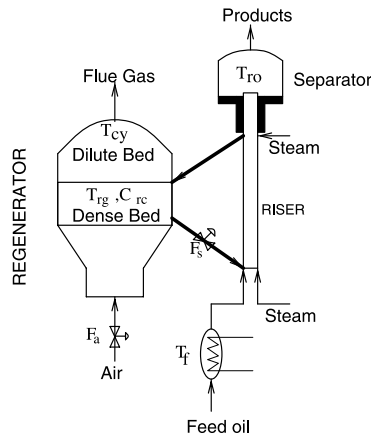


## Preface—Volume 2: Multiparametric Model-Based Control

The unavoidable presence of variations forces the industrial plants to deviate from the desired operational policy. Those time-dependent or time-invariant variations originate from either unexpected or predictable, in nature, phenomena. The unpredictable changes are usually termed as uncertainties and have a wide range and variety of sources. Variations in customer demand, changes in raw materials quality and quantity, fluctuations in process utilities, inevitable alterations in physical properties and uncertainties in discrete states such as equipment availability [1] have a large impact on the economic performance and operation of a plant. On the other hand, predictable and even desirable conditions, such as start-up units, maintenance periods, can also make a continuous process operate in a dynamic or nonnominal mode thus influencing the economics and the transient or steady-state plant behavior.

To illustrate some of these concepts that are associated with plant operation consider the fluidized catalytic cracking plant shown in Fig. 1 and used in several control and operations studies from the open literature [2–4]. This is an important process in refineries as it converts the heavy hydrocarbons contained in the gasoil feed to valuable light components with boiling points in the region of gasoline, naphtha or kerosine. This system operates usually in a dynamic mode due to variations in the process conditions.

The challenge for an engineer should be to determine the optimal operational policy for such a plant, which is translated into driving in an optimal manner some of the characteristic process outputs such as the temperature in the regenerator and in the riser to a target optimal set-point determined from economics. While aiming to achieve this objective, the operator should also guarantee that process constraints corresponding to safety restrictions or product specifications (the temperature of the regenerator, the coke content of the catalyst or the temperature of the products) are satisfied. The manipulated variables at the operator's disposal are the air inlet flowrate to the regenerator and the recycle flow of the catalyst. What hampers the plant operation is (i) the presence of unknown time-varying disturbances, e.g., in the feed load and the feed conditions, (ii) the variations in the economically optimal set-point due to upper-level decisions, (iii) the variability of the plant physical characteristics such as catalyst activity in the riser and (iv) some



**Fig. 1** Motivating example, FCC process.

process design features that have a great impact on the system dynamics, e.g., large inventory size causing increased time-constants or heat and mass recycle leading to disturbance amplifications. These phenomena force the plant to operate under transient nonnominal conditions, thus making operator's undertaking more challenging.

One of the most systematic approaches for obtaining the optimal operational conditions of the system is online control and optimization. Here, after specific information is obtained about the current plant conditions and the uncertainty profile, an optimization problem based on a process model is solved using as search variables the profiles of the manipulated inputs. When this operational strategy is implemented in an open-loop manner, the calculations are repeated periodically or every time a change in the uncertainty variation becomes known to the operators. This method can also be applied in a closed-loop fashion leading to an automatic model-based predictive control (MPC) scheme. MPC, thereby, determines the appropriate future control sequence via online optimal control calculations based on the current process states that in our FCC example pertain to the temperature in the regenerator and the coke fraction deposition on the catalyst. The first element of the sequence is implemented on the plant and the next control values are derived via regular state feedback updates and the repetition of the online computations.

multiparametric model-based control

However, these widely recognized open and the closed-loop optimal control implementations involve significant online computations, while the control or operational action they provide only known implicitly via the solution of an optimization problem. A parametric optimization-based approach for moving off-line these rigorous calculations has been proposed in Volume 1 of this series [5]; aiming to make optimization techniques applicable to a wider range of systems. The schematic description of this attractive alternative and the contrast with the traditional online optimization technique is shown in Fig. 2. The key principle of this technique is that it derives off-line, before any actual process implementation occurs, the explicit

