L1 adaptive controller for unmanned surface vehicle type monohull LSS01 autopilot system and guidance design

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Abstract. The control technology grows rapidly at present, especially in the field of autonomous vehicles. This research presents the application of an L1 adaptive controller to an autopilot system and guidance design for an Unmanned Surface Vehicle (USV). The purpose of the L1 adaptive controller deals with how the adaptive control technology solve the problems related to the performance, robustness, and the time adaptability in the issues of uncertainty conditions. The dynamic behaviors of the USV are modeled with 3 degrees of freedom movement in the planar field, where disturbances are applied onto the system. The parameter values of the vessel will be inserted into the state space dynamic equation. The transient response behavior of the system will be analyzed to show the vessel’s movement through the desired waypoints. The L1 adaptive controller method has a fast adaptation rate without losing robustness, which provides better stability using Lyapunov analysis and abilities to dampening the high-frequency as the disturbance by adding Low Pass Filter (LPF) on the control law architecture. Besides this, the L1 adaptive control is relatively simple and easy for industrial implementation. The results show the effectiveness of the L1 adaptive controller when applied to the USV guidance system.

1. Introduction

Unmanned Surface Vehicle (USV) has the ability to drive without any skippers, so the USV can be operated automatically using navigation devices. The navigation devices are allowing the USV to go through the desired waypoints. The waypoints are coordinate points in the planar field which are the destination point of the vessel. The direction angle of waypoints can be calculated so makes it possible the USV can be controlled to go through coordinate trajectory waypoints. In order to control the USV, it requires a mechanical control action and a vessel’s steering angle. At the time the vessel deployed to the sea, there will certainly experience various external disturbances such as winds, currents, and waves. The control action when the disturbances present or not will definitely has different modes. However, the USV must be able to adapt onto the two conditions.

One method to overcome the external disturbances is by applying the adaptive controller. This type of adaptive control is the L1 adaptive controller [1] which is the development of the Model-Reference Adaptive Controller (MRAC) [2]. MRAC has shown to have good features in terms of performance. For MRAC, fast adaptation is often required to ensure the system behave closely to desired performance [3]. Unfortunately, this can make the system less robust. This controller has a better performance than MRAC to cope with the disturbances because L1 adaptive control addresses this robustness problem by decoupling it with an adaptation rate [4]. The adaptation rate can be set arbitrarily high, whereas
robustness is ensured by adding a low pass filter to the controller. The L1 adaptive control guarantees bounds on transient performance while providing guaranteed robustness.

Application of L1 adaptive control related to the autonomous vessel has been done by Kragelund [5], where it gives better performance under various operational conditions compared with PID gain scheduling and MRAC controller. The current research is conducted to design the L1 adaptive controller for unmanned surface vehicle autopilot system and guidance using waypoints planner. The purpose of the controller is to maintain the position of the vessel to go through the desired waypoints when induced by disturbances. The vessel which is used as the system is the USV of monohull type. This system inherently is characterized by the nonlinear behavior of the dynamic motion of the USV, therefore the L1 adaptive controller is suitable to be applied in order to deal with this condition.

2. USV LSS01 System

2.1 Overview

The USV LSS01 is the monohull vessel that is researched by the Laboratory of System and Cybernetics at the Department of Electrical Engineering – ITS. USV LSS01 is a marine craft that is capable of unmanned operation. Since this unmanned vessel can be remotely operated by pilots form safe locations, they are suitable for operation in dangerous areas. USV is driven by thruster machine and rudder. The thruster is used to generate thrust and the rudder is used to set the direction to the vessel for maneuvering [6].

2.2 Mathematical Model

The mathematical model of USV was obtained by following the 6-dof model of unmanned surface vehicles [7-9]. However, the model was adjusted to the following assumptions:

1. Roll, pitch, dan heave movements are ignored.
2. The vessel has the homogenous mass distribution on xz-plane.
3. The center of gravity and center of buoyancy are located on one vertical line of the z-axis.

