On the Impact of Guidance Commands Mismatch in IMM-Based Guidance Modes Identification for Aircraft Trajectory Prediction

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Abstract—This study presents a sensitivity analysis to model mismatch of an interacting multiple model (IMM) filter when used for aircraft guidance modes identification. The mismatch appears in the guidance command parameters (related to the elevator flight surface and engine throttle), which are assumed to be known filter inputs. First, we analyse the filtering sensitivity when the model mismatch is induced by additive Gaussian noise. Three model mismatch scenarios are considered: i) mismatch on the elevator parameter; ii) mismatch on the throttle parameter; and iii) mismatch on both guidance commands. Such sensitivity analysis is conducted for several realistic trajectories. Second, we consider the case where the guidance parameters are estimated. It is found that a guidance command parameters misspecification clearly affects the IMM performance, therefore such possible mismatch must be taken into account for real-life applicability.

Index Terms—Interacting multiple model filter, guidance mode identification, guidance command parameters, model mismatch.

I. INTRODUCTION

A sequence of path constraints, known as aircraft intents, are required to generate a trajectory in the planning phase. The path constraints are operational instructions that specify how the aircraft should intend to meet the preferences defined in the planned trajectory. In the flight execution phase, however, the operational instructions are not exactly performed in accordance with the planned trajectory. The (auto)pilot uses a sequence of guidance modes to steer the aircraft in such phase. A guidance mode is a combination of commands that specify how the aircraft should behave to perform the desired trajectory. In the vertical plane, two path constraints are required. For instance, at the beginning of the climb phase, setting the throttle at the maximum rate and accelerating the aircraft to meet the planned rate of climb.

The new generation of air traffic management (ATM) systems considers the so-called “trajectory-based operation” concept \cite{11}. In this new concept, trajectory prediction (TP) is a key component. Increasing the TP accuracy is fundamental for the design of next-generation on-board and ground-based decision support tools. For instance, an enhanced TP is required for conflict detection and resolution (CDR) algorithms in a complex multi-aircraft environment, or for optimizing the arrival/departure traffic flows in terminal manoeuvring areas. Therefore, improved TP may result in increased safety, capacity, predictability and cost-efficiency. Within this context, the knowledge of aircraft guidance modes is an important piece for TP in the execution phase. Nevertheless, such knowledge is seldom available in ATM systems.

Interacting multiple model (IMM) filtering \cite{1}, \cite{10} has been used in target tracking for several decades. IMM is a well-known recursive estimation method for systems that contain several modes of operation. An IMM-based filter method was used in \cite{3}, \cite{8} to identify the aircraft guidance modes. Similarly, the IMM filter was used in \cite{9} to estimate the high-lift devices deployment moment, concentrating on the aircraft descent. In \cite{12} a multiple model filter, based on 2D kinematic models, was used to improve the tracking of aircraft for CDR applications. In \cite{7} a multiple model filter was developed to identify aircraft manoeuvres during taxi operations. An enhanced multiple model filter, using a non-linear point mas model to describe 3D aircraft dynamics, was proposed in \cite{6}; showing significant benefits in terms of position estimation accuracy and filter robustness with respect to conventional kinematic-based filters.

Even if the IMM filter has been shown to be a promising solution for guidance modes identification and TP problems, it requires a perfect system knowledge. For instance, both process and measurement functions, the corresponding noise statistics, and the input parameters need to be known to achieve an optimal filter behaviour. In practice, a perfect system knowledge may not be available. In the guidance modes identification of interest, the pair of guidance commands is assumed to be perfectly known, and given to the IMM filter as an input \cite{3}, \cite{8}. In real-life applications, the guidance commands are obtained from the measurements and/or estimated states. The measurements are inherently noisy, and the estimated states are affected by the corresponding estimation error. Therefore, the guidance command parameters are not perfectly known and are affected by a mismatch (with respect to the true ones). In this contribution we assess the impact of a parametric model mismatch in IMM-based aircraft guidance modes identification. It is known that a model mismatch may induce a filter performance degradation, but an IMM filter sensitivity analysis to such mismatch is not available.

