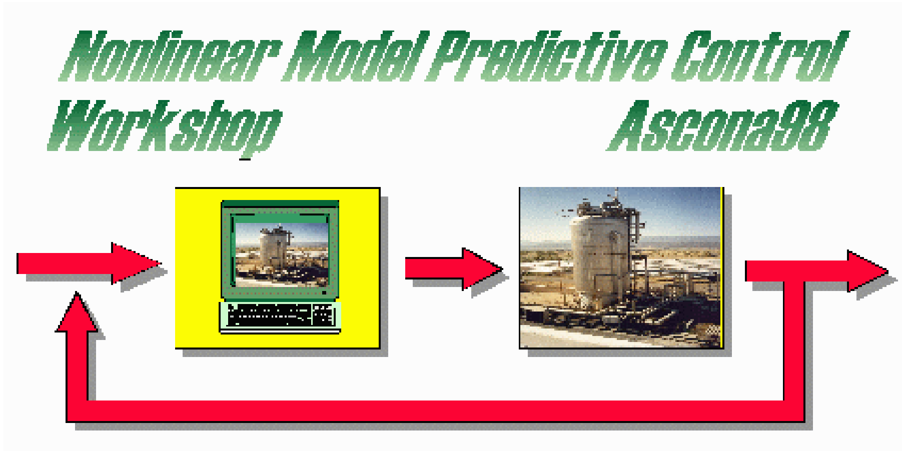

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Efficient Solution of Dynamic Optimization and NMPC Problems

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Large scale optimization strategies have evolved considerably over the past two decades. Currently, continuous variable optimization problems (nonlinear programs) are solved on-line for steady state refinery models with several hundred thousand variables. Moreover, nonlinear model predictive control strategies have been developed with on-line optimization strategies for small chemical processes. To take next step of considering the on-line optimization and nonlinear model predictive control of dynamic chemical processes, a number of limitations and research challenges must be overcome.At present, these strategies have not been incorporated into general purpose software, and there are a number of features that can be exploited for dynamic optimization problems by considering specialized versions of NLP algorithms.

Many of the advances in NLP algorithms have taken place by recognizing and exploiting the framework of Successive Quadratic Programming (SQP) algorithms. These are extensions of Newton type methods for converging to the solution of the KKT (optimality) conditions of the optimization problem. Because of this fast convergence can be expected and a number of standard devices can be added to stabilize the algorithm to converge from poor starting points.

Limitations of these Newton-based methods are also well-known. They experience difficulties in the presence of ill conditioning and extreme nonlinearities. Also, for optimization algorithms, nonconvexity can also lead to a number of difficulties. In addition, the desirable properties of SQP hold only in the presence of analytical derivatives, and in the context of equation based models, second derivatives are also desirable. Finally there is a need for software that allows exploitable structures for specific problem classes.

To address these issues, there are a number of innovations in algorithm design and problem formulation that greatly improve performance and address the above limitations. In addition to the desirable Newton-based convergence properties, SQP methods can be tailored to particular large-scale examples with exploitable structure. As a result, very fast NLP algorithms can be derived for data reconciliation, parameter estimation, nonlinear model predictive control and dynamic optimization. Moreover, inequality constraints and variable bounds in can be treated through advances in interior point strategies. These methods preserve the particular problem structure and scale well in performance for large-scale problems with many constraints. Finally, trust region methods (also in combination with line search strategies) remedy difficulties encountered with ill-conditioned problems. This helps to stabilize convergence in order to obtain strong descent properties.

In this talk, we will provide numerous illustrations of these innovations and demonstrate how they lead to successful numerical algorithms for NMPC and dynamic optimization. Future directions will also be reviewed and open questions will be presented to spark some discussion.

Keywords : nonlinear programming, optimal control, dynamic optimization, model predictive control, successive quadratic programming, interior point

A direct multiple shooting method for real-time optimization of nonlinear DAE processes

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Direct multiple shooting methods have long been known as an effective solution method for off-line optimization problems in ODE and DAE (e.g. [1], [2], [6]). The basic approach of this boundary value method for optimization is a piecewise parametrization of the controls and a multiple shooting parametrization of the state variables. The resulting large but specially structured nonlinear programming problem is then solved by tailored Newton type methods such as successive quadratic programming or generalized Gauss-Newton. Several algorithmic details important for a fast off-line method will be discussed, such as structure exploiting quadratic programming, partitioned high rank updates, use of boundary and algebraic consistency conditions and invariants for gradient and Hessian reduction techniques, and parallel solution approaches (e.g. [5], [3], [7])

The existing general approach has recently been adapted to the specific requirements of real-time optimization ([4]). Special strategies have been developed to minimize the on-line computational effort. They precalculate information as far as possible - e.g. Hessians, gradients and QP presolves for nominal or neighbouring situations - which is not available in the off-line case.

The new methods have been implemented in the modular optimal control package MUSCOD. In typical real-time problems, such as on-line recalculations of control strategies in the presence of disturbances they have proven much faster than fast off-line strategies. Comparisons for a fed-batch fermentation process show a drop of computational costs by an order of magnitude. Extensions to nonlinear model predictive control by the choice of suitable embeddings are discussed.

Keywords : multiple shooting, SQP, DAE, real-time optimization

References

[1] Bock H.G., "Numerical treatment of inverse problems in chemical reaction kinetics", *Modelling of chemical reaction systems, eds. Ebert, Deuflhard, Jäger, Springer series Chemical Physics*, **18**, 102 - 125, (1981).

[2] Bock H.G., Plitt K.J., "A multiple shooting algorithm for direct solution of optimal control problems", *Proc. 9th IFAC World Congress Budapest, Pergamon Press*, (1984).

[3] Leineweber D.B., Bock H.G., Schlöder, J.P., Gallitzendörfer J.V., Schäfer A., Jansohn P.,"A boundary value problem approach to the optimization of chemical processes described by DAE models", submitted to *Comput. Chem. Eng.* (1997).

[4] Leineweber D.B., Bock H.G., Schlöder, J.P., "Fast direct methods for real-time optimization of chemical processes", *Proc. 15th IMACS World Congress on Scientific Computation, Modelling and Applied Mathematics Berlin, Wissenschaft- und Technik-Verlag Berlin*, (1997).

[5] Leineweber D.B., "The theory of MUSCOD in a nutshell", *IWR preprint 96-19*, (1996).

[6] Plitt K.J., "Ein superlinear konvergentes Mehrzielverfahren zur direkten Berechnung beschränkter optimaler Steuerungen", Diplomarbeit, Bonn (1981)

[7] Schulz V.H., Bock H.G., Steinbach M.C., "Exploiting invariants in the numerical solution of multipoint boundary value problems for DAEs", *SIAM J. Sci. Comp.*, **19**, 440 - 467, (1998).

Stability and Robustness of Nonlinear Receding Horizon Control

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The main design strategies for ensuring stability and robustness of nonlinear *RH* (Receding-Horizon) control systems are critically surveyed. In particular, the following algorithms with guaranteed closed-loop stability of the equilibrium are considered: the zero-state terminal constraint [1], the dual mode *RH* controller [2], the infinite-horizon closed-loop costing [2], the quadratic terminal penalty [4], and the contractive constraint [5]. For each algorithm, we analyze and compare feasibility, performance, and implementation issues. For what concerns robustness analysis and design, we consider: monotonicity-based robustness [2], inverse optimality robustness margins [6], nonlinear H_∞ *RH* design [7], and a new nonlinear *RH* design with local H_∞ recovery.

