FAULT ACCOMMODATION USING MODEL PREDICTIVE METHODS

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Contents

Summary

In this chapter we focus on the application of Model Predictive Control (MPC) in the context of fault accommodation. We first discuss the fault accommodation problem, present several failure models, and derive the Model Predictive Control (MPC) algorithm for the no-failure case when the objective is to track the outputs of a reference model.

Following that, we show how the Multiple Models, Switching and Tuning (MMST) methodology can be applied in the context of Failure Detection, Identification and Reconfiguration (FDIR), and discuss its stability and convergence properties. Multiple Model Predictive Control (MMPC) approach is presented and discussed in the case of lock-in-place control actuator failures. Combining the on-line FDI system with the Model Predictive Control (MPC) approach, results in an efficient MMPC algorithm that is well suited for different types of failures and upset conditions encountered during plant operation.

1. Introduction

Modern control theory provides a rich set of tools and techniques for designing optimal controllers based on the mathematical models of system dynamics. A fundamental difference between classical control techniques, such as PID control, and modern control design methods is in the explicit use of system models and model-based control criteria in the latter case.

PID controllers are simple to implement and are widely used in many different industrial branches. However, such controllers do not take into account process characteristics such as nonlinearities, time variations, loop interactions, and constraints. Consequently, PID controllers are not optimal under all conditions, which may result in poor overall performance. As demonstrated in a large number of applications, significant improvements in the system performance can be achieved using multivariable model-based controllers.

Among the many techniques developed within the framework of the modern control theory, Model Predictive Control (MPC) has been demonstrated as an efficient approach in different process control applications (see 6.43.16 Model-based Predictive Control). This approach has been implemented under different names such as Model Algorithmic Control, Dynamic Matrix Control, Receding Horizon Control, Generalized Predictive Control and Internal Model Control. More recently, the stability properties of the MPC have been established, and the approach has been extended to nonlinear systems using nonlinear programming methods and neural network models. An important feature of MPC is that it can be implemented using fuzzy logic for systems that cannot be described by analytical models. MPC has also been demonstrated as a highly efficient approach to failure accommodation. In this chapter we will discuss such applications of the MPC technique.

1.1. Model Predictive Control (MPC)

Model Predictive Control (MPC) is an optimal control approach involving direct use of 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 actuators, 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 fault-tolerant control techniques have been demonstrated as highly effective tools for achieving the control objectives in the presence of critical subsystem or component failures.

MPC Structure: The structure of an MPC scheme is shown in Figure 1.

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 T, 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, 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 illustrated in Figure 2.

