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Judul	: Estimation of UNUSAITS AUV Position of Motion Using Extended Kalman Filter (EKF)
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No. Pemeriksaan	: 2022.06.10.282

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Estimation of UNUSAITS AUV Position of Motion Using Extended Kalman Filter (EKF)

by Teguh Herlambang 13

Estimation of UNUSAITS AUV Position of Motion Using Extended Kalman Filter (EKF)

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***Abstract*—One of the underwater robots is an Autonomous Underwater Vehicle (AUV). AUV is relatively flexible for ocean observation because it does not need cables and can swim freely without obstacles. This paper presents the results of the development of the AUV navigation and guidance system through the estimated trajectory. The AUV motion system has 6 degrees of freedom (DOF). The nonlinear model of six degrees of freedom, applied to AUV, was linearized using Jacobian matrix. The resulted linear system was then implemented as a platform to estimate the trajectory. One of the trajectory estimation methods is the Extended Kalman Filter (EKF) method. This paper implements the EKF method to estimate AUV trajectory for turning and rotating motions. The simulation results show that the EKF method has an accuracy of more than 97% with a position error of within the range of 0.05% - 3% and x position error of 0.0007325 meters, y position error of 0.014337 m meters.**

Keywords— Estimation Position, AUV, 6-DOF, Extended Kalman Filter (EKF)

I. Introduction

Indonesia is an.archipelagic country wih a vast water territory. It has abundant natural potential, but the country also encounters threats such as fish stealing and natural disaster for instance tsunami in Palu and Lombok. This allows strong motivation to do research on Autonomous underwater vehicle. Autonomous Underwater Vehicle (AUV) is an underwater robot that can be controlled from land [1,2]. AUV is often used for defense and security systems, devices for corrosion detection of the bottom of the ship when berthing, and devices for detecting damage to subsea resources [3,4]. Some research related to AUV model, among others, were Chiu et al (2000) used the AUV mathematical model of only 2-DOF [5]. Akcaya et al. (2009) and Nurhadi et al. (2011) used a 3-DOF mathematical model, Akcaya et al used linearization with the help of the linmod tool in Matlab software, Palmer. et al used 3-DOF including surge, heave and pitch, Nurhadi et al used 3-DOF focusing on only translational motion without rotational motion [6,7]. Rezazadegan et al (2013) used a 5-DOF model [8].

Some research related to AUV model, among others , were Healey, AJ (2002) described a navigation system by using EKF mehod in 3 subsystems namely depth, altitude and heading at Naval Postgraduate School (NPS) ARIES AUV in shallow water, followed by Garcia et al (2002) using the Augmented State Kalman Filter (ASKF) method on GARBI AUV [9]. Loebis et al (2004) developed a navigation system by using EKF method, Simple Kalman filter (SKF), Fuzzy Simple Kalman Filter (FSKF), Fuzzy Extended Kalman Filter (FEKF) on the Hammerhead AUV [10], then Kalyan and Balasuriya (2004) using the ECK method with multi sensors for the estimated position of AUV and Forward Looking Sonar (FLS) and Charged Coupled Device (CCD) on NTU AUV [11]. Herlambang et al (2018) using Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) for control AUV system [12].

The navigation.system uses a trajectory estimation approach. The estimation method is widely used in several fields such as the estimation of the missile position [13], water level estimation on the steam drum [14], and, in economic field, stock price estimation [15]. So the estimation method can be used to estimate the AUV position and to monitor AUV whether it goes through the predetermined path. The very significance of this paper is trajectory estimation using Extended Kalman Filter. The contribution of this paper was comparison of the accuracy of the navigation and guidance system performance of turning motion without diving and of rotating without diving by the 6-DOF AUV linear model.