Keywords : Nonlinear Receding Horizon Control, Stability, Robustness

References

[1] S. Keerthi and E. Gilbert "Optimal, infinite-horizon feedback laws for a general class of constrained discrete-time systems", *J. Optimiz. Th. Appl.*, **57**, 265–293, (1988)

[2] H. Michalska and D. Mayne "Robust receding horizon control of constrained nonlinear systems", *IEEE Trans on Automatic Control*, **38**, 1512–1516, (1993)

[3] G. De Nicolao, L. Magni, and R. Scattolini "Stabilizing receding-horizon control of nonlinear time-varying systems", *IEEE Trans. on Automatic Control*, (1998)

[4] H. Chen and F. Algöwer. "A quasi-infinite horizon nonlinear model predictive control scheme with guaranteed stability", *Automatica*, (1998)

[5] T. Yang and E. Polak. "Moving horizon control of nonlinear systems with input saturation, disturbances and plant uncertainty", *Int. J. control*, **58**, 875–903, (1993)

[6] L. Magni and R. Sepulchre "Stability margins of nonlinear receding horizon control via inverse optimality", *System & Control Letters*, **32**, 241–245, (1997)

[7] H. Chen, C. Scherer, and F. Allgöwer "A game theoretical approach to nonlinear robust receding horizon control of constrained systems", *American Control Conference '97*, (1997)

Modeling and Identification for Nonlinear Model Predictive Control: Requirements, Current Status and Future Needs

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Nonlinear model predictive control (NLMPC), despite the wide publicity and the intensive research efforts it attracted over the past few decades, is still being perceived as an academic concept rather than a practicable control strategy. Rarely do we hear reports about successful uses of NLMPC in solving problems of any practical signficance. In stark contrast, linear model predictive control has long established its reputation as a powerful and broadly-applicable tool among the practicing engineers, compiling an impressive track record along the way and leaving a permanent mark on the industrial control practice. Its industrial impact has been nothing short of revolutionary, restructuring the way engineers view and practice control. In attempting to explain the apparent disparity, we can bring to the table a garden variety of issues that are at play. Asked to choose the most important, however, most of us will, without hesitation, point the arrow to one common factor: *the inability to construct a nonlinear model on a reliable and consistent basis.* This brings into focus what is probably the most urgent and pressing question in the realm of nonlinear model predictive control research: "How do we best use available information to build models that are most useful for designing and implementing a nonlinear model predictive controller?" This article is about bringing a perspective to the above question, examining how close we are to providing a useful answer to it, and where and how future research efforts may best be spent in quest for such an answer. We begin our inquiry at the very end of the road map we wish to construct: What attributes do we require of a model in NLMPC applications. This establishes a set of criteria upon which the effectiveness of various modeling strategies available at present can be judged; without a well-defined end objective, any attempt to discuss the workings and failings of a particular modeling strategy would be futile. Understanding the end objective has an added effect of bringing forth future research needs and promising directions: What are the missing components that will enable us to complete the road map to the promised land? Our scrutiny into the current state of the art begins with a critical look at the fundamental modeling, examining what exactly is required to build and use fundamental models in the context of NLMPC and how realistic these requirements are. This will point us to a number of open research issues as well as the need for an alternative (or complementary) framework that enables us to take advantage of information hidden in plant data, an often abundant, yet grossly under-utilized resource for modeling. The question of whether and to what extent science is able to present us with such a framework at current time is investigated next. Popular nonlinear empirical modeling strategies ranging from time series modeling to artificial neural network modeling are examined, again all from the standpoint of how they fit the criteria established earlier. In addition to these well-studied strategies, we put forth a promising new paradigm inspired by linear subspace identification. We end the paper by contemplating a possibility of marrying the two seemingly incompatiables, the fundamental modeling and the empirical modeling. After all, one is likely to have access to both types of information, a priori and a posteriori. An ideal vision then is that of an engineer intertwining the very different ways of modeling to obtain a best possible model with given information.

Keywords :

Nonlinear Model Predictive Control: Challenges and Opportunities

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Linear Model Predictive Control has achieved a state of considerable maturity with a general concensus on a preferred methodology although there remain areas, such as robustness and adaptation, which require further research. Research on Nonlinear Model Predictive Control is at an interesting point. There is a noticeable convergence in the methodologies proposed in the literature, but, in addition to the open areas listed above, there is a daunting challenge: the solution, online, of non-convex optimal control problems. This paper review the convergence in the literature of the methodologies for Nonlinear Model Predictive Control, assessess the challenges arising from uncertainty and non-convexity of the optimal control problem, and attempts to define fruitful avenues for future research.

Keywords : Model Predictive Control, Review

Predictive Control of Constrained Hybrid Systems

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We propose a framework for modeling and controlling systems described by interdependent physical laws, logic rules, and operating constraints, denoted as Mixed Logical Dynamical (MLD) systems. These are described by linear dynamic equations subject to linear inequalities involving real and integer variables. MLD systems include constrained linear systems, finite state machines, some classes of discrete event systems, and nonlinear systems which can be approximated by piecewise linear functions. A predictive control scheme is proposed which is able to stabilize MLD systems on desired reference trajectories while fulfilling operating constraints, and possibly take into account previous qualitative knowledge in the form of heuristic rules. Due to the presence of integer variables, the resulting on-line optimization procedures are solved through Mixed Integer Quadratic Programming (MIQP), for which efficient solvers have been recently developed. Some examples and a simulation case study on a complex gas supply system are reported.

Keywords : Predictive control, Hybrid systems, Dynamic models, Binary logic systems, Boolean logic, Mixed-integer programming, Optimization problems

An Overview of Nonlinear MPC Applications

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This paper provides an overview of nonlinear model predictive control (NMPC) technologies applied in industry, including applications by NMPC vendors and those published by user companies. A brief summary of nonlinear MPC theory is presented to highlight the issues pertinent to nonliear MPC. Then industrial NMPC applications are overviewed in terms of modeling, optimization, control, and implementation issues. A few industrial application cases are discussed in detail to illustrate these issues. A discussion on future needs in nonlinear MPC theory and practice is provided to conclude the paper.

Keywords : Model Predictive Control, industrial NMPC, Nonlinear

Nonlinear Moving Horizon Estimation

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One general approach for constructing a state estimator is to model the evolving state as a stochastic process. The optimal state estimate is the conditional expectation of the state subject to the measured outputs. Without general equivalent statistics for summarizing the past data, however, the size of the estimation problem increases as more data is considered with time. One solution to this problem is to consider only a fixed amount of data. The resulting estimation problem is finite dimensional, so the only implementation barrier is the ability to solve the nonlinear program in real time. By considering a fixed amount of data, we can bound the problem size. However, the approach is suboptimal, because we incorrectly treat the influence of the past data. More importantly, the omission of the past data may lead to instability.

