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# Fault Tolerant Flight Control Using Sliding Modes and Subspace Identification-Based Predictive Control

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**Abstract**: In this work, a cascade structure of a time-scale separated integral sliding mode and model predictive control is proposed as a viable alternative for fault-tolerant control. A multi-variable sliding mode control law is designed as the inner loop of the flight control system. Subspace identification is carried out on the aircraft in closed loop. The identified plant is then used for model predictive controllers in the outer loop. The overall control law demonstrates improved robustness to measurement noise, modeling uncertainties, multiple faults and severe wind turbulence and gusts. In addition, the flight control system employs filters and dead-zone nonlinear elements to reduce chattering and improve handling quality. Simulation results demonstrate the efficiency of the proposed controller using conventional fighter aircraft without control redundancy.



*Keywords:* MPC, Sliding Mode Control, System Identification, Fault Tolerance, Robustness.

## 1. INTRODUCTION

AIRCRAFT safety is of paramount importance, as failure can result in irreparable loss of life and equipment. Recently, there has been a lot of interest in developing reconfigurable control systems which can tolerate system faults to enable safe handling of a damaged aircraft. Due to short reaction time, and non-standard control actions needed for unanticipated faults, an automatic reconfiguration is required, Hajiyev and Caliskan (2003). In 1984, the U.S. Air Force began a program called the Self-Repairing Flight Control System (SRFCS) program. Faults were detected by passing error between actual and ideal outputs through several filters, each representing a model of the aircraft in a certain failure mode. Fault likelihoods were used by a pseudo-surface resolver to optimally allocate control actions, Urnes et al (1990). Maybeck and Stevens (1991) considered multiple model-based adaptive estimation and control in which failures are represented as a vector of unknown system parameters affecting the model structure. Shore and Bodson (2005) used model reference adaptive control based on RLS parameter identification for reconfigurable control.

The inherent capability of model predictive control (MPC) to accommodate for constraints and robustness to certain uncertainties has been advocated as a strong reason for its use in fault tolerance, e.g. Kale and Chipperfiled (2004). Sliding mode control has been proposed as an alternative for fault tolerant flight control, e.g. Hess and Wells (2003). In Edwards et al (2010), SMC is used with a control allocation algorithm for fault tolerant control of a control-redundant along with SMC-based observers for fault signal estimation.

A dominant research stream has focused on using linear models at different trim inputs for deriving the sliding conditions. Such approach induces high cost modelling and designing activities if real industrial applications. In this work, nonlinear SMC and discrete MPC based on subspace-identified model are shown to be a viable approach for fault-tolerant control. The proposed algorithm does not require trimming the aircraft or linearizing it. The control configuration is composed of two cascaded loops. The innermost loop is a multi-variable sliding mode control, which is robust to severe modelling uncertainties. The commands for the inner loop are generated by two MPC controllers in the outer loop. MPC controllers are based on discrete models identified using a subspace method using pseudo-random test signals. The overall control scheme is shown to be robust against modelling errors and multiple faults. Simulations are provided to demonstrate the capability to carry out aggressive combat-like manoeuvres even in the presence of strong wind turbulence and gusts.

The paper is organized as follows. In Section 2, the problem is casted in mathematical terms and a framework is laid for sliding mode control, closed loop subspace identification method and model predictive control. The results are then applied to six degree of freedom, nonlinear model of an F-16 fighter aircraft in Section 3, where the rationale for selecting various controller parameters and identification experiment design is detailed. Various failures, disturbances, crosswind and turbulence are simulated in Section 4 to demonstrate robustness of the designed controller and its ability to perform well under severe conditions and parameter


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uncertainties. Finally, the work is summarized and future research avenues are suggested in the conclusion.

## 2. PRELIMINARIES

Consider the following general flight dynamics model without control redundancy of a rigid aircraft such as a conventional fighter aircraft:

$$\dot{x}(t)=f(x,u)+g(x,u)u(t)+e(t), \quad y(t)=h(x)+n(t) \tag{1}$$

Where, $x \in \mathbb{R}^a, u \in \mathbb{R}^b, y \in \mathbb{R}^c$ are the state, control and output vectors respectively. White Gaussian measurement noise is denoted by $n \in \mathbb{R}^c$, while unmodelled dynamics, disturbances and modelling inaccuracies enter as bounded process noise $e \in \mathbb{R}^a$. Moreover, (1) is subject to the following physical constraints:

$$y_{min} \le y \le y_{max}, |u(t)| \le u_{max}, b < \langle a, c \rangle \tag{2}$$

The last constraint indicates under-actuation since there are *m* controls for *p* outputs. Therefore, in order to make the system square for the purpose of applying standard multivariable sliding mode techniques, e.g. Slotine and Weiping (1991), we have to consider a square subset of the output space $y_1 \in \mathbb{R}^b$, such that the remaining $y_2 \in \mathbb{R}^{c-b}$ outputs are stable. This requirement is not conservative if $y_2$ can be stabilized in a slower outer loop cascaded with a faster inner loop controlling $y_1$, with proper time scale separation between the loops.