Based on those assumptions, then the mathematical model of USV-LSS01 could be defined in 3 degrees of freedom (surge, sway, and yaw) as follows.

\[ \dot{\eta} = J(\eta)v \]  \( (1) \)

\[ M \dot{v} = -C(v)v - (D + D_n(v))v + \tau + \tau_g \]  \( (2) \)

where \( \eta = [x \ y \ \psi]^T \) is the position and orientation vector with coordinates in the earth fixed frame and \( v = [u \ v \ r]^T \) is the linear and angular velocity vector with coordinates in the body-fixed frame. \( J(\eta) \) is a transformation matrix defined as follow,

\[ J(\eta) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \]  \( (3) \)

\( M \) is a sum of the rigid body system inertia matrix and the added mass matrix defined as follow,

\[ M = \begin{bmatrix} m - X_u & 0 & 0 \\ 0 & m - Y_v & m x_g - Y_r \\ 0 & m x_g - Y_r & I_z - N_r \end{bmatrix} \]  \( (4) \)

\( C(v) \) is a sum of the rigid body Coriolis and centripetal matrix and the hydrodynamic Coriolis and centripetal matrix defined as follow,

\[ C(v) = \begin{bmatrix} 0 & 0 & -m(x_g r + v) + Y_v v + Y_r r \\ 0 & 0 & m u - X_u u \\ m(x_g r + v) - Y_v v - Y_r r & -m u + X_u u & 0 \end{bmatrix} \]  \( (5) \)

\( D \) and \( D_n(v) \) each is the linear damping matrix and the nonlinear damping matrix defined as follows,

\[ D = -\begin{bmatrix} X_u & 0 & 0 \\ 0 & Y_v & Y_r \\ 0 & N_v & N_r \end{bmatrix} \]  \( (6) \)
\[ D_n(v) = \begin{bmatrix} X_{[u]|u} & 0 & 0 \\ 0 & Y_{[v]|v} + N_{[r]|v} & Y_{[u]|v} \\ 0 & N_{[v]|v} + N_{[r]|v} & N_{[u]|v} + N_{[r]|v} \end{bmatrix} \]  

Input force of \( \tau \) for the vessel’s system comprises only two components, which are input forces in the direction as surge and yaw. Force vector of input \( \tau \) is defined as follow,

\[
\tau = \begin{bmatrix} \tau_u \\ \tau_v \\ \tau_r \end{bmatrix}
\]

External disturbances (current, wave, and wind) forces and moments vector, \( \tau_E \), are defined as follows,

\[
\tau_E = \begin{bmatrix} \tau_{uE} \\ \tau_{vE} \\ \tau_{rE} \end{bmatrix}
\]

\[
\tau_{uE} = \tau_{uE}^c + \sum_{i=1}^{N} \rho g BL T \cos(\beta) s_i(t) + \frac{1}{2} \rho a V_w^2 C_x (yw) A_i w \\
\tau_{vE} = \tau_{vE}^c + \sum_{i=1}^{N} -\rho g B L T \sin(\beta) s_i(t) + \frac{1}{2} \rho a V_w^2 C_y (yw) A_i w \\
\tau_{rE} = \tau_{rE}^c + \sum_{i=1}^{N} \frac{1}{2} \rho g B L (L^2 - B^2) \sin(2\beta) s_i(t) + \frac{1}{2} \rho a V_w^2 C_N (yw) A_i w H_i w
\]

where \( \beta \) is vessel’s heading angle and \( V_w^2 \) is the wind speed. The wave slope \( s_i(t) \) for the wave component, is defined as.

\[
s_i(t) = A_i \frac{2\pi}{\lambda_i} \sin(\omega_{ei} t + \phi_i)
\]

where \( A_i \) is the wave amplitude, \( \lambda_i \) is the wavelength, \( \omega_{ei} \) is the encounter frequency and \( \phi_i \) is a random phase corresponding to the wave component \( i \). The USV model has three degrees of freedom containing two sets of control surface, namely surge for \( x \)-axis translation velocity and yaw for \( \psi \)-axis angular velocity. The estimated parameters for the vessel are summarized in Table 1.