Although equivalent statistics are generally unavailable for summarizing the past data of nonlinear systems, we may expect that linearized statistics yield satisfactory performance. In order for the approximation to be stable, we need to upper bound the probability distribution of the past data. This requirement is equivalent to lower bounding the cost to go in dynamic programming. However, unlike receding horizon control, the classical dual-mode arguments fail, because there is no fixed origin about which to construct a local invariant region. The lack of locality complicates the stability analysis of the estimator, because the linear statistics need to provide a *global* lower bound of the optimal cost to go.

In this work we investigate strategies to guarantee the stability of moving horizon estimation. Our discussion includes constrained linear and nonlinear estimation. In particular, we demonstrate that by including bounds to guarantee the existence of a decreasing nominal sequence, we can circumvent the issue of a global lower bound to the optimal cost function. We also discuss the relationship of moving horizon estimation to the Kalman filter and demonstrate how the proposed strategies reduce to the Kalman filter if the process is linear and the noise statistics are Gaussian.

Keywords : Nonlinear Estimation, Moving Horizon Estimation, Optimization, Constraints

Nonlinear Predictive Control of a Distillation Column

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Nonlinear model predictive control (NMPC) has gained considerable interest both in the academic and industrial process control community over the past years. By now several NMPC schemes have been proposed, that guarantee stability independent of the chosen performance parameters (see for instance [1] for a review). One specific approach, termed *quasi–infinite horizon nonlinear predictive control*, replaces the traditional zero state terminal equality constraint at the end of the horizon [4] by a terminal region plus a terminal penalty term that serves as an upper bound for the infinite horizon cost (quasi-infinite horizon) [2, 3]. This approach leads to significant computational savings and larger guaranteed regions of attraction as compared to other approaches that also guarantee stability.

In this paper we want to summarize first some new theoretical developments that are based on the concept of the quasi–infinite horizon. Secondly we show the application of the quasi–infinite horizon NMPC approach to a nontrivial process control example, namely control of a high-purity binary distillation column. The column considered has 40 trays and is used for the separation of Methanol and n-Propanol. Since the on-line computational burden for real–time application is not feasible at present if prediction is based on a detailed process model, a nonlinear reduced order model, based on nonlinear wave propagation phenomena, is introduced. This model is of 5th order and is based on a modelling approach proposed in [5]. The states of thsi model describe the position of the waves in the rectifying and stripping section and the concentrations on the feed tray and in the reboiler and condenser respectively. For the evaluation of the quasi-infinite horizon NMPC controller the "real" system is represented by a detailed full order model of the distillation column during simulation. The results obtained with the proposed NMPC scheme using the 5th order reduced model show promising closed-loop behavior. Moreover, the on-line computation time required per control step is in the range of few minutes and thus allows real-time implementation and application of the scheme using standard hard- and software. Using this application we will point out and discuss some of the issues related to the gap between theoretical results and practical needs that is observed today. Finally we will outline key points for the future theoretical development of NMPC.

Keywords : nonlinear predictive control, quasi infinite horizon, distillation control

References

[1] H. Chen and F. Allgöwer, "Nonlinear model predictive control schemes with guaranteed stability", In *Berber R., editor, Nonlinear Model Based Process Control. Kluwer*, 1998, in press.

[2] H. Chen and F. Allgöwer, "A quasi-infinite horizon nonlinear model predictive control scheme with guaranteed stability.", *Automatica, 1998*, vol.34(10).

[3] R. Findeisen, J. Rawlings, "Suboptimal infinite horizon nonlinear model predictive control for discrete time systems", *NATO Advanced Study Institute on Nonlinear Model Based Process Control* and *IfA Technical Report* AUT 97-13, *ETH Zürich*, Aug. 1997.

[4] D.Q. Mayne and H. Michalska, "Receding horizon control of nonlinear systems", *IEEE Trans. Automat. Contr.*, AC-35(7):814-824, 1990.

[5] A. Rehm and F. Allgöwer, "Nonlinear H_∞-control of a high purity distillation column", *Proc. UKACC International Conference on CONTROL'96*, volume 2, pages 1178-1183, 1996.

Nonlinear Model Predictive Control of a Styrene Polymerization Reactor

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Achievable closed-loop performance is often limited by steady-state design. In previous work we have shown how bifurcation analysis can be used to detect regions of infeasible steady-state operation in a jacketed, styrene polymerization reactor. The selected operating point can be close to an infeasible region rendering single input-single output control of reactor temperature impossible, once model uncertainty is considered.

In this paper we apply a multivariable nonlinear quadratic dynamic matrix control (NL-QDMC) strategy to the control of a styrene polymerization reactor. NL-QDMC is an extension of a well-known technique for handling constrained processes based on linear models (QDMC) to nonlinear models. The NL-QDMC algorithm incorporates an Extended Kalman Filter (EKF) to handle state variable and parameter estimation; also included is an integrated white noise disturbance model.

Much of the nonlinear model predictive control literature has focused on problems such as control of systems with multiple steady-states, with temperature as the output variable. While these problems are interesting and certainly provide motivation for nonlinear control, we are interested in the control of variables more directly related to product quality or product properties. We consider the control of polymer properties such as weight average molecular weight (WAMW) and polydispersity or branching. This requires a model/estimator that can estimate additional states, such as molecular weight moments, even when a limited number of measurements is available. If the molecular weight moments are accurately estimated, the WAMW can be readily inferred and controlled. A different approach is the direct estimation of these properties using viscosity measurements.

Another important aspect in polymerization reactor control is the multirate nature of available measurements. Temperature and volume measurements are available continuously while concentrations and molecular weight distribution measurements are only available every 30 to 40 minutes with a delay of 30 to 40 minutes. The development of on-line light scattering and osmometry allow observation of WAMW and NAMW which can be used in the estimator.

There will always be both parametric and structural uncertainty in any model-based estimation and control scheme. We illustrate the effect of both types of uncertainties by using a simplified model for the control strategy, and a more complex model for the "plant" (incorporating the "gel effect", for example). We also show the increased quality of control as additional measurements are used in the control strategy.

Keywords : Reactor, Product Property, NL-QDMC, Estimation, Multirate Sampling

Nonlinear MPC with Large Scale Fundamental Models: Application to a Continuous Kamyr Digester

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Kraft pulping is the most common chemical pulping process which normally utilizes a continuous digester. Yearly U.S. wood pulp production is around 52 million tons with approximately 400 (Kamyr) continuous digesters in operation. Digesters are very capital intensive ($50-$100 million), yet their performance is of paramount importance to maximize the produced pulp quality and yield, reduce the overall operating costs and minimize the adverse environmental impacts of pulp mills. With more pulp and paper companies replacing their pulping processes with modern fiberlines using continuous digesters to meet increasing competitiveness in the global market place and tighter environmental regulations, there is an increasing need for improved control of digesters.