### 2.1 Nonlinear Sliding Mode Control (SMC)

SMC consists of continuous control along with an appropriate switching logic, robust to external disturbance and plant mismatch. Consider a variable transformation $\bar{y} = y\text{-}y_d$, where $y_d$ is the desired value. Time varying sliding surfaces for some constant λ are given as

$$s(y_1,t) = \left(\frac{d}{dt}+\lambda\right)\int_0^t \bar{y}_1\, d\tau = \bar{y}_1 + \lambda\int_0^t \bar{y}_1\, d\tau \tag{3}$$

Considering sliding surfaces to be invariant, ds/dt=0, (3) can be solved to provide "equivalent control" $u_{eq}$

$$u_{eq}(\lambda, \tilde{y}_1) = -(h\hat{g})^{-1}(h\hat{f} - \dot{y}_{1,d} + \lambda\tilde{y}_1) \tag{4}$$

where $\hat{f}$ and $\hat{g}$ are nominal estimates of system dynamics *(f)* and controller gains *(g)* respectively, such that

$$|f - \hat{f}| \le F, \quad \Gamma^{-1} \le \left|\frac{g}{\hat{g}}\right| \le \Gamma \tag{5}$$

and the sign of *g(x)* is known. To ensure stability and satisfy the sliding condition in the presence of uncertainties,

$$\frac{1}{2}\frac{\partial}{\partial t}s^2 \le -\eta|s| \tag{6}$$

Where $\eta \in \mathbb{R}^a$ is strictly positive. The sliding condition ensures invariance of s(t) in the presence of model mismatch and disturbance. Let,

$$k \ge \Gamma(F+\eta)+(\Gamma\text{-}1)|u_{eq}| \tag{7}$$

Then (6) is satisfied if the control law is formulated as:

$$u = -(h\hat{g})^{-1}\left[h\hat{f} - \dot{y}_{1,d} + \lambda\tilde{y}_1 - K.\text{sign}(s)\right] \tag{8}$$

for some constant gain vector *K*.

### 2.2 Model Predictive Control (MPC)

MPC is a nonlinear scheme in which control is determined by optimizing a cost function predicted into the future. Suppose that we have a discrete linear model of the remaining outputs ($y_d$) of the plant as follows

$$\begin{aligned}\bar{x}(k+1) &= A\bar{x}(k)+B\bar{y}_{1,d}(k)+e_2(k),\\ \bar{y}_2(k+1) &= C\bar{x}(k+1)+D\bar{y}_{1,d}(k)+n_2(k)\end{aligned} \tag{9}$$

Here, $y_{1,d}$ acts as the virtual input to the inner loop containing the SMC. The outputs are predicted $N_p$ time-steps into the future using $N_c$ discrete control steps to minimize the following cost function:

$$J_k = \sum_{p=1}^{N_p} \|\bar{y}_2(k+p+1|k)\|_Q^2 + \sum_{c=1}^{N_c} \|y_{1,d}(k+c|k)\|_R^2 \tag{10}$$

Subject to

$$y_{min} \le y \le y_{max} \tag{11}$$

where $\|.\|_Q$ is the weighted 2-norm with positive definite matrices Q and R. The optimization is carried out at each outerloop sampling instant, such that only the first step of the optimized $N_c$ control steps is implemented in the receding horizon strategy, and the cycle is repeated.

### 2.3 Subspace System Identification

In order to implement MPC control in the outer loop, we must have a prediction model for the inner loop under SMC controller. While the relationship between Euler angles $\langle\phi,\theta,\psi\rangle \in y_1$ and body angular rates $\langle p,q,r\rangle \in y_2$ is a well known nonlinear kinematic relation, the relation with flow angles $\langle\alpha,\beta\rangle \in y_2$ depends on the vehicle's aerodynamics. In order to control the flow angles, the inner loop must be identified. There are numerous parameterizations for input-output data, but for multi-variable MPC design, state-space models are a natural choice. State-space models can be