Design of Linear Kalman Filter Based Parameter Estimator for a Micro Air Vehicle

H.S. Murali and M. Meenakshi

Abstract--- *This paper presents a design of parameter estimator for a Micro Air Vehicle (MAV) named Sarika-1. Estimator is needed in applications where all parameters cannot be measured directly due to various reasons. In this work, suitable linear Kalman filter estimator is designed for the longitudinal and lateral dynamics of Sarika-1.The Linear Discrete Kalman filter is designed to estimate its longitudinal state variables viz. angle of attack, forward velocity, pitch rate and pitch angle and the lateral state variables viz. Side slip angle, roll rate, yaw rate, and bank angle. Filter is designed in MATLAB and is verified using its offline simulation. For the simulation, the measurement data of pitch rate and normal acceleration collected at the time of real flight are used for longitudinal dynamics and lateral acceleration, roll rate and yaw rate collected at the time of real flight are used for lateral dynamics. It is found that the estimated values of the state variables matches well with the corresponding actual values.*

Keywords--- *Micro Air Vehicle, Linear Kalman Filter, Parameter Estimator, Longitudinal Dynamics, Lateral Dynamics*

I. INTRODUCTION

MICRO Aerial Vehicles are remotely piloted or self-piloted aircraft that can carry cameras, sensors, communications equipment or other payloads. MAVs should be thought of as aerial robots, as six-degree-of-freedom machines whose mobility can deploy a useful micro payload to a remote location where it may perform any of a variety of missions, including reconnaissance and surveillance, targeting, tagging and bio-chemical sensing[1],[2].These missions are highly challenging and necessitate the design of autonomous MAVs. The first challenging step in achieving such MAV autonomy is the design and development of a robust flight stabilization system because, the uncertainties in the mathematical model associated with the low Reynolds number flight are not fully understood and is high.

MAVs have very low moments of inertial property; hence they are highly vulnerable to rapid angular accelerations. Another potential source of instability for MAV is the relative magnitudes of wind gusts, which are much higher at the MAV scale than for larger aircraft. An average wind gust can immediately effect a dramatic change in the flight path of these vehicles. In addition, the pilot may find it difficult to control the aircraft based on visual cues, if its dynamic modes are of high frequency and are lightly damped. Hence, robust flight controller plays an important role to simplify the task of operating the MAV while enhancing the utility of MAVs for a wide range of missions. One of the requirements of the controller design is the suitable feedback signals, which are the measurement signals. However, Limited payload capacity of small UAVs restricts the type and quality of the sensors and also the computational resources that can be placed on-board. Due to the limited payload and non-availability of light weight sensors for all the parameters under consideration for the feedback, it is not possible to measure all the parameters directly. The state parameters that cannot be measured are to be estimated by the use of a proper estimator[3],[4].

To address such problem, this paper presents the design and validation of Kalman filter based state parameter estimator for the longitudinal and lateral dynamics of Micro air vehicle named Sarika-1. Linear Kalman filters are independently designed in discrete domain to estimate its longitudinal state parameters of forward velocity, angle of attack, pitch rate and pitch angle using normal acceleration and pitch rate as measurement signals and lateral state parameters of side slip angle, roll rate, yaw rate, and bank angle using lateral acceleration, roll rate and yaw rate as measurement signal [5],[6].

The organization of this paper is as follows: Section 2 explains about the micro air vehicle. Next the principle of design of Kalman filter is explained in section 3. The result and analysis is given in section 4 and finally the conclusion in section 5.

II. THE MICRO AIR VEHICLE

Sarika-1 is shown in Fig. 1, which is a remotely piloted small flying vehicle of about 1.28 m span and 0.8 m length and weights around 1.75 kg at take-off. It has a rectangular wing of planform area of 0.2688 m2 and a constant area square section fuselage of width 0.06 m[7],[8]. The control surfaces are elevators, ailerons and rudder. The power plant is a 4 cc propeller engine (OSMAX -25LA), which uses methanol plus castor oil as fuel, with 10 to 15 % nitro-methane to boost the engine power. Sarika-1 has a provision to carry video camera and sensor payloads.