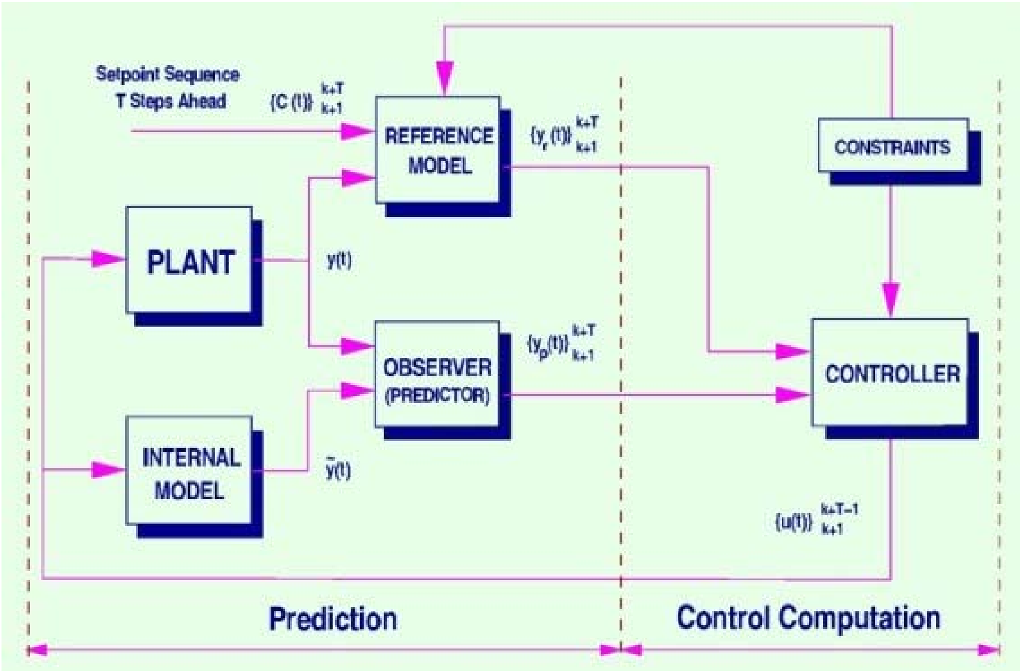

Figure 1: Structure of the Model Predictive Controller (MPC)

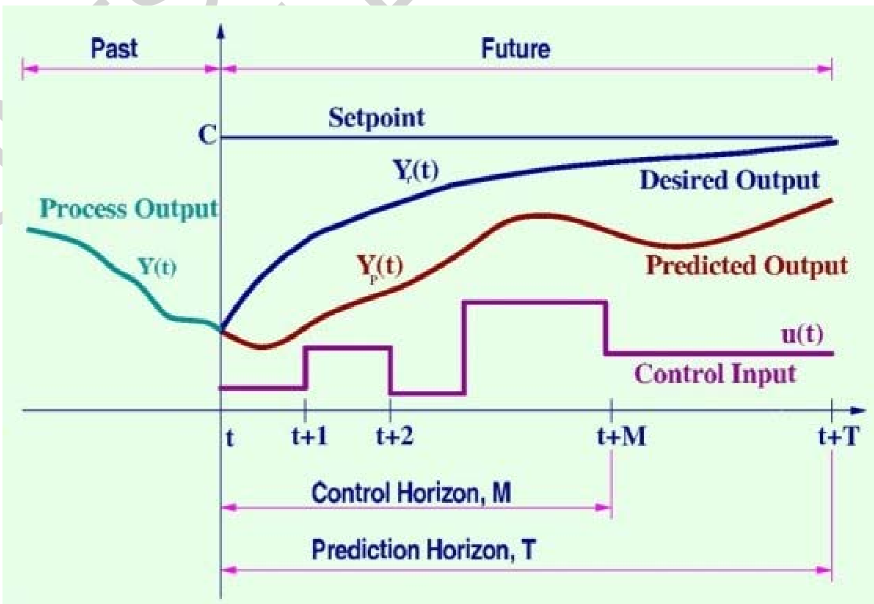

Figure 2: The Model Predictive Control Philosophy

1.2. Failure Accommodation

In the past several years there has been substantial progress in the area of fault-tolerant and reconfigurable control designs, particularly in the area of flight control. The results so far have demonstrated the potential of the reconfiguration techniques to maintain automatically the desired aircraft performance despite severe control actuator failures and structural or battle damage.

Several of those approaches have been extensively tested through simulations, and even flight tested. Other applications of fault-tolerant control techniques are discussed in 31.9, Fault-tolerant Systems. However, only a few of the proposed techniques take explicitly into account position and rate limits on the control actuators.

One of the promising techniques for on-line reconfigurable control design is that based on the concept of Multiple Models, Switching and Tuning (MMST), shown schematically in Figure 3. The technique has been used extensively in the area of Failure detection and Identification (FDI), and Adaptive Reconfigurable Control (ARC) in aerospace applications.

The concept of MMST, developed by Professor Narendra at Yale, 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.

The basic idea is to set up such identification models and corresponding controllers in parallel, as shown in Figure 3, 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, where the switching interval is a parameter chosen by the designer.