II. SYSTEM MODEL AND METHODOLOGY

A. Aircraft Motion Model

A simplification of the three degree of freedom (3DoF) aircraft point-mass model in the vertical plane results in the so-
called gamma-command model [2], where vertical equilibrium is assumed. This is the model considered:

\[
\begin{align*}
\frac{dh}{dt} &= \dot{h} = vsin\gamma, \\
\frac{ds}{dt} &= \dot{s} = \sqrt{v^2 \cos^2 \gamma - W_s^2 + W_t}, \\
\frac{dv}{dt} &= \dot{v} = \frac{1}{m} [T(\pi, v, h) - D(v, h, m, \xi)] - g \sin \gamma, \\
\frac{dm}{dt} &= \dot{m} = -q(T, v, h), \\
\frac{dr}{dt} &= \dot{r} = \tau(h)\dot{h}, \\
\frac{dp}{dt} &= \dot{p} = p_h(\tau, p)\dot{h},
\end{align*}
\]

where the state vector, \(x = [h, s, v, m, \tau, p]^T\), is composed of the geometric altitude, the along path distance, the true air-speed, the aircraft mass, the temperature, and the air pressure. \(\gamma\) and \(\pi\) stand for aerodynamic flight path angle (FPA) and the engine throttle, respectively. \(T\) is the total thrust delivered by the aircraft engines, \(D\) is the aerodynamic drag, \(q\) is the total fuel flow, \(W_s\) is the cross-wind component, \(W_t\) is the along path wind component, and \(g\) is the gravitational acceleration.

It is worth noting that \(D\) also depends on the setting of the high-lift devices (i.e., flaps and/or slats) and landing gear. This aircraft configuration is denoted in the equations above by \(\xi\), \(\tau_h\) and \(p_h\) are, respectively, the partial derivative of the temperature and pressure with respect to the altitude.

**B. Filtering**

An IMM filter is considered as the guidance mode estimation method. The algorithm contains four steps: i) interaction; ii) filtering; iii) updating; and iv) combination [1]. In the interaction step, the mixed initial conditions are computed to feed the filtering step. A bank of Kalman-type filters is used in the filtering step, each one matched to a given mode. Each filter provides a state estimate, and then an updated model probability is computed (using each filter innovations’ likelihood). The estimated/identified mode is taken as the one with maximum probability. The final estimated state vector and the corresponding estimation error covariance are obtained in the combination step.

**C. Guidance Modes and System Model**

A hybrid stochastic process \(\{\theta_k, x_k\}\) is defined on a complete probability space and the positive time process. The process \(\{\theta_k\}\) is assumed to be a discrete-time Markov chain with a discrete-valued component, i.e., \(\theta_k : \Omega \rightarrow \Theta\), with \(\Theta = \{N\} \) guidance modes. For each mode value \(\theta \in \Omega\), \(\gamma_k\) and \(\pi_k\) satisfy solutions of a mode-dependent set of algebraic equation (i.e., \(\gamma_k - u_\gamma(\theta_k, x_{k-1}) = 0\) and \(\pi_k - u_\pi(\theta_k, x_{k-1}) = 0\)). These algebraic equations are required to close the ordinary differential equations (ODEs) in (1).

A set of \(N = 12\) possible guidance modes are considered to cover the whole aircraft trajectory in the vertical plane. All pairs of guidance commands (e.g., CAS-THR refers to flying at a constant calibrated airspeed with a minimum/maximum throttle rate) are summarized in Table I. The first and second columns show the guidance commands that steer, respectively, the two independent aircraft actuators (i.e., elevator and throttle). The third column gives the two guidance command parameters that are needed to obtain the mathematical model of the system dynamics, for each guidance mode.

