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Trajectory Estimation of Autonomous Surface Vehicle Using Extended Kalman Filter

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Abstract. Autonomous Surface Vehicle (ASV) is a ship that can move autonomously in the water surface. In this work, we focus on Touristant ASV with the following specifications: length 4 meters, diameter 1.5 meters and height 1.3 meters. The main objective of this work is estimating the position of ASV based on the linear ASV model under the influence of wind speed and wave height, where the linear model is obtained from the linearization of the original nonlinear ASV model. In this work, we apply the Extended Kalman Filter (EKF) method to the linear ASV model in order to produce a small error in position. There are 2 simulations for the implementation of the EKF method, with 200 and 300 iterations. The error of position resulting from the simulation shows that the estimation accuracy of position is 95% - 98% where the error of position in the x-axis is 0.01 meters, the error of position in the y-axis is 0.012 meters and the error of position in the plane XY is 0.011 meters.

1. Introduction

An unmanned surface ship or commonly called Autonomous Surface Vehicle (ASV) is a surface vessel capable of automatically moving without any crew on it. One of many ways utilizing a surface vessel is as a tourist attraction. Developing unmanned surface vessels or ASVs can help the government revitalize the mode of marine tourism across the NKRI teritory [1].

ASV can also increase the income of a country, especially from the marine tourism sector. Some marine tourisms in the water area of East Java, Indonesia, namely Gresik Delegan Beach in the north coast of Java and Papuma Beach - Jember in the south coast of Java. Delegan Gresik Beach is one of the touristic places located in Gresik by, offering numerous natural attractions of marine environment and coastal views in the north coast of Java. To make visitors enjoy the beauty of the beach, Delegan Beach is provided with a simple boat controlled by humans, but it could be risky. Such a boat can get an accident due to its operator's negligence, lack of professionalism, or other misconduct [2].

In the last few years, there is a rapid development of technology in Autonomous Surface Vehicle (ASV). Unmanned Surface Vehicle (USV) or ASV (Autonomus Surface Vehicle) is a boat robot that can move from one location to another in an automatic fashion. Such automatic movement requires the estimation of position of the ASV. Many studies have been conducted related to position estimation including its application to ASV by leveraging the Ensemble Kalman Filter and Square Root Ensemble Kalman Filter methods [1,3], estimation for the pathways of Autonomous Underwater Vehicle (AUV) using EnKF and EnKF-SR [4,5], and Fuzzy Kaman Filter [6], estimation for missiles using EnKF-SR [7].

In this paper, the estimation of position was applied to the 3-DOF (surge, sway and yaw) linear model resulting from the linearization of the 3-DOF nonlinear model. The position estimation was made by using the Extended Kalman Filter method, which is an extension of the classical Kalman Filter method, observed quite reliable in the linear model. The estimation of ASV position is used to observe the ASV position to check whether it had passed the predetermined trajectory. The objective of this work was the estimation of ASV position by using the linearized motion models.

2. Autonomous Surface Vehicle

The Touristant ASV considered in this work contains Global Positioning Systems (GPS), gas, sensors, bluetooth, pH sensors, and telemetry. The complete profile and specification of Touristant ASV are written in Figure 1 and Table 1.
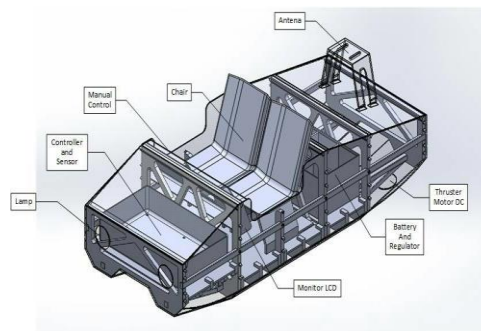

Figure 1. Touristant ASV Profile

Table 1. Specification of Touristant ASV

Length	4.12 m
Bean	1.625 m
Depth	1.027 m
DWL	0.3 m
AP	-2.618 m
FP	2.618 m

The study uses the equation of water vehicle motion with 3 degrees of freedom from 6 degrees of freedom, that is, surge, sway and, yaw. [7].

