UNIVERSITI PUTRA MALAYSIA

ROBUST OFFSET-FREE CONTROL OF NONLINEAR SYSTEMS USING MODEL PREDICTIVE CONTROL AND INTEGRAL ACTION

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FK 2019 21

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By

AYMAN WILLIAM HERMANSSON

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

January 2019

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DEDICATIONS

To Mamma och Pappa

To Norida, Aida, Adam and Aydeen

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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January 2019

Chair: Associate Professor Mohd Halim Shah Ismail, PhD
Faculty: Engineering

Model Predictive Control (MPC) is an advanced control setup that uses optimization to determine the controlled input. The MPC was initially a linear approach that has grown to include non-linear systems, robust stability, and offset-free control, which have increased the complexity through; more intricate modeling requirements, increased tuning demands, and a higher computational load.

In this work, the aim is to reduce the aforementioned complexities when applying MPC to nonlinear processes. The first step is to use multiple linear models as a way of describing the non-linear process. The piecewise linear (PWL) description captures the nonlinear process without requiring a non-linear model.

The first objective is to use the PWL for a multi-model description of the process giving rise to multiple model predictive control (MMPC). The PWL models are combined, using a Bayesian approach, into a single model for use in the optimization in MPC. The technique is not a new approach, but one that had not been applied to a pH-control system before.

For the next objective, an MMPC-I approach is developed to introduce integral action into the MMPC, to handle uncertainties such as disturbances and modeling errors. The new method is suggested to circumvent the complications associated with the tuning of an observer.

The combination of MPC and the integral controller was further developed by using the multi-model in a min-max approach to get min-max MPC-I. The min-max configuration using the worst-case scenario for the models rather than weighing them together. This objective would improve the handling of parametric uncertainties, reducing overshoots and oscillations.

The final objective was to develop a Robust MPC-I controller. The disturbance, parametric uncertainty, and integral controller are all accounted for in the input to state practical stability (ISpS) approach. A proof is given that the Robust MPC-I is indeed ISpS for nonlinear systems with bounded uncertainties.

The different combinations of MPC and integral controllers were tested on the pH-control system and compared to PID and observer-based MPC. The MMPC showed excellent behavior when set-point tracking giving at least 25% improvement compared to PID, concerning rise time, settling time and overshoot. However, the MMPC would not achieve offset-free control when disturbances or model errors were present. The inclusion of integral action removed the offset for both MMPC-I and the min-max MPC-I. The MMPC-I managed to reduce the settling time and overshoot for set-point tracking, disturbance rejection and model errors, leading to a 15% reduction in root mean square error (RMSE) compared to the PID. The min-max MPC-I showed similar improvements compared to the PID, though RMSE improvement were just 10%. The reduction compared to the observer-based MPC was even more significant (22%) as it could not achieve offset-free control for all cases. The Robust MPC-I was proven to be stable through mathematical proof, as well as showing improvement compared to the min-max MPC-I. The RMSE was reduced by a further 10%. Lastly, it was shown that the Robust MPC-I reduced the computational time compared to the observer-based MPC by an average of 25%.

A model predictive controller with adaptive I-controller is presented in this thesis to reduce the complexity of the controller. The steps needed in controller tuning and the computational times have been improved compared to the observer-based controller. The robust min-max-MMPC-I is shown to produce better control compared to PID and the observer based model predictive controller.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KAWALAN OFFSET BEBAS MANTAP BAGI SISTEM TIDAK LINEAR MENGGUNAKAN MODEL RAMALAN DAN AKSI TINDAKAN

Oleh

AYMAN WILLIAM HERMANSSON

Januari 2019

Pengerusi: Profesor Madya Mohd Halim Shah Ismail, PhD
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Model predictive control (MPC) adalah persediaan kawalan maju yang menggunakan pengoptimaan untuk menentukan input kawalan. Asalnya MPC adalah pendekatan linear mudah yang telah berkembang dengan meliputi sistem tidak linear, kestabilan teguh dan persediaan kawalan offset bebas dimana telah meningkatkan kompleksiti melalui kerumitan keperluan model, peningkatan permintaan sasaran dan bebanan pengiraan.

Dalam kajian ini, matlamatnya adalah untuk mengurangkan masalah kerumitan keperluan model, permintaan sasaran dan bebaban apabila menggunakan aplikasi MPC untuk proses tidak linear. Linear Piecewise (PWL) menjelaskan proses ketidaklinearan tanpa memerlukan model ketidaklinearan. PWL adalah model linear pelbagai yang menerangkan proses peningkatan kepada Kawalan ramalan model pelbagai (MMPC). PWL adalah menggunakan gabungan pendekatan Bayesian, didalam model tunggal untuk didgunakan dalam pengoptimaan MPC. DImana ianya bukanlah teknik yang baharu, tetapi ianya belum pernah diaplikasi untuk sistem pengawalan-pH. Seterusnya, pendekatan penyesuaian I-pengawal (MMPC-I) dibangunkan untuk memperkenalkan tindakan integral kedalam MMPC, bagi mengatasi ketidakpastian seperti gangguan dan kesilapan pemodelan. Kaedah baharu ini dicadangkan untuk mengelakkan komplikasi berkaitan dengan penalaan pemerhati.

Kombinasi MPC dan pengawalan tindakan (integral action) telah dibangunkan dengan menggunakan model kepelbagaian dalam pendekatan min-max untuk mendapatkan min-max MPC-I. Konfigurasi min-max menggunakan senario kes terburuk untuk model sebaliknya menimbangkan mereka bersama, Ini akan

memberi penambahbaikan dalam pengendalian ketidaktentuan parametrik, mengurangkan overshoot dan ayunan.

Akhirnya, pengawalan MPC-I yang teguh telah dibangunkan. Kesemua gangguan seerti, ketidaktentuan parametrik dan pengawalan integral telah diambilkira dalam pendekatan input menyatakan kestabilan praktikal (input to state practical stability) (ISpS). Bukti telah diberikan bahawan keteguhan MPC-I adalah ISpS untuk sistem tidak linear dengan ketidaktentuan batasan.

