A multiple model-based sliding innovation filter and its application on aerospace actuator

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ABSTRACT

In this work, the newly developed filtering technique referred to as the sliding innovation filter (SIF) is combined with multiple model strategies to enhance the performance of the filter when the system changes its structure and/or parameters. This is particularly useful for a system, such as an aerospace system, experiences a fault and continued operation is critical. The proposed method is tested on an aerospace actuator system and the results are discussed.

Keywords: sliding innovation filter, multiple models, fault detection, robust estimation

1. INTRODUCTION

Estimation is used widely in fault and diagnosis applications. These applications require checking the plant status through some sensors and the information that are provided by them. The estimation process analyzes the sensors' signals, and extract the full information from them. This information may contain the hidden states, which can be defined as the inaccessible or unmeasurable system's dynamic behavior, the system's parameters, and the system's health. The latter gives a good ability of tracking the system status and flags an alert once a fault occurs [1-10]. Due to the sensors limitations, noise presents within its output. Therefore, the estimation techniques in used are called filters, as the processes need to eliminate the effect of any disturbances or noise as much as possible. This improves the system response when it is merged with the controller [11-21].

There are two major categories in filtering estimation; the first involves in finding the optimal or best solution given some constraints like Kalman filter (KF) [22-37], the Extended [38-43], and Sigma-Point (i.e. Unscented, Cubature and Central differences) KF [44-61]. The second category depends on formulating the filter according to stability functions, i.e. Lyapunov function. The sliding mode observer (SMO) [62-86], and the smooth variable structure (SVSF) [87-103] and sliding innovation (SIF) [104-112] filters belong to this category. From their names, the first category suffers from lack of robustness and stability, and the fact that it has several constraints, while the second category does not offer optimal solution. One way to enhance the performance and reduce the limitations is by combining at least two filters together, one from each category [113-123]. Another way to achieve that is by using several models and fuse them together as in interacting multiple model (IMM) [124-135].

This brief paper targets the application of combining SIF with IMM into an aerospace actuator. The paper is organized as follows. The IMM, and SIF are introduced in Section 2. The actuator under study is mentioned in Section 3. The results are summarized and discussed in Section 4. The paper is then concluded in Section 5.

2. IMM-SIF

This section summarizes the algorithms of SIF and IMM-SIF.

2.1 SIF

The sliding innovation filter was developed on 2020 in [110]. It uses the true state as a hyperplane, which is then used as a reference for the estimation. The estimate is forced to stay within its neighborhood to guarantee the stability. The filter consists of two steps:

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1- **Prediction Stage**, where the a priori estimate and its measurement, $\hat{\mathbf{x}}_{k+1|k}$ and $\hat{\mathbf{z}}_{k+1|k}$, respectively, are calculated using the following equations:

$$\hat{x}_{k|k-1} = f\left(\hat{x}_{k-1|k-1}, u_{k-1}\right) \tag{1}$$

$$\hat{z}_{k|k-1} = H_k \hat{x}_{k|k-1} \tag{2}$$

2- **Correction Stage**, where the a posteriori estimate and its measurements, $\hat{\mathbf{x}}_{k|k}$ and $\hat{\mathbf{z}}_{k|k}$, respectively, are calculated using the following

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + \left[H_k^{+}\left(z_k - \hat{z}_{k|k-1}\right)\right]^{\circ} sat\left(\left|z_k - \hat{z}_{k|k-1}\right|, \Psi_k\right) \tag{3}$$

$$\hat{z}_{k|k} = H_k \hat{x}_{k|k} \tag{4}$$

Where Ψ_k is the designed boundary layer, H_k^{+} is the pseudoinverse vector of H_k, $A^{\circ}B$ is schur product that is done by multiplying each element of A with it corresponding element in B, and sat is the saturated function.

2.2 IMM-SIF

The proposed filter, which is the interacting multiple model sliding innovation filter (IMM-SIF), is based on [106] and is summarized here. The filter consists of three stages:

1- **Prediction Stage**: We calculate the a priori estimate, and its covariance matrix for model j, $\hat{x}_{j,k|k-1}$, and $P_{j,k|k-1}$, respectively. We use the following equations:

$$\hat{x}_{j,k|k-1} = f_j(\hat{x}_{k-1|k-1}, u_{k-1}) \tag{5}$$

Obtaining the Jacobian matrix $A_{j,k|k-1}$, and then calculating $P_{j,k|k-1}$ as follows:

$$P_{j,k|k-1} = A_{j,k|k-1} P_{k-1|k-1} A_{k|k-1}^{T} + Q_{k-1} \tag{6}$$

Where Q_{k-1} is the system covariance matrix. Then we calculate the innovation covariance matrix, $S_{j,k|k-1}$, with the use of measurement's noise covariance matrix, R_k, as follows:

$$S_{j,k|k-1} = H_k P_{j,k|k-1} H_k^{\mathrm{T}} + R_k \tag{7}$$

2- **Correction Stage**: We calculate the a posteriori estimate and its covariance matrix, and likehood function for model j, $\hat{x}_{j,k|k}$, $P_{j,k|k}$ and $\Lambda_{j,k+1}$, respectively. We use the following equations:

