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Ensemble and Fuzzy Kalman Filter for position estimation of an autonomous underwater vehicle based on dynamical system of AUV motion

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A B S T R A C T

An underwater vehicle is useful in the monitoring of the unstructured and dangerous underwater conditions. One of the unmanned underwater vehicle is AUV. AUV is a robotic device that is driven through the water by a propulsion system, controlled and piloted by an onboard computer, and maneuverable in three dimensions. This research explains about position estimation of AUV based on the Ensemble Kalman Filter (EnKF) and the Fuzzy Kalman Filter (FKF). EnKF is used as the estimation method of AUV's position that maneuvering in 6 DOF (Degrees of Freedom) with the specified trajectory. The estimation results are simulated with Matlab. The simulations show the AUV position estimation based on the EnKF with some of the different ensembles and the comparison results of the position estimation between the EnKF and the FKF. The final result of these study shows that Ensemble Kalman Filter is better to estimate the trajectory of the dynamical equation of AUV motion with the error estimation of EnKF is 92% smaller in the x-position dan y-position, 6.5% smaller in the z-position, 93% smaller in the angle dan the computation of time is 50% faster than the estimation results of FKF.

1. Introduction

Indonesia is a maritime country that has marine resources in the large quantities. The resources include species of flora, fauna, microbes, coral reefs, renewable resources or nonrenewable resources and others. That resources need a maintenance and monitoring regularly for safety of the country. Monitoring the condition of the unstructured and dangerous underwater needs an underwater vehicle that can overcome the condition. Vehicle that can be used for that monitoring is an unmanned underwater vehicle.

Unmanned underwater vehicle is being developed currently and it can be applied in several sector in life. That vehicle is important in many underwater activities because it has a high-speed, endurance and ability to dive more safely than humans (Yuh, 1994). One of the unmanned underwater vehicle is AUV (Autonomous Underwater Vehicle). AUV is a robotic device that driven through the water by a propulsion system, controlled and driven by the computer, and maneuverable in three dimensions (Von Alt, 2003).

A device that driven by a computer need an algorithm to guide and to control it's motion in the positioning, moreover the Global Positioning System (GPS) signal is not available underwater. Hence, Some innovative navigation strategy are designed for AUV. The Typhoon AUV is navigated based on the Unscented Kalman Filter (Allotta et al., 2016). The other algorithm is the Fuzzy Kalman Filter (FKF) that can be a positioning controller of AUV based on the determined trajectories (Ermayanti, Apriliani, Nurhadi, & Herlambang, 2015) and the FKF is also able to estimate performance parameters at off-nominal health conditions with fairly good accuracy (Rodger, 2012). Beside that, other algorithm is two stage rule based on the precision positioning control method for the linear piezoelectrically actuated table or LPAT (Kuo, Tarng, Nian, & Nurhadi, 2010). In CNC machine, one of the control method is TGPID (Nurhadi & Tarng, 2011). Beside a guidance and control, an optimization is needed in the positioning. Some research about optimization in the positioning is applied. In LPAT, a multistage rule based on the positioning optimization is applied to get a high precision LPAT (Nurhadi, 2011).

AUV is important in the underwater activities, so development of AUV should be done. One such development is the trajectory estimation of AUV. The estimation requires an appropriate method, such as a Data Assimilation. Data assimilation is an estimation

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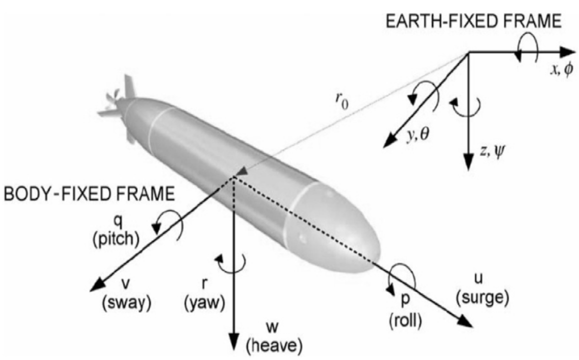

Fig. 1. Coordinate system of 6 DOF AUV (Yang, 2007).