Kombinasi MPC yang berlainan dan pengawalan integral telah diuji ke atas sistem pengawalan-pH dan dibandingan dengan PID dan MPC berasaskan pemerhati. MMPC menunjukkan kelakuan yang cemerlang apabila jejakan set-point memberi nilai paling kurang 25% penambahbaikan berbanding dengan PID, berkaitan peningkatan masa (settling time), penetapan masa dan overshoot. Walaubagaimanapun, MMPC tidak dapat mencapai pengawalan offset-free apabila kehadiran gangguan atau kesilapan model (model errors). Kemasukkan tindakan integral telah mengeluarkan offset unuk MMPC-I dan min-max MPC-I. MMPC-I dapat mengurangkan peningkatan masa dan overshoot untuk jejakan set-point, penolakan gangguan dan kesilapan models, yang menghasilkan pengurangan 15% dalam root mean square errors (RMSE) berbanding dengan PID. Min-max MPC-I menunjukkkan penambahbaikan yang sama dengan PID, walaupun penambahbaikan RMSE han-yalah 10%. Akhirnya, keputusan menunjukkan MPC-I teguh telah mengurangkan jangkamasa pengiraan terhadap MPC berasaskan pemerhatian dengan kadar purata sebanyak 25%.

Model reamalan pengawalan dengan adaptasi pengwalan-I di bentangkan dalan tesis ini untuk mengurangkan kerumitan pengawalan, langkah-langkah yang perlu dalan penalaan pengawalan dan bilangan pengiraan telah memberi penambahbaikan berbanding pengawalan berasaskan pemerhatian (observer based controller). Keteguhan min-max MMPC-I ini telah menunjukkan pengawalan yang lebih baik berbanding PID dan model ramalan pengawalan berasaskan pemerhati.

ACKNOWLEDGEMENT

La ilaha il Allah

Thanks to; Dr. Syafiie for his supervision, help, and support, Dr. Halim, Dr. Samsul, Dr. Intan, and Dr. Mus'ab for their help and support.

Thanks to my wife for her love, patience and support, this would never have been completed (or started) without you.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy.The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
ANN	Artificial Neural Networks
ARX	Autoregressive Exogenous Model
BMI	Bilinear Matrix Inequality
CSTR	Continuously Stirred Tank Reactor
DCS	Distributed Control Systems
DMC	Dynamic Matrix Control
ELM	Extreme Learning Machine
GA	Genetic Algorithm
GPC	Generalized Predictive Control
IMC	Internal Model Control
ISpS	Input to State practical Stability
ISS	Input to State Stability
LFT	Linear Fractional Transformation
LMI	Linear Matrix Inequality
LTI	Linear time invariant
LTV	Linear time varying
MHE	Moving Horizon Estimation
MIMO	Multiple-Input-Multiple-Output
MISO	Multiple-Input-Single-Output
MMPC	Multiple Model Predictive Control or alternatively Multi-Model Predictive Control
MMPC-I	Multiple Model Predictive Control with I-controller
MPC	Model Predictive Control
MPC-I	Model Predictive Control with I-controller
NARX	Nonlinear Autoregressive eXogenous model
NMPC	Nonlinear Model Predictive Control
PFC	Predictive Functional Controller
PID	Proportional Integral Derivative Controller
PSO	Particle Swarm Optimization
PWL	PieceWise Linear
QDMC	Quadratic programming solution of DMC
RHC	Receding Horizon Control
RMHE	Robust Moving Horizon Estimation
SDP	Semidefinite Programming/Optimization
SISO	Single-Input-Single-Output
SMOC	Shell Multi-variable Optimizing Controller
SR-MPC	Safe and Robust MPC
T-S	Takagi-Sugeno

NOTATION AND LIST OF SYMBOLS

The following notation is used throughout this thesis. Scalars are denoted by lower case letters (a, b), vectors in bold lower case letters $(\mathbf{x}, \mathbf{u})$, matrices in upper case letters (A, B), and sets in calligraphic letters $(\mathcal{X}, \mathcal{U})$.

$\cdots$	...and so forth
$\triangleq$	left-hand side is dened by the right-hand side
$\subset$	is a proper subset of
$\subseteq$	is a subset of
$\in$	belongs to
$\forall$	for all
$\exists$	there exists
$\Rightarrow$	implies
$\Leftarrow$	is implied by
$\Leftrightarrow$	equivalence, if and only if
$\mathbb{R}$	the set of real numbers
$\mathbb{R}^+$	the set of positive real numbers
$\mathbb{R}^n$	space of n-dimensional vectors with real entries
$\mathbb{R}^{m\times n}$	space of matrices with real entries, m rows and n columns
$\mathbb{N}$	the set of nonnegative integers
$\mathbb{N}^+$	the set of positive integers
$\cap$	intersection
$\cup$	union
I	identity matrix
0	matrix with zero entries
A^T	the transpose of matrix A
A^{-1}	the inverse of matrix A
$\overline{\sigma}_A$	maximum eigenvalue of matrix A
$\underline{\sigma}_A$	minimum eigenvalue of matrix A
$\frac{\partial}{\partial x} f(\bar{x}, \bar{y})$	Jacobian matrix of function $f(x, y)$ with respect to x evaluated at $x = \bar{x}$ and $y = \bar{y}$
$\|v\|$	norm of vector v
$\|v\|_p$	p-norm of vector x
$v(k)$	vector signal at time k, for discreet time systems
$v(k+j\|k)$	predicted value of v at $k+i$ given known value at time k
$v(j)$	equivalent short form of $v(k+j\|k)$
$\hat{v}(k+j\|k)$	model of variable v
$\tilde{v}(k+j\|k)$	deviation variable for the model of v
v_{sp}	set-point/operating point of v
n_v	dimension of vector v
x	state vector
u	input vector