We calculate the correcting gain:

$$K_k = H_k^{+} diag\left(sat\left(\left|z_k - H_k \hat{x}_{j,k|k-1}\right|, \Psi_k\right)\right) \tag{8}$$

Then we update the a priori estimate and covariance matrix using:

$$\hat{x}_{j,k|k} = \hat{x}_{j,k|k-1} + K_{j,k}\left(z_k - H_k \hat{x}_{j,k|k-1}\right) \tag{9}$$

$$P_{j,k|k} = \left(I - K_{j,k} H_k\right) P_{j,k|k-1} \tag{10}$$

We also calculate the likehood function:

$$\Lambda_{j,k} = \frac{exp\left(\frac{-\frac{1}{2}\left(z_k - H_k \hat{x}_{j,k|k-1}\right)\left(z_k - H_k \hat{x}_{j,k|k-1}\right)^{T}}{S_{j,k|\mathrm{k}-1}}\right)}{\sqrt{\left|2\pi S_{j,k|\mathrm{k}-1}\right|}} \tag{11}$$

3- **Fusion Stage**: We calculate the overall a posteriori estimate and its covariance matrix for the filter using the following steps:

We update mode probability for model j, $\mu_{j,k}$, using the mixing probabilities, p_{ij}, and the likehood function as follows:

$$\mu_{j,k} = \frac{1}{\sum_{j=1}^{n} \Lambda_{j,k+1} \sum_{i=1}^{n} p_{ij}\mu_{i,k}} \Lambda_{j,k+1} \sum_{i=1}^{r} p_{ij}\, \mu_{i,k}, j = 1, \dots, n \tag{12}$$

We fuse the outputs from each model together using

$$\hat{x}_{k|k} = \sum_{j=1}^{r} \mu_{j,k} \hat{x}_{j,k|k} \tag{13}$$

$$P_{k|k} = \sum_{j=1}^{r} \mu_{j,k} \left\{ P_{j,k|k} + \left(\hat{x}_{j,k|k} - \hat{x}_{k|k}\right)\left(\hat{x}_{j,k|k} - \hat{x}_{k|k}\right)^{T} \right\} \tag{14}$$

3. SYSTEM UNDER SCOPE

In this research, we applied IMM-SIF to ball screw actuator (BSA) proposed by [136], which different from model used in [106]. The BSA can be used in aerospace application as shown in Fig. 1. The mechanics of BSA is illustrated by Fig. 2. In [136], the mathematical model was derived, and it is listed here as follows:

$$x_{k+1} = \begin{bmatrix} x_{1,k} + T x_{2,k} \\ x_{2,k} + \frac{T}{J}\left(\mathrm{T_{m,k}} - \left(\sigma_0 W + \sigma_1 \left(x_{2,k} - \frac{\sigma_0 |x_{2,k}|}{F_C + (F_S - F_C) e^{-\left|\frac{x_{2,k}}{v_S}\right|^{\delta_v}}} x_{3,k} \right) + \sigma_2 x_{2,k} \right) \right) \\ x_{3,k} + T \left(x_{2,k} - \frac{\sigma_0 |x_{2,k}|}{F_C + (F_S - F_C) e^{-\left|\frac{x_{2,k}}{v_S}\right|^{\delta_v}}} x_{3,k} \right) \end{bmatrix} \tag{15}$$

Where all the parameters are summarized by table (1).

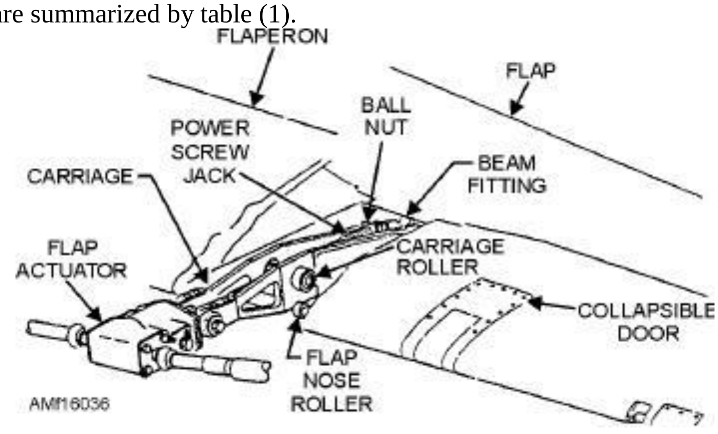

Fig 1. The ball-screw actuator in airplane's wing [137].

