be seen in Figure 1. The control system design stage is described in the next subsection.

![Control System Block Diagram](image)

2.1. Trajectory Data

There are 5 trajectories reference as shown in Figure 2, namely A, B, C, D and E trajectories. The use of the trajectory as a reference is determined based on the conditions of the sea waters when the ship will sail. Trajectory A is used as a reference if when the sea currents are in a calm condition. Trajectory B and C are used when the current speed is 3 knots, the difference between trajectories B and C is only in the direction of the current. If the currents come from the north (above), then path B is used as a reference. Meanwhile, if the currents come from the south (bottom), then the trajectory used as a reference is trajectory C. Trajectory D and E are used as references when the ocean currents have a speed of 7 knots. Path D acts as a reference when the current direction is from north. If the direction of the ocean currents is from the south, the path E is used as a reference. The port where the ship departs is the Port of Ketapang, Banyuwangi. Meanwhile, the port that the ship will go to is Gilimanuk Port, Jembrana.
2.2 Weather Data
Based on data obtained from the official Maritime BMKG website, it was found that the wave height in the North Bali Strait area varied from 1.00 to 1.50 meters throughout January 2021. As for the average current speed data, it varied between 3 to 7 knots.

2.3. Ship Specification Data
The specifications of the ship used can be seen in Table 1.

| L_{pp} (Lenght perpendicular) | 73.15 meter |
| B (Breadth) | 15.2 meter |
| T (Draught) | 3.6 meter |
| V (Speed) | 4.63 m/s (9 Knot) |
| m (mass of ship) | 2940 Ton |
| Cb (Block Coefisien) | 0.734 |
| A_a (Rudder area) | 4.6 m^2 |
| X_g (Center of Gravity) | 3.45 m |

2.4 Ship Modeling
The ship modeling is based on previous research [4]. Ship modeling is divided into two (2), namely ship modeling with low frequency and high frequency disturbances. Low-frequency modeling can be seen in equation (1-7) by first calculating the hydrodynamic coefficient [5].

\[
M \ddot{y}_L + D(v_L - v_C) = \tau_L + \omega_L \tag{1}
\]

\[
M = \begin{bmatrix}
m' - Y_v' & m'x_{gy}' - Y_r' \\
0 & 0 & 1
\end{bmatrix} \tag{2}
\]

\[
D = \begin{bmatrix}
-X_{ux} & 0 & 0 \\
0 & -Y_{y}' & Y_{y}' \\
0 & -N_{x}' & -N_{r}'
\end{bmatrix} \tag{3}
\]

\[
\dot{x}_L = [u_L \ v_L \ r_L \ x_L \ y_L \ \psi_L]^T \tag{4}
\]
\[ A_L = \begin{bmatrix} 0 & I \\ 0 & -M^{-1}D \end{bmatrix} \]  
\[ B_L = \begin{bmatrix} 0 \\ -M^{-1}b \end{bmatrix} \]  
\[ E_L = \begin{bmatrix} 0 \\ -M^{-1} \end{bmatrix} \]  

While the high frequency ship modeling can be seen in equation (8).

\[
\begin{bmatrix}
\dot{\xi}_x \\
\dot{\xi}_y \\
\dot{\xi}_\psi \\
\dot{x}_H \\
\dot{y}_H \\
\dot{\psi}_H
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
-2\zeta \omega_0 & 0 & 0 & -\omega_0^2 & 0 & 0 \\
0 & -2\zeta \omega_0 & 0 & 0 & -\omega_0^2 & 0 \\
0 & 0 & -2\zeta \omega_0 & 0 & 0 & -\omega_0^2 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\xi_x \\
\xi_y \\
\xi_\psi \\
x_H \\
y_H \\
\psi_H
\end{bmatrix} +
K_w
\begin{bmatrix}
w_x \\
w_y \\
w_\psi
\end{bmatrix}
\]

Where,

\[ \omega_0 = 0.4 \frac{g}{H} \]  
\[ K_w = 2\zeta \omega_0 \tau_w \]

According to [6], the high frequency and low frequency wave equations can be rewritten as in equation (11).

\[
\begin{bmatrix}
\dot{x}_L \\
\dot{x}_H
\end{bmatrix} =
\begin{bmatrix}
A_L & 0 \\
0 & A_H
\end{bmatrix}
\begin{bmatrix}
x_L \\
x_H
\end{bmatrix} +
\begin{bmatrix}
B_L \\
0
\end{bmatrix} \tau_L +
\begin{bmatrix}
1 \\
0
\end{bmatrix} \begin{bmatrix}
w_L \\
w_H
\end{bmatrix}
\]

2.5 Modelling of Sea Current

Sea currents are modeled using equation (12-14) [5]. Sea current modeling consists of two (2) components, namely the velocity component in equation (12) and the direction component in equation (13-14).