II. Autonomous Underwater Vehcile

The profile of UNUSAITS AUV is as shown in Figure 2. Figure 1 show that AUV has six degrees of freedom (6-DOF), that is, surge, sway, heave, roll, pitch and yaw. The equation of AUV motion is influenced by the outer force as follows [3]:

$$\tau = \tau_{hidrostatis} + \tau_{addedmass} + \tau_{drag} + \tau_{lift} + \tau_{control} \quad (1)$$

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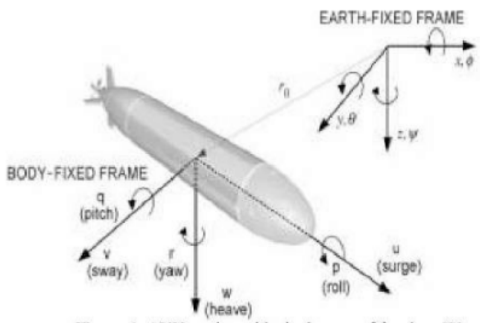

Figure 1. AUV motion with six degrees of freedom [3]

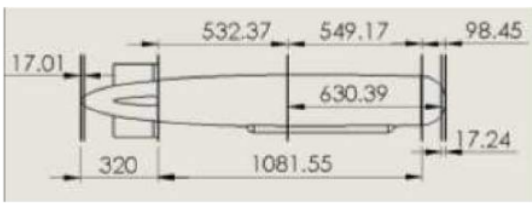

Figure 2. Profile of UNUSAITS AUV [16]

The UNUSAITS AUV's movement has 6 degrees of freedom (6 DOF), that is, 3 (three) degrees of freedom for the direction of translational motion on the x-axis (surge), y-axis (sway), and z-axis (heave) and the other 3 (three) degrees of freedom for rotational motion on x-axis (roll), y-axis (yaw), and z-axis (pitch). The UNUSAITS AUV specifications include, among others, weight of 16 kg, length of 1.5 m, and a diameter of 20 cm [16]. The general description of 6-DOF of AUV can be expressed in the equation [3,4]:

$$\eta = [\eta_1^T, \eta_2^T]^T, \quad \eta_1 = [x, y, z]^T, \quad \eta_2 = [\emptyset, \theta, \Psi]^T;$$

$$v = [v_1^T, v_2^T]^T, \quad v_1 = [u, v, w]^T, \quad v_2 = [p, q, r]^T;$$

$$\tau = [\tau_1^T, \tau_2^T]^T, \quad \tau_1 = [X, Y, Z]^T, \quad \tau_2 = [K, M, N]^T;$$

In which η shows the vector position and orientation on EFF, And, τ denotes the force vector and moment working on AUV on BFF, surge (u), sway (v), heave (w), roll (p), pitch (q) and yaw (r). The total force and moment working on AUV can be obtained by combining hydrostatic force, hydrodynamic force and thrust force. In this case it is assumed that the diagonal inertia tensor (I_o) is zero, to obtain the total force and moment of the whole model as follows [3]:

Surge:

$$m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})] = X_{|u|u}u|u| + X_{\dot{u}}\dot{u} + X_{wq}wq + X_{qq}qq + X_{vr}vr + X_{rr}rr + X_{prop} \quad (1)$$

Sway :

$$m[\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(pq + \dot{r})] = Y_{res} + Y_{|v|v}v|v| + Y_{r|r|}r|r| + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{ur}ur + Y_{wp}wp + Y_{pq}pq + Y_{uv}uv + Y_{uu\delta_r}u^2\delta_r \quad (2)$$

Heave :

$$m[\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(rp - \dot{q}) + y_G(rq + \dot{p})] = Z_{res} + Z_{|w|w}w|w| + Z_{q|q|}q|q| + Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_{uq}uq + Z_{vp}vp + Z_{rp}rp + Z_{uw}uw + Z_{uu\delta_s}u^2\delta_s \quad (3)$$

Roll:

$$I_x\dot{p} + (I_z - I_y)qr + m[y_G(\dot{w} - uq + vp) - z_G(\dot{v} - wp + ur)] = K_{res} + K_{p|p|}p|p| + K_{\dot{p}}\dot{p} + K_{prop} \quad (4)$$

Pitch :

$$I_y\dot{q} + (I_x - I_z)rp + m[z_G(\dot{u} - vr + wq) - x_G(\dot{w} - uq + vp)] = M_{res} + M_{w|w|}w|w| + M_{q|q|}q|q| + M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_{uq}uq + M_{vp}vp + M_{rp}rp + M_{uw}uw + M_{uu\delta_s}u^2\delta_s \quad (5)$$