**Table 1. Nomenclature of USV-LSS01**

| Symbols | Explanation |
|---------|-------------|
| \( \dot{V}_x \) | Y-axis added mass caused by \( \dot{v} \) |
| \( X_x \) | X-axis added mass caused by \( \dot{u} \) |
| \( \dot{Y}_x \) | Y-axis added mass caused by \( \dot{v} \) |
| \( N_x \) | N-axis added mass caused by \( \dot{r} \) |
| \( X_y \) | X-axis linear damper caused by \( u \) |
| \( Y_y \) | Y-axis linear damper caused by \( v \) |
| \( N_r \) | N-axis linear damper caused by \( r \) |
| \( I_x \) | Inertial moment with respect to \( O_b Z_b \) |
| \( X_{[u]|u} \) | X-axis non-linear damper caused by \( u \) |
| \( Y_{[v]|v} \) | Y-axis non-linear damper caused by \( v \) |
| \( Y_{[r]|r} \) | Y-axis non-linear damper caused by \( v \) and \( r \) |
| \( Y_{[v]|v} \) | Y-axis non-linear damper caused by \( r \) and \( v \) |
| \( N_{[v]|v} \) | N-axis non-linear damper caused by \( v \) |
| \( N_{[r]|r} \) | N-axis non-linear damper caused by \( r \) and \( v \) |
| \( N_{[r]|r} \) | N-axis non-linear damper caused by \( v \) |
| \( N_{[v]|v} \) | N-axis non-linear damper caused by \( r \) |
| \( \rho \) | Seawater density |
| \( L \) | Length of the vessel |
| \( B \) | Breadth of the vessel |
| \( T \) | Draft of the vessel |
| \( \rho_a \) | Air density |
| \( A_{f \text{w}} \) | Wind Frontal projected area |
| \( A_{l \text{w}} \) | Wind Lateral projected area |
Symbols | Explanation
---|---
$A_F c$ | Water Frontal projected area
$A_L c$ | Water Lateral projected area
$L_{OA}$ | Vessel length of overall
$H_p W$ | Centroid of $A_F w$ above waterline
$H_L W$ | Centroid of $A_L w$ above waterline
$C_x (y w)$ | X-axis wind coefficient
$C_y (y w)$ | Y-axis wind coefficient
$C_K (y w)$ | Yaw-axis wind coefficient

The mathematical model of unmanned vessel is derived from the kinematics and the dynamics physical analysis which looking for the relation between velocity and position as well as the relation between force and force moment. The mathematical model was expressed in the state space equation is shown in equation 14.

$$ \dot{x} = f(x) + g(x,u) + d(t); x = [x_1, ..., x_3]^T $$

Where state variables are defined as follows.

$$ x_1 = x_B $$
$$ x_2 = \dot{x}_1 = u $$
$$ x_3 = y_B $$
$$ x_4 = \dot{x}_3 = v $$
$$ x_5 = \psi $$
$$ x_6 = r $$

Thus, the state space equation is obtained as follows.

$$ \dot{u} = \frac{(m - Y_v)}{(m - X_u)} v r - \frac{X_u}{(m - X_u)} u - \frac{X_{[u]} v}{(m - X_u)} |u| u + \frac{1}{(m - X_u)} \tau_v $$
$$ \dot{v} = \frac{(X_u - m)}{(m - Y_v)} u r - \frac{Y_v}{(m - Y_v)} v r - \frac{Y_{[u]} v}{(m - Y_v)} |v| v - \frac{Y_{[v]} r}{(m - Y_v)} |r| v $$
$$ \dot{r} = \frac{(Y_v - X_u)}{(I_z - N_r)} u v - \frac{N_r v}{(I_z - N_r)} r r - \frac{N_{[v]} |v| v}{(I_z - N_r)} |r| v - \frac{N_{[r]} |r| r}{(I_z - N_r)} |v| v + \frac{1}{(I_z - N_r)} \tau_r $$

In order to find the system parameters, the model of temporary disturbances is ignored. The matrix form is separated into the equations to correspond with $x$, $y$, and $\psi$ axis. Polynomial forms for estimation are compiled in equation (17).

$$ \dot{u} = (A(1) v r - A(2) u - A(3) |u| u + A(4) \tau_u $$
$$ \dot{v} = (A(5) v r - A(6) u - A(7) |v| v - A(8) |r| v - A(9) |v| r) $$
$$ \dot{r} = -A(10) |v| v - A(11) |r| v - A(12) |v| r - A(13) |r| r - A(14) r + A(15) \tau_r + A(16) u v $$

Furthermore, by completing the model of equation (16) into equation (17) above, it is obtained the new form in the state space equation (18) as follows.
\[
\begin{bmatrix}
\dot{u} \\
\dot{v} \\
\dot{r}
\end{bmatrix}
= \begin{bmatrix}
-A(2) - A(3)|u| \\
-A(5)r \\
-A(16)v
\end{bmatrix} A(1)r
\begin{bmatrix}
-A(6) - A(7)|v| - A(8)|r| \\
-A(10)|v| - A(11)|r| \\
-A(12)|v| - A(14)|r|
\end{bmatrix} \begin{bmatrix}
0 \\
-|v| \\
-|r|
\end{bmatrix}
+ \begin{bmatrix}
A(4) & 0 \\
0 & 0 \\
0 & A(5)
\end{bmatrix} \begin{bmatrix}
\tau_u \\
\tau_v \\
\tau_r
\end{bmatrix}
\]

