UNIVERSITI PUTRA MALAYSIA

MODEL PREDICTIVE CONTROL DESIGN FOR A NONLINEAR FOUR-TANK SYSTEM

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FK 2008 86

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By

SHADI ANSARPANAHI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

December 2008

DEDICATION

I dedicate this dissertation to:

My Father; My Sun

and

My Mother; My Moon

Abstract of thesis to be presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Master of Science

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Chairman: Samsul Bahari B. Mohd Noor, PhD

Faculty: Engineering

In recent years, MPC has become a prominent advanced control technique, especially in large industrial processes. However, for enormous complexity, non-convexity and computational reasons, MPC practice and applications have been restricted to linear plants. During the last decade, many formulations have been developed for MPC formulation of linear and nonlinear, stable and unstable plants but still there remain some unsolved issues which depend on plant specifications. Instability, unfeasibility, non-convexity and lack of robustness are examples of unsolved issues.

In this thesis a control system has been designed for a highly nonlinear and non-minimum phase Four-Tank system. Then constrained optimization is employed in the MPC formulation to repair violation on boundaries. It also leads the system to work with the best performance. Additionally, the influence of most effective tuning parameters in MPC strategy has been investigated. In particular main part of the thesis has focused on performance criteria based on good reference tracking in model predictive control

domain. Regarding to investigate the performance of this algorithm and due to application of “nonlinear Four-Tank system” in control theory and industry, this system is considered as a plant to be examined under this method. The most attractive aspect of this system is; the time-varying movement of a right half plane transmission zeros across the imaginary axis. This system’s configuration makes the process difficult to control under the previous controllers. This problem appears to be one of the most important and practical designs of nonlinear system in process control.

In this thesis, besides good performance, the algorithm enjoys from relative simplicity and faster response in compare with the algorithms developed in other previous works. The problems of complexity of algorithm, non-convexity of the optimization, especially when working with nonlinear plants are the most common problems in the control design criteria. Since linear model predictive control is used instead of nonlinear model predictive control; these problems are avoided to be appeared in this work. All the results in this study show fast performance in controlling the Four-Tank system. Both of the weighting matrices are considered so that a system is fast enough smooth control signals and they are tuned till the desired performance is achieved.. Low value of prediction horizon and weighting matrices are more preferable to reduce number of free variable and avoid complexity of analysis.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PELAKSANAAN KAWALAN PREDIKTIF MODEL LELURUS BAGI SISTEM EMPAT-TANGKI TAK LELURUS

Oleh

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Pengerusi: Samsul Bahari B. Mohd Noor, PhD

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Sejak kebelakangan ini, penggunaan MPC telah diperluaskan dengan teknik penggunaan kawalan termaju terutamanya di dalam industri penapisan dan juga petrokimia. Walaubagaimanapun, penggunaannya hanya terhad kepada model lelurus sahaja kerana masalah kekompleksan, tidak cembung dan perkomputeran. Di dalam sistem dinamik aplikasi dunia nyata yang kebanyakannya bukan lelurus, pengunaannya terpaksa dianggarkan supaya dapat digunapakai ke atas konvensional MPC. Model-model seperti ini selalunya tidak mengambilkira kepada dinamik sistem sepenuhnya, terutamanya di bahagian yang tidak hampir dengan keadaan sasaran. Untuk kes-kes sebegini, model bukan lelurus digunakan untuk menentukan kejituan sifat sesebuah loji. Dalam dekad terakhir ini, banyak formulasi telah dibangunkan untuk model lelurus dan bukan lelurus serta stabil dan tidak stabil. Akan tetapi, masih banyak lagi isu-isu yang belum diselesaikan.

Penyelidikan ini terbahagi kepada dua bahagian. Bahagian pertama meliputi gambaran keseluruhan keadaan semasa teknik kawalan prediktif model lelurus, teknologi teknik kawalan prediktif model bukan lelurus serta penerangan ringkas tentang prinsip kawalan prediktif dan garis panduan sebahagian teori, pengkomputeran dan juga aspek implementasi strategi kawalan. Dengan menggunakan kaedah yang diperjelaskan, model kawalan prediktif telah direka untuk sistem berterusan bukan lelurus.