By using a simplified nonlinear model [8]:

$$(m - X_{\dot{u}})\dot{u} = X_{|u|u}|u|u + (1 - h)X_{prop} + (m + X_{vr})vr + (mx_G + X_{rr})r^2 + X_{\delta\delta}\delta^2 + X_{ext}, \tag{1}$$

$$(m - Y_{\dot{v}})\dot{v} + (mx_G - Y_{\dot{r}})\dot{r} = -(m - Y_{ur})ur + Y_{uv}uv + Y_{|v|v}|v|v + Y_{|v|r}|v|r + Y_{\delta}\delta + Y_{ext}, \tag{2}$$

$$(mx_G - N_{\dot{v}})\dot{v} + (I_z - N_{\dot{r}})\dot{r} = -(mx_G - N_{ur})ur + N_{uv}uv + N_{|v|v}|v|v + N_{|v|r}vr + N_{\delta}\delta + N_{ext}, \tag{3}$$

From the above equation, what is meant by X_{ext}, Y_{ext} and N_{ext} is an interference from outside of the surge, sway and yaw motion. In this paper, we consider the following external interference or environmental factors: the wind speed's force, wave height's force, wind speed's moment and wave height's moment. So, the equations can be written as follows;

$$X_{ext} = X_{wind} + X_{waves}$$
$$Y_{ext} = Y_{wind} + Y_{waves}$$
$$N_{ext} = N_{wind} + N_{waves}$$

From the description of X_{ext}, Y_{ext} and N_{ext}, the following *nonlinear* equations are obtained:

Surge

$$(m - X_{\dot{u}})\dot{u} = X_{|u|u}|u|u + (1 - h)X_{prop} + (m + X_{vr})vr + (mx_G + X_{rr})r^2 + X_{\delta\delta}\delta^2 + X_{wind} + X_{waves}, \quad (4)$$

$$(m - Y_{\dot{v}})\dot{v} + (mx_G - Y_{\dot{r}})\dot{r} = -(m - Y_{ur})ur + Y_{uv}uv + Y_{|v|v}|v|v + Y_{|v|r}|v|r + Y_\delta\delta + Y_{wind} + Y_{waves}, \quad (5)$$

$$(mx_G - N_{\dot{v}})\dot{v} + (I_z - N_{\dot{r}})\dot{r} = -(mx_G - N_{ur})ur + N_{uv}uv + N_{|v|v}|v|v + N_{|v|r}vr + N_\delta\delta + N_{wind} + N_{waves}. \quad (6)$$

Next, the examples are written as follows:

$$U_{surge} = X_{|u|u}|u|u + (m + X_{vr})vr + (mX_G + X_{rr})r^2 + X_{\delta\delta}\delta^2 + X_{wind} + X_{waves}$$
$$V_{sway} = -(m - Y_{ur})ur + Y_{uv}uv + Y_{|v|v}|v|v + Y_{|v|r}|v|r + Y_{wind} + Y_{waves}$$
$$N_{yaw} = -(mX_G - N_{ur})ur + N_{uv}uv + N_{|v|v}|v|v + N_{|v|r}vr + N_{wind} + N_{waves}$$

From the above examples of U_{surge}, V_{sway} and N_{yaw}, then substituted into the equation $(4-6)$, so that

$$(m - X_{\dot{u}})\dot{u} = (1 - h)X_{prop} + U_{surge} \quad (7)$$
$$(m - Y_{\dot{v}})\dot{v} + (mX_G - Y_{\dot{r}})\dot{r} = Y_\delta\delta + V_{sway} \quad (8)$$
$$(mX_G - N_{\dot{v}})\dot{v} + (I_z - N_{\dot{r}})\dot{r} = N_\delta\delta + N_{yaw} \quad (9)$$

From the equation $(7 - 8)$ then formed into *state space* $\dot{u}, \dot{v}$ dan $\dot{r}$, so that

Surge

$$\dot{u} = T_1\big((1 - h)X_{prop} + U_{surge} \big) \quad (10)$$

Sway

$$\dot{v} = T_2\big(Y_\delta\delta + V_{sway} \big) + T_3\big(N_\delta\delta + N_{yaw}\big) \quad (11)$$

Yaw

$$\dot{r} = T_4\big(Y_\delta\delta + V_{sway} \big) + T_5\big(N_\delta\delta + N_{yaw}\big) \quad (12)$$

3. Extended Kalman Filter (EKF)

The Extended Kalman Filter (EKF) algorithm can be seen in [8]:

1. System and measurement models.

$$x_{k+1} = A_k x_k + B_k u_k + G_k w_k \quad (13)$$
$$z_k = H_k x_k + v_k \quad (14)$$
$$x_0 \sim N(\bar{x}_0, P_{x_0}); \; w_k \sim N(0, Q_k); \; v_k \sim N(0, R_k) \quad (15)$$

