Navigation and guidance control system of UNUSAITS AUV based on dynamical system using ensemble kalman filter square root

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Abstract. This study presents the development of navigation system of AUV. It is in initial in the form of a nonlinear system model to determine the trajectory for the AUV motion control. The non-linear system model of UNUSAITS AUV is then implemented in the Square Root Ensemble Kalman filter (SR-EnKF) to estimate the trajectory of the AUV. The developed EnKF algorithm covers two types of simulations. The contribution from this paper is trajectory or position estimation of nonlinear UNUSAITS AUV system with 6-DOF AUV model. The result of model estimation is presented based on numeric study and simulation. The first simulation is dedicated to generate 400 ensembles, and the second simulation is to generate 400 ensembles. The second simulation shows that the 500 ensembles give more accurate results. A further examination on the accuracy has been performed by accounting for the RMSE of actual condition and the estimation from the simulation, which yields the range of accuracy between 97% up to 99%.

1. Introduction
Since ocean is about two-thirds of the whole earth surface, sources of energy for the life of mankind, in future, rely on the living and non-living resources in oceans. So far, the oceans have not been maximally explored due to the hazardous underwater environment [1]. With the marine robotics, autonomous underwater vehicles (AUV) have been in successful operation under complex environmental condition. The AUV development have been done for scientific and commercial purposes such as underwater exploration, underwater defense system equipment, sensor off board submarines, and observation of underwater structures [2,3,4]. Various hydrostatic force and moments expressed collectively in terms of hydrodynamic coefficients of mathematical model [5].

AUV is controlled and navigated by a computer on its supporting ship to move and maneuver using six degrees of freedom (6-DOF). To navigate and control AUV needs a navigation and guidance system. Several researches and AUV development conducted in the years of 2000s cover, among others, REMUS AUV developed by Prestero [6] and Bluefin Robotics AUV developed by Panish and Taylor in the Laboratory of AUV MIT [7]. Several researches on AUV navigation and guidance system conducted within the years of 2000s varied in their foci. Loebis et al described a navigation system by EKF, Simple Kalman Filter (SKF), and Fuzzy Simple Kalman Filter (FSKF) methods [8]. Bartolini [9] described a navigation system by EKF applied to REMUS AUV and Ermayanti [10] described a navigation system by Fuzzy Kalman Filter (FKF) applied to linear model of AUV, and Herlambang [11] using Ant Colony Optimization and Particle Swarm Optimization (PSO) (ACO) for control AUV system. Trajectory or position estimation introduced in the 1961s, and its well-known estimation method is the Filter Kalman method [12]. Kalman filter functioning as a
powerful mathematical tool for stochastic estimation from noisy sensor measurements is an effective candidate method for positioning [13]. Another tool is an extension of the Filter Kalman called the Ensemble Kalman Filter (EnKF) [14].

The very significance of this paper is trajectory or position estimation of nonlinear 6-DOF AUV model. Model estimation result is presented based on numeric study and simulation. This study proposes to validate trajectory or position estimation of AUV numerically. This paper includes two simulations. The first simulation and the second one are carried out respectively by generating 400 and 500 ensembles.

2. Autonomous Underwater Vehicle

The Profile UNUSAITS AUV are listed in Table 1. This study used AUV specifications of UNUSAITS AUV and equation of motion in 6-DOF AUV as follows [15]:

Surge:

\[ m\ddot{u} - nr + \omega q - x_0(q^2 + r^2) + y_0(pr - \dot{r}) + z_0(pr + \dot{q}) \approx X \]  

Sway:

\[ m\ddot{v} - wp + ur - y_0(r^2 + p^2) + z_0(qr - \dot{p}) + x_0(pq + \dot{r}) \approx Y \]  

Heave:

\[ m\ddot{w} - uq + vp - z_0(p^2 + q^2) + x_0(rp - \dot{q}) + y_0(rg + \dot{p}) \approx Z \]  

Roll:

\[ I_x\dot{\phi} + (I_x - I_y)qr + m[y_0(\dot{w} - uq + vp) - z_0(\dot{v} - wp + ur)] \approx K \]  

Pitch:

\[ I_y\dot{\theta} + (I_y - I_x)rp + m[x_0(\dot{u} - nr + \omega q) - x_0(\dot{w} - uq + vp)] \approx M \]  

Yaw:

\[ I_z\dot{\psi} + (I_z - I_x)pq + m[x_0(\dot{r} - wp + ur) - y_0(\dot{r} - wp + ur)] \approx N \]  

So equation 1 - 6 can be write as follows:

\[
\begin{bmatrix}
\dot{u} \\
\dot{v} \\
\dot{w} \\
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix} =
\begin{bmatrix}
\dot{u} & 0 & 0 & 0 & m_x & -m_y \\
0 & \dot{v} & 0 & 0 & -m_x & m_y \\
0 & 0 & \dot{w} & 0 & -m_y & m_x \\
0 & -m_z & 0 & \dot{p} & 0 & 0 \\
m_z & 0 & -m_y & 0 & \dot{q} & 0 \\
-m_z & 0 & m_x & 0 & 0 & \dot{r}
\end{bmatrix}
\begin{bmatrix}
u \\
v \\
w \\
p \\
q \\
r
\end{bmatrix} +
\begin{bmatrix}
f_1 \\
f_2 \\
f_3 \\
f_4 \\
f_5 \\
f_6
\end{bmatrix}
\]  

(7)

