

Optimal Process Operation by Using Economics Optimizing Nonlinear Model Predictive Control

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Dedication

This dissertation is dedicated

to the memory of my beloved father

Abdelrahman Noureldin Idris (1940-2010)

*You are exceptionally appreciated for inculcating in me the valuable meanings of fortitude
and determination and for your purposeful commitment to my academic progress!*

May God rest your soul.

&

to my mother

Muna Yousif Mohammed Ali

Your graces and sacrifices are myriad and beyond being lumped in words!

May your life be satiated with vivacity, robust health and merriments in a lap of luxury,

&

may God lengthen your life.

Abstract

Process profitability is a decisive criterion for successful long-term operation of industrial processes. Economics-driven optimization based on rigorous first-principles models has been progressively integrated into the operation of chemical processes in order to improve the competitiveness of these processing units. Decisions on the most profitable conditions are usually made based on infrequent optimizations of stationary rigorous first-principles models (real-time optimization, RTO). However, the neglect of the dynamic process behaviour in these models can lead to feasibility issues and performance degradation. The inclusion of rigorous dynamic models in the decision-making policies makes it possible to overcome these difficulties and therefore higher process efficiency and profitability can simultaneously be achieved. This can be realized by using different strategies of economics-based nonlinear model predictive control (NMPC).

Nonlinear model predictive control is perhaps the most advanced feedback control technique that introduced a significant impact on the industrial chemical processes. Its abilities to handle multivariable control systems, to incorporate constraints into the control problem formulation and to enable the integration of economics optimizing criteria into the feedback control design are the most outstanding advantages among many others.

An economics optimizing NMPC controllers to optimize and control the operations of a non-minimum phase continuous stirred tank reactor (CSTR) and the operations of a complex dynamics pilot-scale continuous catalytic distillation (CCD) process are investigated in this thesis. This direct economic optimization scheme is compared with a compromise scheme, the economics-oriented tracking controller. Besides the inherent nonlinearity of these processes, non-minimum phase behaviour, input multiplicity and local minima are among the complex phenomena encountered in both case studies. Different control structures are used to explore the potential benefits of the dynamic online economics-based nonlinear control strategies. Online state and disturbance estimation is an integral part of the investigated NMPC control schemes particularly in the presence of disturbances and plant-model mismatch. Two conceptually different state and disturbance estimation techniques are used in this thesis namely the extended Kalman filter (EKF) and the nonlinear gain-scheduling observer, which is a modified version of the extended Luenberger observer (ELO).

In this thesis, global as well as local optimization algorithms are used. The global optimization algorithm is used primarily to locate the optimal region (i.e. good initial guess) to a local optimization algorithm and to avoid those potentially optimal parts of the space from being overlooked. The local optimization algorithm finds the best point in that optimal region.

The outcome of this work indicates that by using direct economics optimizing NMPC the plant economics can be handled better while guaranteeing the product specifications. The economics of the process can be enhanced when more degree of freedom are manipulated at the price of more complex optimization problems. The concept of the economics optimizing NMPC can straightforwardly be applied to similar chemical processes and the findings and conclusions deduced from this work are important for analogous chemical processes.

Zusammenfassung

Die Prozess-Rentabilität ist ein entscheidendes Kriterium für einen erfolgreichen langfristigen Betrieb industrieller Prozesse. Ökonomische Optimierungen basierend auf rigorosen Modellen wurden schrittweise in den Betrieb von chemischen Prozessen integriert, um die Wettbewerbsfähigkeit zu verbessern. Die Entscheidungen für die profitabelsten Bedingungen basieren in der Regel auf der Grundlage unregelmäßiger Optimierungen von stationären rigorosen Modellen (*real-time optimization*, *RTO*). Allerdings kann die Vernachlässigung des dynamischen Prozessverhaltens in diesen Modellen zu Unzulässigkeit und Suboptimalität führen. Die Einbeziehung dynamischer rigoroser Modelle in die Entscheidungsfindung macht es möglich, diese Schwierigkeiten zu überwinden und damit eine höhere Prozesseffizienz und damit höhere Rentabilität zu erreichen. Dies kann durch verschiedene Strategien der ökonomie-basierten nichtlinearen Modellprädiktiven Regelung (*NMPC*) realisiert werden.