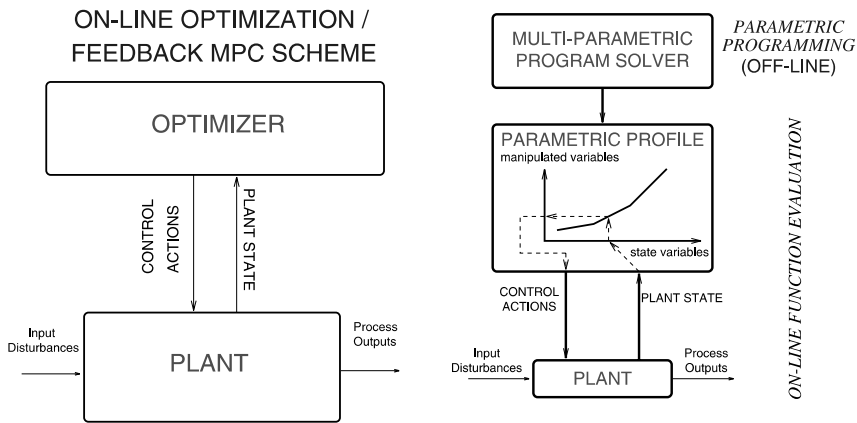


Fig. 2 Online optimization vs. off-line parametric programming approach.

mapping of the optimal decisions in the space of the plant uncertainty variations and the plant current conditions using multiparametric programming algorithms. Thus, online optimization reduces to simple function evaluations for identifying the optimal control action. Another important advantage is that the resulting parametric control law or operational policy consists of explicit closed-form expressions that can provide precious insight into the closed-loop system features.

Furthermore, this novel parametric programming approach features the following advantages:

- It is not limited to steady state or discrete time dynamic systems. Thus, it portrays accurately transient plant evolution.
- It addresses directly the presence of path constraints, (e.g., upper limits on the riser temperature in the motivating FCC example) that have to be satisfied over the complete time domain and not merely at particular time points.
- The closed-loop feedback controller derived from this technique has been developed to the extent of dealing efficiently with the presence of unpredicted or unmodeled uncertainties.
- In the presence of nonvanishing disturbances, a robust tracking controller has been designed using parametric optimization techniques.
- The explicit control law has also been designed for hybrid systems (e.g., plants that inter-mix logical discontinuous decisions with the continuous plant operation such as the possible switch in our motivating example between the partial and the complete combustion mode).

All the above issues are illustrated in this book through a series of chapters covering theoretical advances, algorithms, and applications. The book consists of two

main parts: Part I presents theoretical developments in the area of model-based control based on parametric programming techniques, as described in Volume 1 of this series, and Part II presents application of the theory to a wide spectrum of applications in the area of process, biomedical, and automotive systems. All the chapters include a clear introduction and appropriate references allowing even the nonexperts to follow the latest developments and see how different topics can be put in context of the model-based control framework.

Traditional online control and optimization problems require a repetitive solution of optimization problem at each time interval. Chapter 1 in Part I presents a novel approach for deriving the control law as a set of explicit functions of the state variables for discrete time control systems. Each of these functions is valid in a polyhedral region in the space of the state variables. For the implementation of this controller on a real system, when a value of the state measurement or estimate becomes available, the polyhedral region corresponding to the value of the state variables is identified and the controller is obtained by substituting this value into the corresponding explicit function. The online control and optimization problem therefore reduces to simple function evaluations. Chapter 2 considers the case of hybrid systems which are characterized by the simultaneous presence of dynamics and logical conditions. The focus is on piece-wise affine systems which are reformulated and solved as multiparametric mixed integer programs and the solution consists of switching between different integer solutions corresponding to different affine systems. Uncertainty and disturbances are almost always present in control problems. At the same time, the satisfaction of physical and technical constraints is vital, amongst others, for the safety, operability, acceptable energy, and environmental performance of any process system. This issue is addressed within a model-based parametric control framework in Chapter 3. The solution is given by a robust control law which is affine in the state variables, and with a guaranteed performance of avoiding violation of any constraint in the presence of uncertainty and disturbances. Chapters 4 and 5 consider the case when the model is described by continuous time systems. Two algorithms, based upon control vector parameterization and a variational approach exploiting the structure of the multipoint boundary value Euler–Lagrange optimality conditions, are proposed. The optimal control profiles are given by nonlinear functions of the state variables, even for linear systems. It is shown that a much simpler control law consisting of fewer regions than that for discrete time linear systems can be obtained. The derived controller also guarantees satisfaction of constraints within the time intervals and not just at the time interval points as in the discrete time formulation, proposed in Chapter 1.

