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An Overview of Adaptive Approaches in Flight Control

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Abstract
Multi-mode switching between controllers corresponding to different modes of operation is needed in those cases when the transition from one mode to another results in substantial flight-critical variations in the aircraft dynamics. To address this problem, a general framework for multi-modal flight control is proposed. The framework is based on the Multiple Models, Switching and Tuning (MMST) methodology, combined with Model-Predictive Control (MPC), and the use of different robust mechanisms for switching between the multi-modal controllers. It was shown that many different switching control strategies can be naturally derived from the basic framework, which demonstrates the generality of the proposed approach.
Key words: MMST, MPC, Mode prediction, Flight control, Switching, Optimization

I. Introduction

Multi-modal control can be broadly defined as a set of control strategies used to achieve the pre-specified objectives for a controlled vehicle in different modes of operation. Modes of operation are related to the vehicle dynamics and its environment. For instance, in the case of air vehicles, possible modes of operation include mission modes and internal and external modes. Those are described below.

Mission Modes: During a mission, the vehicle goes through different modes of operation. For instance, during a strike mission an advanced combat aircraft goes through take-off, super-cruise, low-altitude ingress, target strike, air combat maneuvering, low altitude egress, powered approach, and landing.In general, in those modes, different control strategies are used to achieve the desired performance. In this context, the desired performance includes not only the requirement for accurate tracking of commanded signals, but also that of optimal guidance to assure low signature, optimum fuel consumption etc.

One widely used strategy for air vehicles operating in different flight regimes is Gain Scheduling shown in Figure 1

Figure 1.

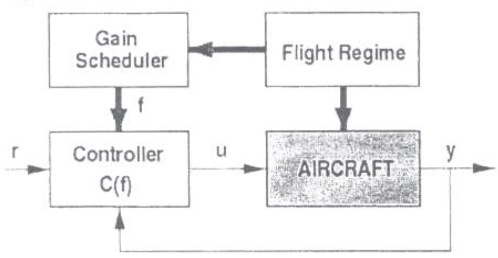

Figure 1: Gain Scheduling

closed-loop system.

While this strategy has been widely used in practice, its main disadvantage is that the stability and robustness of the overall system is difficult to predict, particularly in the presence of unanticipated events such as disturbances, failures, battle damage, et cetera.

Internal Modes: Common variations of the air vehicle dynamics during different segments of a mission are due to fuel consumption, store release, weight changes (in the case of air drops), usage of different engines (as in hypersonic vehicles), et cetera. During transitions between these modes either a sufficiently robust baseline control strategy or a gain-scheduled controller can be used.

However, of particular importance in this context are *failure modes* since unexpected failures of flight-critical subsystems or components can lead to substantial performance degradation and even to the loss of the vehicle. Such failures include sensor, control effector, actuator and engine failures, and failures of avionics subsystems and the flight computer. While there are methods available for on-line Failure Detection and Identification (FDI) and Adaptive Reconfigurable Control (ARC) of advanced fighter aircraft [1,2,3], a comprehensive approach that can handle multiple simultaneous failures of flight-critical subsystems and components has not been developed yet.

External Modes: can be described as those arising from unexpected variations in the environments encountered by the vehicle. These include: (i) Loss of communication with the command center or other team members; (ii) Very large external disturbances; (iii) Battle damage; and (iv) Sudden pop-up threats. In such cases, advanced identification, FDI-ARC, and estimation algorithms are needed to stabilize the vehicle and achieve at least some minimum tolerable performance. While some of the partial solutions to this problem are available [4,6,8], there is a need to develop a comprehensive Autonomous Intelligent Flight Control Systems (AI-FCS) that can achieve the desired objectives despite encountering unanticipated modes of operation. The design of such AI-FCSs is one of the key research areas in **SSCI.**

Multi Modal Control Systems (MMCS) and AI-FCS should have a capability to handle efficiently mission modes under unexpected internal and external variations. This objective should be achievable with the available control authority, which emphasizes the importance of real-time Control Input Redundancy Management for on-line MMCS and AI-FCS.