(18)

Where \(Y_u = \tau_u\) and \(Y_r = \tau_r\). The coefficients of equation (18) are all outlined in Table 2, which are USV body parameters [6,10]:

| Parameters | Value |
|------------|-------|
| \(A_1\)  | -0.0152 |
| \(A_2\)  | 0.1305 |
| \(A_3\)  | 0.0000 |
| \(A_4\)  | 0.0508 |
| \(A_5\)  | 0.6245 |
| \(A_6\)  | -0.0075 |
| \(A_7\)  | 0.1831 |
| \(A_8\)  | -0.0111 |
| \(A_9\)  | 0.0139 |
| \(A_{10}\)  | 0.0194 |
| \(A_{11}\)  | 0.0505 |
| \(A_{12}\)  | 0.0268 |
| \(A_{13}\)  | -0.4451 |
| \(A_{14}\)  | 0.7005 |
| \(A_{15}\)  | 106.4701 |
| \(A_{16}\)  | 0.0385 |

3. USV Autopilot System and Guidance Design

3.1 General Design of Autopilot System and Guidance

The system is created in two-part, that is the system design for controller validation and system design for waypoint guidance as shown in Figure 1.

![Figure 1. Block diagram of autopilot system and guidance](image)

The first part of designing the autopilot system is setting the translation velocity and angular velocity by the direction of the \(x\)-axis (surge) and \(\psi\)-axis (yaw) which the L1 adaptive controller regulates the magnitude of the thruster motor force and thruster propeller block angle appropriate to the desired
performance specification. The desired output response characteristic is formed as one order response, without overshoot, zero offsets, settling time and time constant that is shown in Table 3.

| Table 3. Design specification performance |
|------------------------------------------|
| Angle | Time constant | Settling time | Error Steady State | Overshoot |
| Surge | 1.5 s         | (±5%)         | Zero              | 0%        |
| Yaw  | 0.5 s         |               |                   |           |

The guidance system design is a waypoint control setting system. In this research, the USV had to be able to go through the desired waypoint from the waypoint planner without entering the time parameters so that the USV speeds are constant. The control variable in the guidance system is the yaw axis.

3.2 Feedback Linearization
The linearization process is done by creating a variable equation. Which the input of the dynamic equation is responsible against the surge and yaw movement. A new parameter with the time constant is added, as well as a new reference input value. Therefore, the output feedback linearization in the form of thrust input and steering angle on the unmanned vessel can be set by the output of surge and yaw velocity due to following the reference signal provided. The surge and yaw accelerations are linearized to produce a steady-state value and expressed in the form of following equations (19) and (20).

\[
\begin{align*}
\dot{u} &= A(2)u - \lambda u + \tau_u \\
\tau_u &= 1/A(4)(-A(1)v r - A(3)|u|u + \tau_u + \lambda u) \\
\dot{r} &= A(14)r - \lambda r + \tau_r \\
\tau_r &= 1/A(15)(-A(16)uv + A(10)|v|v + A(11)|v|v + A(12)|v|r + A(13)|r|r - \tau_r + \lambda r)
\end{align*}
\]

3.3 Trajectory Waypoint Navigation Design
The main purpose of this research is to analyze the USV movements through the specified waypoints. In this subsection, the determination of the waypoint coordinates that will be passed by the vessels is carried out by using the polynomial interpolation method. There are two scenarios of path to show the USV movements, namely half-ellipse motion and circular motion as shown in Figures 2 and 3.

![Figure 2. Half-ellipse motion trajectory reference](image-url)
The waypoints that the USV will pass through has 5 meters tolerance. If the USV has been in a tolerance radius, then the waypoint navigation change waypoint reference to next waypoint. And if there is no longer waypoint, then the simulation will stop automatically.

4. L1 Adaptive Controller Design
The L1 adaptive controller design aims to allow the output to be able to follow the state predictor reference as desired. The L1 adaptive controller functions can generate stability when there are external disturbances such as wind, wave, and ocean current. In order to design the L1 adaptive it is required the design of control law, state predictor, and adaptive law. The general architecture of the L1 adaptive controller is shown in Figure 4.