Dalam tesis ini kestabilan dan kekuatan algorithm yang dicadanangkan danpada kemudahan perhubungan dan kekurangan penaksiran masa berbanding dengan algorithm yang dihasilkan sebelum ini. Masalah penaksiran masa yang panjang, algorithm yang komplex, optimum yang tidak sekata dan bahasian kestabilan yang terhad, terutama apabila pemprosesan plant yang tidak linear adalah. Masalah utama yang berlaku dalam kriteria merekabentuk kawalan. Masalah-masalah ini telah diatasi dalam projek ini. Kesimpulannaya, kesemua keputusan menunjukkan pendekatan MPC dalam tesis ini akan memberi jaminan kepada kestabilan gelung tertutup. La menstabilkan sistem empat-tangki ketika menggunakan masalah paksaan optimum. Kamalan horizon yang rendah dan berat matrik adalah dipilih untuk mengelak berakunya masa penaksiran yang panjang dan komleks.

ACKNOWLEDGEMENTS

First of all, I would like to thank the Lord for his enormous support during my life, and then I wish to thank a number of people who in various ways made my graduate studies possible.

I would like to express my gratitude to the supervisory committee members, Dr. Samsul Bahari B. Mohd Noor and Dr. Mohammad Hamiruce Marhaban for proposing this challenging project and for their confidence in my abilities and also for their great guide and help through out the work.

I would like to gratefully acknowledge my family specially my parents for their great help, patience, care, guidance, enormous support and understanding of family time lost during my studies. I would not have passed through these years without them.

In addition, special thanks are due to two of my great friends, Dr. Hosein Eliasi for his invaluable comments, consultation and guidance that kept me on the right track during the work. Besides, the help of Mr. Majid Farrokhfar is certainly appreciated for guiding in a lot of computer related problems.

Many thanks go out to my best friend, Parisa, who deserve my deep gratitude. Besides all my friends and home mates were great assets and helped me throughout all these years of my graduate studies.

Last but not least, I wish to thank Head of Electrical and Electronic department, Dr. Hashim B. Hizam. As well I wish to thank the Deputy Dean of Graduate School in Engineering Faculty Dr. Norman Mariun and also thank the Deputy Dean and all the staffs of Graduate School for their nice cooperation during my years at Universiti of Putra Malaysia.

APPROVAL

I certify that an Examination Committee met on 19th December 2008 to conduct the final examination of Shadi Ansarpanahi on her Master Degree thesis titled “Model Predictive Control Design for a Nonlinear Four-Tank System” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the student be awarded the Master Degree.

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DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institutions.

SHADI ANSARPANAHI

Date:

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LIST OF ABBREVIATIONS

Symbols

s	Complex variable used in Laplace transform
z^{-1}	Backward shift operator
$(M)_{ij}$	Element ij of matrix M
$I_{n\times n}\ (n\times n)$	Identify matrix
I	Identify matrix of appropriate dimension
$\widehat{x}(t+j\,\vert t)$	Expected the value of $\widehat{x}(t+j)$ with available information at time t
$\delta(P(.))$	Degree of polynomial P(.)
det(M)	Determinant of matrix M
$\min\limits_{x\in X} J(x)$	The minimum value of J(x) for all value of $x\in X$

Model Parameters and Variables

m	Number of input variables
n	Number of output variables
u(t)	Input variables at instant t
y(t)	Output variables at instant t
x(t)	State variables at instant t
e(t)	Discrete white noise zero mean
d	Dead time of the process expressed in sampling time unit
$A(z^{-1})$	Process left polynomial matrix for LMFD
$B(z^{-1})$	Process right polynomial matrix for LMFD

$C(z^{-1})$	Coloring polynomial matrix

Controller Parameters and Variables

N_{p_1}	Lower value of prediction horizon
N_{p_2}	Higher value of prediction horizon
$N\ (N_p)$	Number of points of prediction horizon ($N = N_{p_2} - N_{p_1}$)
N_u	Control horizon (N_c)
λ_Q & λ_R	Weighting factor for control increment
δ	Weighting factor for predicted error
u	Vector of future control increments for the control horizon
y	Vector of predicted outputs for prediction horizon
f	Vector of predicted free response
w	Vector of future reference
$\overline{U}$	Vector of maximum allowed values of manipulated variables
$\underline{U}$	Vector of minimum allowed values of manipulated variables
$\overline{Y}$	Vector of maximum allowed values of output variables
$\underline{Y}$	Vector of minimum allowed values of output variables
$\overline{A}(z^{-1})$	Polynomial $A(z^{-1})$ manipulated by Δ