Continuous digesters are very complex plug-flow reactors in which the lignin which binds wood chips together is broken down through a combination of chemical and thermal effects. A number of co-current and counter current zones are employed in a typical configuration. Some of the challenging characteristics of these reactors which preclude efficient control include: (i) long residence times (on the order of 10 hours), (ii) complex nonlinear dynamic behavior, (iii) key process variables are unmeasurable in real-time, and (iv) the biological feedstock varies stochastically. Although accurate fundamental models of this unit operation have been available for some time, recent work in our group has extended these descriptions to include more accurate transport and reaction effects. The models that result are distributed in nature and must be converted to a lumped form, although the resulting models are typically of very high dynamic order ($\sim$1000 states). Two challenges for real-time application of model-based control for such systems are: (i) Jacobian/discretization calculation, and (ii) Hankel model reduction. In this work, a model predictive control approach will be presented for Kappa number control in the digester, which directly addresses the real-time issues of model reduction. A multi-rate formulation is adopted to enable periodic sampling of key measurements (Kappa number) and higher frequency measurement of temperature and compositions. An inferential configuration will be introduced which allows both the estimation of unmeasured feed fluctuations as well as the estimation of the unmeasured Kappa and residual alkali strength profiles. Hence, the available measurements and the fundamental model are utilized in an efficient manner to reproduce the profile which is to be controlled. Comparisons will be shown between MPC using: (i) linear identified models, (ii) linear reduced Jacobian models, and (iii) updated reduced Jacobian models. Simulations will include deterministic input changes in the setpoint and measured/unmeasured disturbances, as well as stochastic disturbance variations.

Keywords : nonlinear model predictive control, continuous pulp digester, model reduction

Stability, Feasibility, Optimality and the Number of Degrees of Freedom in Constrained Predictive Control

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Recent work redresses the stability problems of Generalized Predictive Control by invoking endpoint constraints. These however demand deadbeat input and output predicted responses which can lead to violation of physical limits on actuation. Replacing output endpoint constraints by a stabilizing state constraint has the effect of removing the requirement for deadbeat responses in terms of the output predictions but not the input predictions; input predictions must still allow for only a finite number of control moves if the associated optimization problem is to be finite dimensional. Identifying the whole class, F, of stabilizing predictions makes it possible to avoid deadbeat responses for both inputs and output, even if one is to use finite dimensional subsets Fn of F. An attractive alternative to this approach is to combine optimization over a finite control horizon, N, with optimal state feedback control beyond N. It is then possible to show that, so long as N is large enough, this finite dimensional control strategy provides an exact solution to the ideal infinite dimensional optimization problem. However implementation depends on the solution of a Quadratic Program, and this imposes an impracticable computational burden for N large. This paper discusses recent techniques that can be used overcome the above problem and pays particular attention to the number of degrees of freedom. The motivation is to derive algorithms which use a small number of degrees of freedom but have some desirable attributes: (i) stability; (ii) guaranteed feasibility; (iii) return to optimality just as soon as this becomes feasible. The device used is linear interpolation between (i) the extension (referred to as the "tail") of the optimal predictions at the previous time instant; (ii) a mean level solution; and (iii) the unconstrained optimum. Capturing the "tail" allows the construction of Lyapunov type of arguments to guarantee stability, including the mean level solution addresses the problem of feasibility, while defining the unconstrained optimum guarantees converges to it just as soon as it becomes feasible. The geometric conditions for achieving the above interpolation are developed and the minimum number of degrees of freedom is identified. Then under some weak assumptions it is possible to show the resulting algorithms will outperform other alternatives, as illustrated by means of numerical examples. A further reduction of the degrees of freedom is considered briefly at the conclusion of the paper.

Keywords : Model Predicitve Control, Stability, Optimality

An Industrial Perspective of NMPC: Trends, Challenges and Requirements

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In the past 15-20 years, MPC technologies have penetrated a significant portion of the process industries and harvested a large amount of economic benefit. In the next 5-10 years, we will see widespread use of MPC technologies. We will see dynamic unification of process control and real-time optimization (RTO). We will also see the emergence of the enterprise optimization, i.e., the cross-functional integration and optimization of the supply chains, the production processes and the distribution channels. To the academic and industrial research communities, these new developments will create new opportunities and pose new challenges and requirements

This paper will discuss where the opportunities lie and what the main challenges are in the near future. It will focus on the advanced process control (APC) technologies in general and nonlinear MPC in particular. In an industrial R&D perspective, this paper will explain the tremendous amount of potential benefits in the cross-functional integration and optimization, describe the recent industrial technology trends for capturing those benefits, and explore, in particular, how nonlinear MPC might fit in this environment and what the foreseeable challenges and requirements are.

Two important trends that have developed in the past 2-3 years will be discussed in detail. One trend is MPC becoming an industrial standard. There is a tremendous amount of vested interest, technical and financial, in exploiting and expanding the standard MPC technologies. The other trend is the emergence of the cross-functional integration and optimization. It will cause a paradigm shift in the industry, overhaul the current existing implementation infrastructures, change many systems and software design priorities, and require all the tools and applications to be compatible with this scheme.

Both trends will have significant impact on nonlinear MPC technologies. The impact will be analyzed in terms of compatibility, conversion cost if any, and integration. Along this line, this paper will assess the current standing of the industrial MPC applications and their infant cousins – nonlinear MPC applications, predict what the foreseeable impacts are, explore where the new opportunities lie, and finally, present some new technical challenges and special requirements for industrial use of nonlinear MPC technology.

Keywords :

Optimization based control of transient processes

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Transient operation of chemical processes is characterized by intentionally time-varying profiles of state and manipulated variables. This includes cases where the considered time interval of interest is of finite length as in the operation of batch and semi-batch processes or during load changes, start up, and shut down of continuous processes. The definition further comprises cases with an infinite time interval and periodically varying state and manipulated variables such as pressure swing adsorption, simulated moving bed chromatography, or periodically forced chemical reactors.

The overall objective to operate these processes in an economically optimal manner can be reached by two fundamentally different approaches. The first possibility is to optimize the trajectory off-line and to track the calculated profiles using an appropriate controller. The second way is to implement a controller which is able to directly maximize an economic objective on-line. With respect to the problem formulation, the second class includes the tracking part of the first approach as a special case since the deviation from calculated trajectories can always be chosen as objective function. Optimization based control algorithms such as model predictive control (MPC) may be used in both cases. Since transient processes are not kept in the vicinity of a single operating point by definition, all concepts which rely on local linearization have to be applied very carefully and a proper treatment of the full nonlinearities is generally unavoidable.

This contribution discusses available formulations and specific problems in the field of optimization based control of transient processes from an application oriented point of view. Currently known concepts are summarized, and available results are illustrated by a number of batch reactor control and optimization problems. Areas are highlighted where further research activity is needed.

In the field of trajectory optimization and tracking the emphasis is on the design of optimal trajectories and the assessment of inherent controllability limitations. In particular, the question is treated how setpoint tracking with a specified degree of performance can be achieved by some (or a given class of) controllers. Ideally, some kind of controllability constraint should be added to the design problem to guarantee feasibility of the tracking problem. However, there is neither an adequate understanding nor a computationally feasible approach available at the moment which could be applied for this purpose.

When transient processes are optimized on-line the variable profiles are calculated on the control level. This approach has the advantage that uncertain models or varying objectives can be more easily accounted for, but requires high computational resources in real-time. Furthermore, feasibility of the stated optimization problems becomes at least as important as optimality. Here, the need for sufficient information on the future behavior of the processes generally conflicts with the ability to solve only comparatively small problems. Clearly, the choice of the future time horizon considered during the on-line optimization is a key issue on the way to handle both requirements simultaneously.