Basic elements of MMCS and AI-FCS include:

- Redundancy management
- Mode prediction
- Disturbance estimation and rejection
- Failure Detection and Identification (FDI) and Damage Detection and Identification (DDI) as a part of the Health Management System (HMS),
- State estimation and filtering, and
- Decision making subsystem(s).

An AI-FCS under development by SSCI, is shown in Figure 2.

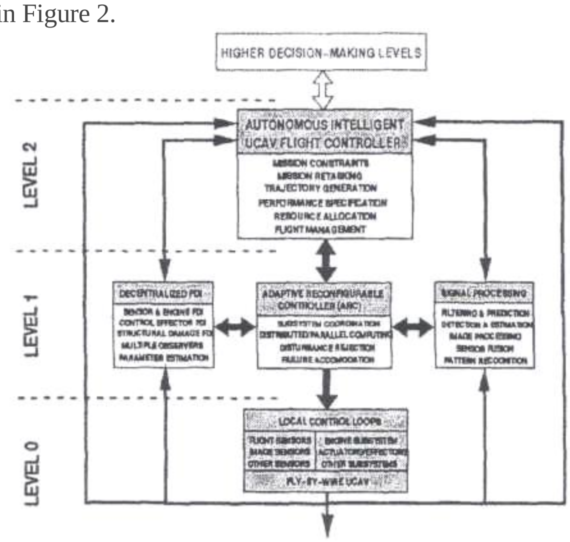

Figure 2: Structure of the AI-FCS

In this context, of particular importance is *mode prediction*, since, based on the models of the vehicle and its environment, the transitions between different modes can be predicted, and this information can be used to choose the best control strategy. Such a MMCS is shown in Figure 3.

The overall AI-FCS should, hence, combine the following strategies:

- MMST, where multiple observers can be used for specifying a number of different modes of operation related to failures, battle damage and the presence of large disturbances;

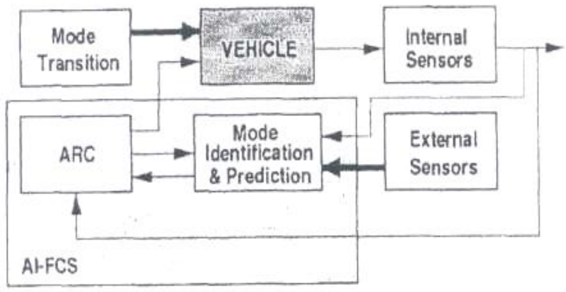

Figure 3: Structure of the Multi-Modal Control System

- MPC that can be used for prediction of the modes of operation and for ARC in the presence of failures and uncertainties under different constraints; and
- Multi-layer hierarchical control structure for specifying the links between the executable levels and decision-making subsystems.

Model-Predictive Control *(MPC)*

MPC is an optimal control approach involving direct use of both linear and nonlinear internal models of a plant and on-line optimization techniques to assure that the objective of tracking a desired trajectory is achieved under constraints on the control inputs, states and outputs.

One of the most important aspects of the MPC is that it can explicitly account for both position and rate limits on the control effectors, which is a unique capability in comparison with other available control strategies.

Other important aspects include the fact that the internal model of the MPC can be either linear or nonlinear, and that it can be identified and changed on-line for a fully adaptive MPC design. In addition, the MPC-based multiple model FDI-ARC schemes have been demonstrated as highly effective for achieving the control objectives in the presence of severe subsystem or component failures.

Structure of an MPC scheme is shown in Figure 4.

The internal model of the plant has the same input as the actual plant, and its output approximates the true output.

The observer (predictor) predicts the future output *of* the plant *T* steps ahead based on the internal model, while, over the same prediction horizon 7, the reference model generates a trajectory that the future outputs should follow.