Table 1. The parameters of equation (18) [136].

Parameter	Value	Parameter	Value
T	0.0001	v_s	0.15313
J	0.007046	σ_0	13882
F_c	0.67893	σ_1	8.6776
F_s	0.72088	σ_2	0.0649
δ_v	0.9998	T_m	*Random input*

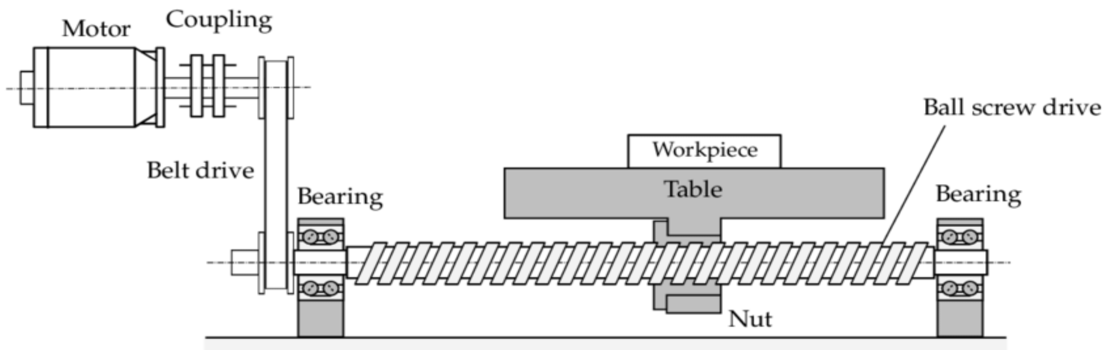

Fig 2. The ball-screw actuator in airplane's wing [138].

4. RESULTS AND DISCUSSION

In this work, the IMM-SIF is applied to system in section 3. Fig. 3 shows the filter's outputs, while the root mean squared error (RMSE) and the maximum absolute error (MAE), which are calculated using:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{ns}\left(x_{Actual,i} - x_{Prediction,i}\right)^2}{ns}} \tag{19}$$

$$MAE = \max(|x_{Actual} - x_{Prediction}|) \tag{20}$$

Are summarized by Table 2 and Table 3. ns represents the number of the data. The actual and estimated modes are shown in Fig. 4 and their probabilities are summarized by table 4. The results show that the IMM-SIF estimates the states with RMSE (compared to the maximum absolute values) to be of $9.998 \times 10^{-5}\%$, $3.5 \times 10^{-3}\%$ and $1.762 \times 10^{-5}\%$, respectively, and for MAE (compared to the maximum absolute values) to be of $5.78 \times 10^{-5}\%$, $2.1 \times 10^{-3}\%$ and $1.01 \times 10^{-5}\%$, respectively. The IMM-SIF identifies the normal operation with a probability level of 97.17%, while it obtains the leakage operation with the highest probability level of 95.05%. The results indicate that the proposed algorithm has a good performance with negligible error. The operation mode is also retrieved with minimum error.

Table 2. RMSE of the simulated results

	$RMSE$ in		
IMM − SIF	x_1 (m)	$x_2(m/s)$	x_3
	5.779×10^{-07}	5.811×10^{-06}	5.752×10^{-09}

Table 3. MAE of the simulated results

	MAE in		
IMM − SIF	x_1 (m)	$x_2(m/s)$	x_3
	9.999×10^{-07}	9.999×10^{-06}	9.999×10^{-09}

Table 4. IMM-SIF Mode Probability Results (Confusion Matrix)

	Actual Condition		
Predicted Condition		Normal	Leakage
	Normal	97.17 %	2.83 %
	Leakage	4.91 %	95.09 %