Keywords : transient processes, tracking control, controllability, on-line optimization

A Predictive Command Governor for Nonlinear Systems under Constraints

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A command governor (CG) is described for solving set-point tracking problems for nonlinear systems when pointwise-in-time input and/or state related inequality constraints have to be fulfilled. A CG is a nonlinear device which is added to a primal compensated system. The CG action, based on the current state, set-point and prescribed constraints, is finalized to select, at any time, a command sequence under which the constraints are possibly fulfilled with acceptable tracking performance. It is shown how to use off-line an iterative algorithm so as to restrict to a fixed finite integer the infinite number of time-instants over which the prescribed constraints must be checked in order to test admissibility of command sequences. An analysis based on a Lyapunov function argument shows that, if the reference becomes constant, the CG output converges to the closest admissible approximation to the set-point. An example is presented to illustrate the method.

Keywords : Control under constraints, Nonlinear systems, Predictive control

Efficient nonlinear modeling using wavelets and related compression techniques

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Nonlinear dynamic models offer obvious advantages when compared to linear models, in terms of more accurate predictions. While this capability is valuable for direct use in model-based control, the development of nonlinear models is tedious. Development of nonlinear models can rely on (a) first-principles models with parameters determined experimentally, or (b) black-box models with both structure and parameters determined experimentally. The first approach does not pose excessive requirements on the amount of data needed for parameter identification, but frequently requires a non-trivial modeling effort for the development of detailed differential/algebraic equations. The second approach requires large amounts of data and cannot easily make use of first-principles or empirical information. A number of investigators have suggested that a mix of the two approaches could combine their advantages and minimize their disadvantages. The approach proposed in this work falls in this category. We focus on stable Volterra models, which are notorious for requiring large amounts of data for the identification of the coefficients of their higher-order terms. Our main proposition is that a Volterra model's kernel can be efficiently parameterized in terms of bases for which only few coefficients will be nonzero. Prior knowledge of process dynamics (first-principles or empirical) can be used to determine what groups of coefficients in the new basis representation are practically zero and, consequently, need not be identified. For example, knowledge about the slow decay of kernel coefficients multiplying input values of the distant past can be used to effectively parameterize these coefficients in terms of a quadratic "surface" pattern. Wavelet bases, among others, can be used for such a parameterization of a Volterra model's kernel. In our previous work [1], we have shown how this parameterization can be effectively used with linear models. In this presentation, we discuss how the same ideas can be extended to Volterra models and illustrate the applicability of the proposed approach with simulation examples. We also discuss possible refinements of the idea and directions for further research.

Keywords : Volterra series, wavelet, compression, identification

References

[1] Nikolaou M., P. Vuthandam, "FIR Model Identification: Parsimony through Kernel Compression with Wavelets", *AIChE J.*

, **44, No. 1**, 141-150 (1998).

Analytical Model Predictive Control

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Model predictive control (MPC) is a very broad controller-synthesis methodology. This is due to the optimization-based nature of MPC and the great number of tunable parameters that a model predictive controller can possess. Its optimization-based nature allows one to use any desirable performance index irrespective of the type of process model available. Its considerable number of tunable parameters provide many degrees of freedom to obtain a desirable closed-loop response. The tunable parameters include model horizon, prediction horizon, control horizon, reference trajectory (set-point filter), and penalty matrices in the performance index. Each of the parameters has a distinct effect on the closed-loop performance and this effect in general is not "monotonic". The performance of an MPC can be as non-robust and aggressive as a deadbeat controller, or can be as robust and slow as a steady state controller.

This paper deals with short-prediction-horizon MPC. In particular, it evaluates the pros and cons of using such model predictive controllers. The class of nonlinear processes described by a discrete-time state-space nonlinear model are considered. The general problem of MPC is formulated, and it is then shown that in special cases the MPC law is equivalent to analytical control methods such as input-output linearization, model state feedback control, modified internal model control, proportional integral control, and proportional integral derivative control. This equivalence allows one to solve the problem of optimal constraint handling in the analytical control methods. A model predictive controller with short prediction horizons may have an analytical form and is of low computational cost. However, it may not be applicable to processes whose delay-free parts are nonminimum-phase, and in the presence of constraints its closed-loop performances may suffer from "short-sighted-ness". Furthermore, when process deadtimes are not balanced, a model predictive controller with short prediction horizons may be ill-defined (corresponding optimization problem may have infinite number of solutions).

Keywords : Model Predictive Control, Input-Output Linearization, Input Constraints, Optimization

Multivariable Nonlinear Control of Cement Mills

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In this talk, we will study multivariable nonlinear control strategies for a cement grinding circuit. We will show why nonlinear control is requested in order to deal with typical unmeasured perturbations (hardness change of the clinker) and subsequently compare two alternative strategies : a nonlinear predictive controller and a state feedback controller based on Lyapunov design. Merits and disadvantages of both approaches will be discussed.

Keywords : Predictive control, Nonlinear control, Multivariable control, Cement mills, Industrial applications

References

[1] Magni L., G. Bastin, V. Wertz, "Multivariable nonlinear predictive control of cement mills", *IEEE Transactions on Control Systems Technology*, to appear.

[2] Jadot F., G. Bastin, V. Wertz, L. Magni, "Preventing cement mills from plugging by robust state feedback stabilisation", *Proc. Control 97*, Sydney (Australia), pp. 248-251, (October 1997).

[3] G. De Nicolao, L. Magni and R. Scattolini, " Stabilizing receding horizon control of Nonlinear Time-Varying Systems", *IEEE Trans on Automatic Control*, to appear.

[4] Boulvin M., C. Renotte, A. Vande Wouwer, M. Remy, L. Tarasiewics, P. César, " Modeling, simulation and evaluation of control loops for a cement grinding process", *Proceedings of European Control Conference* (CD Rom), Brussels, paper TH-E-H4, 6 pages, (July 97).

Some Practical Issues and Possible Solutions for Nonlinear Model Predictive Control

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While many Nonlinear Model Predictive Control (NMPC) algorithms have been proposed for control of nonlinear systems with constraints, their practical implementation faces many obstacles. In general, an NMPC algorithm solves an on-line optimization problem at each sampling time. In contrast to linear MPC where usually a quadratic program needs to be solved, the on-line optimization problem is generally non-convex for NMPC. Thus, practical implementation of NMPC becomes difficult for any reasonably nontrivial nonlinear systems.

To overcome this difficulty, Zheng recently proposed a NMPC algorithm which combines the best features of an exact optimization approach and approximation approach. The basic idea is to compute only the first control move ($\Delta u(k|k)$), which is actually implemented, exactly, while approximating the rest of control moves ($\Delta u(k+i|k), i \geq 1$), which are never implemented. Specifically, $\Delta u(k+i|k), i \geq 1$, can be approximated by linear controllers which can be computed analytically off-line based on linearized models. The number of decision variables for the on-line optimization problem equals the number of inputs, regardless of the control horizon (versus the number of inputs times the control horizon for a conventional NMPC algorithm). Furthermore, in contrast to almost all the NMPC algorithms which use an open-loop control strategy, a closed loop control strategy is incorporated into the algorithm.