Yaw :

$$I_z\dot{r} + (I_y - I_z)pq + m[x_G(\dot{v} - wp + ur) - y_G(\dot{u} - vr + wq)] = N_{res} + N_{v|v|}v|v| + N_{r|r|}r|r| + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_{ur}ur + N_{wp}wp + N_{pq}pq + N_{uv}uv + N_{uu\delta_r}u^2\delta_r \quad (6)$$

Translational motion u, v and w are representation of surge, sway and heave. Rotational motion p, q and r are representation of roll, pitch and yaw. The nonlinear system of AUV model can be linearized with Jacobian matrix where the nonlinear AUV system in general as follows :

$$\dot{x}(t) = f(x(t), u(t), t)$$
$$y(t) = g(x(t), u(t), t) \quad (7)$$

So the Jacobian matrix is formed as follows [10] :

$$\frac{\partial f(\bar{x}, \bar{u}, t)}{\partial x} = \begin{bmatrix} \frac{\partial f_1(\bar{x}, \bar{u}, t)}{\partial x_1} & \frac{\partial f_1(\bar{x}, \bar{u}, t)}{\partial x_2} & \cdots & \frac{\partial f_1(\bar{x}, \bar{u}, t)}{\partial x_n} \\ \frac{\partial f_2(\bar{x}, \bar{u}, t)}{\partial x_1} & \frac{\partial f_2(\bar{x}, \bar{u}, t)}{\partial x_2} & \cdots & \frac{\partial f_2(\bar{x}, \bar{u}, t)}{\partial x_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial f_n(\bar{x}, \bar{u}, t)}{\partial x_1} & \frac{\partial f_n(\bar{x}, \bar{u}, t)}{\partial x_2} & \cdots & \frac{\partial f_n(\bar{x}, \bar{u}, t)}{\partial x_n} \end{bmatrix} \quad (8)$$

So equation 1 - 6 can be expressed as follows :

$$\begin{bmatrix} 1 & 0 & 0 & 0 & \frac{mz_G}{m-X_{\dot{u}}} & \frac{-my_G}{m-X_{\dot{u}}} \\ 0 & 1 & 0 & -\frac{mz_G}{m-Y_{\dot{v}}} + & 0 & \frac{(mx_G - Y_{\dot{r}})}{m-Y_{\dot{v}}} \\ 0 & 0 & 1 & \frac{my_G}{m-Z_{\dot{w}}} & -\frac{(mx_G + Z_{\dot{q}})}{m-Z_{\dot{w}}} & 0 \\ 0 & -\frac{mz_G}{I_x-K_{\dot{p}}} & \frac{my_G}{I_x-K_{\dot{p}}} & 1 & 0 & 0 \\ \frac{mz_G}{I_y-M_{\dot{q}}} & 0 & -\frac{(mx_G+M_{\dot{w}})}{I_y-M_{\dot{q}}} & 0 & 1 & 0 \\ -\frac{my_G}{I_z-N_{\dot{r}}} & \frac{(mx_G-N_{\dot{v}})}{I_z-N_{\dot{r}}} & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \end{bmatrix} \quad (2) \quad (9)$$

Where $f_1, f_2, f_3, f_4, f_5, f_6$ expressed as follows :

$$f_1 = \frac{X_{res} + X_{|u|u}u|u| + X_{wq}wq + X_{qq}qq + X_{vr}vr + X_{rr}rr + X_{prop} - m[-vr + wq - x_G(q^2 + r^2) + pq\, y_G + pr\, z_G]}{m - X_{\dot{u}}} \quad (10)$$

$$f_2 = \frac{Y_{res} + Y_{|v|v}v|v| + Y_{r|r|}r|r| + Y_{ur}ur + Y_{wp}wp + Y_{pq}pq + Y_{uv}uv + Y_{uu\delta_r}u^2\delta_r - m[-wp + ur - y_G(r^2 + p^2) + qr\, z_G + pq\, x_G]}{m - Y_{\dot{v}}} \quad (11)$$