y	output vector (measurements)
y_m	measured value of y
u_I	vector of integral action vector
w	input disturbance vector
v	output disturbance vector
$*$	indicates symmetric structure
Q, R	weighting matrices
$J_1^{Np}(\tilde{x}(k\|k))$	cost function from 1 to N_p with the starting point $\tilde{x}(k\|k)$
$J_1^{Np*}(\cdot)$	optimal cost
$J_0^{\infty}(\cdot)$	cost function for infinite horizons
$J_0^{\infty*}(\cdot)$	optimal cost for infinite horizons
$N_p,\ N_c$	prediction and control horizon
$\mathcal{X},\ \mathcal{U},\ \mathcal{W}$	allowable sets for $x,\ u,\ w$
Ω	the set specifying the polytope of allowable models
Co	the convex hull spanned by all alowable models
$\lambda_i(k)$	the weight of model i at time k
$A_i(k)$	model matrix A for model i computed at time k
$F, F(c)$	feedback matrix
$\alpha_i(\cdot)$	$\mathscr{K}_\infty$-function
c_n	concentration of stream n mol/l
f_n	flow of stream n
$[X]$	concentration of of species X mol/l

CHAPTER 1

INTRODUCTION

1.1 Background

The main focus of the thesis lies in model predictive control (MPC) of nonlinear systems. MPC is the favored control technique when an advanced control scheme is implemented (Maciejowski (2002); Camacho and Bordons (2004); Bequette (2007)). This is highlighted by the application in as various fields as the metal ore industry (Jovanovic and Miljanovic (2015)), the food industry (Kondakci and Zhou (2017)) and the nuclear industry (Eliasi et al. (2012)). The traditional process industry is where it has had its major impact (Qin and Badgwell (2003)) with a growing number of applications since its first implementation in the 1970s. The first software introduced were the IDCOM, but earlier applications were done at Shell Oil utilizing their MPC tool referred to as dynamic matrix control (DMC). Though these techniques were not direct developments from the linear quadratic controllers developed in the 1960s, they have plenty in common. Recurring features include the utilization of a linear model to predict the behavior of the process and that the control performance is obtained based on the optimization of a quadratic objective. However, one of the strengths of MPC, the constraint handling, was not addressed stringently in the early approaches. The constraint handling was rather a part of the second generation setups and software; IDCOM-M, QDMC as well as newcomers with software such as HICON and setups like predictive functional control (PCF) to name a few. One of the major developments in the 1980s was the Shell multivariable optimizing controller (SMOC), which heralded the use of state-space models into MPC. The state-space model has more or less become the norm in research, while still not totally embraced by the industry (Qin and Badgwell (2003)). This is because most software-based model identification usually relies on response modeling, which will be the model applied the MPC as well. As could be expected the MPC performs best when the time is set aside to do fundamental modeling rather than relying solely on empirical modeling.

In the 1990s the application in industry, particularly in the process industry, continued growing, which can be seen in the quadrupling seen between the two surveys carried out in 1995 (Qin and Badgwell (1997)) and 2000 (Qin and Badgwell (2003)). This coincided with a wider interest from the academic world in the 1990s (Qin and Badgwell (2003)). The application and theory for applying MPC to linear or systems that could be considered linear enough to use a linear model was fairly well defined by the end of the 1990s. This included the setup required to achieve a guaranteed robust stability. However, already at this early stage of research, it was noted that those inclusions have increased the complexity of the MPC. This has led to an increasing demand for the process engineers as the service and maintenance has become more complex (Qin and Badgwell (2003)). Though, the development of nonlinear considerations as well as an extension into robust stability seemed a rapid development in 2003 (Qin and Badgwell (2003)). The actual implementation of nonlinear MPC has lagged behind with a widening gap between the research and the applications (Ogawa and Kano (2008); Mayne (2015); Forbes et al. (2015)). The major explanation for this is the additional effort needed to describe the nonlinear process while combining linear MPC or PID in conjunction with manual intervention can achieve the required control (Ogawa and Kano (2008)). There is hence a certain need to reduce the complexity of the different techniques for robust nonlinear MPC to enable a wider application in industry and the control improvement that could be achieved with it. The different problems faced in robust MPC, as well as in stochastic MPC, was reviewed by Mayne (2015) and is calling for simplified approaches for robust MPC amongst others.

1.2 Problem Statement

The current focus of the research in the field of nonlinear MPC is dealing with robustness as well as offset-free control (Mayne (2014); Goodwin et al. (2014)). Robustness is a matter of guaranteeing stability while the control system is affected by uncertainties, whereas offset-free control is a matter of removing the control error while the control system is affected by uncertainties. Though many approaches have been proposed there has been a very low level of application of it to the process industries (Mayne (2014)). The problems relating to the offset-control is the inclusion of an observer to estimate states and disturbances. The drawbacks of using an observer are;

- the additional tuning of the observer gain, particularly for robust behavior, (Tatjewski (2014), Pannocchia (2015), Goodwin et al. (2014)).
- the increase in computational load (Mohammadkhani et al. (2015)).
- the set-up may not give offset-free control, particularly when dealing with a nonlinear system (González et al. (2008), Tatjewski (2014)).

The increased complexity associated with the two first items is mirrored for robust approaches, as it also requires more extensive tuning and increased computational load. Another issue is that most approaches focus on a single uncertainty, though, there are some examples where parametric uncertainty, bounded disturbances, and unmeasured states are considered (Ding and Pan (2016)). Thus, there is a need to produce a controller that can:

- reduce the complexity, by making the tuning needs less demanding,
- speed up the computations, and increase the applicability of the setup, by producing a controller that can handle, set-point tracking, disturbances, modeling error, and unmeasured states.
- prove that the setup is guaranteed to be robust.

1.3 Research Objectives

The primary aim of this work is to develop techniques that will achieve an acceptable level of control of nonlinear systems while producing an offset-free controller that has lower complexity than the observer based approach. Following on from the problems statement the objectives of this study is:

1. to implement a multi-model predictive controller (MMPC) based on a Bayesian weighting approach for controlling the highly nonlinear pH process.
2. to develop an adaptive integral controller to combine with the MMPC (MMPC-I) to achieve offset-free control.
3. to develop the MMPC-I controller to improve handling of parametric uncertainty by combining a min-max approach with the adaptive integral action controller.
4. to develop a robust offset-free MPC and prove that the setup is robustly stable.