The purposes of this paper are to illustrate several key issues (in addition to prohibitively high on-line computational demand) in the implementation of a conventional Nonlinear Model Predictive Control algorithm on a reasonably large industrial process—the Tennessee Eastman Process—and to test the effectiveness of the Nonlinear Model Predictive Control algorithm recently proposed by Zheng for control of large nonlinear systems with constraints. In particular, we show why a conventional Nonlinear Model Predictive Control algorithm may fail to provide integral control under very reasonable conditions (i.e., integral control is guaranteed if and only if a global solution is implemented and the output horizon is infinite) and illustrate this undesirable behavior through simulations on the Tennessee Eastman process. We argue and illustrate through simulations that Zheng's algorithm may be preferred based on considerations of on-line computational demand, integral control, and robust performance.

Keywords : Nonlinear Model Predictive Control, Integral Control, Robustness, Application

An Analytic IMC Controller Synthesis Approach For Nonlinear Systems

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Most of the model based controllers represent an inversion of the process model generated either explicitly or implicitly. For controller synthesis in nonlinear case, the inversion is difficult, and the only available practice in the current literature is computing the local zeros at every point along the current trajectory to determine invertibility first. In this contribution, we propose an IMC based analytic scheme for calculating control effort for stable nonlinear processes.

We consider a nonlinear single-input single-output system represented in standard notation;

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ y &= h(x) \end{aligned} \tag{1}$$

and differentiate the output n times to obtain a set of ODEs for the control effort u and its derivatives. If the system exhibits nonminimum-phase behavior, minimum phase approximation is achieved by reversing time in the unstable zero dynamics.

The desired trajectory in the IMC context is defined by

$$(\epsilon \frac{d}{dt} + 1)^n y_d(t) = e \tag{2}$$

where e(t) is the difference between y_{sp} and the disturbance estimate. The filter time constant ϵ is the tuning parameter. This trajectory, representing a single ODE of nth order, can be converted to a set of n first order ODEs whose state variables are the desired output and its derivatives up to (n-1)th order. In order that the process follow the desired trajectory, we replace in the first set of ODEs derived from the process equations, the output and its derivatives with the desired output and its derivatives. Resulting equations, together with the set of ODEs defining the desired trajectory, are then simultaneously integrated for the control effort.

The proposed scheme is shown via simulation to give good set point tracking characteristics for illustrative examples of one linear and two nonlinear processes with perfect models extracted from the literature.

Keywords : Nonlinear systems, IMC controller

Continuous-time Predictive Control of Constrained Nonlinear Systems

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A receding horizon control strategy for constrained nonlinear systems based on continuous optimization of an infinite horizon performance cost is described. This work differs from standard approaches to nonlinear predictive control in two major respects. Firstly, the use of an infinite horizon cost obviates the need for traditional end-point stability constraints which can lead to excessive control activity and consequent problems of feasibility with respect to input constraints. Secondly, a continuous-time control law which does not rely on computationally expensive nonlinear optimization algorithms is obtained by exploiting the structure of the constrained optimization problem.

To avoid the computational difficulties of predicting an infinite horizon performance cost, we minimize a convex upper bound on the standard quadratic cost. By expressing input predictions as a finite-dimensional perturbation of an L^2-stabilizing control law, this modified cost is obtained as an explicit function of the perturbation parameters and initial prediction state. The structure of the perturbation is determined from the conditions for future feasibility with respect to constraints given current feasibility, and the resulting input and state predictions evolve as outputs of an autonomous nonlinear system.

Polytopic state and input constraints are characterized in terms of an admissible region in the system state space augmented by perturbation parameters. Subject to smoothness conditions on the system dynamics, the normal to the boundary of the admissible region is a smooth function of prediction extremum points. An asymptotically optimal control law is then obtained by continuously adapting perturbation parameters on the basis of the gradient of the modified cost and asymptotically convergent estimates of prediction extrema. Closed-loop stability and convergence are guaranteed by the stability properties of predictions and the propagation of the guarantee of feasibility.

Keywords : Adaptive optimization, Constraints, Infinite horizon, Continuous-time

Iterative active-set method for efficient on-line MPC design

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Model Predictive Control (MPC) offers an effective methodology to take into account hard constraints in control design. Unfortunately MPC requires high computational demands for on-line solution at each sampling period of a nonlinear (usually quadratic) mathematical programming problem. For fast processes and with the currently available computing power, this may be yet a computationally prohibitive task as witnessed by the fact that constrained MPC is nowadays applied mainly to control of (slow) chemical processes but very seldom to control of (fast) electromechanical systems. The objective of the present work is to broaden the applicability of constrained MPC by exploiting a combination of active set and dynamic programming techniques in the solution of optimal constrained control problems. More specifically, the attention will be focussed on the following MPC problem:

Predictive model

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k \\ z_k &= Dx_k + Eu_k + g \\ & \quad E \text{ square}, det(E) \neq 0. \end{aligned}$$

Cost

$$J(u) = \sum_{k=0}^{\infty} x_k^T Q x_k + u_k^T R u_k, \quad Q = Q^T \geq 0, \quad R = R^T > 0.$$

Constraints

$$\begin{aligned} &\|z_k\|_\infty \leq 1, \quad 0 \leq k < N \\ &u_k = Fx_k, \quad k \geq N, \ F \text{ optimal LQ feedback gain for the above cost.} \end{aligned}$$

The Active Set Method, that is a method which iteratively searches the set of active constraints characterizing the optimal solution, will be applied to the solution of the associated optimization problem. The key idea for an efficient solution is the derivation of a computationally cheap and elegant procedure to update the solution whenever a single constraint is added to or removed from the Active Set. The proposed algorithm exhibits two nice properties: i) it provides the optimal control law in a Linear Time Varying Feedback form, where the feedback gains clearly depend on the optimal Active Set; ii) is capable of updating the feedback gains, after an addition or removal of an active constraint, by order N computations, N being the control horizon.

Keywords : Predictive control, linear quadratic methods, quadratic programming, dynamic programming, computational aspects

Nonlinear Model Predictive Control : constrained optimization and practical stability

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In this paper, we propose a solution for the two major difficulties provided by the extension of Model Predictive Control (MPC) to nonlinear systems : the constrained nonlinear optimization resolution and the stability study.

A constrained optimization algorithm has been developed to take in consideration on-line control requirements : the constraints satisfaction at any time and the computational time. It combines an interior penalty method and the efficient Levenberg-Marquardt's algorithm. The algorithm convergence is proved under a constraints qualification assumption which is a sufficient condition of feasability for the nonlinear optimization problem. It points out the link between the reference trajectory sensibilities and the admissible control variables.

One way to ensure the stability of receding horizon control is to introduce a terminal constraint, often denoted $x(t+T) = 0$. It expresses a finite-time commandability and implicitly forces the optimization convergence which is quite restrictive. In this paper, the stability of the resulting closed-loop system is investigated by using the notion of practical stability, first introduced by LaSalle [3] in 1961 for continuous-time systems and Hurt [1] in 1967 for discrete-time systems. It can be viewed as a robust stability in spite of bounded disturbances and seems to be well-adapted to nonlinear predictive control. The global approach of the optimization and the stability problems allows to relax the usual terminal constraint by defining a "receding-like constraint" and to state the stability in the neighbourhood of an equilibrium point. The efficiency and the robustness of the NMPC are illustrated through a chemical example.