If we write completely, so the discrete models in equation (7) can be written generally in a nonlinear function below

\[ x_{k+1} = f(x_k, u_k) + w_k \]  

(8)

\[ z_k = Hx_k + v_k \]  

(9)

\[ w_k \] is the noise of system and \[ v_k \] is the noise of measurement [16].
Figure 1. Translational and Rotational Motion in AUV [17]

Figure 2. Profile of UNUSAITS AUV [18]

3. Square Root Ensemble Kalman Filter
The algorithm of Square Root Ensemble Kalman Filter (SR-EnKF) can be seen [19,20,21]:

\[
x_{k+1} = f(x_k, u_k) + w_k
\]
\[
z_k = Hx_k + v_k
\]
\[
w_k \sim N(0, Q_k), v_k \sim N(0, R_k)
\]

1. Initialization
   Generate Ensemble as the first guess \( \bar{x}_0 \)
   \[
x_{0,i} = [x_{0,1}, x_{0,2}, \ldots, x_{0,N}] \]
   The first Mean Ensemble:
   \[
   \bar{x}_{0,i} = x_{0,i} 1_N
   \]
   The first Ensemble error:
   \[
   \tilde{x}_{0,i} = x_{0,i} - \bar{x}_{0,i} = x_{k,i}(I - 1_N)
   \]

2. Time Update
   \[
   \tilde{x}_{k,i} = f(\tilde{x}_{k-1,i}, u_{k-1,i}) + w_{k,i}
   \]
   Where \( w_{k,i} = N(0, Q_k) \)
   Mean Ensemble:
   \[
   \bar{x}_{k,i} = \tilde{x}_{k,i} 1_N
   \]
   Error Ensemble:
   \[
   \tilde{x}_{k,i} = \bar{x}_{k,i} - \bar{x}_{k,i} = \tilde{x}_{k,i}(I - 1_N)
   \]

3. Measurement Update
   \[
   z_{k,i} = Hx_{k,i} + v_{k,i}
   \]
   Where \( v_{k,i} \sim N(0, R_k) \)
\[ S_k = H \tilde{x}_{k-1}^-, E_k = (v_1, v_2, \ldots, v_N) \] and
\[ C_k = S_k S_k^T + E_k E_k^T \]

Mean Ensemble:
\[ \bar{x}_{k,i} = \tilde{x}_{k,i}^- + \tilde{x}_{k,i}^- S_k^T C_k^{-1} (\bar{x}_{k,i} - H \tilde{x}_{k,i}^-) \]

Square Root Scheme:
- eigen value decomposition from
\[ C_k = U_k \Lambda_k U_k^T \]
- determine matrix
\[ M_k = \frac{1}{\lambda_k^2} U_k^T S_k^{-1} \]
- determine SVD from
\[ M_k = Y_k L_k V_k^T \]

Ensemble Error:
\[ \tilde{x}_{k,i} = \tilde{x}_{k,i}^- V_k (I - L_k L_k^T)^{-1} \]

Ensemble Estimation:
\[ \hat{x}_{k,i} = \tilde{x}_{k,i}^- + \bar{x}_{k,i} \]

4. Simulation Result
The simulation was done by implementing Square Root Ensemble Kalman Filter (SR-EnKF) algorithm in non-linear model of AUV. The results of the simulation were evaluated, then they were compared. Those by EnKF-SR were compared to the real condition. This simulation covered two kind of simulations, of which the first simulation generated 400 ensemble and the second simulation generated 500 ensemble. Initial condition used were \( u_0 = 0 \ m, v_0 = 0 \ m, \omega_0 = 0 \ m/s, p_0 = 0 \ rad, q_0 = 0 \ rad \) and \( r_0 = 0 \ rad \).

Figure 3 shows the trajectory estimation result of AUV by generating 500 ensembles. Figure 3 shows the trajectory estimation result in XY plane, whereas Figure 4 shows that of in XZ plane. Figure 3 and 4 show the result of the trajectory estimation highly accurate with tracking error of translational motion of 0.00166 m/s with accuracy of 99.924%. Error of rotational motion was 0.00021 m/s.
Figure 4. Trajectory XZ Plane Estimation of UNUSAITS AUV with 500 ensemble

Figure 5. Trajectory XYZ Plane Estimation of UNUSAITS AUV with 500 ensemble

Figure 5 shows that in XYZ plane and UNUSAITS AUV moved forward and turned around within XY plane to the right direction and dived moving right and left. In general as seen in the Table 1, the two simulations result were highly accurate. The first numeric simulation was by generating 400 ensembles with error of x-axis 0.2124 m, y-axis 0.0529 m and accuracy 99.28% and z-axis 0, 0.030143 m and accuracy 99.6%. The second simulation by generate 500 ensemble with tracking error of x-axis 0.57 m, y-axis 0.257 m and accuracy 99.65 %, z-axis 0.0243 m. Considering time simulation of the two simulations, the result of the simulation with 400 ensembles was faster than that with 500 ensembles because the more ensembles were generated, the longer time the simulation took.
5. Conclusion

Based on the discussion of the numeric simulation results of both simulations, the conclusion is that the Square Root Ensemble Kalman Filter method could be effectively applied to estimate nonlinear system trajectory of UNUSAITS AUV with quite high accuracy. Of the two simulations by generating both 400 and 500 ensembles, the result of the simulations were both accurate.

Open problem. How to implemented Particle Filter for trajectory estimation of AUV.

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