The optimization technique commonly used in the context of MPC is a constrained Sequential Quadratic Programming (SQP) algorithm. It is based on a quadratic cost functional *J* that depends on the values of the tracking error over the prediction horizon T, and on the control input values over the control horizon *M*. This cost functional is subject to the constraints on states, output and inputs. The MPC algorithm calculates an optimal sequence of control inputs by minimizing *J* over *T*, applies the first element of the input sequence to the plant, and repeats the procedure. The concept of MPC is shown in figure 5.

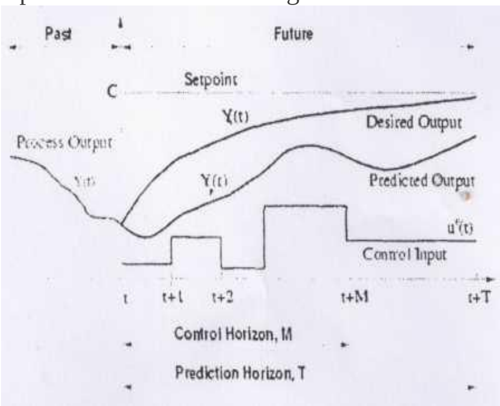

Figure 5: **Model Predictive Control Philosophy**

We will next discuss the applications of the MMST concept in the design of MMCS and AI-FCSs.

Multiple Models, Switching, and Tuning (MMST)

The concept of MMST has been extensively used by SSCI in the context of both aircraft and spacecraft control [5]—[10]. Its main advantages over single model-based adaptive controllers are summarized below:

1. The MMST-based schemes can achieve effective control reconfiguration and excellent overall performance even in the case of severe failures when single model adaptive controllers fail to achieve the objective.
2. MMST appears to be the only available approach that can be used to solve the problem of efficient adaptive control reconfiguration for TAFA in the presence of severe wing damage.

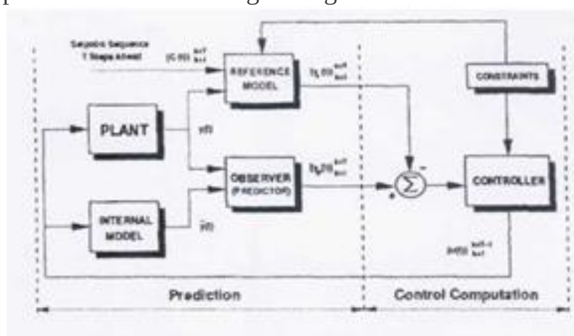

Figure 4: Structure of the Model Predictive Controller (MPC)

3. A particularly attractive feature of the MMST controllers is that they result in a stable overall system despite the presence of severe failures and wing damage.

The basic comparison of the MMST controller with a single model adaptive controller is described in Figure 6.

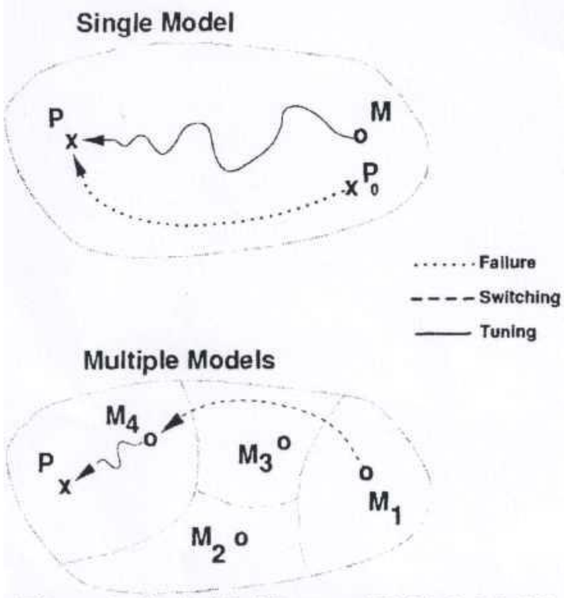

Figure 6: Single Model versus Multiple Model Adaptation

As shown in the figure, failure may cause the plant dynamics to switch abruptly from some nominal point P_o in the parametric space, to the point P corresponding to the failed plant.