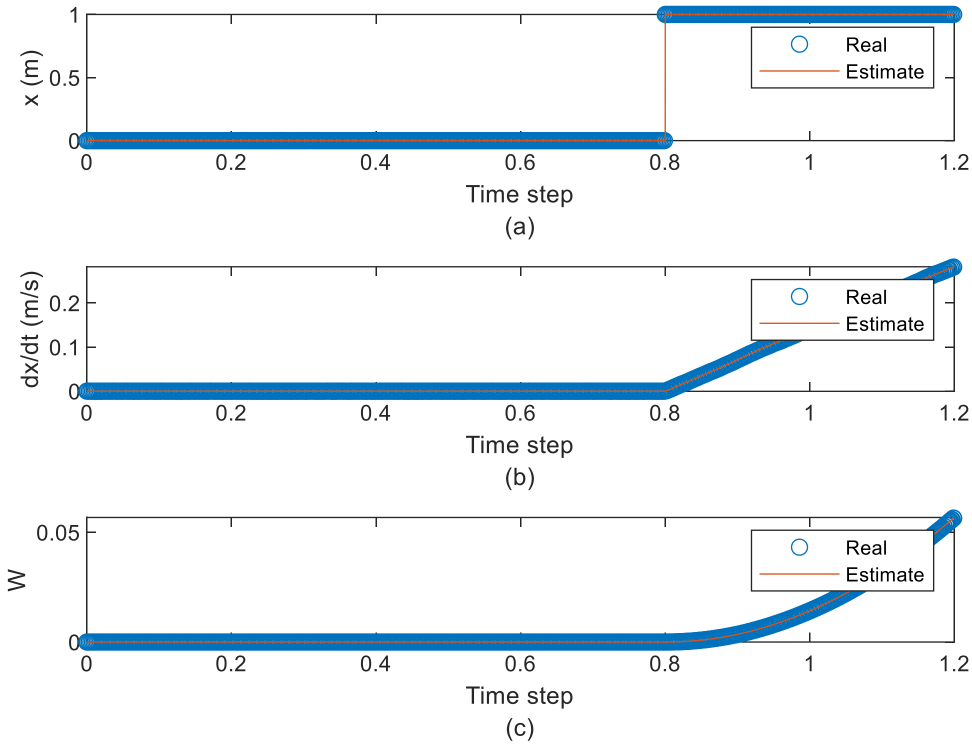

Fig. 3. The experimental EHA states with time.

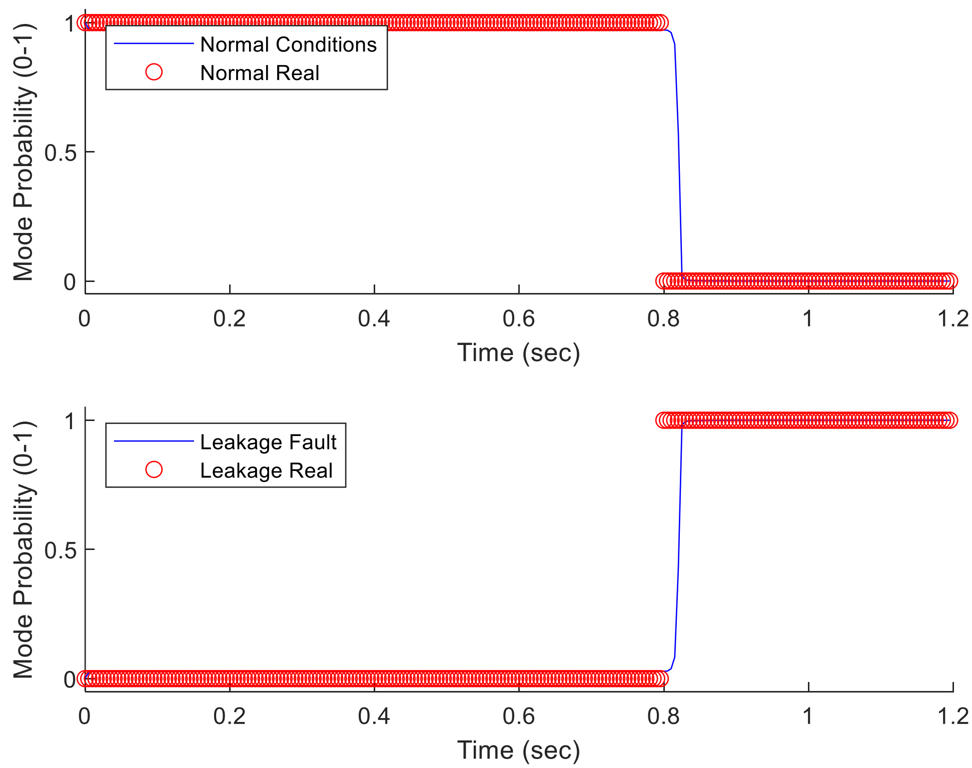

Fig 4. Calculated mode probabilities over time for the system using IMM-SIF.

5. CONCLUSIONS

In this very brief work, the IMM-SIF was used to estimate the states of ball-screw actuator system during normal and faulty conditions. The results showed that the IMM-SIF predict the estimates with maximum RMSE and MAE values of $3.5 \times 10^{-3}\%$ and $2.1 \times 10^{-3}\%$, respectively. IMM-SIF predict the operation mode with accuracy value of at least 95.15%. For future work, an experimental setup will be used to verify the results and a more comprehensive study and comparison will be completed.

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