1.4 Scope of the Study

The focus of the study is to improve the model predictive controller to reduce the complexity of setup and application when robustness and offset-free control is desired.

Offset-free control relies on removing offset under uncertainty. The uncertainties considered in the study are; bounded disturbances, parametric uncertainty (modeling error), set-point tracking (where the control sequence is not known in advance) and an unmeasurable state (hence the exact condition for the model is not known). The primary criteria for these uncertainties are that it should be no remaining offset. However, for good control, there is also a desire to have a fast response, without having too much oscillations or large overshoot. The level of control is measured through the indicators; rise time, settling time and maximum relative overshoot. To get a qualitative comparison as well the proposed approaches are compared to the standard PID-controller as well as the observer based model predictive controller.

The robustness is studied based on mathematical analysis based on Lyapunov stability theory to prove that the system is robust under the bounded uncertainty conditions.

The proposed controllers were tested on a simulated pH-neutralization system. pH-control is one of the hardest control problems in process control and often use as a test bench for various controllers.

1.5 Outline and Contributions

The two focus points this thesis is to improve the applicability of the MPC setup by making the implementation of the MPC more straightforward and to produce a controller that can handle a multitude of uncertainties. The scene is set to explore the MPC implementation in Chapter 2, with the review of the literature as well as introduction of the system to implement and test the controllers on. The pH system was chosen due to severely nonlinear behavior creating an excellent problem to test a controller on.

Chapter 3 introduces the Bayesian weighting as a way of getting an adaptive MPC based on multiple models. The obtained Bayesian MMPC is then implemented on the pH system to demonstrate that the approach can handle severe non-linearities. Thus demonstrating that the Bayesian MMPC approach can be implemented on a pH control system.

In Chapter 4 the adaptive integral controller is introduced to be able to achieve offset-free control for the MMPC. Integral action is usually incorporated using an observer and an augmented model. The augmented model both works by including and approximating the disturbance. Observer tuning is generally considered a difficult task, while the adaptive integral control is creating an easily implemented way of achieving offset-free control of a nonlinear system. The level of ease is based on the consideration that linear MPC as well as I-controller are both widely used control approaches and can be implemented by most control engineers. The novel MMPC I-controller combination (MMPC-I) is also tested using the pH-system to show that it can create good disturbance rejection.

Further development is discussed in Chapter 5. The MMPC-I controller was able to handle the disturbances that it was targeted for but started having issues when modeling errors were present. The standard way of dealing with the so-called parametric uncertainty is to introduce a min-max approach based on linear matrix inequalities (LMI). The adaptive integral action is combined with a min-max approach to get a novel offset-free controller with strengthened capability of handling modeling errors. The min-max MMPC-I is further tested on the pH-control system.

A robust offset-free controller is presented in Chapter 6. The adaptive integral action controller is fully incorporated into the MPC and the resulting setup is proven to be input to state practically stable (ISpS). The novel approach is thus proven to be robustly stable for the cases of bounded disturbances, parametric uncertainties as long as the adaptive integral controller output is bounded. The controller is then tested on the pH-system to demonstrate that it can achieve offset-free control for tracking of set-points, bounded disturbances, parametric uncertainties and unmeasurable states.

Lastly, Chapter 7 summarizes the findings, limitations and presents suggestions for future work.

The relation between the different chapters are further highlighted in Figure 1.1. The models for control and simulation discussed in Chapter 2 is used in all following chapter. The MMPC developed in Chapter 3 is used in Chapter 4 as well but in combination with an I-controller. The I-controller is used again in Chapter 5, but the optimization is changed to min-max to increase handling of modeling errors. Chapter 6 proves a robust behavior while using the I-controller in MPC.

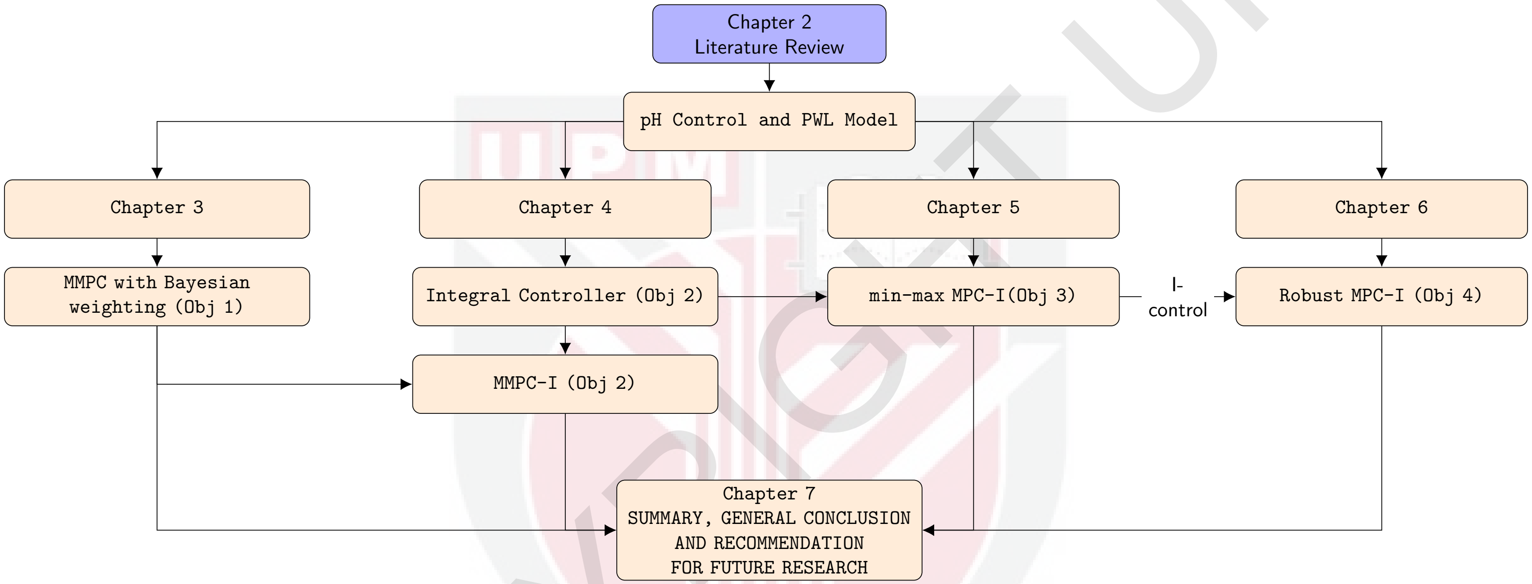

Figure 1.1: Flow chart for the thesis.