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Fig. 1: Sarika–1 Micro Air Vehicle

Linearized state space model representing small perturbation lateral dynamics are developed for a straight and level flight at an assumed constant altitude of 100 m above ground level at Bangalore (or 1000 m above the sea level) trimmed at five operating points in the speed range of 15 - 26 m/s. The longitudinal state variables are x=[Δuα q θ]^T, where, Δu, α, q and θ indicate forward speed, angle-of-attack, pitch rate and pitch attitude angle respectively. The linearized longitudinal state equations [9] are:

$$\begin{aligned}\Delta\dot{u} &= \left(X_u + X_{Tu}\right)\Delta u + X_\alpha \alpha + \frac{Z_u}{U1} q - g\left(\cos\theta_1\right)\theta + X_{\delta e}\delta_e \\ \dot{\alpha} &= \frac{Z_u}{U1}\Delta u + \frac{Z_\alpha}{U1}\alpha + \left(\frac{Z_q}{U1} + 1\right) q + \frac{Z_{\delta e}}{U1}\delta_e \\ \dot{q} &= \left(M_u + M_{Tu}\right)\Delta u + \left(M_\alpha + M_{T\alpha}\right)\alpha + M_q q + M_{\delta e}\delta_e \\ \dot{\theta} &= q \end{aligned} \quad (1)$$

Where, δe is the elevator deflection. The elevator is actuated by miniature electro- mechanical servo systems. The dynamics of the servo actuator is given by,

$$\dot{\delta}_e = -9.5\delta_e + 15.8051u \quad (2)$$

The measured variables are normal acceleration and pitch rate of the vehicle. The normal acceleration, az is given by,

$$a_z = U1(\dot{\alpha} - q) \quad (3)$$

Where, U1 is the steady state velocity of the vehicle. The coefficients of linearized model are stability derivatives pertaining to force equations in forward and vertical directions and moment equation about the pitch axis. These parameters are determined by the analytical approach given by Roskam[9],[10]. They are refined using the data generated from the wind- tunnel experiments. The dynamics of Sarika1 modeled at 22 m/sec. is given by

$$\begin{bmatrix}\Delta\dot{u}\\ \dot{\alpha}\\ \dot{q}\\ \dot{\theta}\\ \dot{\delta}_e\end{bmatrix} = \begin{bmatrix} 0.9936 & 0.1148 & -0.0008 & -0.1956 & 0.0022 \\ -0.0015 & 0.9482 & 0.0194 & 0.0001 & 0.1005 \\ -0.0010 & -0.4286 & 0.9936 & 0.0001 & 4.4391 \\ -0.0000 & -0.0043 & 0.0200 & 1.000 & 0.0459 \\ 0 & 0 & 0 & 0 & 0.8270 \end{bmatrix} \begin{bmatrix}\Delta u\\ \alpha\\ q\\ \theta\\ \delta_e\end{bmatrix} + \begin{bmatrix}0\\0\\0\\0\\1\end{bmatrix} u \quad (4)$$

$$\begin{bmatrix}a_z\\ q\end{bmatrix} = \begin{bmatrix} -1.2354 & -41.5612 & -0.0758079.4471 \\ 0 & 0 & 1.000\ \ 0\ \ \ 0 \end{bmatrix} \begin{bmatrix}\Delta u\\ \alpha\\ q\\ \theta\\ \delta_e\end{bmatrix} \quad (5)$$

The Lateral state variables y=[β, p, r, ϕ]T where, β, p, r, ϕ are side slip angle, roll rate, yaw rate, and back angle respectively[11]. The linearized lateral state equations are:

$$\begin{aligned}\dot{\beta} &= \frac{Y_\beta}{U_1}\beta + \frac{Y_p}{U_1}p + \frac{Y_r}{U_1}r + \frac{g}{U_1}\phi + \frac{Y_{\delta_a}}{U_1}\delta_a + \frac{Y_{\delta_r}}{U_1}\delta_r \\ \dot{p} &= \frac{L_\beta + A_1(N_\beta + N_{T\beta})}{1 - A_1B_1}\beta + \frac{L_p + A_1(N_p + N_{T\beta})}{1 - A_1B_1} \end{aligned} \quad (6)$$

$$\dot{r} = \frac{N_\beta + N_{T\beta} + B_1L_\beta}{1 - A_1B_1}\beta + \frac{N_p + N_{T\beta} + B_1L_p}{1 - A_1B_1}p + \frac{N_r + B_1L_r}{1 - A_1B_1}r + \frac{N_{\delta_a} + B_1L_{\delta_a}}{1 - A_1B_1}\delta_a + \frac{N\delta_r + B_1L_{\delta_r}}{1 - A_1B_1}\delta_r$$