\[ V_c(t) = V_c(0) + t(\omega(t) - \mu_0 V_c(0)) \]  
\[ u_c = V_c \cos(\beta - \psi) \]  
\[ v_c = V_c \sin(\beta - \psi) \]

2.6 Control System Design

2.6.1 Ship's Heading Angle Control System.

The trajectory guidance method used is the LOS (Line of Sight) guiding method as in equation (15), where \((x_k, y_k)\) is the desired trajectory point and \((x(t), y(t))\) is the actual trajectory point [6]. The result of equation (15) is the reference heading angle value which acts as the setpoint value of this control system.

\[ \psi_{\text{ref}}(\text{deg}) = \tan^{-1}\left(\frac{y_k - y(t)}{x_k - x(t)}\right) \]

The ship's heading angle controller is designed using the Fuzzy-PID algorithm as shown in [7]. However, the fuzzy system used to set the PID controller parameters in this study uses a Sugeno fuzzy type. In addition, the designed fuzzy system is also added with a scaling factor to increase the
adaptability of the compiled control system [8]. The Fuzzy-PID system and the scaling factor have the same two (2) variables, namely e and Δe. These two input variables also have the same architecture, which consists of seven membership functions and is triangular in shape. The input variable e has a range of -35 to 35, while Δe has a range of -7 to 7. The output variable from the scaling factor is the value of gain A for the input variable e, and the value of gain B for the input variable Δe. The architecture of the output variables A and B can be seen in Figures 3 and 4. The rulebase used in this fuzzy scaling factor system can be seen in Table 2.

### Table 2. Rulebase Fuzzy Scalling Factor

| e | Δe | NB | NM | NS | Z | PS | PM | PB |
|---|---|---|---|---|---|---|---|---|
| A | B | A | B | A | B | A | B | A | B | A | B | A | B |
| NB | B | S | VB | S | B | S | B | S | B | S | B | S | B | S |
| NM | B | M | VB | M | B | S | B | S | B | S | B | M | M | M |
| NS | B | B | VB | M | B | M | S | S | B | M | M | M | M | M |
| Z | B | VB | VB | VB | S | B | S | S | S | B | VB | VB | B | VB |
| PS | B | B | VB | M | B | S | S | B | M | VB | M | B | VB | M |
| PM | B | M | B | M | B | S | B | S | B | S | VB | M | B | M |
| PB | B | S | B | S | B | B | S | B | S | VB | S | B | S | S |

![Figure 3. Arsitektut Variabel Output “A”](image3.png)

![Figure 4. Arsitektur Variabel Output “B”](image4.png)

The output variables of the Fuzzy-PID system are in the form of constants Kp', Kd' and α according to [8]. The output variables Kp' and Kd' have the same architecture, which consists of 5 membership functions with a value range of 0-1. While the output variable consists of 4 membership functions with a value range of 15-40. The arrangement of the output variables of the Fuzzy-PID system can be seen in Figures 5 and 6. The fuzzy rulebase used in the Fuzzy-PID system can be seen in Table 3 for the output variables Kp' and Kd' and Table 4 for the output variable α.

### Table 3. Rulebase Fuzzy-PID Kp' dan Kd'

| e | Δe | NB | NM | NS | Z | PS | PM | PB |
|---|---|---|---|---|---|---|---|---|
| Kp' | Kp' | Kp' | Kp' | Kp' | Kd' | Kd' | Kd' | Kd' |
| NB | M | S | S | M | VS | B | S | VB | VS | B | S | B | M | S |
| NM | B | VS | M | S | S | M | VB | S | M | S | B | VS | M | VS |
| NS | VB | VS | B | VS | B | S | B | VB | B | S | B | VS | VB | VB |
| Z | VB | VS | VB | VS | VB | VS | VB | VS | VB | VS | VB | VS | VB | VB |
| PS | VB | VS | B | VS | B | S | B | VB | B | S | B | VS | VB | VS |
| PM | B | VS | M | S | S | M | VB | S | M | S | B | VS | M | VS |
| PB | M | S | S | M | VS | B | S | VB | VS | B | S | M | M | S |
Table 4. Rulebase Fuzzy-PID α

| e | NB | NM | NS | Z | PS | PM | PB |
|---|----|----|----|---|----|----|----|
| NB | S  | MS | M  | B | M  | MS | S  |
| NM | S  | MS | MS | M | MS | MS | S  |
| NS | S  | S  | MS | MS | MS | S  | S  |
| Z  | S  | S  | S  | MS | S  | S  | S  |
| PS | S  | S  | MS | MS | S  | S  | S  |
| PM | S  | MS | MS | M | MS | MS | S  |
| PB | S  | MS | M  | B | M  | MS | S  |

Figure 5. Architecture Variable Output Kp’ and Kd’

Figure 6. Architecture Variable Output α

2.6.2 Ship Speed Control System

The ship speed control system uses a Sugeno fuzzy logic control system with one input variable and an output variable each. The variable that acts as an input is the value of the distance between the ship and the trajectory point to be addressed. Equation (16) is used to calculate the distance value. While the output variable used is in the form of RPM value which will be converted into ship speed in m/s units. The fuzzy architecture for this speed control system can be seen in Figure 7. Speed control system a rulebase is also used as can be seen in Table 5.