Die nichtlineare modellbasierte prädiktive Regelung ist unter den Vertretern der gehobenen Regelungstechnik der mit der größten Bedeutung für industrielle chemische Prozesse. Ihre Fähigkeit zur Mehrgrößenregelung, die Modellgleichungen als Nebenbedingungen in das Optimierungsproblem zu integrieren und die Einbeziehung der allgemeinen wirtschaftlichen Optimierungskriterien in das Regeldesign zu ermöglichen sind die wichtigsten Vorteile.

In dieser Arbeit wird ein ökonomie-orientierter optimierender NMPC- Regler zur Optimierung und Steuerung eines kontinuierlichen Rührkessels (*CSTR*) mit Nicht-minimalphasen-Charakteristik und zum Betrieb eines kontinuierlichen katalytischen Destillations- (*CCD*)-Verfahrens mit einer komplexen Dynamik mittels Simulation im Pilotmaßstab untersucht. Dieses direkt ökonomisch optimierende Schema wird mit einer ökonomie-orientierten Folgeregelung verglichen. Neben der inhärenten Nichtlinearität dieser Prozesse tragen die Nichtminimalphasen-Charakteristik, die Multiplizität von Eingangsgrößen und lokale Minima zur Komplexität dieser beiden Fallstudien bei. Verschiedene Kontrollstrukturen werden verwendet, um die potenziellen Vorteile von dynamischen online-ökonomie-basierten nichtlinearen Regelstrategien zu identifizieren. Eine online Zustands- und Störungsabschätzung ist ein wesentlicher Bestandteil der untersuchten NMPC Regelschemata, besonders in Gegenwart von Störungen und Modellfehlern. Zwei konzeptionell unterschiedliche Zustands- und Störungsschätzer wurden in dieser Arbeit verwendet, und zwar der erweiterte Kalman-Filter (*Extended Kalman Filter*, *EKF*) und ein nichtlinearer gain scheduled-Beobachter (*Gain-scheduled Observer*), eine modifizierte Version des erweiterten Luenberger Beobachters (*Extended Luenberger Observer*, *ELO*).

In dieser Arbeit werden sowohl globale als auch lokale Optimierungsalgorithmen eingesetzt. Der globale Optimierungsalgorithmus wird verwendet, um den optimalen Bereich (d.h. gute Anfangsbedingungen) für einen lokalen Optimierungsalgorithmus zu finden und zu vermeiden, potenzielle optimale Bereiche des Suchraumes zu übersehen. Der lokale Optimierungsalgorithmus optimiert innerhalb dieser optimalen Regionen.

Das Ergebnis dieser Arbeit zeigt, dass durch die Verwendung direkt ökonomie-optimierender NMPC-Regler das ökonomische Potential der Beispielprozesse unter Einhaltung der Produktspezifikationen besser ausgenutzt werden kann. Die Wirtschaftlichkeit der Verfahren kann verbessert werden, wenn mehr (auch dynamische) Freiheitsgrade in der Optimierung erlaubt sind, zu dem Preis erhöhter Komplexität der Optimierungsprobleme. Das Konzept der hier verwendeten ökonomie-optimierenden NMPC-Regler kann auf andere chemische Prozesse übertragen werden und auch die Ergebnisse und Schlussfolgerungen aus den hier dargestellten Fallstudien sind relevant für analoge chemische Prozesse.