$$\dot{\phi} = p$$

Where $A_1 = \frac{I_{xz}}{I_{xx}}$ and $B_1 = \frac{I_{xz}}{I_{zz}}$ and δ is replaced with δa and δr to represent aileron and rudder control surfaces respectively. The measured variables of the lateral dynamics are lateral acceleration, roll rate, and yaw rate. the lateral acceleration measured with respect to the c.g. of the vehicle is

$$a_y = U_1\left(\dot{\beta} + r\right) \quad (7)$$

The dynamic derivatives are calculated using analytical approach, while static and control derivatives are calculated based on the wind tunnel generated data. The lateral dynamics of Sarika-1 at 22 m/s flight speed is given by

$$\begin{bmatrix}\dot{\beta}\\ \dot{r}\\ \dot{p}\\ \dot{\emptyset}\\ \dot{\delta}_a\\ \dot{\delta}_r\end{bmatrix} = \begin{bmatrix} 0.9778 & 0.0002 & -0.0194 & 0.0097 & -0.0036 & -0.0470 \\ -1.8128 & 0.9664 & 0.0264 & -0.0090 & -3.5364 & -0.0676 \\ 1.0465 & -0.0041 & 0.9614 & 0.0052 & 0.1503 & 3.4276 \\ -0.0183 & 0.0197 & 0.0002 & 0.9999 & -0.0367 & -0.0009 \\ 0 & 0 & 0 & 0 & 0.8270 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.8270 \end{bmatrix} \begin{bmatrix}\beta\\ r\\ p\\ \emptyset\\ \delta_a\\ \delta_r\end{bmatrix} + \begin{bmatrix} -0.0000 & -0.0004 \\ -0.0367 & -0.0009 \\ 0.0015 & 0.0356 \\ -0.0002 & -0.0000 \\ 0.0182 & 0 \\ 0 & 0.0182 \end{bmatrix} u \quad (8)$$

$$\begin{bmatrix}a_y\\ p\\ r\end{bmatrix} = \begin{bmatrix} -11.7970 & 0.0127 & -19.87809.8100 & & -41.6260 & -258.0823 \\ 0 & 1.000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.000 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix}\beta\\ r\\ p\\ \emptyset\\ \delta_a\\ \delta_r\end{bmatrix} \quad (9)$$

III. PRINCIPLES OF KALMAN FILTER

The Kalman filter is essentially a set of mathematical equations that implement a predictor-corrector type estimator that is optimal in the sense that it minimizes the estimated error covariance when some presumed conditions are met[12]. In this work we are using the Linear Discrete Kalman filter to estimate the unknown state variables of the lateral dynamics of the vehicle. In general, the system dynamics and measured outputs are represented by

$$\dot{X} = AX + BU + GW; Y = CX + V \quad (10)$$

Where W(t) =Process noise vector and V(t)= Sensor noise vector With the assumptions that $X(0) \sim (\widetilde{X}_0, P_0)$, $W(t) \sim (0, Q)$ and $V(t) \sim (0, R)$ are mutually orthogonal, W(t) and V(t) are uncorrelated white noise and $E[W(t)W^T(t+\tau)=Q\delta t, Q \geq 0$, $EV(t)VT(t+\tau)=R\delta t, R>0$.

It is to make sure that the error $\widetilde{X}(t) \triangleq X(t) - \widehat{X}(t)$ becomes very small, ideally zero as $t \rightarrow \infty$

$$\dot{\widehat{X}}(t) = A\widehat{X} + BU + K_e[Y - \widehat{Y}] \quad (11)$$

Where

$\widehat{X} = E(X)$, estimate of state X, $\widehat{Y} = E(Y)$, estimate of output Y

$\widehat{Y} = E(CX + V) = E(CX) + E(V) = CE(X) = C\widehat{X}$ and K_e is the Kalman gain.