Keywords : Nonlinear predictive control, constrained optimization, practical stability, internal model

References

[1] Hurt J., "Some stability theorems for ordinary difference equations", *SIAM J. Num. Anal.*, **4**, 582–596, (1967).

[2] Keerthi S.S., Gilbert E.G., "Optimal infinite-horizon feedback laws for a general class of constrained discrete-time systems : stability and moving-horizon", *Journal of optimization theory and applications*, **57**, 265–293, (1988).

[3] LaSalle J.P., Lefschetz S., "Stability by Lyapunov's direct method with applications", *New York Academic*, (1961).

Exact Linearisation is a Special Case of Non-linear GPC

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The Multivariable Continuous-time Generalised Predictive Controller (CGPC) has been recast in a state-space form [1, 2] and shown to include Generalised Minimum Variance (GMV) and an new algorithm, Predictive GMV (PGMV) as special cases; it is noted that, unlike the transfer function approach, the state-space approach extends readily to the nonlinear case.

There has been a recent resurgence of interest in non-linear control driven by Geometrical Control Theory; to avoid proliferation of references the books of Isidori [3] and Marino and Tomei [4] are used as a summary of such results. The purpose of this paper is to recast our results on the Multivariable Continuous-time Generalised Predictive Controller in a geometric setting. In particular, the construction of the nonlinear GMV is shown to follow the same steps as the development of the *Exact Linearisation via Feedback* given in Section 4.2 of [3].

Thus is shown that a special case of CGPC is identical to the corresponding controller resulting from Exact Linearisation. This result makes it clear how GPC is able to control systems with unstable inverse dynamics. In particular an alternative (prediction-free) version of GPC is shown to provide one possible extension of exact linearisation to cope with nonlinear systems with unstable dynamics.

A two link-manipulator with delayed measurement is used as an illustrative example. The Bond Graph technique, together with symbolic algebra, is used to generate the controller.

Keywords : Generalised Predictive Controller; Exact Linearisation; Generalised Minimum Variance Control

References

[1] P. J. Gawthrop, H. Demircioglu, and I. Siller-Alcala. Multivariable continuous-time generalised predictive control: A state-space approach to linear and nonlinear systems. *Proc. IEE Pt. D: Control Theory and Applications*, To appear 1998.

[2] P.J. Gawthrop, H. Demircioglu, and I. Siller-Alcala. Multivariable continuous-time generalised predictive control: A state-space approach to linear and nonlinear systems. CSC Research Report CSC-98001, Centre for Systems and Control, University of Glasgow, URL http://www.mech.gla.ac.uk/Control/reports.html, 1998.

[3] A. Isidori. *Nonlinear Control Systems: An Introduction. 3rd Ed.* Springer-Verlag, New York, 1995.

[4] Riccardo Marino and Patrizio Tomei. *Nonlinear Control Design: Geometric, Adaptive & Robust.* Prentice Hall, 1995.

Optimal and Suboptimal Nonlinear Predictive Control Algorithms Applied for the Quadratic Hammerstein and Volterra Models

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Abstract. Predictive control algorithms have been worked out mainly to control linear plants. There is a great demand to apply control ideas for nonlinear systems. Using predictive control algorithms for nonlinear systems is a promising technique. GPC (Generalized Predictive Control) developed by Clarke has been extended for different nonlinear input/output models. The nonlinear process models applied are the Hammerstein series model, the Volterra series model, the parametric generalized Hammerstein model and the parametric Volterra model, a special class of the parametric recursive polynomial NARMAX model. Extended horizon one-step-ahead and long-range optimal predictive control algorithms are derived. A quadratic cost function is minimized, which considers the quadratic deviations of the reference signal and the output signal predicted in a future point beyond the dead time and also punishes big control increments. For prediction of the output signal on the basis of the information of the input and output signal available up to the actual time point predictive model is needed. Predictive transformation of the parametric nonlinear dynamic models are given. Incremental model is advantageous since the cost function contains the control increment and not the control signal itself. Incremental transformation of the non-parametric models, which are predictive, and of the predictive equations of the parametric forms are also described. Suboptimal solutions of the optimal control algorithms are discussed with different assumptions for the control signal during the control horizon. The suboptimal algorithms work almost as good as the optimal algorithms, however instead of a vector optimization a scalar optimization can be used. The effect of the different strategies and the effect of the tuning parameters is investigated through simulation examples.

Keywords : Predictive control, Nonlinear control, Optimal control, Nonlinear system

References

[1] Haber R., "Transformation of the absolute descriptions of linear and non-linear processes to their incremental forms.", *Int. Journal of Systems Science.*, **Vol. 23**, pp. 935-955,(1992).

[2] Haber R., "Predictive control of nonlinear dynamic processes.", *Applied mathematics and Computation*, **Vol. 70**, pp. 169-184,(1995).

Integrating Predictive and Switching Control: Basic concepts and an experimental case study

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The paper is concerned with the integration of predictive and switching control in order to achieve a structure suitable for application in wide range control of a class of nonlinear processes. The switching structure considered consists in a bank of predictive controllers. Each controller is tuned to a given operating subrange of the process and associated to a local model describing the plant under this operating conditions. The switching among controllers is performed by comparing a measure of the predictive errors yielded by the corresponding local models and choosing the best. In order to ensure stability, a minimum dwell time is respected in each controller. Each of the predictive controllers in the bank is designed by running a suitable adaptive predictive controller in a (detailed) model of the plant with constant (for each local controller) operating settings, and recording the result yielded at convergence. Both the bank of predictors and the bank of predictive controllers are implemented using a shared state realization.

The use of this structure in the control of the oil outlet temperature in a distributed collector solar field is described. The field used in the experiments reported is a 0.5MW ACUREX field located in Plataforma Solar de Almeria, in the south of Spain. The experiments reported document the way the structure considered works, in particular the advantage of the switching structure over a single constant linear controller.

Keywords : Switching Control, Nonlinear Control, Predictive Control, Solar Energy

Nonlinear receding horizon control of internal combustion engines

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This paper presents the application of the Nonlinear Receding Horizon (NRH) strategy presented in [1, 2] to idle speed control of internal combustion engines. The controller synthesis is based on a nonlinear estimated $NARX$ model of the engine describing the dynamics of the pressure p inside the intake manifold and of the cranckshaft speed n as functions of the position of the idle-speed air actuation system α and of the spark advance ψ [3]. Starting from idle speed conditions, the performance of the controller are tested against engine charges due to accessory torque loads. The NRH control law is computed off-line and can be applied on-line by means of a suitably trained interpolating neural net [4, 5]. With reference to a commercial $1400\,cm^3$ engine model, comparisons between the Linear Quadratic regulator [6] presently used in large scale applications and the NRH approach are illustrated.

Keywords : Internal Combustion Engines, Receding Horizon Control, Neural Network

References

[1] G. De Nicolao, L. Magni, and R. Scattolini. "Stabilizing predictive control of nonlinear ARX models" *Automatica*, **33**, 1691–1697, (1997).

