State estimation using filtering methods applied for Aircraft landing maneuver

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1. ABSTRACT AND INTRODUCTION

The most common application of state estimation methods is for validation of aerodynamic database, on Aircraft flight maneuver performance characteristics. The focus of this work is on adaptation of familiar filtering methods for landing maneuver problem such that, the Aircraft states at the time of touchdown can precisely be estimated. The mathematical model for symmetrical two point landing maneuver (main wheel in contact with the ground and nose wheel airborne) consists of; non-linear flight mechanics equation representing Aircraft longitudinal dynamics. The measurement data is obtained from a non-linear 6 DOF pilot in loop simulation using FORTRAN. These data is additively mixed with process and measurement noises that are used as an input for posterior corrections. With the state values just before the initiation of flare as initial conditions, filters such as Upper Diagonal factorized form of Adaptive Extended Kalman Filter (UD-AEKF) and Unscented Kalman Filter (UKF) are implemented in Matlab environment. The estimated states, performance metrics of the filters and possible outcome of purely relying on the Aircraft measurement data were discussed.

The important states that govern the landing impact loads are vertical sink speed ($\dot{h}$), pitch angle (θ), pitch rate ($\dot{\theta}$), pitch acceleration ($\dot{q}$), true vertical (a_z) and longitudinal acceleration (a_x) [1]. While the inertial measurement sensors provides the translation acceleration (a_x, a_z) attained at the time of touch down, the limitation of using these data is imposed from noisy measurement, sensor bias and drift, location of sensor with respect to Aircraft Center of Gravity (CG), missing data and so on. EKF is a popular filtering algorithm used for recursive state and parameter estimation due to its excellent filtering properties and is based on a first order approximation of non-linear system dynamics [2]. To adapt for landing dynamics, the Upper diagonal (UD) form and an adaptive tuning process using fuzzy logic interface are implemented for state error covariance matrix and process noise covariance matrix respectively. Yet another algorithm implemented using Matlab is on UKF, which basically propagate finite set of points, called sigma points, through the nonlinear dynamics and by approximating the distribution through a weighted sum and outer (cross) product of the propagated points [3]. This work is unique of its kind, to apply these non-linear filtering algorithms on Aircraft landing maneuver problem as against the reported literatures majorly dealing with target position, velocity tracking problem of (2×2) observation equation [4 - 5].

The states such as $y(t) = [u, w, \theta, q, h]$ are obtained as measurement data from 6 DOF simulation, generated for a high performance Aircraft at a terrain of 840m above mean sea level. These data corresponds to three sets of flared landing maneuvers that varies by the application of flare technique with identical initial sink rate$(\dot{h})$. Random process noise and measurement noise are added to represent the uncertainty in the mathematical model and measurements respectively.

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2. RESULTS & DISCUSSION

The initiation of flare maneuver at a height of ~50ft above the ground level is taken as initial values for the augmented state (x_a) and considered to have a bias of 10% from the actual values. The presence of adaptive tuning process (Fuzzy logic interface) in UD-AEKF eases out the importance of initial values. For the UKF, (2 x Number of states + 1) sigma points were created and appropriate scaling and tuning parameters were set.