Acronyms

CARIMA	Controlled autoregressive integrated moving average
CARIMA	Controlled auto regressive moving average
CRHPC	Constrained receding horizon predictive control
DMC	Dynamic matrix control
EHAC	Extended horizon adaptive control
EPSAC	Extended prediction self-adaptive control
GMV	Generalized minimum variance
GPC	Generalized predictive control
LMFD	Left matrix fraction description
LMI	Linear matrix inequalities
LQ	Linear quadratic
LQG	Linear quadratic Gaussian
LP	Linear programming
MAC	Model algorithm control
MILP	Mixed integer linear programming
MIMO	Multi input multi output
MIP	Mixed integer programming
MIQP	Mixed integer quadratic programming
MPC	Model predictive control
NLP	Nonlinear programming
PFC	Predictive functional control
PID	Proportional integral derivative

QP	Quadratic programming
RMPCT	Robust model predictive control technology
SGPC	Stable generalized predictive control
SISO	Single input single output

CHAPTER 1

INTRODUCTION

1.1 Preface

Due to increments of the world wide competition and major changes in marketing and business during the past decades, process industry has confronted a major change in the market. Therefore it is necessary to develop all the aspect of process control technologies such as: modeling, dynamic trajectory optimization, integrated software tools and high-performance industrial process control. Process dynamics tend to become too complex to be efficiently controlled by the current generation of control and optimization techniques. One of the advanced control technology which made a significant impact on industrial control engineering is model predictive control. The model predictive control technology is uses to steer processes closer to their physical limits in order to obtain a better economic production and to meet all the performances to attract the customers (Tyagunov, 2004). This is perhaps one of the most appealing and attractive approaches in industrial process control practice for our century. To see more examples of model predictive control application one can refer to (Clarke, 1988; Camacho and Bordons, 2004; Allgower and Zheng, 2004).

1.2 Model Predictive Control Technology

Model Predictive Control (MPC) , also known as moving or receding horizon control, is a feedback control scheme that has originated in industry as a real-time computer control algorithm to solve linear multi-variable problems that have constraints and time delays. It is a form of control in which the current control action is obtained by solving on-line, at each sampling instant, a finite horizon open-loop optimal control problem, using the current state of the plant as the initial state; the optimization yields an optimal control sequence and the first control in this sequence is applied to the plant (Tyagunov, 2004; Camacho and Bordons, 2004). Due to recent developments model predictive controller is suggested as a candidate to replace PID controller. It has received an ever growing interest and a great deal of attention for applications in industrial process control especially in chemical, oil and petrochemical industry. Main advantages of MPC are as follows (Tyagunov, 2004):

1) It can be used in most real world industry due to its ability in solving problems of multi-input multi-output (MIMO) system.
2) The concepts of MPC came from industry.
3) It is able to control a large number of processes, consist of those with non-minimum phase, long time delay, input / output constraints or open-loop unstable characteristics.
4) Able to handle the process constraints.

5) It can be applied to batch processes where the future reference signals are known.

Model predictive control of a system could be applied to process industries including chemical plants, oil refineries, petrochemical industries and etc. At first the model predictive control was offered for linear system then it is extended to nonlinear systems (Mayne and Michalska, 1990; Oliveira and M. Morari, 2000; Allg¨ower et al., 1999). Linear MPC refers to a family of MPC schemes in which linear models are used to predict the system dynamics and considers linear constraints on the states and inputs and a quadratic cost function. Even if the system is linear, the closed-loop dynamics are in general nonlinear due to the presence of constraints. NMPC refers to MPC schemes that are based on nonlinear models and/or consider non-quadratic cost functional and general nonlinear constraints on the states and inputs (Camacho and Bordons, 2004).

1.2.1 Different Model Predictive Control Algorithms

In this section, the most popular methods of MPC are described. Model predictive control algorithms are just differing in the modeling of plant, noise and cost function for deriving optimal input. For example DMC[1] uses a step response to model a process. MAC[2] uses an impulse response of the process and etc. The most applicable and representative algorithm of model predictive control are as follows DMC, MAC, GPC[3],

[1] Dynamic Matrix Control
[2] Matrix Algorithm Control
[3] Generalized Predictive Control