The top figure illustrates the case when adaptation using a single model may be too slow to identify the new operating regime and reconfigure the controller. In such a case placing several models in the parametric set, switching to the model close to the dynamics of the failed plant, and adapting from there can result in fast and accurate control reconfiguration.

The concept of MMST is based on the idea of describing the dynamics of the system using different models for different operating regimes; such models identify in some sense the current dynamics of the system and are consequently referred to as the identification models or observers.

The basic idea is to set up such identification models (observers) and corresponding controllers in parallel, Figure 7, and to devise a suitable strategy for switching among the controllers to achieve the desired control objective. While the plant is being controlled using one of these controllers, the identification models are run in parallel to generate some measure of the corresponding identification errors and find a model which is, in some sense, closest to the current operating regime of the plant.

Once such a model is found, the switching mechanism switches to (or stays at) the corresponding controller assuring overall stability.

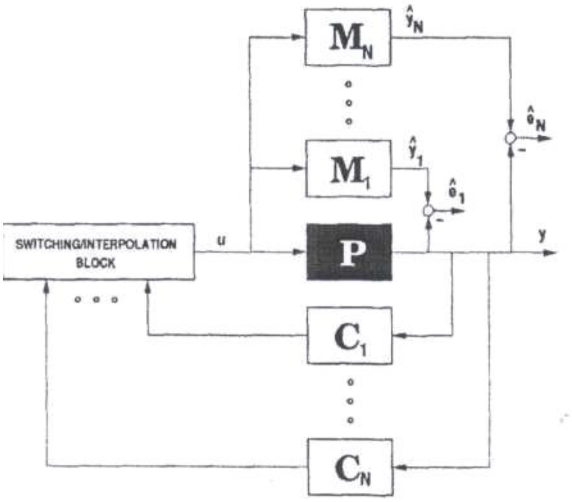

Figure 7: Structure of the Multiple Model-Based Control System

In the context of reconfigurable control design in the presence of parametric uncertainties and/or sensor, actuator and structural failures, the identification models (observers) M_{If}...,M_N from Figure 7 correspond to different regions in the parameter space characterizing different types of failures, while C/,...,C/v denote the corresponding controllers. Such an approach was used in [5,7,9,10] for adaptive reconfigurable control design, yielding excellent performance of the overall system in the presence of severe failures and battle damage.

II. Design of Multi-Modal Algorithms using Combined Switching Controllers

In general, the aircraft dynamics is characterized by transitions between different modes of operation. Such variation in the dynamics may be due to transitions between different flight regimes, or the effect of large external disturbances, or to subsystem and/or component failures. In such cases, different strategies for FDI-ARC and AI-FCS design are needed for different modes of operation.

In this context, one viable approach is that based on MMST. To take into account different constraints, an adaptive MPC needs to be used within the multiple model framework.

The emphasis of the overall design then needs to be on different performance specifications and different control strategies in different modes of operation, and a multi-modal approach to on-line control redesign for transition between different modes and control reconfiguration in the presence of failures.

One of the related problems is the choice of the most suitable control strategies in different modes of operation. As it is well known, the Inverse Dynamics Control Law (IDCL) algorithm [23] is computationally simple and easy to implement. However, it does not take into account explicitly position and rate limits on the control effectors, which may cause unacceptable transients and even instability of the overall system. On the other hand, the MPC strategy takes these constraints into account but is computationally intensive. Hence a viable compromise is a control strategy that uses the IDCL as long as there is no rate or position limiting, and switches to the MPC when one or more inputs are about to saturate. The proposed scheme is shown in Fgure *R.*

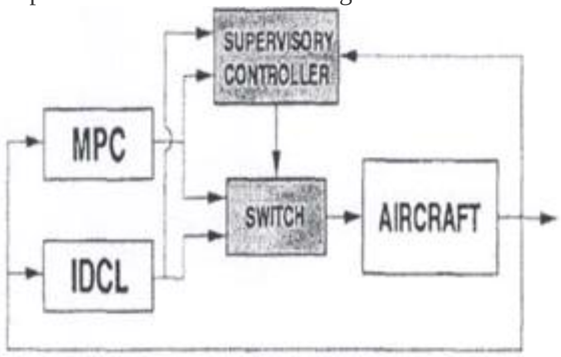

Figure 8: A Combined IDCL/MPC Controller

Such a scheme needs to be developed in the context of MMST to assure overall stability and robustness to uncertainties.