REFERENCES

Abonyi, J., Bodizs, A., Nagy, L. and Szeifert, F. 2000. Hybrid fuzzy convolution model and its application in predictive control. *Chemical Engineering Research and Design* 78 (4): 597–604.

Abonyi, J., Chován, T., Nagy, L. and Szeifert, F. 1999. Hybrid convolution model and its application in predictive pH control. *Computers & Chemical Engineering* 23: S227–S230.

Açıkmeşe, B., Carson, J. and Bayard, D. 2011. A robust model predictive control algorithm for incrementally conic uncertain/nonlinear systems. *International Journal of Robust and Nonlinear Control* 21 (5): 563–590.

Åkesson, B. and Toivonen, H. 2006. A neural network model predictive controller. *Journal of Process Control* 16 (9): 937 – 946.

Åkesson, B., Toivonen, H., Waller, J. and Nyström, R. 2005. Neural network approximation of a nonlinear model predictive controller applied to a pH neutralization process. *Computers & Chemical Engineering* 29 (2): 323–335.

Åkesson, J. and Hagander, P. 2003. Integral actiona disturbance observer approach. In *European Control Conference (ECC), 2003*, 2577–2582. IEEE.

Alamo, T., Muñoz de la Peña, D., Limon, D. and Camacho, E. 2005. Constrained min-max predictive control: modifications of the objective function leading to polynomial complexity. *IEEE Transactions on Automatic Control* 50 (5): 710–714.

Altınten, A. 2007. Generalized predictive control applied to a pH neutralization process. *Computers & Chemical Engineering* 31 (10): 1199–1204.

Angeli, D., Casavola, A., Franzè, G. and Mosca, E. 2008. An ellipsoidal off-line MPC scheme for uncertain polytopic discrete-time systems. *Automatica* 44 (12): 3113–3119.

Arefi, M., Montazeri, A., Poshtan, J. and Jahed-Motlagh, M. 2006. Nonlinear model predictive control of chemical processes with a Wiener identification approach. In *Industrial Technology, 2006. ICIT 2006. IEEE International Conference on*, 1735–1740. IEEE.

Aufderheide, B. and Bequette, B. 2003. Extension of dynamic matric control to multiple models. *Computer and Chemical Engineering* 27: 1079–1096.

Azimzadeh, F., Palizban, H. and Romagnoli, J. 1998. Online optimal control of a batch fermentation process using multiple model approach. In *Decision and Control, 1998. Proceedings of the 37th IEEE Conference on*, 455–460. IEEE.

Bagheri, P., Mardanlou, V. and Fatehi, A. 2011. Multiple Model Predictive Control of Multivariable pH Process Using Adaptive Weighting Matrices. In *The 18th IFAC World Congress*, 12366–12371.

Bello, O., Hamam, Y. and Djouani, K. 2014a. Coagulation process control in water treatment plants using multiple model predictive control. *Alexandria Engineering Journal* 53 (4): 939–948.

Bello, O., Hamam, Y. and Djouani, K. 2014b. Control of a coagulation chemical dosing unit for water treatment plants using MMPC based on fuzzy weighting. *Journal of Water Process Engineering* 4: 34–46.

Bello, O., Hamam, Y. and Djouani, K. 2014c. Fuzzy dynamic modelling and predictive control of a coagulation chemical dosing unit for water treatment plants. *Journal of Electrical Systems and Information Technology* 1 (2): 129–143.

Bequette, B. W. 2007. Non-Linear Model Predictive Control: A Personal Retrospective. *The Canadian Journal of Chemical Engineering* 85: 408–415.

Betti, G., Farina, M. and Scattolini, R. 2012. An MPC algorithm for offset-free tracking of constant reference signals. In *2012 IEEE 51st IEEE Conference on Decision and Control (CDC)*, 5182–5187.

Betti, G., Farina, M. and Scattolini, R. 2013. A robust MPC algorithm for offset-free tracking of constant reference signals. *Automatic Control, IEEE Transactions on* 58 (9): 2394–2400.

Borrelli, F., Bemporad, A. and Morari, M. 2017. *Predictive Control for Linear and Hybrid Systems*. Cambridge University Press.

Boyd, S., El Ghaoui, L., Feron, E. and Balakrishnan, V. 1994. *Linear matrix inequalities in system and control theory*. SIAM.

Brooms, A., Kouvaritakis, B. and Lee, Y. 2001. Constrained MPC for uncertain linear systems with ellipsoidal target sets. *Systems & Control Letters* 44 (3): 157 – 166.

Bumroongsri, P. and Kheawhom, S. 2012. An off-line robust MPC algorithm for uncertain polytopic discrete-time systems using polyhedral invariant sets. *Journal of Process Control* 22 (6): 975–983.

Cai, H., Li, P., Su, C. and Cao, J. 2018. Double-layered nonlinear model predictive control based on HammersteinWiener model with disturbance rejection. *Measurement and Control* 51 (7-8): 260–275.

Camacho, E. and Bordons, C. 2004. *Model Predictive Control*. 2nd edn. Springer, Berlin.

Cannon, M., Buerger, J., Kouvaritakis, B. and Raković, S. 2011. Robust tubes in nonlinear model predictive control. *Automatic Control, IEEE Transactions on* 56 (8): 1942–1947.