![L1 Adaptive Controller Diagram](image)

**Figure 4.** The architecture of the L1 adaptive controller

4.1 Control Law
The controller of L1 adaptive is obtained by passing the adaptation result $\hat{\theta}^T x(s)$ and input signal $k_g r(s)$ on low pass filter so that the high frequencies due to the accumulation of disturbances can be damped. The desired system response has zero error steady state so that the $k_g$ gain value is designed in the following equation.

$$u(s) = C(s)(-\hat{\theta}^T x(s) + k_g r(s))$$

$$k_g(u,r) = \frac{1}{c^T(sI - A_m)^{-1}b} + \lambda(u,r)$$ (21)
The gain value is obtained for the x-axis (surge) of 0.7972 and ψ-axis (yaw) of 2.7005. The control law will evaluate the estimation value of the controller parameters obtained from the state predictor. In the control law design, the determination of filter cut-off LPF is done based on a trial and error method when the system was run. Finally, the selected LPF value is ω_c = 9.

\[ C(s) = \frac{\omega_c}{1 + \omega_c} \]  

(22)

Because the form of the first-order equation is installed in series by the system, the time constant filter should not be slower than the state predictor and the plant. Therefore, the determination of ω_c is at least 2 times faster than the slowest system time constant.

4.2 State Predictor

State predictor  \( \hat{x}(t) \) as shown in equation (9) is a modification of the reference model in the MRAC, where the input signal of state predictor is obtained from the control signal output  \( u(t) \).

\[
\hat{x}(t) = A_m \hat{x}(t) + b(u(t) + \theta^T x(s)) \\
\dot{\hat{y}}(t) = c^T \hat{x}(t) + du(t)
\]  

(23)

The value of  \( Am, b, \) and  \( c \) in the state predictor design is the same as the plant parameters. The difference lies in the input, output, and state predictor variables in the form of estimation value as indicated in Figure 2. State predictor output formed the estimation of controller parameter (\( \hat{\theta}(t) \)) changing the controller behavior so that the plant adapted to approach the ideal state predictor responses. The excess use of the state predictor is the ability to pass through the LPF so that some high-frequency disturbances can be damped with an estimate of an unknown  \( \hat{\theta}(t) \). This parameter was provided from the adaptation law.

4.3 Adaptation Law

The adaptation law as shown in equation (10) which estimates the unknown  \( \hat{\theta}(t) \) parameter. This value comes from the derivative of the Lyapunov stability function as described in the following equation.

\[
\dot{\hat{\theta}}(t) = \Gamma \text{Proj}(\hat{\theta}(t), -x(t) \dot{x}(t))Pb \\
\dot{x} = \dot{x}(t) - x(t)
\]  

(24)

The adaptive law design is divided into two steps such as determining the gain adaptation and designing the projection operator. In this research, the gain adaptation is determined by various adaptation velocities such as \( \Gamma = 10, 100, \) and 1000. The operator projection selecting the adaptation scheme based on the controller parameters against the adaptive law output.

\[ \text{Proj}(\theta, y) = \begin{cases} 
\begin{pmatrix} y \\ y - \frac{\nabla f}{\| \nabla f \|} (\nabla f, y) f(\theta) \end{pmatrix} & \text{if } f(\theta) < 0 \\
\begin{pmatrix} y \\ y - \| \nabla f \| (\nabla f, y) f(\theta) \end{pmatrix} & \text{if } f(\theta) \geq 0 \text{ and } \nabla f^T y < 0 \\
\begin{pmatrix} y \\ y - \| \nabla f \| (\nabla f, y) f(\theta) \end{pmatrix} & \text{if } f(\theta) \geq 0 \text{ and } \nabla f^T y > 0 
\end{cases} \]  

(25)

\[ f(\theta) = (\epsilon_\theta + 1)\theta^T \theta - \theta_{\text{max}}^2 \]  

(26)

Where  \( f(\theta) \) is a convex function and  \( \nabla f \), which is a vector gradient from the function which evaluates  \( \theta \). The next step is implementing Equation (7) to (11) into Simulink blocks using MATLAB as shown in Figure 5 where every part of the L1 adaptive control system is interconnected.
4.4 Open Loop Response