The guidance modes are categorized in four groups: i) the elevator is used to command a constant Mach, a constant calibrated airspeed, or a constant factor\(^1\), while the throttle is fixed to guide the aircraft with the maximum/minimum thrust force in a climb/descent profile; ii) the elevator is used to keep the vertical speed at a constant value to fly with a constant rate of climb, while the throttle sets the speed (i.e., Mach/calibrated airspeed) or the constant factor in a climb/descent; iii) a constant ground flight path angle is set by elevator, while the throttle operates equal as the throttle of the second group; and iv) the elevator is used to steer the aircraft with a constant vertical speed, constant ground flight path angle, or constant pressure altitude, while the throttle setting is kept as the throttle setting in the first group.

**TABLE I: Guidance Modes in Vertical Plane**

<table>
<thead>
<tr>
<th>Command 1</th>
<th>Command 2</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Elevator)</td>
<td>(Throttle)</td>
<td>vector</td>
</tr>
<tr>
<td>MACH</td>
<td>THR</td>
<td>(p = [\bar{\theta}_h, \bar{\pi}])</td>
</tr>
<tr>
<td>CAS</td>
<td>THR</td>
<td>(p = [\bar{\gamma}_{CAS}, \bar{\pi}])</td>
</tr>
<tr>
<td>ACC/DEC</td>
<td>THR</td>
<td>(p = [\bar{k}, \bar{\pi}])</td>
</tr>
<tr>
<td>VS</td>
<td>CAS</td>
<td>(p = [\bar{\gamma}<em>g, \bar{\pi}</em>{CAS}])</td>
</tr>
<tr>
<td></td>
<td>ACC/DEC</td>
<td>(p = [\bar{\gamma}_g, \bar{k}])</td>
</tr>
<tr>
<td>FPA</td>
<td>THR</td>
<td>(p = [\bar{\gamma}_g, \bar{\pi}])</td>
</tr>
<tr>
<td>ALT</td>
<td>THR</td>
<td>(p = [\bar{\gamma}_g, \bar{\pi}])</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(p = [\bar{\gamma}_g, \bar{k}])</td>
</tr>
</tbody>
</table>

\(h_p\) is the pressure altitude, \(v_g\) is the ground speed, \(v_h\) is the aircraft (operational) vertical speed (i.e., rate of climb/descent), \(\bar{\gamma}_{CAS}\) is the calibrated airspeed (taken from the indicated airspeed broadcast by the ADS-B) and \(\bar{\gamma}_g\) is the displayed altitude, \(\bar{k}\) is the Mach number. In this study, such simulator is used to generate the trajectories, based on a gamma-command aircraft motion model and the Eurocontrol’s Base of Aircraft Data (BADA) v4.1 aircraft performance model [4]. The simulator generates noiseless trajectories, and then, the additive noise is added.

\(^1\)The constant factor specifies the ratio of rate of climb to the total energy (i.e., potential plus kinetic energy)[5].
For each guidance mode \( \theta_k \) (i.e., a pair of guidance commands), the nonlinear discrete state-space model is given by

\[
\begin{align*}
x_k &= f_{k-1}(\theta_k, x_{k-1}, \gamma_k, \pi_k) + w_{k-1}, \\
y_k &= h_k(\theta_k, x_k) + v_k,
\end{align*}
\]

(2)

where \( k \) refers to the discrete-time instants; \( x_k \) is the state vector at time instant \( k \); \( y_k \) is the observation vector at time instant \( k \); \( f_{k-1}(\cdot) \) and \( h_k(\cdot) \) are the known nonlinear system model functions (process and measurement, respectively); \( w_{k-1} \) and \( v_k \) are the process and measurement noise, and \( \theta_k, \pi_k, \) and \( \gamma_k \) stand for the guidance mode, engine throttle and flight path angle at time instant \( k \), respectively.