Cannon, M., Cheng, Q., Kouvaritakis, B. and Raković, S. 2012. Stochastic tube MPC with state estimation. *Automatica* 48 (3): 536–541.

Cao, Y. and Lin, Z. 2005. Min–max MPC algorithm for LPV systems subject to input saturation. *IEE Proceedings-Control Theory and Applications* 152 (3): 266–272.

Carson, J., Açıkmeşe, B., Murray, R. and MacMartin, D. 2013. A robust model predictive control algorithm augmented with a reactive safety mode. *Automatica* 49 (5): 1251 – 1260.

Casavola, A., Famularo, D. and Franze, G. 2005. Norm-bounded robust MPC strategies for constrained control of nonlinear systems. *IEE Proceedings - Control Theory and Applications* 152 (3): 285–295.

Casavola, A., Mosca, E. and Angeli, D. 2000. Robust command governors for constrained linear systems. *IEEE Transactions on Automatic Control* 45 (11): 2071–2077.

Cervantes, A., Agamennoni, O. and Figueroa, J. 2003. A nonlinear model predictive control system based on Wiener piecewise linear models. *Journal of Process Control* 13 (7): 655 – 666. Selected Papers from the sixth {IFAC} Symposium on Bridging Engineering with Science - {DYCOPS} - 6.

Chen, Q., He, D. and Yu, L. 2012. Input-to-state stability of min-max MPC scheme for nonlinear time-varying delay systems. *Asian Journal of Control* 14 (2): 489–501.

Chi, Q., Fei, Z., Liu, K. and Liang, J. 2015. Latent-variable Nonlinear Model Predictive Control Strategy for a pH Neutralization Process. *Asian Journal of Control* .

Chien, I.-L. and Fruehauf, P. 1990. Consider IMC tuning to improve controller performance. *Chem. Eng. Prog.* 86: 33–41.

Chisci, L., Rossiter, J. and Zappa, G. 2001. Systems with persistent disturbances: predictive control with restricted constraints. *Automatica* 37 (7): 1019–1028.

Chung, C.-C., Chen, H.-H. and Ting, C.-H. 2010. Grey prediction fuzzy control for pH processes in the food industry. *Journal of food engineering* 96 (4): 575–582.

Copp, D. and Hespanha, J. 2014a. Nonlinear Output-Feedback Model Predictive Control with Moving Horizon Estimation. In *Proc. of the 53nd Conf. on Decision and Contr.*.

Copp, D. and Hespanha, J. 2014b, Nonlinear Output-Feedback Model Predictive Control with Moving Horizon Estimation, Tech. rep., University of California, Santa Barbara, Santa Barbara.

Copp, D. and Hespanha, J. 2017. Simultaneous nonlinear model predictive control and state estimation. *Automatica* 77: 143–154.

Costa, T., Fileti, A., Oliveira-Lopes, L. and Silva, F. 2014. Experimental assessment and design of multiple model predictive control based on local model networks for industrial processes. *Evolving Systems* 1–11.

Couper, J., Penney, W. and Fair, J. 2009. *Chemical Process Equipment revised 2E: Selection and Design*. 2nd edn. Gulf Professional Publishing.

Cutler, C. and Ramaker, B. 1980. Dynamic matrix control-a computer control algorithm. In *Proceedings of the joint automatic control conference*, Wp5–B. American Automatic Control Council Piscataway, NJ.

Cuzzola, F., Geromel, J. and Morari, M. 2002. An improved approach for constrained robust model predictive control. *Automatica* 38 (7): 1183–1189.

Das, B. and Mhaskar, P. 2015. Lyapunov-based offset-free model predictive control of nonlinear process systems. *The Canadian Journal of Chemical Engineering* 93 (3): 471–478.

Das, B. and Mhaskar, P. 2018. Adaptive output-feedback Lyapunov-based model predictive control of nonlinear process systems. *International Journal of Robust and Nonlinear Control* 28 (5): 1597–1609.

Del Re, L., Allgöwer, F., Glielmo, L., Guardiola, C. and Kolmanovsky, I. 2010. Automotive model predictive control. *Lecture Notes in Control and Information Science* .

Díaz-Mendoza, R. and Budman, H. 2010. Structured Singular Valued based robust nonlinear model predictive controller using Volterra series models. *Journal of Process Control* 20 (5): 653–663.

Ding, B. 2010. *Modern predictive control*. CRC press Boca Raton, USA.

Ding, B., Huang, B. and Xu, F. 2011. Dynamic output feedback robust model predictive control. *International Journal of Systems Science* 42 (10): 1669–1682.

Ding, B. and Pan, H. 2016. Output Feedback Robust MPC for LPV System with Polytopic Model Parametric Uncertainty and Bounded Disturbance. *International Journal of Control* 89 (8): 1554–1571.

Ding, B., Xi, Y., Cychowski, M. and OMahony, T. 2007. Improving off-line approach to robust MPC based-on nominal performance cost. *Automatica* 43 (1): 158–163.

Ding, B., Xi, Y., Cychowski, M. and OMahony, T. 2008. A synthesis approach for output feedback robust constrained model predictive control. *Automatica* 44 (1): 258–264.

Ding, B., Xi, Y. and Li, S. 2004. A synthesis approach of on-line constrained robust model predictive control. *Automatica* 40 (1): 163–167.

Dougherty, D. and Cooper, D. 2003. A practical multiple model adaptive strategy for single-loop MPC. *Control Engineering Practice* 11 (2): 141–159.

Doyle III, F., Ogunnaike, B. and Pearson, R. 1995. Nonlinear model-based control using second-order Volterra models. *Automatica* 31 (5): 697 – 714.

Draeger, A., Engell, S. and Ranke, H. 1995. Model predictive control using neural networks. *Control Systems, IEEE* 15 (5): 61–66.

Dubravić, A., Šehić, Z. and Burgić, M. 2014. Orthonormal functions based model predictive control of pH neutralization process. *Tehnički vjesnik* 21 (6): 1249–1253.

Eliasi, H., Menhaj, M. and Davilu, H. 2012. Robust nonlinear model predictive control for a PWR nuclear power plant. *Progress in Nuclear Energy* 54 (1): 177 – 185.