The USV mathematical model test is a scheme in an open-loop. The USV input plant is given a reference as the velocity of $x$-axis and $\psi$-axis to show the USV output. The start-up scenario of the USV plant on the $x$-axis (surge) was given by a thrust-force reference input of 7.7 Newton. Then the USV steering is made straight up to the first 50 seconds. It is bent by 0.3 radians or 17.18 degrees at 51 seconds until the simulation time ended in 150 seconds. Therefore, the experiment results obtained by the USV velocity of open-loop plant response in the $x$-axis (surge) and $\psi$-axis (yaw) are listed on the following Table 4.

| Angle  | Time constant | Settling time | Error Steady State | Overshoot |
|--------|---------------|---------------|--------------------|-----------|
| Surge  | 7.665 s       | ±23.03        | ±0.085             | 0%        |
| Yaw    | 4.89 s        | ±14.75        | ±0.0774            | 1.75%     |

Figures 6 and 7 show the velocity response of the open-loop USV plant on the $x$-axis (surge), $y$-axis (sway), and $\psi$-axis (yaw). The response result of the translation velocity on $x$-axis reached a settling time at 23.03 seconds with a value of 3 m/s. The response of $\psi$-axis in the USV open-loop experiment is acquired second-order response because of the overshoot value is 0.0066 rad/s or 1.75% from the steady-state value. The heading angle response also occurred as an error steady state of 0.0773 rad/s or 0.378 degrees. At the time of 55 seconds in parallel with the deflection of USV steering, the angular velocity of 0.3773 rad/s, was declined the translation velocity at surge motion of 0.085 m/s because of the USV position not straight anymore. As a consequence of that, the thrust force-velocity was split towards the yaw and surge axis.
5. Experiment Results and Analysis

5.1 Autopilot System Simulation with an L1 Adaptive Controller

In the previous L1 adaptive controller, the design of adaptive law has been explained with three scenarios, namely by comparing the experiment with the three differences adaptation gain. The L1 adaptive controller experiment results with the difference of adaptation gain against $\psi$-axis (yaw) are described Figure 8 as in the following.

In the first scenario, the adaptive rate is set at 10. The simulation results indicate the response of the USV heading angle in the form of 2nd-order system response with the maximum overshoot peak of 0.348 m/s. Therefore the response from the first simulation is not suitable as an adaptive rate reference to control the USV vessel maneuvers.
In the second scenario, the adaptive rate is set at 100. The simulation results show the response of the USV heading angle as a 2nd-order system response. The system response slightly oscillated at the time of 13.0 seconds at value of 0.302 m/s and slowed down to the steady-state condition. This second simulation eventually is better than the first simulation.

In the third scenario, the adaptive rate is set at 1,000. The simulation results indicate the response of the USV heading angle as a 1st-order system response without overshoot. At the time of 14 seconds, the heading angle showed a value of 0.5, which means it corresponded to the state predictor model.

In the USV maneuvering system experiment, overall the system scenario has no error steady state but the system criteria as the desired controller design occur in the third scenario to when it is set on the adaptation gain of 1000. So that the adaptive rate value will be taken to be the part of the L1 adaptive controller design.

The next step of the autopilot system experiment examined the translation velocity response at x-axis (surge) and the angular velocity at $\psi$-axis (yaw). The scenario experiment is performed by giving the signal experiment step with a constant value of 3 m/s in the x-axis (surge) and 0.3 rad/s or 17.18 degree in $\psi$-axis (yaw) at the time of 10 seconds until the final simulation of 40 seconds. Response criteria of USV plant output with the expected L1 adaptive control is a system as a 1st-order response, no overshoot, zero offsets, settling time (±5%) and time constant of 1.5 seconds at the x-axis and 0.5 seconds at the $\psi$-axis. Data response results of the system experiment with the L1 adaptive control is presented in Table 5 as follows.

**Table 5.** The system response of the USV with an L1 adaptive controller

| Angle | Time constant | Settling time | Error Steady State | Overshoot |
|-------|---------------|---------------|--------------------|-----------|
| Surge | 7.665 s       | ±23.03        | ±0.085             | 0%        |
| Yaw   | 4.89 s        | ±14.75        | ±0.0774            | 1.75%     |

Figures 9 and 10 indicate that there is no split of the force vector. It is because of the capability of the L1 adaptive controller to adjusting the controller parameters so that it approached the state predictor reference. By the L1 adaptive controller, the system response has a time constant of 1.356 seconds in the x-axis and 0.49 seconds in $\psi$-axis.