$$f_3 = \frac{Z_{res} + Z_{|w|w}w|w| + Z_{q|q|}q|q| + Z_{uq}uq + Z_{vp}vp + Z_{rp}rp + Z_{uw}uw + Z_{uu\delta_s}u^2\delta_s - m[-uq + vp - z_G(p^2 + q^2) + rp\, x_G + rq\, y_G]}{m - Z_{\dot{w}}} \quad (12)$$

$$f_4 = \frac{K_{res} + K_{p|p|}p|p| + K_{prop} - \left((I_z - I_y)qr + m\begin{bmatrix} y_G(-uq + vp) - \\ z_G(-wp + ur) \end{bmatrix}\right)}{I_x - K_{\dot{p}}} \quad (13)$$

$$f_5 = \frac{M_{res} + M_{w|w|}w|w| + M_{q|q|}q|q| + M_{uq}uq + M_{vp}vp + M_{rp}rp + M_{uw}uw + M_{uu\delta_s}u^2\delta_s - ((I_x - I_z)rp + m[z_G(-vr + wq) - x_G(-uq + vp)])}{I_y - M_{\dot{q}}} \quad (14)$$

$$f_6 = \frac{N_{res} + N_{v|v|}v|v| + N_{r|r|}r|r| + N_{ur}ur + N_{wp}wp + N_{pq}pq + N_{uv}uv + N_{uu\delta_r}u^2\delta_r - ((I_y - I_z)pq + m[x_G(-wp + ur) - y_G(-vr + wq)])}{I_z - N_{\dot{r}}} \quad (15)$$

Furthermore linear system is obtained as follows [7]:

$$\dot{x}(t) = A\,x(t) + Bu(t)$$

$$y(t) = Cx(t) + Du(t) \quad (16)$$

with

$$A = J_A = \begin{bmatrix} \begin{matrix}1&0&0\\0&1&0\\0&0&1\end{matrix} & \begin{matrix} 0 & \frac{mz_G}{m-X_{\dot{u}}} & \frac{-my_G}{m-X_{\dot{u}}} \\ -\frac{mz_G}{m-Y_{\dot{v}}}+ & 0 & \frac{(mx_G-Y_{\dot{r}})}{m-Y_{\dot{v}}} \\ \frac{my_G}{m-Z_{\dot{w}}} & -\frac{(mx_G+Z_{\dot{q}})}{m-Z_{\dot{w}}} & 0 \end{matrix} \\ \begin{matrix} 0 & -\frac{m\,z_G}{I_x-K_{\dot{p}}} & \frac{m\,y_G}{I_x-K_{\dot{p}}} \\ \frac{m\,z_G}{I_y-M_{\dot{q}}} & 0 & -\frac{(m\,x_G+M_{\dot{w}})}{I_y-M_{\dot{q}}} \\ -\frac{my_G}{I_z-N_{\dot{r}}} & \frac{(mx_G-N_{\dot{v}})}{I_z-N_{\dot{r}}} & 0 \end{matrix} & \begin{matrix}1&0&0\\0&1&0\\0&0&1\end{matrix} \end{bmatrix}^{-1}$$

$$\begin{bmatrix} a_1 & b_1 & c_1 & d_1 & e_1 & g_1 \\ a_2 & b_2 & c_2 & d_2 & e_2 & g_2 \\ a_3 & b_3 & c_3 & d_3 & e_3 & g_3 \\ a_4 & b_4 & c_4 & d_4 & e_4 & g_4 \\ a_5 & b_5 & c_5 & d_5 & e_5 & g_5 \\ a_6 & b_6 & c_6 & d_6 & e_6 & g_6 \end{bmatrix} \quad (17)$$