Part II presents some recent exciting developments, which demonstrate the applicability of the tools developed in Part I to engineering systems. The controllers developed in Part I can be implemented on a simple computational software and hardware platform such as microchips and have been tested on a variety of process, biomedical and automotive systems. Chapter 6 addresses simultaneous design and control problems for chemical process systems such that the control issues are taken into account at the process design stage. Derivation of the parametric controller, discussed in Chapter 1, allows the direct incorporation of the derived

model-based parametric controller in the simultaneous design and control problem. A two-stage optimization approach is used to solve the problem resulting in designs that are economically optimal and have improved operability benefits in the presence of uncertainties and disturbances. Chapters 7 and 8 present application of parametric controllers to two biomedical engineering problems. An explicit insulin delivery rate for people with the type I diabetes is derived in Chapter 7. The controller aims to keep the blood glucose concentration at the desired level in the presence of meal disturbances. The negative deviations from the desired glucose level are considered to be more dangerous than the positive deviations, and to address this issue multiobjective controllers are derived. These controllers are based upon asymmetric weightings on positive and negative deviations in the objective functions and by prioritizing constraints corresponding to different glucose levels. Uncertainty in model parameters is also addressed by deriving a feasible controller for a population of patients. These controllers can be stored and implemented through a microchip that can be integrated with glucose sensors, opening avenues for advanced model-based portable insulin delivery systems. Chapter 8 addresses the issue of the delivery of anaesthetic agents for patients undergoing surgery. An introduction to anaesthesia is provided and a new compartment model which allows simultaneous regulation of mean arterial pressure, cardiac output, and unconsciousness of the patient is proposed. The model is validated by carrying out dynamic simulations and then used for the derivation of model based and parametric controllers. The key advantage of these controllers is that they allow the anaesthesiologist to focus on more critical aspects and also carry out “what-if” kind of scenario analysis. In Chapter 9 the implementation and testing of the parametric controllers, for the first time through a microchip on a real system, is discussed. A partially simulated exothermic pilot plant reactor system is considered. The cooling water flow rate is obtained as an explicit function of the temperature and concentration in the reactor. The superior performance of the parametric controller over traditional controllers is also demonstrated. Chapter 10 presents an overview of the potential and achievements of the implementation of model-based controllers on a microchip by using parametric control techniques. The chapter includes success stories for the design of parametric controllers for air separation units, active valve train of automotive systems, pilot plant reactors, and biomedical systems. The first two projects, carried out in close collaboration with industrial partners, clearly highlight the impact that parametric controllers are making in the automation sector.

This book is the outcome of research work carried out over the last fifteen years at the Centre for Process Systems Engineering of Imperial College London. We hope that by the end of the book the reader will be able to thoroughly understand almost all aspects of multiparametric model-based control, judge the key characteristics and particulars of the various control problems and techniques and be able to implement this new technology in practice.

Many colleagues, former research associates, and current PhD students and post-doctorate associates have been involved in our research program in parametric programming and control over the years. While a number of them are involved in

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## References

- 1 PISTIKOPOULOS, E. N., Uncertainty in process design and operations, *Comput. & Chem. Eng.* 19 (1995), pp. S553–S563
- 2 HOVD, M., SKOGESTAD, S., Procedure for regulatory control structure selection with application to the FCC process, *AIChE J.* 39 (1993), pp. 1938–1952
- 3 LOEBLEIN, C., PERKINS, J. D., Structural design for on-line process optimization: application to simulated FC C process, *AIChE J.* 45 (1999), pp. 1030–1040
- 4 SAKIZLIS, V., Design of Model-Based Controllers via Parametric Programming. PhD dissertation, Imperial College London, London, UK, 2003
- 5 PISTIKOPOULOS, E. N., GEORGIADIS, M. C., DUA, V., Multiparametric Programming—Theory, Algorithms and Application, Wiley-VCH, Weinheim, Germany, 2006, Volume 1 of this book series