2. Initialization

$$\hat{x}_0 = \bar{x}_0 \quad (16)$$
$$p_0 = P_{x_0} \quad (17)$$

3. Time Update

Estimation : $\hat{x}_{k+1}^- = A_k \hat{x} + B_k u_k$ $\quad (18)$

Error *covariance*: $P_k^- = A_k P_k A_k^T + G_k Q_k G_k^T$ $\quad (19)$

4. Measurement Update

Kalman gain : $K_{k+1} = P_{k+1}^T H_{k+1}^T \big(H_{k+1} P_{k+1}^- H_{k+1}^T + R_{k+1}\big)^{-1}$ $\quad (20)$

Estimation : $\hat{x}_{k+1} = \hat{x}_{k+1}^- + K_{k+1}\big(z_{k+1} - H_{k+1}\hat{x}_{k+1}^-\big)$ $\quad (21)$

Error covariance $P_{k+1} = \big[I - K_{k+1} H_{k+1}\big]P_{k+1}^-$ $\quad (22)$

4. Linearization of Nonlinear Model of ASV

The linear model that we want to get is as follows:

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

$$y(t) = Cx(t) + Du(t)$$

To determine $\dot{x}(t)$ the Jacobi matrix can be formed given as follows:

$$J_{x1} = \begin{bmatrix} \frac{\partial \Sigma_X}{\partial u} & \frac{\partial \Sigma_X}{\partial v} & \frac{\partial \Sigma_X}{\partial r} \\ \frac{\partial \Sigma_Y}{\partial u} & \frac{\partial \Sigma_Y}{\partial v} & \frac{\partial \Sigma_Y}{\partial r} \\ \frac{\partial \Sigma_N}{\partial u} & \frac{\partial \Sigma_N}{\partial v} & \frac{\partial \Sigma_N}{\partial r} \end{bmatrix} \tag{23}$$

From the differential reduction above obtained

$$A = J_{x2} = \begin{bmatrix} T_1 & 0 & 0 \\ 0 & T_2 & T_3 \\ 0 & T_4 & T_5 \end{bmatrix} J_{x1} \tag{24}$$

So, we can get J_{x2} is

$$A = J_{x2} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ b_{21} & b_{22} & b_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \tag{25}$$

So

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{r} \end{bmatrix} = J_{x2} \begin{bmatrix} u \\ v \\ r \end{bmatrix} + J_{u2} \begin{bmatrix} X_{prop} \\ \delta \\ \delta \end{bmatrix} \tag{26}$$

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ b_{21} & b_{22} & b_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix} + \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & B_{22} & B_{23} \\ 0 & C_{32} & C_{33} \end{bmatrix} \begin{bmatrix} X_{prop} \\ \delta \\ \delta \end{bmatrix} \tag{27}$$

From equation (15) to differentiate controls in sway and yaw motion then δ will be redefined δ_1 for *sway* and δ_2 for *yaw*. For more details, it will be written as follows:

$$\dot{u} = a_{11}u + a_{12}v + a_{13}r + A_{11}X_{prop} \tag{28}$$

$$\dot{v} = b_{21}u + b_{22}v + b_{23}r + B_{22}\delta_1 + B_{23}\delta_1 \tag{29}$$

$$\dot{r} = c_{31}u + c_{32}v + c_{33}r + C_{32}\delta_2 + C_{33}\delta_2 \tag{30}$$

To determine $y(t)$ can be taken C as identity matrix and $D = 0$.