$$B = J_B = \begin{bmatrix} \begin{matrix}1&0&0\\0&1&0\\0&0&1\end{matrix} & \begin{matrix} 0 & \frac{mz_G}{m-X_{\dot{u}}} & \frac{-my_G}{m-X_{\dot{u}}} \\ -\frac{mz_G}{m-Y_{\dot{v}}}+ & 0 & \frac{(mx_G-Y_{\dot{r}})}{m-Y_{\dot{v}}} \\ \frac{my_G}{m-Z_{\dot{w}}} & -\frac{(mx_G+Z_{\dot{q}})}{m-Z_{\dot{w}}} & 0 \end{matrix} \\ \begin{matrix} 0 & -\frac{m\,z_G}{I_x-K_{\dot{p}}} & \frac{m\,y_G}{I_x-K_{\dot{p}}} \\ \frac{m\,z_G}{I_y-M_{\dot{q}}} & 0 & -\frac{(m\,x_G+M_{\dot{w}})}{I_y-M_{\dot{q}}} \\ -\frac{my_G}{I_z-N_{\dot{r}}} & \frac{(mx_G-N_{\dot{v}})}{I_z-N_{\dot{r}}} & 0 \end{matrix} & \begin{matrix}1&0&0\\0&1&0\\0&0&1\end{matrix} \end{bmatrix}^{-1}$$

$$\begin{bmatrix} A_1 & B_1 & C_1 & D_1 & E_1 & G_1 \\ A_2 & B_2 & C_2 & D_2 & E_2 & G_2 \\ A_3 & B_3 & C_3 & D_3 & E_3 & G_3 \\ A_4 & B_4 & C_4 & D_4 & E_4 & G_4 \\ A_5 & B_5 & C_5 & D_5 & E_5 & G_5 \\ A_6 & B_6 & C_6 & D_6 & E_6 & G_6 \end{bmatrix} \quad (18)$$

$$C = \begin{bmatrix} 1&0&0&0&0&0 \\ 0&1&0&0&0&0 \\ 0&0&1&0&0&0 \\ 0&0&0&1&0&0 \\ 0&0&0&0&1&0 \\ 0&0&0&0&0&1 \end{bmatrix} \text{ and } D = 0$$

$$\text{So} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = A \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix} + B \begin{bmatrix} X_{prop} \\ \delta_r \\ \delta_s \\ K_{prop} \\ \delta_s \\ \delta_r \end{bmatrix} \quad (19)$$

III. Extended Kalman Filter

The Extended Kalman Filter (EKF) algorithm can be seen [17]:

Model system and measurement model

$x_k = f(x_{k-1}, u_{k-1}, w_{k-1})$

$z_k = h(x_k, v_k)$

$x_0 \sim N(\bar{x}_0, P_{x_0})$, $w_k \sim N(0, Q_k)$, $v_k \sim N(0, R_k)$

1. Initialization

   $\hat{x}_0 = \bar{x}_0$

   $P_0 = P_{x_0}$

2. Time Update

   Estimation: $\hat{x}_k = f(\hat{x}_{k-1}, u_{k-1}, 0)$

   Error covariance : $P_k^- = A_k P_{k-1} A_k^T + W_k Q_{k-1} W_k^T$

3. Measurement Update

   Kalman Gain: $K_k = P_k^- H_k^T [H_k P_k^- H_k^T + V_k R_k V_k^T]^{-1}$

   Estimation : $\hat{x}_k = \hat{x}_k^- + K_k(z_k - h(\hat{x}_k^-, 0))$

   Error covariance : $P_k = (I = K_k H_k) P_k^-$

IV. Computational Result

This simulation has been carried out by implementing an algorithm of Extended Kalman Filter (EKF) in AUV linear model. The computational result was evaluated and compared between real condition to estimation result with EKF. This simulation consistted of two types of simulations, in which the first a turning trajectory without diving and the second simulation a rotating trajectory.