1) Example of control vector derivation: As stated in Section II, a custom trajectory simulator is used to generate a set of vertical plane validation trajectories (VTs). For each mode, the computed control vector (e.g., (5)) requires the corresponding guidance parameters. The following set of constraints apply to derive the control policies under mode \( \theta_k = \tilde{\theta}^1 \triangleq \text{MACH-THR} \):

\[
\begin{align*}
\pi_k &= \bar{\pi} \\
M_k &= M \bar{M} \\
M_k - M_{k-1} &= 0
\end{align*}
\]

(3)

Evaluation of Mach number in terms of state components (\( v \) and \( \tau \)) yields:

\[
M_k = \frac{v_k}{\sqrt{\kappa R T_k}}
\]

(4)

where \( R = 287.053 \text{ Jkg}^{-1}\text{K}^{-1} \) is the ideal gas constant of the air; \( \kappa = 1.40 \) is the specific heat ratio of the air. Considering the international standard atmospheric (ISA) model and (1), (3) and (4), the control policies in this mode lead to,

\[
\begin{align*}
\gamma_k &= u_s(\tilde{\theta}^1, x_{k-1}) = \arcsin\left(\frac{T(\pi, v, h) - D(v, h, m, \xi)}{m(g + \frac{\gamma }{2} c_\beta \kappa RM^2)}\right) \\
\pi_k &= u_s(\tilde{\theta}^1, x_{k-1}) = \bar{\pi}
\end{align*}
\]

(5)

where \( c_\beta \) stands for the ISA temperature gradient with respect to altitude below the tropopause, and \( g \) is the gravity acceleration. For each mode, the computed control vector (e.g., (5) in mode MACH-THR) requires the corresponding guidance parameters.

III. RESULTS AND DISCUSSION

As stated in Section II, a custom trajectory simulator is used to generate a set of vertical plane validation trajectories (VTs), considering the gamma-command model, ISA conditions, and neglecting the wind effect (i.e., \( v = v_g \) and \( \gamma = \gamma_g \)). Each VT represents a part of a flight descent, for an Airbus A320 aircraft that is steered with two actuators (i.e., elevator and throttle), and taking into account that high-lift devices are retracted. 12 VTs are simulated to cover all guidance modes (see Table II).

A. Additive Noise on the Guidance Parameters

Four scenarios are considered to analyse the impact of a possible model mismatch: i) the optimal scenario as a benchmark (i.e., guidance mode identification without model mismatch), ii) uncertainty on the elevator parameter, while the throttle parameter is perfectly known, iii) uncertainty on the throttle parameter, while the elevator parameter is perfectly known, and iv) model mismatch in both elevator and throttle parameters. \( M, \bar{v}_{\text{CAS}}, v_h \), and \( \gamma_g \) are extracted from the measurements, and \( \bar{k} \) and \( \bar{\pi} \) are considered to be known. In addition, uncertainty is only induced to the mode that must be identified, that is, for the remaining modes that are not the true one we consider the true guidance parameters. The latter allows to assess the model mismatch impact on the desired guidance mode. For instance, if the aircraft is steered with the MACH-THR mode, \( \bar{v}_{\text{CAS}}, v_h, \gamma_g \), and \( \bar{k} \) are perfectly known, while \( M \) and/or \( \bar{\pi} \) are noisy.

Fig. 1 shows the guidance modes (GM) and the corresponding estimated mode probabilities, with respect to the along path distance, for the 12 VTs. For each VT, the upper subplot shows the true mode, and the remaining ones show the model probability given by the IMM-based filter for the four scenarios. As stated in Section II, the guidance modes are categorised in four groups, which are shown respectively in Fig. 1a, 1b, 1c, and 1d. For each VT, 500 Monte Carlo runs are performed to obtain statistically meaningful results.

Fig. (1a) shows the IMM filtering performance in both optimal and non-optimal scenarios, for the first set of guidance modes (MACH-THR, CAS-THR, and DEC-THR, respectively, from left to right). The model probability of an optimal scenario shows a good performance of the IMM filter. The sensitivity of the IMM filter in the MACH-THR mode is more visible in the case that the throttle parameter is uncertain, while the filter is more robust to the Mach variations. The IMM filter is more sensitive to the calibrated airspeed uncertainty and the variation of the constant factor (CAS-THR, and DEC-THR modes). Note that \( M, \bar{v}_h, \gamma_g \), and \( \bar{k} \) are perfectly known in VT2, and \( M, v_{\text{CAS}}, v_h, \) and \( \gamma_g \) are perfectly known in VT3. The fact that the flight path angle in VT2, and vertical speed in VT3, suffer small changes during the flight, induces a misidentification in these VTs (FPA-CAS and VS-DEC are identified in some parts of VT2 and VT3). Therefore, in addition to the guidance parameter uncertainty in VT2 and VT3, these misidentifications impact the filtering performance in both non-optimal scenarios.