5. Computational Result

In this section, we discuss the simulation of the application of the Extended Kalman Filter (EKF) algorithms to the linearized model of AUV. The simulation results were assessed, and the real system was compared to the estimation results obtained using EKF method. Two types of simulation were carried out, that is, the first simulation by 100 iterations, and the second one by 200 iterations.
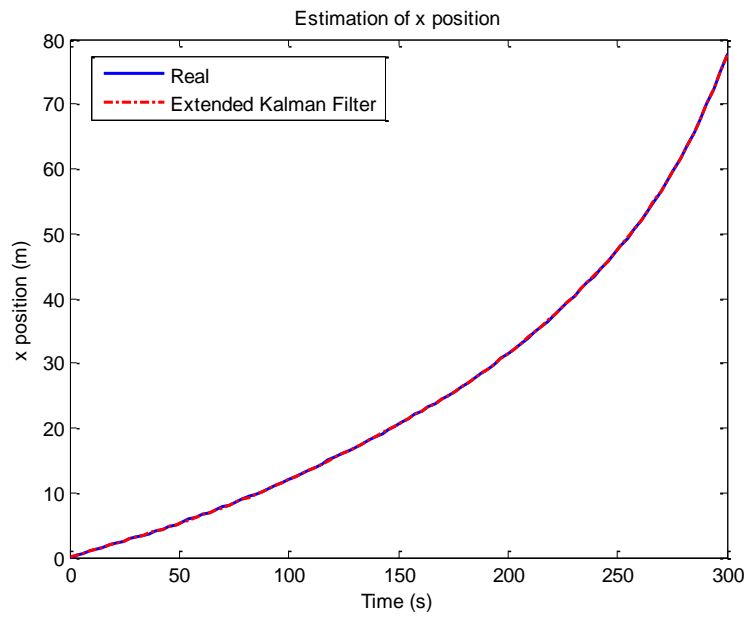
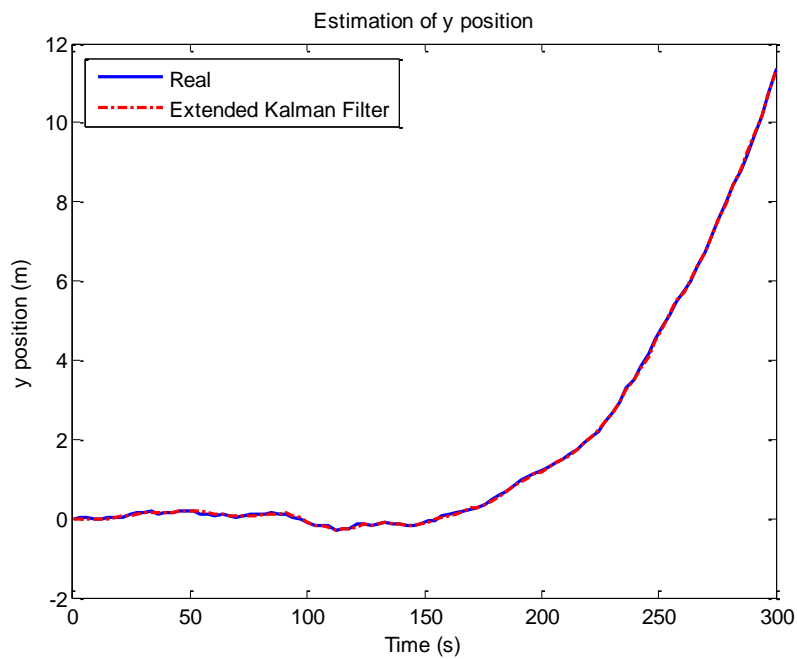**Figure 2**. Estimation of x Position of ASV using EKF with 300 iteratios

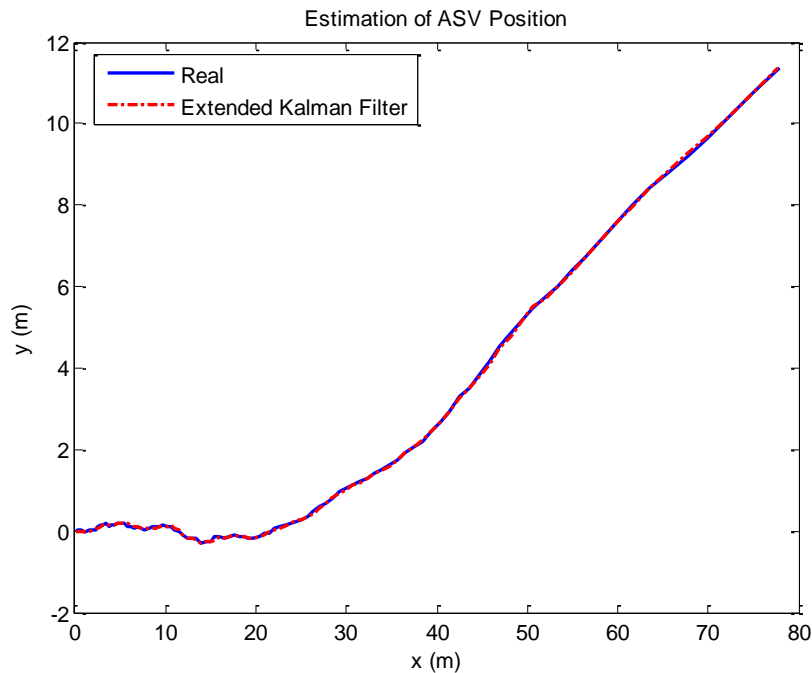**Figure 3**. Estimation of y Position of ASV using EKF with 300 iteratios

Figure 4. Estimation of XY Plane of ASV Trajectory using EKF with 300 iteratios

From Figures 2 and 3, we can observe that the ASV can move along the predefined path at the x-axis, where the EKF method has high accuracy of around 96%. The error in the case of 300 iterations is 0.00865 m for position in the X direction and 0.00876 m for position in the Y direction. Figure 4 displays that the Touristant AUV can also follow the predefined path in the XY plane by first moving forward and then dragging to the left direction, forward motion until 80 meters at the simulation time of 300 seconds. From the graph, we can see that the EKF method has a high accuracy of approximately 96% - 97,6%. Table 1 also shows the ration of position error generated from the simulation using the 200 and 300 iterations. Accurate position errors are generated by assuming that ASV operates in waters where wind speed and wave height do not occur or cause significant changes. However, with the presence of environmental factors it can also affect ASV performance, although the environmental factors that affect it are not too strong, but still have an effect on performance, if compared to those without environmental factors.