The main feature of this approach is that, in linear time-invariant systems, it can be shown to result in a stable overall system in which asymptotic convergence of the output error to zero is guaranteed under relatively mild conditions.

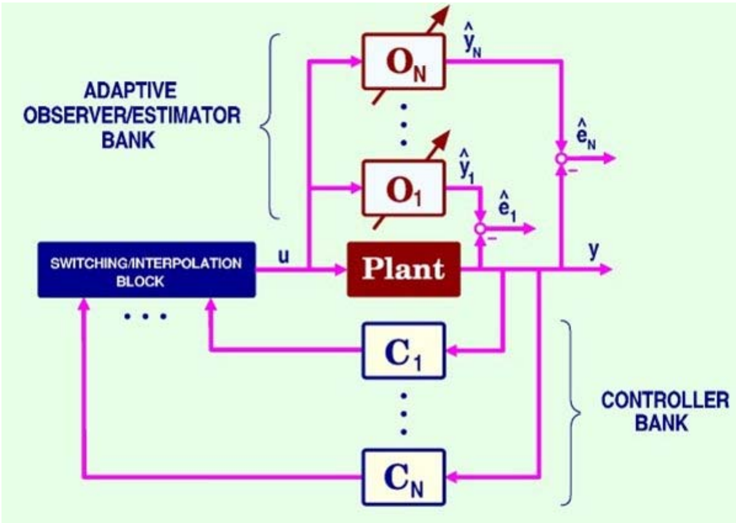

Figure 3. Structure of the Multiple Model-Based Controller: Outputs of the parallel observers $O_1, O_2, ...O_N$ are used to find that closest in some sense to the current plant dynamics, and switch to the corresponding controller

In the context of reconfigurable control design in the presence of parametric uncertainties and/or sensor, actuator and structural failures, the identification models (observers) $O_1,...,O_N$ from Figure 3 correspond to different regions in the parameter space characterizing different types of failures, while $C_1,...,C_N$ denote the corresponding controllers.

Multiple Model-Predictive Control: One of the important practical problems encountered in the MMST control design is that of position and rate limits on the control actuators.

To address this issue, the MMST approach can be combined with the MPC technique, resulting in the Multiple Model-Predictive Control (MMPC) technique. Such a reconfigurable control approach includes multiple predictive models, whose role is to identify the nature and instant of the failure of one or more control actuators.

This information is in turn used to switch to the corresponding model-predictive controller to achieve the control objective. This is discussed in more detail in the following sections.

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Biographical Sketches

Dr. Jovan D. Bošković received his BS, MS and Dr. Sc. degrees in Automatic Control in 1980, 1985 and 1992, respectively, all from University of Belgrade, Yugoslavia. From 1986 to 1989 and from 1992 to 1996 he was a Research Fellow with the Center for Systems Science, Department of Electrical

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Dr. Raman K. Mehra received his BS degree from Punjab Engineering College, Chandigarh, India in 1964, and MS and PhD degrees from Harvard University in 1965 and 1968, respectively. From 1972 to 1976 he was Associate Professor of Engineering and Applied Mathematics at Harvard University and Manager at Systems Control, Inc. from 1969 to 1972. As founder and president of Scientific Systems Company, Inc. (SSCI), he is responsible for overall technical and financial management of R&D projects, and supervision of professional staff of engineers and scientists. Since the inception of the company in 1976, Dr. Mehra has directly managed over two hundred R&D projects. He has also developed new approaches for multivariable digital control and applied methods of state-space forecasting to business, energy, socio-economic and hydrological time series. He is responsible for getting the company into new fields such as Unmanned Aerial Vehicles, space vehicles, robotics, load management, power system control, financial modeling and forecasting, nonlinear optimization of flight vehicles, missile guidance and control, process control, and nuclear and fossil power plant control. Dr. Mehra published over two hundred fifty papers in refereed journals and conferences. He is an IEEE Fellow and a recipient of numerous awards in the area of automatic control.