The second group of guidance modes (VS-MACH, VS-CAS, and VS-DEC, respectively, from left to right) is shown in Fig. (1b). Despite the good results obtained for the optimal scenario, the model mismatch impact on the filter is clear for both non-optimal scenarios. In this group, the sensitivity of the IMM filter is larger when the uncertainty is added to the vertical speed. Again, the misidentification (an estimated constant ground flight path angle) impact the filtering performance when the model mismatch is induced in the elevator parameter. The model mismatch—induced by the
parameter uncertainty associated with the throttle—in the third scenario does not impact the filtering performance. This shows the robustness of the IMM filter to the speed variations, as well as to the uncertainty on the ratio of rate of climb/descent to the total energy. Fig. (1c) shows the performance of the filtering approach when the elevator is used to set the ground flight path angle, leading to a constant flight path angle. The results are similar to the ones shown in Fig. (1b). In fact, using the elevator to steer the aircraft at a constant vertical speed or a constant ground flight path angle is equivalent from a filtering perspective.

Fig. (1d) shows the results for the last group of VTs. For VT10, the optimal IMM provides a good performance. Notice that when the elevator is used to set the vertical speed and the throttle is set to the minimum rate, the IMM is less sensitive than for the scenario where the model mismatch is induced on the elevator parameter. Notice that flying at a constant pressure altitude results in flying at a constant vertical speed and a constant flight path angle ($\dot{v}_h = 0$ ft/min, $\dot{\gamma}_g = 0$ deg). Therefore, the filter identifies the three guidance modes (i.e., VS-THR, FPA-THR, and ALT-THR) with similar probabilities in VT12. Surprisingly, the filter is not affected by the model mismatch in ALT-THR.

In all the modes, the filter is more sensitive when the model mismatch appears simultaneously in both guidance parameters. The average comparative performance results are shown in Table III. The percentage is obtained as the guidance mode identification output of each non-nominal scenario compared to the output of the optimal IMM results. From these results we can identify which modes are more affected (w.r.t. the optimal IMM) by the mismatch, and which command induces a larger performance degradation.

### B. Estimated guidance parameters

In this section, the guidance command parameters at each time instant $k$ are estimated from the estimated state vector at the previous time instants ($\hat{p}_k = \int_{0}^{t} f_\theta(\hat{x}_{k-2},k-1)$). It is worth mentioning that, estimating the guidance parameters using the state obtained at previous time instants may induce a delay on the guidance mode identification. $\bar{M}$, $\bar{v}_{CAS}$, $\bar{v}_h$, and $\bar{\gamma}_g$ and $\bar{k}$ are the parameters of the interest that may be obtained from the estimated state vector, while the throttle parameter (i.e., $\pi$) is not, and then it is out of the scope of this study. The estimated parameters are given by:

$$M_k = \frac{\hat{v}_{h,k-1}}{\sqrt{\kappa R h_{k-1}}}$$

$$\bar{v}_{CAS,k} = \frac{2 \rho_0}{\mu \sigma_0} \left(1 + \frac{\bar{h}_{k-1} - \bar{h}_{k-2}}{\Delta} \right)^{\frac{3}{2}} \left(1 + \frac{\mu}{2R} \left(\frac{\bar{v}_{h,k-1}}{\bar{h}_{k-1}} \right)^2 - 1 \right)$$

$$\bar{k}_k = \frac{\bar{h}_{k-1} - \bar{h}_{k-2}}{\Delta} + \frac{1}{\bar{g} \Delta} \left(\bar{v}_{h,k-1} - \bar{v}_{h,k-2}\right)$$

$$\bar{v}_h = \frac{1}{\Delta} \hat{h}_{k-1} - \bar{h}_{k-2}$$

$$\bar{\gamma}_g = \sin \left(\frac{\hat{h}_{k-1} - \hat{h}_{k-2}}{\bar{v}_{h,k-1}}\right)$$