In Table 2, it appears below that by 300 iterations it gives a higher accuracy 200 iterations. According to the numerical results, the EKF method has a sufficiently high accuracy in the case of 200 or 300 iterations. However, from the computation time, the EKF with 200 iterations is faster since there is no looping for a number of iterations. Thus, we can conclude that the EKF method can be implemented on an ASV platform.

Table 2. Comparison of the values of RMSE using Extended Kalman Filter based on the iteration of 200 and

300 iterations

	200 Iterations		300 Iteration	
	RMSE	Accuracy	RMSE	Accuracy
X	0.00912 m	97,1 %	0.00865 m	97,6 %
Y	0.00934 m	97 %	0.00876 m	97,3%
XY	0.0288 m	96,8 %	0.0241m	97,15%
Time	4,67 s		7,241 s	

6.   Conclusion

According to the simulation results and the analysis in the previous section, the Extended Kalman Filter (EKF) could be used as a method to estimate the trajectory of a Touristant ASV with sufficiently high accuracy. If the number of iterations is higher, we obtain a higher accuracy, however the computational time is also longer. We can see from the numerical results that the accuracy of estimation for EKF that generates 300 iterations is higher than 200 iterations.

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Open problem. How to implement H-infinity for the estimation of ASV position

Acknowledgement

References

[1]. Nurhadi, H., Herlambang, T and Adzkiya, D. 2019, "Position Estimation of Touristant ASV Using Ensemble Kalman Filter", International Conference on Mechanical Engineering, 28-29 August 2019

[2]. Adzkiya, D ., Nurhadi, H., and Herlambang, T, 2019, "Design of Sliding Mode Control for Linearized Touristant ASV Model", *International Conference on Advance Mechatronics, Intelligent Manufactre, and Industrial Automation,* IEEE , ICAMIMIA 2019,Malang, Indonesia, Oct 9 – 10.

[3]. Nurhadi, H., Herlambang, T and Adzkiya, D. 2019, "Trajectory Estimation of Autonomous Surface Vehicle using Square Root Ensemble Kalman Filter", *International Conference on Advance Mechatronics, Intelligent Manufactre, and Industrial Automation,* IEEE , ICAMIMIA 2019,Malang, Indonesia, Oct 9 – 10.

[4]. Herlambang, T., Djatmiko E.B and Nurhadi H., 2015, "Ensemble Kalman Filter with a Square Root Scheme (EnKF-SR) for Trajectory Estimation of AUV SEGOROGENI ITS", *International Review of Mechanical Engineering* IREME Journal, Vol. 9, No. 6. Pp. 553-560, ISSN 1970 – 8734. *Nov.*

[5]. Herlambang, T., Djatmiko E.B and Nurhadi H., 2015, "Navigation and Guidance Control System of AUV with Trajectory Estimation of Linear Modelling", *Proc. of International Conference on Advance Mechatronics, Intelligent Manufactre, and Industrial Automation,* IEEE , ICAMIMIA 2015,Surabaya, Indonesia, pp. 184-187, Oct 15 – 17.

[6]. Ermayanti, E., Aprilini, E., Nurhadi H, and Herlambang T, 2015, "Estimate and Control Position Autonomous Underwater Vehicle Based on Determined Trajectory using Fuzzy Kalman Filter Method", *International Conference on Advance Mechatronics, Intelligent Manufactre, and Industrial Automation (ICAMIMIA)*-IEEESurabaya Indonesia, 15 – 16 Oktober 2015

[7]. Herlambang, T., 2017, "Design of a Navigation and Guidance System of Missile with Trajectory Estimation Using Ensemble Kalman Filter Square Root (EnKF-SR). International Conference on Computer Applications and Information Processing Technology (CAIPT)-IEEE, Bali Indonesia 8-10 Augsut 2017.

[8]. Herlambang, T, Subchan, and Nurhadi, H., 2019, "Estimation of UNUSAITS AUV Position of Motion Using Extended Kalman Filter (EKF)", *International Conference on*

Advance Mechatronics, Intelligent Manufactre, and Industrial Automation, IEEE ,
ICAMIMIA 2019,Malang, Indonesia, Oct 9 – 10.