Ellis, M., Liu, J. and Christofides, P. 2015. *Economic Model Predictive Control*. Springer.

Ellis, M., Zhang, J., Liu, J. and Christofides, P. 2014. Robust moving horizon estimation based output feedback economic model predictive control. *Systems & Control Letters* 68: 101–109.

Errouissi, R., Yang, J., Chen, W. and Al-Durra, A. 2016. Robust nonlinear generalised predictive control for a class of uncertain nonlinear systems via an integral sliding mode approach. *International Journal of Control* 1–13.

Falugi, P. and Mayne, D. 2014. Getting robustness against unstructured uncertainty: a tube-based MPC approach. *IEEE Transactions on Automatic Control* 5 (59): 1290–1295.

Falugi, P., Olaru, S. and Dumur, D. 2010. Multi-model predictive control based on LMI: from the adaptation of the state-space model to the analytic description of the control law. *International Journal of control* 83 (8): 1548–1563.

Fatehi, A., Sadeghpour, B. and Labibi, B. 2013. Nonlinear System Identification in Frequent and Infrequent Operating Points for Nonlinear Model Predictive Control. *Information Technology And Control* 42 (1): 67–76.

Ferramosca, A., González, A. and Limon, D. 2017. Offset-free multi-model economic model predictive control for changing economic criterion. *Journal of Process Control* 54: 1–13.

Findeisen, R., Allgöwer, F. and Biegler, L. 2007. *Assessment and future directions of nonlinear model predictive control*. , vol. 358. Springer.

Fjeld, M., Asbjørnsen, O. and Åström, K. 1974. Reaction invariants and their importance in the analysis of eigenvectors, state observability and controllability of the continuous stirred tank reactor. *Chemical Engineering Science* 29 (9): 1917–1926.

Forbes, M., Patwardhan, R., Hamadah, H. and Gopaluni, R. 2015. Model Predictive Control in Industry: Challenges and Opportunities. *IFAC-PapersOnLine* 48 (8): 531 – 538. 9th IFAC Symposium on Advanced Control of Chemical Processes ADCHEM 2015.

Fruzzetti, K., Palazoğlu, A. and McDonald, K. 1997. Nolinear model predictive control using Hammerstein models. *Journal of process control* 7 (1): 31–41.

Garcia, C. 1984, Quadratic Dynamic Matrix Control of Nonlinear Processes, Presented at the AIChe, Annual Meeting, San Fransisco, Ca.

Garcia, C. and Morari, M. 1982. Internal model control. A unifying review and some new results. *Industrial & Engineering Chemistry Process Design and Development* 21 (2): 308–323.

Gautam, A., Chu, Y. C. and Soh, Y. C. 2012. Optimized Dynamic Policy for Receding Horizon Control of Linear Time-Varying Systems With Bounded Disturbances. *IEEE Transactions on Automatic Control* 57 (4): 973–988.

Gerkšič, S., Juricic, D., Strmcnik, S. and Matko, D. 2000. Wiener model based nonlinear predictive control. *International Journal of Systems Science* 31 (2): 189–202.

Ghaffari, V., Naghavi Vahid, S. and Safavi, A. 2013. Robust model predictive control of a class of uncertain nonlinear systems with application to typical CSTR problems. *Journal of Process Control* 23 (4): 493–499.

Gomm, J., Doherty, S. and Williams, D. 1996. Control of pH in-line using a neural predictive strategy. In *UKACC International Conference on CONTROL '96*, 1058–1063. IET.

González, A., Adam, E. and Marchetti, J. 2008. Conditions for offset elimination in state space receding horizon controllers: A tutorial analysis. *Chemical Engineering and Processing: Process Intensification* 47 (12): 2184–2194.

Goodwin, G., Kong, H., Mirzaeva, G. and Seron, M. 2014. Robust model predictive control: reflections and opportunities. *Journal of Control and Decision* 1 (2): 115–148.

Grancharova, A. and Johansen, T. 2009. Computation, approximation and stability of explicit feedback minmax nonlinear model predictive control. *Automatica* 45 (5): 1134 – 1143.

Grancharova, A. and Johansen, T. 2012. *Explicit nonlinear model predictive control: Theory and applications*. , vol. 429. Springer Science & Business Media.

Grüne, L. and Pannek, J. 2011, In Nonlinear Model Predictive Control, In *Nonlinear Model Predictive Control*, 43–66, Springer, 43–66.

Guay, M., Adetola, V. and DeHaan, D. 2015. *Robust and Adaptive Model Predictive Control of Nonlinear Systems*. Institution of Engineering and Technology.

Gustafsson, T., Skrifvars, B., Sandström, K. and Waller, K. 1995. Modeling of pH for control. *Industrial Engineering Chemistry Research* 34: 820–827.

Gustafsson, T. and Waller, K. 1983. Dynamic modeling and reaction invariant control of pH. *Chemical Engineering Science* 38 (3): 389–398.

Guzey, D. and McClements, D. 2006. Formation, stability and properties of multilayer emulsions for application in the food industry. *Advances in Colloid and Interface Science* 128: 227–248.

Haber, R., Bars, R. and Schmitz, U. 2012. *Predictive control in process engineering: From the basics to the applications*. John Wiley & Sons.

Halldorsson, U., Ali, A., Unbehauen, H. and Schmid, C. 2002. Adaptive predictive control of a neutralization plant using local model networks. In *Proceedings of the IFAC World Congress, Barcelona*.

He, D., Huang, H. and Chen, Q. 2014. Quasi-min–max MPC for constrained nonlinear systems with guaranteed input-to-state stability. *Journal of the Franklin Institute* 351 (6): 3405–3423.

Hong, T., Morris, A., Karim, M., Zhang, J. and Luo, W. 1996. Nonlinear control of a wastewater pH neutralisation process using adaptive NARX models. In *Systems, Man, and Cybernetics, 1996., IEEE International Conference on*, 911–916. IEEE.