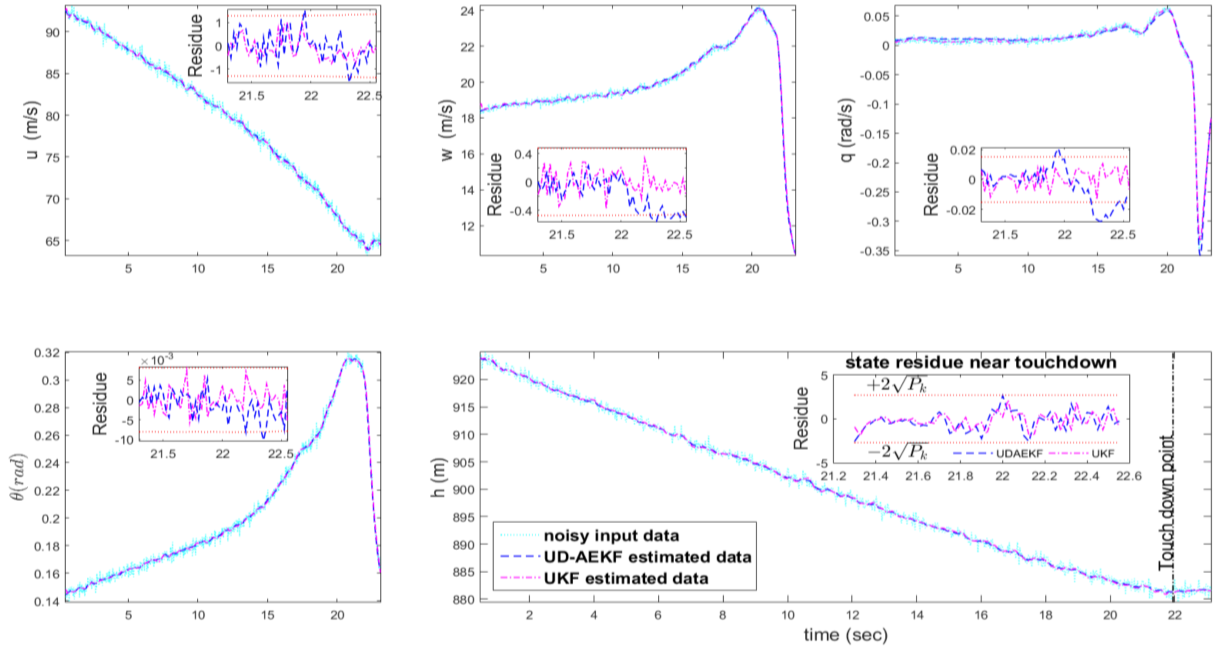

Figure 1. Estimated Aircraft states and residues (inset) for case 3 of flared landing using UDAEKF and UKF algorithms

Table 1. Aircraft states as PRSSE (%) at touch down time stamp for several flared landing cases

Aircraft states	Case 1 of flared landing		Case 2 of flared landing		Case 3 of flared landing	
	UD-AEKF : PRSSE (%)	UKF : PRSSE (%)	UD-AEKF : PRSSE (%)	UKF : PRSSE (%)	UD-AEKF : PRSSE (%)	UKF : PRSSE (%)
Longitudinal acceleration (a_x)	(+) 1.8	(+) 0.9	(+) 7.0	(+) 3.9	(-) 8.3	(-) 6.4
Vertical acceleration (a_z)	(-) 14.1	(-) 11.3	(+) 3.3	(+) 3.2	(+) 4.3	(+) 3.5
Pitch acceleration ($\dot{q}$)	(-) 4.0	(-) 4.0	(+) 7.0	(+) 7.7	(+) 1.2	(+) 3.0
Vertical sink rate ($\dot{h}$)	(-) 2.8	(-) 3.4	(+) 4.1	(+) 3.6	(+) 5.7	(+) 6.2

$$PRSSE(\%) = \sqrt{\frac{(x_m - x_e)^2}{x_m^2}} * 100$$

Where x_m is the noisy input data and x_e is the estimated states from filtering methods. (+) indicates over quantified and (-) indicates under quantified measurements

Figure 1 shows the estimated states such as (u, w, θ, q, h) of the Aircraft during landing for case 3 of flared landing. The state estimates obtained from UDAEKF and UKF filtering methods are compared against the noisy measurement data obtained through 6 DOF simulation. Inset in Figure 1 shows the performance of the filters in the form of state error bounds near touchdown time steps.

The necessary condition is to have the state errors within the theoretical bounds of $\pm 2\sqrt{(P_k)}$, where P_k is the state covariance matrix. Both these filters were able to predict the true states of the Aircraft near touchdown; with residues being minimal for UKF method as compared with UD-AEKF. This is primarily due to the linear approximation of state equations and fuzzy adaptation of process noise covariance matrix for every time step in UD-AEKF as against fair propagation of sigma points in UKF. The computational time for UKF is two and half times faster as compared with UD-AEKF which involves a fuzzy logic interface step.

Table 1 shows the states that govern the landing impact loads such as $a_x, a_z, \dot{q}, \dot{h}$ for three sets of flared landing cases obtained from the filtering methods. A comparative metrics called Percentage Root Sum Square Error (PRSSE) is used as an indicator for quantifying the error. The emphasis for true aircraft state estimation at the time of touchdown is noticeable from the comparative data presented. The results on vertical acceleration (a_z) is discussed here. The Case 2 and Case 3 of flared landing indicates that the measured value of a_z are higher than the estimated value. For Case 1 of flared landing, measured value for a_z is lower than estimate. The over quantification of measurement data, in case of hard landing event, translates into inevitable downtime for thorough inspection. On the other hand, the under quantification of measurement leads to ignorance, causing higher nominal stresses for the landing gear and its attachment components.

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