![Figure 9. The USV translation velocity response with the L1 adaptive controller](image-url)
Figure 10. The USV heading angular velocity response with the L1 adaptive controller

Figure 11. Comparison of heading angular velocity response with the state predictor using the L1 adaptive controller

In Figure 11 above it can be seen that the slight difference occurs during the transient response between USV heading angle and state predictor. However, the small difference value can be ignored as it does not affect the USV steering angle in maneuvering. The experiment results obtained RMSE (root mean square error) value between the response of USV heading angular velocity with the state predictor reference model in the order of $1.4294 \times 10^{-4}$ rad/s. The main function in the L1 adaptive control system is to alter the controller parameters $\hat{\theta}(t)$ to be able to engineer the control signal, conforming against the changes of the USV plant behavior.

5.2 Autopilot Simulation with Waypoint Navigation

In this section, the USV waypoint control experiment results are provided by using the L1 adaptive controller. This experiment was conducted by involving the external disturbance in the form of wind, currents, and waves. The L1 adaptive controller used has a selected parameter from the experiment results that have been done before. The simulation is done in three scenarios that have been designed. The scenario performed is the same as the USV vessel must be able to pass the waypoint movement in the form of straight, half oval, and full circle motion. The size and the direction of disturbance are presented in the following Table 6.

Table 6. The system response of the USV with L1

| Disturbance | Value  | Direction |
|-------------|--------|-----------|
| Wind        | 2.0 m/s| -0.1 rad  |
| Current     | 0.5 m/s| 0.1 rad   |
| Wave        | 1.0 m  | 0.1 rad   |
Figure 12 shows the comparison simulation result of the USV guidance system response with the disturbance at the time the L1 adaptive controller active and inactive. Figure 13 shows the result of the USV heading angle with waypoint guidance. In the second scenario, the half-oval motion, it can be seen that the USV control using L1 adaptive controller still providing good results despite the external disturbance is given. The capability of quick adaptation and robust make the response of steering angle is not oscillating and when sharp angle change is set the response of heading is also not oscillating. Waypoints passed by the vessel, although the disturbance is given, produce a fairly smooth line and able to approach the desired waypoints. The USV cross tracks error position against a line is connecting the waypoints to the L1 adaptive controller at the rate of 0.2974 meters.

![Figure 12. The USV position response by an L1 adaptive controller with the disturbances (first scenario)](image12)

![Figure 13. The steering angle response by an L1 adaptive controller with the disturbances (first scenario)](image13)

Figure 14 shows the comparison simulation result of the USV guidance system response with the disturbance at the time the L1 adaptive controller is active and inactive. Figure 15 shows the result of the USV heading angle with the waypoint guidance. In the third scenario, for the circular motion it can be seen that the USV control using L1 adaptive controller still providing good results despite the external disturbance is induced. The capability of quick adaptation and robust make the response of steering angle is not oscillating and when sharp angle change is set the response of heading is also not oscillating. Waypoints passed by the vessel, although the disturbance is given, produce a fairly smooth line and able to approach the desired waypoints. The USV cross tracks error position against a line is connecting the waypoints to the L1 adaptive controller at the rate of 0.3028 meters.

![Figure 14](image14)

![Figure 15](image15)
Figure 14. The USV position response by the L1 adaptive controller with the disturbances (second scenario)

Figure 15. The steering angle response by the L1 adaptive controller with the disturbances (second scenario)

6. Conclusions

From the results of the discussion, several conclusions can be taken as follows:

1. In this research of the USV setting system design with the L1 adaptive method exhibits the L1 adaptive controller produces USV response of the translation velocity at x-axis (surge) and angular velocity at θ-axis (yaw) that appropriately meet to the desired design criteria such as 4.591 seconds in the x-axis and 1.48 seconds in θ-axis.

2. The USV heading angle response with the L1 adaptive controller against the response of the state predictor reference model has an RMSE value equal to 1.4294 × 10^{-4} rad/s.

3. The USV position response by the L1 adaptive controller at the time based on the force of the external disturbances such as wind, currents, and waves produces a fairly smooth tracking line motion and able to reach or approach the desired waypoints as well. It was proven by the results which demonstrate notably small error in waypoint average. The first and second scenario of the USV motions, respectively, produce cross-track errors equal to 0.2974 and 0.3028 meters RMS.

4. The autopilot and USV monohull LSS01 vessel guidance system result is indicating that the L1 adaptive controller can influence the USV response. On the other side, it can overcome the external disturbance so that the USV following the waypoint with quick response and smooth line.
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