# Chemical Process Control: A German Perspective

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Demands on the control of chemical processes have been growing steadily during the last decades. Reasons for this development are on one hand tighter specifications on the quality of chemical products and the demand to confine energy consumption and waste of raw material, as well as environmental considerations. On the other hand there has been a tendency to change the way chemical plants are operated. E.g. the trend to just-in-time production requires frequent load changes which can cause dynamical problems. Or, a single process unit, like a reactor, is used for synthesizing several different products (multi-purpose plants) requiring learning, adapting or highly robust control schemes. Higher integration of energy and material is an additional reason for growing requirements on the control of chemical processes.

In many cases the classical PID-control concept is not sufficient to suit these requirements any more. Two areas can be distinguished for improving control performance of chemical plants: The development and use of advanced *control strategies* and the development and application of better *controller design algorithms*.
The control strategy determines e.g. sensor and actuator locations based on controllability and observability analysis or pairing of controlled and manipulated variables. The actual controller configuration on basis of the control strategy is determined by the controller design algorithm. Typically a significant increase in performance can be gained by customizing a control strategy for a specific chemical process. However this approach is very dependent on the characteristics of each specific process. Development of better controller design techniques will cause improvements for a whole class of processes.
This paper focuses on developments in controller design that we think can have a significant impact on the solution of practical process control problems, and try to summarize the discussion in Germany on this subject.

Chemical processes are characterized by a number of specific features that have to be taken into consideration in controller design.
Of crucial importance is the lack of knowledge about the plant behavior. Even detailed models, typically consisting of a large number of nonlinear differential, differential algebraic and/or partial differential equations, are often not sufficient to allow for exact prediction of the plant behavior. Furthermore it is usually very difficult to obtain such models. Compared to other fields like mechanical or electrical engineering with their much older history, there is an urgent need in chemical engineering to develop systematic methodologies and tools for process model development. For a discussion of recent trends in modelling see e.g. [1].
Most chemical processes are strongly nonlinear in nature and many of them are multivariable systems with a large number of manipulated and controlled variables. Also, most state variables, especially those describing the product quality, cannot be measured directly. In the rare cases when those states are accessible they can typically only be measured with large time de-

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lays and significant sensor noise. In addition manipulated variables are usually constrained.

The most restricting characteristics are the strongly nonlinear behavior and the uncertainties associated with models describing the processes.
There have been developments in control theory during the past years that address problems in connection with the above features.
Following ideas from linear geometric control theory [2], a nonlinear geometric control theory was developed since the beginning of the 80s [3]. Geometric theory is concerned with control problems like disturbance decoupling, noninteracting control and exact linearization. Especially exact linearization techniques can have significant influence on many practical process control problems. Different from operating point linearization, exact linearization does not neglect terms of higher order in the Taylor series expansion of the nonlinear system, but a nonlinear control law is used to explicitly compensate those higher order terms rendering a system with linear behavior. If the dynamic behavior of all states is exactly linearized we talk about state linearization [4]. If only the input/output behavior is exactly linearized, this is called input/output linearization [5]. In either case, the exactly linearized system can be controlled then using standard linear techniques.
Although there has already been quite a number of practical applications of nonlinear geometric control (e.g. [6, 7]) several restrictions apply: Not all processes can be exactly linearized and not every disturbance can be decoupled. Furthermore the corresponding state feedback control law can easily consist of several thousand lines of code. This, together with the fact that no guarantee for robustness can be given when the design is based on an inaccurate process model, restricts the general applicability of geometric nonlinear control at the moment. Inclusion of robustness and development of an output feedback theory are current issues of research.

Linear predictive control schemes have been successfully applied in industrial process control problems for a long time [8]. Its generalization, nonlinear predictive control, is a further approach that directly allows for incorporation of process nonlinearities. Predictive control is a control scheme in which the controller calculates, at every time step, future moves of the manipulated variables that optimize a performance objective on a finite prediction horizon [9]. Calculation of manipulated variable actions involves on-line optimization where a nonlinear programming problem has to be solved repeatedly. The main advantage over other nonlinear controller design methods is the possibility to deal with process constraints in a systematic manner. Current research focuses on the inclusion of robustness into the predictive control framework.

The disadvantage of most nonlinear control schemes is the lack of a systematic consideration of model uncertainties. In this respect linear multivariable control theory is very well developed. Advancements during the last decade do not only allow for robustness analysis of existing control systems but also for design of robust controllers. Especially $H_\infty$-optimization [10] has attracted a lot of attention. $H_\infty$-optimization can be used to synthesize a dynamic output feedback controller which stabilizes the closed loop system and shapes the singular value of certain closed loop transfer matrices that are connected to performance or robustness (loop-shaping). Usually physical performance objectives relate well to loop-shaping design specifications. A major drawback is that robustness can only be achieved for modelling errors that are described as unstructured uncertainty [11]. This way unwanted conservatism is often introduced. $\mu$-optimal control theory [12] is a kind of generalization of $H_\infty$-control theory, that

allows for incorporation of information about the structure of different uncertainty sources. Parametric uncertainty is a typical example for structured uncertainty. Another advantage of $\mu$-theory is that robust performance can be treated in a straightforward manner analog to robust stability.
$H_\infty$-optimal controllers can be found with rather little off-line computing cost through repeated solution of two algebraic Riccati equations. $\mu$-optimal controllers cannot be found in such a straightforward way. Even robustness analysis with $\mu$ involves significant computing effort for problems of only moderate size. Except for the so called D-K-iteration [13] which is to a large extend a heuristic approach to $\mu$-optimal controller synthesis, no systematic synthesis technique is known to date. Nevertheless $\mu$-analysis and synthesis has been successfully applied to a number of practical process control problems (e.g. [14, 15]).

Robust linear multivariable controller design usually leads to dynamic compensators of high order. Nonlinear control schemes also lead to complex control laws that require powerful on-line computing capacities. Due to a broad invasion of distributed process control systems into chemical plants, such complex control laws constitute no insurmountable difficulty any more. Also, chemical processes are usually governed by rather slow time constants, that even allow to solve nonlinear on-line optimization problems, that arise e.g. in nonlinear predictive control.

Despite these promising developments, modern control theory has not had a significant impact on the majority of industrial chemical processes. However many remarkable improvements could be achieved with modern methods for some processes which are difficult to control. Open questions that have to be addressed in the future in order to make the theory more attractive for industrial applications are the need to develop better process models and a methodology to systematically quantify modelling errors. There is especially a need for an uncertainty description (beyond parametric uncertainty) for nonlinear systems. This has to be the basis for the development of a robust nonlinear control theory. In order to be able to judge better the possibilities and the potential of advanced design techniques, fundamental limits to control system performance of linear and nonlinear systems also have to be better understood.

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