[2] G. De Nicolao, L. Magni, and R. Scattolini. "Stabilizing receding-horizon control of nonlinear time-varying systems", *IEEE Trans. on Automatic Control*, 1998.

[3] R. Scattolini, G. De Nicolao, M. Cittadini, C. Rossi, and C. Siviero. "Modelling internal combustion engines via NARX identification techniques", *IEEE Mediterranean Control Conference, Cyprus*, (1997).

[4] T. Parisini and R. Zoppoli. "A receding-horizon regulator for nonlinear systems and a neural approximation", *Automatica*, **31**, 1443–1451, (1995).

[5] L. Cavagnari, L. Magni, and R. Scattolini. "Neural network implementation of a nonlinear receding-horizon controller", *Conference on Control Applications*, (1998).

[6] G. De Nicolao, C. Rossi, R. Scattolini, and M. Suffritti. "An automatic synthesis procedure of idle speed linear quadratic regulators through identification experiments", *IFAC Workshop Advances in Automotive Control*, (1998).

Exploring the Potentiality of Using Multiple Model Approach in Nonlinear Model Predictive Control

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Any model or controller has one limited interval of operation or validity, i.e., a region where it represents the system's behavior and works well. Many factors (such as: use of linear models to represent nonlinear systems, hypotheses made during the modeling, experimental conditions, etc.) contribute for reduction of the interval of validity of a model or controller. A model or controller that is valid in a given operating conditions is called local model or submodel. Certainly, the final objective is the attainment of a global model or controller. A way of reaching this objective is to represent all the region of operation through a network of local models also called multiple models. The use of local model network (LMN) has shown to be very attractive to modeling and identification of nonlinear systems. An extension of this idea to a local control network has also shown to be a promising area. Attempts to apply LMN in predictive control have fallen into unattractive complex optimization problems. The present work aims to exploit the powerful advantages of this paradigm by the proposition of a Nonlinear Model Predictive Control based on a linear local model network (LLMN). Unconstrainded problems and input-constrained problems are addressed in this formulation. A methodology for the selection of the optimal, or quasi-optimal, trajectory in the hypercone of local models is proposed in a semi-analytical context. The benchmark problem: a continuous stirred tank reactor with van der Vusse reaction [1], is used to illustrate the subject in the scope of this work. This problem has interesting static and dynamic features that can be used to test the algorithms.

Keywords : nonlinear model predictive control, local model network, van der Vusse reaction

References

[1] Chen H., Kremling A., Allgöwer F., "Nonlinear Predictive Control of a Benchmark CSTR", *in Proceedings of 3rd European Control Conference*, 3247–3252, (1995).

Performance and Computational Implementation of Nonlinear Model Predictive Control on a Submarine

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We explore the implementation of Nonlinear Model Predictive Control (NMPC) on a nonlinear model of a submarine whose task is to track a fixed distance above the ocean floor. The key features are that:

- We develop an explicit method for the computation of approximate solutions of the finite-horizon, input and state constrained, open-loop optimal control problems on a discrete-time version of the system, forming the receding-horizon control law.
- We apply an Extended Kalman Filter to generate the state estimates used to introduce feedback into the NMPC.
- We analyse the performance of the constrained, discrete-time NMPC on a simulation of the continuous-time nonlinear system.

Throughout, our focus is to use this physically comprehensible system as a test-bed for generalisable theory. This paper intersects and extends another examination of the submarine system [1].

The optimisation method relies on the computation of the gradient of the quadratic cost function with respect to the control values using the Method of Lagrange Multipliers [2]. Input constraints are included by projection methods while state constraints are effected by introducing penalty functions to the cost.

Convergence of these gradient-based optimisation steps is shown to depend upon the control penalty, R, in the quadratic cost function. Specifically, cheap control (small R) induces poor conditioning of the cost surface but, equally, encourages the early inputs to converge first. Since these early inputs of the finite-horizon, open-loop control are precisely those applied in the receding-horizon closed-loop strategy, approximate optimisation is appropriate for NMPC. The import of this is that cheap control reflects the objective of the bulk of practical problems in this area.

Keywords : Receding Horizon Control, implementation, optimisation, state constraints, input constraints

References

[1] G. J. Sutton and R. R. Bitmead, "Experiences with Model Predictive Control applied to a nonlinear constrained submarine", submitted for publication to 37^{th} *IEEE CDC*, (1998).

[2] A. E. Bryson Jr, Y-C. Ho, *Applied Optimal Control: optimization, estimation and control*, Ginn and Co., (1969).

Nonlinear Model Predictive Control based on stable Wiener and Hammerstein models

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Model Predictive Control (MPC) is an attractive control strategy, particularly for complex real-world processes. Therefore, conventional MPC schemes based on linear models have enjoyed wide-spread acceptance and success as an effective technique for dealing with control problems. In recent years research is focused on MPC using nonlinear models. But the derivation of these models can be very time consuming especially if the process is not well understood. Furthermore, the nonlinear control schemes that employ more realistic nonlinear process descriptions typically sacrifice the simplicity associated with linear techniques in order to achieve improved performance. Thus, the direct use of nonlinear models often leads to high order nonlinear optimization problems.
A Nonlinear Model Predictive Control (NMPC) scheme based on stable Wiener and Hammerstein models has been developed that retains the characteristics of linear MPC including capabilities to control time-invariant nonlinear stable processes. In order to estimate the future output signal the q-th degree Wiener and Hammerstein model is represented by a truncated Volterra-series.

$$y(k) = y_{00} + \underbrace{\sum_{i=0}^{m} g_l(i)u(k-i)}_{\text{linear}} + \underbrace{\sum_{n=2}^{q}\left(\sum_{i=0}^{m} g_{Wn}(i)u(k-i)\right)^n}_{\text{Wiener}} + \underbrace{\sum_{n=2}^{q}\left(\sum_{i=0}^{m} g_{Hn}(i)u^n(k-i)\right)}_{\text{Hammerstein}}$$

If the series is considered as the nonlinear extension of the linear impulse response model then g_l is the linear, g_{W2} or g_{H2} represent the quadratic and g_{Wq} or g_{Hq} represent the q-th degree kernel. y_{00} is the value of y if all input signals u are equal to zero. $y(k)$ indicates the output and $u(k)$ the input signal at the sampling instant k. The optimal manipulated variable is calculated by minimizing a quadratic cost function depending on the j-step prediction. Furthermore hard input and soft output constraints are implemented in the NMPC algorithm.
The nonlinear control algorithm was tested in two case studies of chemical processes in comparison with other control schemes. In the first case the developed NMPC is applied to a pH neutralization process. The time invariant nonlinear titration curve within the process can be approximated in the relevant operating range by a 3rd degree polynomial. The second case study represents a highly nonlinear benchmark CSTR (continuously fed stirred tank reactor). The non-minimum-phase process is identified - using reduced Volterra-series - as a 2nd degree Wiener model. Although the Wiener model is only a very simplified description of the process the optimal operating point could be reached by the NMPC.

Keywords : Nonlinear models, Predictive Control, Process models, Volterra-series