Figure 7. Architecture Fuzzy Variable Input Distance (a) and Variable Output RPM (b)

Table 5. Rulebase Fuzzy Speed Control

| Jarak | U   |
|-------|-----|
| N     | S   |
| M     | M   |
| F     | F   |
3 Results

3.1 Trajectory Guidance Route A
Route A is a trajectory condition without any disturbance. As explained before, in the simulation process the ship departs from the Port of Ketapang to the Port of Gilimanuk. The results of the ship's movement in a simulation can be observed in Figure 8. It can be seen in Figure 8 that the ship as a whole has been able to follow the predetermined trajectory points.

![Figure 8. Trajectory Guidance Route A](image)

3.2 Trajectory Guidance Route B
Route B is a trajectory condition with a disturbance of sea current speed of 3 knots moving from the north. In addition to disturbances in the form of currents, disturbances in the form of waves are also simulated which have 2 variations in height values, 1 meter and 1.5 meters. The results of the ship's movement for Route B in simulation can be seen in Figure 9 (a) for a wave height of 1 meter and (b) for a wave height of 1.5 meters.

![Figure 9. Trajectory Guidance Route B with Wave Height 1 meter (a) and 1.5 meter (b)](images)
3.3 Trajectory Guidance Route C

Route C has the same sea current speed conditioning as in route B of 3 knots, but the direction of the current is the opposite. The wave conditioning on route C still uses the same value for conditioning on route B. The results of the ship's movement for the simulated condition of route B can be seen in Figure 10 (a) for a wave height of 1 meter and (b) for a wave height of 1.5 meters.

![Figure 10. Trajectory Guidance Route C with Vave height 1 meter (a) and 1.5 meter (b)](image)

3.4 Trajectory Guidance Route D

Route D is the trajectory that is used as a reference when the speed of the sea current is 7 knots. The movement of sea currents on route D is simulated moving from the north. The disturbances in the form of waves are also simulated which have 2 variations in height values, 1 meter and 1.5 meters. The results of the simulation can be seen in Figure 11a and Figure 11b.

![Figure 11. Trajectory Guidance Route D with Wave height 1 meter (a) and 1.5 meter (b)](image)

3.5 Trajectory Guidance Route E

The last trajectory guidance simulation is on Route E. The speed of ocean currents on track E is conditioned to be the same as track D, but the current moves from the south. The simulation results can be seen in Figure 12 (a) for a wave height of 1 meter and (b) for a wave height of 1.5 meters.
Figure 1. Trajectory Guidance Route E with Wave Height 1 meter (a) and 1.5 meter (b)

3.6 Trajectory Error Analysis

Determination of the success of the control system in performing trajectory guidance is determined based on the trajectory error value. The trajectory error value is a value that represents the deviation occurred by the ship when measured from the trajectory point on the trajectory it passes. This value is obtained by calculating the closest distance of the ship at each point of the trajectory it crosses. Based on the simulation results, it can be observed that the ship for each trajectory guidance process on all trajectories has been able to follow the trajectory points on the predetermined trajectory. For further analysis, the average error value for each path can be observed in Table 6.

| Route | Disturbance | Current Speed | Wave Height | Average Error |
|-------|-------------|---------------|-------------|---------------|
| A     | -           | -             | 1 meter     | 0.48 meter    |
| B     | 3 Knot (North) | 3 Knot (North) | 1 meter | 2.35 meter |
|       |             |               | 1.5 meter  | 2.22 meter   |
| C     | 3 Knot (South) | 3 Knot (South) | 1 meter | 3.64 meter |
|       |             |               | 1.5 meter  | 3.11 meter   |
| D     | 7 Knot (North) | 7 Knot (North) | 1 meter | 1.92 meter |
|       |             |               | 1.5 meter  | 1.97 meter   |
| E     | 7 Knot (South) | 7 Knot (South) | 1 meter | 3.86 meter |
|       |             |               | 1.5 meter  | 3.93 meter   |

4 Conclusion.

The success of a control system in carrying out trajectory guidance can be seen from the trajectory error that occur on each trajectory. Because the method used is the LOS method, the error value must be less than or equal to 2 Lpp. Based on the standard error used in the research results [9] the standard error is less or equal to 0.5 Lpp. From the simulation results of all routes, the error that occurs is less than half of the LPP. The main dimension of the ship used in this study have an LPP value of 73.15 meters. Thus, the trajectory error must be 36.58 meters. Based on the analysis results, it can be observed that the trajectory error value for each conditioning has a value of 36.58 meters. Therefore, it can be concluded that the proposed control system is capable of carrying out the
trajectory guidance process in the presence of weather disturbances in the form of sea currents and sea wave heights.

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