Table 1
AUV SEGOROGENI ITS specification.

Specification	Size
Weight	15 Kg
Overall length	980 mm
Beam	188 mm
Controller	Ardupilot Mega 2.0
Communication	Wireless Xbee 2.4 GHz
Camera	TTL Camera
Battery	Li-Po 11.8 v
Propulsion	12 V motor DC
Propeller	3 blades OD; 40 mm
Speed	1,94 knots (1 m/s)

Source: Ermayanti et al. (2015)

method that combines mathematical models and measurement data (Lewis, Laksmivarahan, & Dhall, 2006). One of the data assimilation method is Kalman Filter. Kalman Filter is an estimation method for the linear dynamic stochastic system (Apriliani, Arif, & Sanjoyo, 2010). Some applications and modifications of Kalman Filter have been made to get a more accurate estimate and the computing time is shorter. Some modifications of the Kalman Filter are the ensemble Kalman filter (EnKF) and the Fuzzy Kalman Filter (FKF). EnKF is an estimation method for the non linear dynamic stochastic system based on measurement data, while the Fuzzy Kalman Filter is a modification of Kalman Filter that generate the variable state of system with the Fuzzy. EnKF is an effective method for estimation, one of that application is estimation of mobile robot position (Apriliani, Subchan Yunaini, & Hartini, 2013).

The authors developed a navigation and guidance control of AUV using the EnKF and FKF. The FKF estimation is the research before by Ermayanti et al. (2015) that gives the AUV position estimation based on the Fuzzy Kalman Filter. Each methods derive the estimation by using the 6 DOF (Degrees of Freedom) of the dynamical model of AUV that applied to the each estimation algorithm. The research before do a linearization to the dynamical model of AUV that applied in the FKF method, consequently the non linear model of AUV is become the linear form. In this occasion, we want to apply the non linear model of AUV using the EnKF to get the position estimation without any linearization like the research before. Therefore, we want to calculate the time computation and accuracy of the Enkf that compared with the FKF. This is simulated with Matlab and the Simulations show the AUV position estimation of each methods.

2. Dynamical model of AUV motion

There are two coordinate system needed which are used to describe the motion of AUV: earth-fixed (inertial) coordinates and body-fixed coordinates (Yang, 2007). Fig. 1 completely shows the definition of that coordinate system. Earth-fixed coordinates are used to describe the position and orientation of AUV. That coordinates are the x-axis that pointing north, the y-axis that pointing east and the z-axis that pointing towards the center of the earth. Body-fixed coordinates are used to describe the velocity and acceleration of the vehicles. Its origin is usually set at the center of gravity or the center of buoyancy, the x-axis is positive towards the bow, the y-axis is positive towards starboard, and the z-axis is positive downward. AUV that used in this research is AUV SEGOROGENI ITS. AUV SEGOROGENI ITS can be used for monitoring underwater and has specification in Table 1. AUV SEGOROGENI ITS uses only one propeller on the tail of AUV which will produce x_{prop} and additional moments K_{prop} (Herlambang, Djatmiko, & Nurhadi, 2015).

Table 2
The notation of AUV's equation of motion.

Motion	Forces and moments	Linear and angular velocities	Position and Euler angles
Surge (x-direction)	X	u	x
Sway (y-direction)	Y	v	y
Heave (z-direction)	Z	w	z
Roll (rotation about x)	K	p	ϕ
Pitch (rotation about y)	M	q	θ
Yaw (rotation about z)	N	r	ψ

The motion of AUV is 6 DOF, that is, three translations and three rotations along x, y, and z axis (Fossen, 1994). The general 6 DOF (Degrees of Freedom) motion equations of AUV are non linear system. That equations consist of surge, sway, heave, roll, pitch and yaw. Table 2 depicts the definition of the notation for AUV's equation of motion. That equation of AUV motion as follows (Yang, 2007):

- Surge

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

- 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

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