(6)

where $\bar{h}$, $\bar{v}$, $\bar{\gamma}$, and $\bar{\rho}$ are the estimated state components; $\Delta$ stands for the time difference between two consecutive time steps; $\mu = \frac{\gamma_{in}}{\rho_0}$ and $\sigma_0$ are the standard atmospheric pressure and density at mean sea level, respectively.

The result considering the estimated parameters are shown in Fig. 2. In this case, all the guidance parameters are noisy through the whole trajectories (i.e., mismatch in both elevator and throttle parameters, and for all the considered modes). Table IV shows the average root mean square error (RMSE) of the guidance parameters. Obviously, accurate estimated parameters result in better filter performance. This can be seen in VT1 that is relatively robust to the small variation of $\bar{M}$. Regarding the average RMSE for the constant factor $\bar{k}$ in VT3, this value implies a 30% increase w.r.t. the nominal value, then the filter performance is clearly impacted by such large model mismatch. In the case that the elevator or throttle are used to steer the aircraft at a constant vertical speed or a constant flight path angle, the filter identifies all the modes containing VS and/or FPA with almost the same probability. Therefore, VT4 - VT9 (Fig. 2b and 2c) are misidentified. The IMM correctly identifies the modes associated with the minimum throttle rate in VT10 and VT11. VT12, when the aircraft flies at a constant pressure altitude, is the less impacted by the mismatch.

### Table II: VTs

<table>
<thead>
<tr>
<th>VT</th>
<th>GM</th>
<th>Command1</th>
<th>Command2</th>
<th>Initial Condition</th>
<th>End Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MACH-THR</td>
<td>$\bar{M} = 0.81$</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 27000$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 330$ kt, $m = 53500$ kg</td>
<td>$\bar{h}_p = 36000$ ft</td>
</tr>
<tr>
<td>2</td>
<td>CAS-THR</td>
<td>$\bar{v}_{CAS} = 250$ kt</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 5000$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 250$ kt, $m = 53000$ kg</td>
<td>$\bar{h}_p = 10000$ ft</td>
</tr>
<tr>
<td>3</td>
<td>DEC-THR</td>
<td>$\bar{\pi} = 0.3$</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 3500$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 193$ kt, $m = 53000$ kg</td>
<td>$\bar{v}_{CAS} = 280$ kt</td>
</tr>
<tr>
<td>4</td>
<td>VS-MACH</td>
<td>$\bar{v}_h = -1500$ ft/min</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 25000$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 330$ kt, $m = 54000$ kg</td>
<td>$\bar{h}_p = 30000$ ft</td>
</tr>
<tr>
<td>5</td>
<td>VS-CAS</td>
<td>$\bar{v}_h = -1000$ ft/min</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 10000$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 280$ kt, $m = 54000$ kg</td>
<td>$\bar{h}_p = 14000$ ft</td>
</tr>
<tr>
<td>6</td>
<td>VS-DEC</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 7000$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 250$ kt, $m = 54000$ kg</td>
<td>$\bar{h}_p = 10000$ ft</td>
</tr>
<tr>
<td>7</td>
<td>FPA-MACH</td>
<td>$\bar{\pi} = -2.25$ deg</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 10000$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 280$ kt, $m = 54000$ kg</td>
<td>$\bar{h}_p = 14000$ ft</td>
</tr>
<tr>
<td>8</td>
<td>FPA-CAS</td>
<td>$\bar{\pi} = -2.25$ deg</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 7000$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 250$ kt, $m = 54000$ kg</td>
<td>$\bar{h}_p = 10000$ ft</td>
</tr>
<tr>
<td>9</td>
<td>FPA-DEC</td>
<td>$\bar{\pi} = -5$ deg</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 10000$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 250$ kt, $m = 58000$ kg</td>
<td>$\bar{h}_p = 12000$ ft</td>
</tr>
<tr>
<td>10</td>
<td>VS-THR</td>
<td>$\bar{v}_h = -1000$ ft/min</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 2000$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 150$ kt, $m = 55000$ kg</td>
<td>$\bar{v}_{CAS} = 197$ kt</td>
</tr>
<tr>
<td>11</td>
<td>FPA-THR</td>
<td>$\bar{\pi} = -5$ deg</td>
<td>$\bar{\pi} = 0$</td>
<td>$\bar{h}<em>p = 5000$ ft, $s = 0$ NM, $\bar{v}</em>{CAS} = 193$ kt, $m = 53000$ kg</td>
<td>$\bar{v}_{CAS} = 250$ kt</td>
</tr>
</tbody>
</table>
Fig. 1: For each simulated VT: (upper subplot) true GM and (lower subplots) IMM-based model probabilities for the four scenarios. GM colour code at the bottom of the figure.