The Kalman gain can be calculated by the expression $K_e = PC^T R^{-1}$Where P is the Riccati matrix, which can be solved from the filter ARE

$$AP + PA^T - PC^T R^{-1} CP + GQG^T = 0, \text{ initialize} \widehat{X}(0) \quad (12)$$

Thus $\dot{\widehat{X}}(t) = A\widehat{X} + BU + K_e[Y - C\widehat{X}]$, where Y is the measurement vector.

The Kalman filter for Sarika-1 is implemented in MATLAB. The offline simulation is done for the validation of the designed estimator by using the data of lateral acceleration, roll rate and yaw rate collected at the time of real flight.

IV. RESULTS AND ANALYSIS

The estimated versus the actual state variables are plotted and the error between the actual and estimated values of all the Longitudinal and lateral parameters is plotted in Fig.2 and Fig.3 respectively. It is observed from the simulation results that the estimated state values match with the actual values and the error is becoming very small as required.

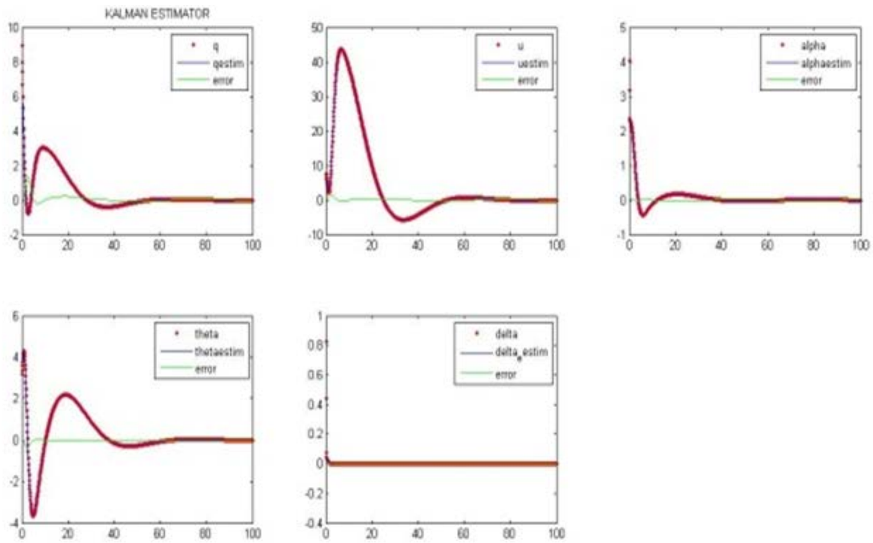

Fig. 2: Graph Indicating the Predicted, Estimated and Error Values of Longitudinal Parameters

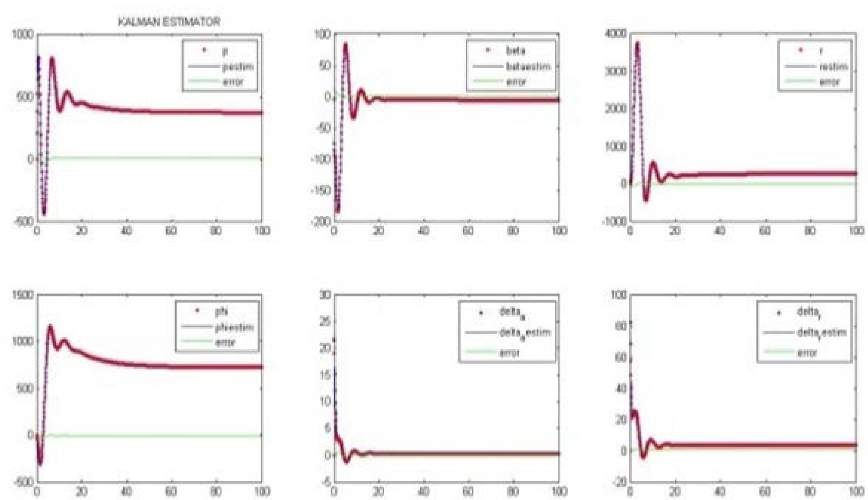

Fig. 3: Graph Indicating the Predicted, Estimated and Error Values of Lateral Parameters

V. Conclusion

Design and validation of state parameter estimator for lateral dynamics of Sarika-1 is explained. From the simulation results it can be concluded that the Kalman filter designed is working well as an estimator for the MAV applications. The data used for the simulation are the one collected at the time of real flight. Hence the designed estimator can be implemented in real time applications.

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