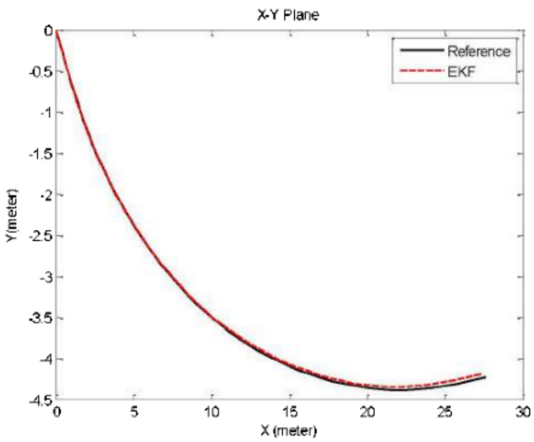

Figure 3. Computational Result for Turning motion of AUV on XY plane using EKF

Initial condition in simulation used were $u_0 = 0\,m$, $v_0 = 0\,m$, $w_0 = 0\,m$, $p_0 = 0\,rad$, $q_0 = 0\,rad$ and $r_0 = 0\,rad$, and assuming u (surge), v (sway), w (heave), p (roll), q (pitch), r (yaw). The value of Δt was $\Delta t = 0{,}1$ .Figure 3 shows that the AUV position determined as a reference was passed quite accurately by the EKF method with an accuracy of around 97% with an x position error of 0.0087679 meters and a Y position error of 0.02217 meters or an accuracy of 98%.

Figure 4 shows just a straight line because the simulation was only for turning without diving with an accuracy of 98%. Figure 5 shows that AUV moved to or following the position or trajectory specified in the XYZ plane.

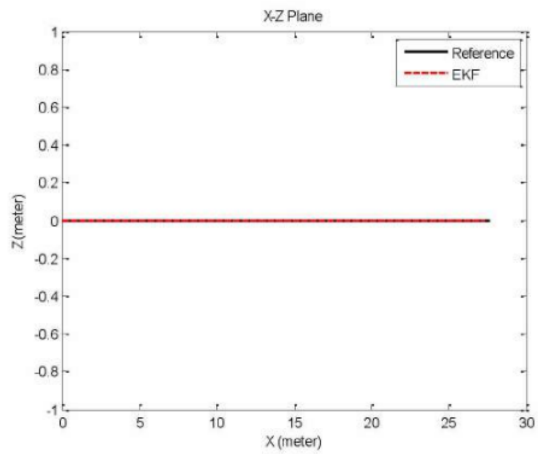

Figure 4. Computational Result for turning motion of AUV on XZ plane using EKF

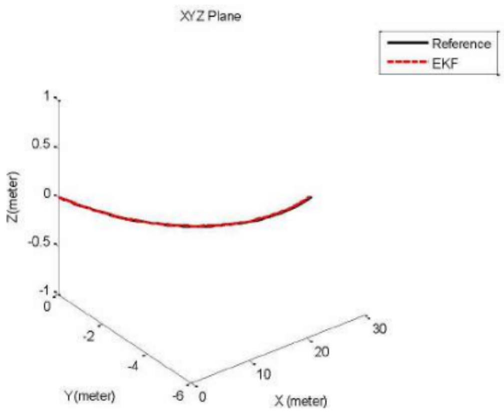

Figure 5. Computational Result for turning motion of AUV on XYZ plane using EKF

Figure 5 is a combination of Figures 3 and Figure 4 depicted in three dimensions with an accuracy of around 97.5%. While Figure 6-8 show the simulation results for elliptical circular motion.

Figure 6 shows that with the application of the EKF method, AUV could move following the determined path of the ellipse. The EKF algorithm in the form of predictions and corrections applied to the 6-DOF linear model could minimize errors in both the XY and XZ fields. Figure 6 it indicates that the accuracy of the EKF method was quite high, around 96% with an x position error of 0.0007325 meters and a Y position error of 0.014337 meters. Figure 7 shows just a straight line because the simulation was only for moving round the ellipse without diving with an accuracy of around 98%.