An important aspect of such an approach is that even in the cases when the IDCL is used to control the aircraft, the MPC estimator is running an providing predicted values of the state of the system, which is an important information for higher decision-making levels.

III. Parameter Estimation-Based Switching Control

Another approach that appears well suited for the problem under consideration is that based on estimation-based switching among the controllers.
This approach is motivated by our results obtain in [9], and is illustrated in Figure 9.

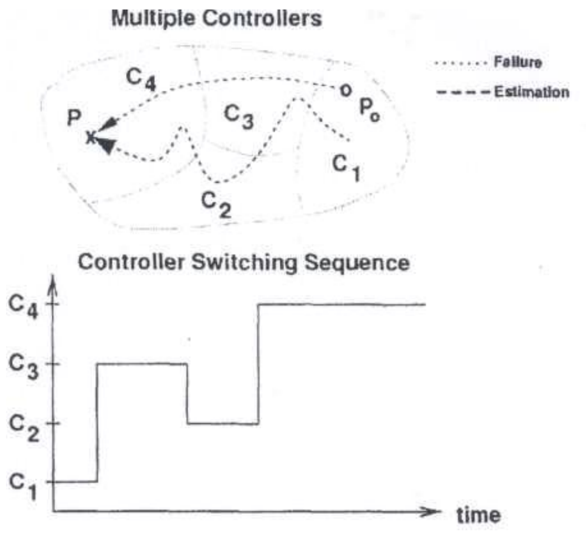

Figure 9: Parameter Estimation-Based Switching

The basic idea is to use the on-line estimates of the aircraft parameters to decide which controller to choose in a particular flight regime or mode of operation. As seen in the Figure, if the plant dynamics abruptly switches from the point P_o to point P in the parametric set, the estimate will moves through the parametric set trying to identify the model corresponding to the point P. The parametric set is divided into subsets so that each subset there is a corresponding controller *Cj*,...,C_4 that achieves the objective for all values of parameters from the subset. As the estimate moves into a particular subset, the scheme switches to the corresponding controller. To prevent chattering, a hysteresis switching rule can be used.

A particularly attractive feature of this approach is that it appears that the stability of the overall system can be explicitly proved, which is not the case with standard gain-scheduled controllers.

Prediction-Based Switching Control

An interesting observation in this context is that, conceptually, there is no difference between parameter estimation-based switching control and prediction-based switching control. In particular, let the plant go through transitions among different sets in the *state space,* where, for each set we have the corresponding controller *Cj*,...,C_N. If the controller gains are changed based on the variation of some of the state variables, we have *gain scheduling.* If the gains are changed based on on-line parameter estimates, we have *indirect adaptive control*

In the previous sections we discussed switching between different controllers based either on the control input or parameter estimates. Another promising strategy is that based on the *predicted state* of the system. In particular, we can run the MPC to arrive at the values of the state *T* steps ahead. If the predicted state moves to a different set in the state space, we can switch to the corresponding controller based on this prediction.

IV. Conclusions

In this paper we propose a general framework for multi-mode switching in flight control. From the flight control design point of view, multi-mode switching between controllers corresponding to different modes of operation is needed in those cases when the transition from one mode to another results in substantial flight-critical variations in the aircraft dynamics.

To address this problem, a general framework for multi-modal flight control is proposed. The frame work is based on the Multiple Models Switching and Tuning (MMST) methodology, combined with Model-Predictive Control (MPC), and using different robust mechanisms for switching between the multi-modal controllers. It is shown that many different switching control strategies can be naturally derived from the basic framework, which demonstrates the generality of proposed approach.

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