Fig. 2: For each simulated VT: (upper subplot) true GM and (lower subplot) IMM-based mode probabilities for the model mismatched induced by estimation error of guidance parameters. GM colour code at the bottom of the figure.
In the vertical plane, the aircraft is steered with two actuators (i.e., elevator and throttle), and several guidance flight modes can be defined. Knowledge on the active guidance mode is required, for instance, to enhance the trajectory prediction accuracy, to improve collision detection and resolution algorithms, for separation management, or airport congestion management in terminal maneuvering areas. Kalman filter-based interacting multiple model (IMM) filtering has been recently proposed to identify in real time the active aircraft guidance mode. Such approach provides good performance under nominal conditions, that is, with a perfectly known system model. In the guidance mode identification problem of interest, the implies that the guidance command parameters are perfectly known, which is not the case in practice. In real-life applications, such guidance command parameters are estimated or extracted from the measurements available. The goal of this contribution was to assess the sensitivity of the IMM-based guidance mode identification to a possible model mismatch, induced by the guidance command parameters. Two cases were considered: i) guidance parameters with additive Gaussian noise, to emulate real noisy measurements, and ii) estimated guidance parameters computed from the state estimates, then having an inherent estimation error. Such analysis was provided for a representative set of validation trajectories. The main outcome of such study is that, in general, the performance of the filter is clearly degraded if using uncertain guidance command parameters. This shows the need for robust IMM filtering techniques, able to deal with a possible model mismatch, in real-life applications.

### IV. Conclusion

In the vertical plane, the aircraft is steered with two actuators (i.e., elevator and throttle), and several guidance flight modes can be defined. Knowledge on the active guidance mode is required, for instance, to enhance the trajectory prediction accuracy, to improve collision detection and resolution algorithms, for separation management, or airport congestion management in terminal maneuvering areas. Kalman filter-based interacting multiple model (IMM) filtering has been recently proposed to identify in real time the active aircraft guidance mode. Such approach provides good performance under nominal conditions, that is, with a perfectly known system model. In the guidance mode identification problem of interest, the implies that the guidance command parameters are perfectly known, which is not the case in practice. In real-life applications, such guidance command parameters are estimated or extracted from the measurements available. The goal of this contribution was to assess the sensitivity of the IMM-based guidance mode identification to a possible model mismatch, induced by the guidance command parameters. Two cases were considered: i) guidance parameters with additive Gaussian noise, to emulate real noisy measurements, and ii) estimated guidance parameters computed from the state estimates, then having an inherent estimation error. Such analysis was provided for a representative set of validation trajectories. The main outcome of such study is that, in general, the performance of the filter is clearly degraded if using uncertain guidance command parameters. This shows the need for robust IMM filtering techniques, able to deal with a possible model mismatch, in real-life applications.

### REFERENCES