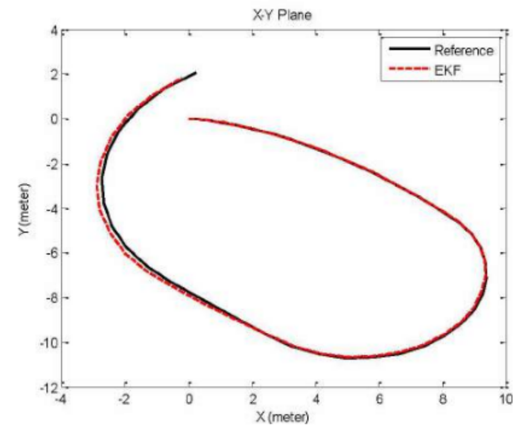

Figure 6. Computational Result for rotating motion of AUV on XY plane using EKF

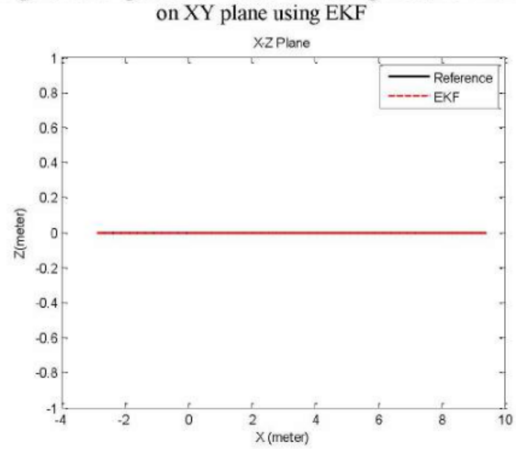

Figure 7. Computational Result for for rotating motion of AUV on XY plane using EKF

Figure 8 shows that AUV could move following the path specified in the XYZ field with an accuracy of around 96%. The two simulation results for turning without diving and turning ellipse without diving have a fairly high accuracy, and this was in line with the estimation that each 6-DOF motion also had a fairly small error of around 0.099621 m/s for translational motion and that of 0.02271 rad/s for rotational motion that can be seen in Table 2

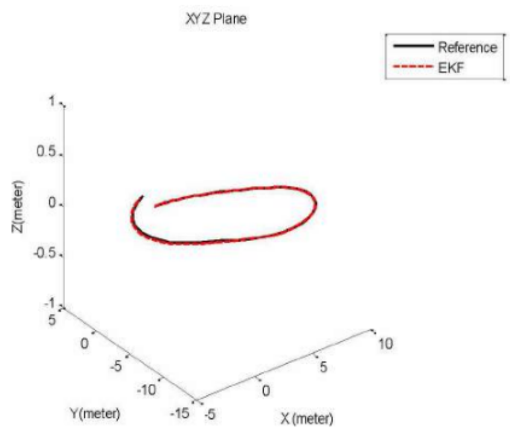

Figure 8. Computational Result for rotating motion of AUV on XYZ plane using EKF

Table 2. RMSE value from Computational Result Using EKF

	Turning Motion		Rotating Motion	
	RMSE	Accuracy (%)	RMSE	Accuracy (%)
Surge	0.0033624 m/s	98.2%	0.099621 m/s	96.2%
Sway	0.0010689 m/s	97.8%	0.045428 m/s	95.8%
Heave	0.00016359 m/s	97.5%	0.01875 m/s	96.9%
Roll	0.00022747 rad/s	96.9%	0.48122 rad/s	97 %
Pitch	0.0015682 rad/s	98.6%	0.04411 rad/s	96.5%
Yaw	0.00011478 rad/s	97.2%	0.02271 rad/s	95.7%
X	0.0087679 m	97.2%	0.0007325 m	96.3 %
Y	0.02217 m	98 %	0.014337 m	96.2 %
Z	0 m	97.4 %	0 m	96 %
Time	5.712 s		7.314 s	

V. CONCLUSION

Based on the analysis of the two simulation results, Extended Kalman Filter (EKF) method can be applied to estimate linear system position of UNUSAITS AUV with considerably high accuracy of more than 97% with a position error of within the range of 0.05% - 3% and x position error of 0.0007325 meters, y position error of 0.014337 m meters. Of the two simulations of turning and rotating motion, the estimation results were all accurate.

ACKNOWLEDGMENT

High appreciation to the Ministry of Research and High Education (Kemenristekdikti), Republic of Indonesia for the fund for my research conducted in the year of 2019 with contract number 061/SP2H/LT/MONO/L7/2019 and 946/PKS/ITS/2019. Appreciation to The Center of Excellence for Mechatronics and Industrial Automation (PUI-PT MIA-RC ITS) Kemenristekdikti, Republic of Indonesia.

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