Contents

1	Introduction	1
2	Nonlinear Model Predictive Control	5
2.1	Introduction and literature review	5
2.2	Conventional Tracking Control (CTC)	9
2.2.1	Stability of the target tracking NMPC formulation	10
	Terminal penalty term approach	11
	Terminal equality constraint approach	12
	Terminal region constraint approach	12
2.3	Economics Optimizing Control (EOPC)	13
2.4	Economics-oriented Tracking Control (EoTC)	14
2.4.1	Stability of the economics-driven NMPC formulations	15
2.5	General computational perspective of the NMPC	16
2.5.1	Solution approaches of the optimal control problem	17
2.5.2	Finite parametrization techniques	17
2.6	Computational obstacles	18
2.6.1	Non-minimum phase behaviour	18
2.6.2	Steady-state multiplicity	19
2.6.3	Locally optimal solutions	19
2.7	Summary and conclusions	20
3	State and disturbance estimation	21
3.1	Introduction	21
3.1.1	Observability	21
	Kalman criterion	22

Hautus criterion	22
Observability of nonlinear systems	23
3.1.2 Observer prerequisites	23
Simulation condition	23
Convergence condition	24
3.2 Discrete-time Luenberger Observer	24
3.2.1 Extended Luenberger Observer	25
3.2.2 Nonlinear gain-scheduled state estimation	26
3.3 Discrete-time Kalman Filter	26
3.3.1 Extended Kalman filter	28
3.4 Disturbance estimation	28
3.5 Summary and conclusions	29
4 CASE STUDY I: Continuous Stirred Tank Reactor	31
4.1 Introduction	31
4.2 Process description	31
4.3 Isothermal operation of the CSTR	32
4.4 Non-isothermal operation of the CSTR	33
4.5 Simplification of the dynamic model	34
4.6 Dynamic characteristics of the CSTR reactor	35
4.7 Summary	37
5 CASE STUDY II: Catalytic Distillation Column	39
5.1 Introduction	39
5.2 Advantages of Reactive Distillation	40
5.3 Classification of reactive distillation processes	41
5.4 Process description	43
5.4.1 Dynamic model of the CD column	45
5.4.2 Simplification of the dynamic model	52
5.4.3 System Characteristics	56
5.5 Summary and conclusions	56

6	Control of the continuous stirred tank reactor	61
6.1	Introduction	61
6.2	Operation conditions and assumptions	61
6.3	Nonlinear state and disturbance estimation	62
6.4	Implication of input multiplicity	66
6.5	Implementation of the control algorithm	69
6.6	Maximizing control (MC)	70
6.7	The NMPC-associated economic cost function	71
6.8	Isothermal operation	74
6.9	Non-isothermal operation	76
6.10	Summary and conclusions	84
7	Control of the Continuous Catalytic Distillation Process	85
7.1	Introduction	85
7.2	Control studies	86
7.2.1	Control structure CS 1	88
7.2.2	Control structure CS 2	89
7.2.3	The economic NMPC strategies	92
	Moving horizon economics optimizing control	92
	Economics-oriented tracking control	94
7.2.4	Economical control structure ECS 1	95
7.2.5	Economical control structure ECS 2	97
7.2.6	Economical control structure ECS 3	101
7.2.7	Economical control structure ECS 4	103
7.2.8	Economical control structure ECS 5	105
7.2.9	Economical control structure ECS 6	109
7.3	Summary and conclusions	111
8	Numerical Simulation, Optimization and Control Algorithms of the Catalytic Distillation Process	113
8.1	Introduction	113
8.2	Numerical solution of the model	113
8.3	Optimization algorithms	115

8.3.1	glcSolve-DIRECT	115
8.3.2	SNOPT-SQP	122
8.4	Control algorithm	125
8.5	Summary and conclusions	126
9	Summary, outlook and future prospects	127
9.1	Summary	127
9.2	Outlook	128
9.3	Future directions	129
A	The Operating Parameters of the Nonlinear CSTR Reactor	131
A.1	The costs of the reactant, product and energy	132
B	Some Operating Parameters and Miscellaneous Data related to the Nonlinear CCD Process	133
B.1	The cost of reactants, product and energy	133
B.2	Component boiling points	134
B.3	Binary azeotropes temperature	134
B.4	Antoine coefficients	134
B.5	Wilson binary parameters	134
B.6	Constants and parameters	135
B.7	Reaction kinetics data	135
B.8	The predicted vapour-liquid compositions of the binary systems	135
B.9	Numerical simulation	138
B.10	The modified setting parameters of the SNOPT optimization solver	139
C	Nomenclature	141