Huang, R., Biegler, L. and Patwardhan, S. 2010. Fast offset-free nonlinear model predictive control based on moving horizon estimation. *Industrial & Engineering Chemistry Research* 49 (17): 7882–7890.

Huang, R., Patwardhan, S. C. and Biegler, L. 2013. Robust stability of nonlinear model predictive control with extended Kalman filter and target setting. *International Journal of Robust and Nonlinear Control* 23 (11): 1240–1264.

Huang, S. and Lee, T. H. 2013. *Applied predictive control*. Springer Science & Business Media.

Imsland, L., Findeisen, R., Bullinger, E., Allgöwer, F. and Foss, B. 2003. A note on stability, robustness and performance of output feedback nonlinear model predictive control. *Journal of Process Control* 13 (7): 633–644.

Ipanaqué, W. and Manrique, J. 2011. Identification and Control of pH using Optimal Piecewise Linear Wiener Model. In *World Congress*, 12301–12306.

Jiang, Z. and Wang, Y. 2001. Input-to-state stability for discrete-time nonlinear systems. *Automatica* 37 (6): 857–869.

Johansen, T. and Foss, B. 1992. Nonlinear local model representation for adaptive systems. In *Intelligent Control and Instrumentation, 1992. SICICI'92. Proceedings., Singapore International Conference on*, 677–682. IEEE.

Jovanovic, I. and Miljanovic, I. 2015. Contemporary advanced control techniques for flotation plants with mechanical flotation cells: A review. *Minerals Engineering* 70 (Supplement C): 228 – 249.

Jungers, M., Oliveira, R. and Peres, P. 2011. MPC for LPV systems with bounded parameter variations. *International Journal of Control* 84 (1): 24–36.

Jutila, P., Orava, P. and Salmelin, B. 1981. A physico-chemical model and simulation of pH-process in continuous stirred tank reactors. *Mathematics and Computers in Simulation* 23 (2): 99–106.

Kavsek-Biasizzo, K., Skrjanc, I. and Matko, D. 1997. Fuzzy predictive control of highly nonlinear pH process. *Computers & Chemical Engineering* 21: S613–S618.

Kelkar, B. and Postlethwaite, B. 1994. Fuzzy-model based pH control. In *Fuzzy Systems, 1994. IEEE World Congress on Computational Intelligence., Proceedings of the Third IEEE Conference on*, 661–666. IEEE.

Kerrigan, E. and Maciejowski, J. 2004. Feedback min-max model predictive control using a single linear program: robust stability and the explicit solution. *International Journal of Robust and Nonlinear Control* 14 (4): 395–413.

Khani, F. and Haeri, M. 2015. Robust model predictive control of nonlinear processes represented by Wiener or Hammerstein models. *Chemical Engineering Science* 129: 223–231.

Kittisupakorn, P., Thitiyasook, P., Hussain, M. and Daosud, W. 2009. Neural network based model predictive control for a steel pickling process. *Journal of Process Control* 19 (4): 579 – 590.

Kondakci, T. and Zhou, W. 2017. Recent Applications of Advanced Control Techniques in Food Industry. *Food and Bioprocess Technology* 10 (3): 522–542.

Kothare, M., Balakrishnan, V. and Morari, M. 1996. Robust constrained model predictive control using linear matrix inequalities. *Automatica* 32 (10): 1361–1379.

Kouvaritakis, B. and Cannon, M. 2001. *Non-linear Predictive Control: theory and practice*. IET.

Kouvaritakis, B. and Cannon, M. 2015. *Model predictive control: Classical, robust and stochastic*. Springer.

Kouvaritakis, B., Rossiter, J. and Schuurmans, J. 2000. Efficient robust predictive control. *Automatic Control, IEEE Transactions on* 45 (8): 1545–1549.

Kumar, D. and Budman, H. 2014. Robust nonlinear MPC based on Volterra series and polynomial chaos expansions. *Journal of Process Control* 24 (1): 304–317.

Kuo, L. and Melsheimer, S. 1998. Wastewater neutralisation control using a neural network based model predictive controller. In *American Control Conference, 1998. Proceedings of the 1998*, 3896–3899. IEEE.

Kvasnica, M. 2009. *Real-time model predictive control via multi-parametric programming: theory and tools*. VDM-Verlag.

Kwon, W. and Han, S. 2006. *Receding horizon control: model predictive control for state models*. Springer Science & Business Media.

Lahiri, S. 2017. *Multivariable Predictive Control: Applications in Industry*. John Wiley & Sons.

Langson, W., Chryssochoos, I., Raković, S. and Mayne, D. 2004. Robust model predictive control using tubes. *Automatica* 40 (1): 125–133.

Ławryńczuk, M. 2010. Suboptimal nonlinear predictive control based on multivariable neural Hammerstein models. *Applied Intelligence* 32 (2): 173–192.

Ławryńczuk, M. 2011. On-line set-point optimisation and predictive control using neural Hammerstein models. *Chemical Engineering Journal* 166 (1): 269–287.

Ławryńczuk, M. 2013a. *Computationally Efficient Model Predictive Control Algorithms*. Springer.

Ławryńczuk, M. 2013b. Practical nonlinear predictive control algorithms for neural Wiener models. *Journal of Process Control* 23 (5): 696–714.

Lazar, M., Muñoz De La Peña, D., Heemels, W. and Alamo, T. 2008. On input-to-state stability of min–max nonlinear model predictive control. *Systems & Control Letters* 57 (1): 39–48.

Lee, Y. and Kouvaritakis, B. 2000. Robust receding horizon predictive control for systems with uncertain dynamics and input saturation. *Automatica* 36 (10): 1497 – 1504.

Li, D. and Xi, Y. 2010. The Feedback Robust MPC for LPV Systems With Bounded Rates of Parameter Changes. *IEEE Transactions on Automatic Control* 55 (2): 503–507.

Li, S., Liu, X. and Yuan, G. 2014. Application of Supervisory Predictive Control Based on TS Model in pH Neutralization Process. In *Applied Mechanics and Materials*, 867–870. Trans Tech Publ.

Li, S. and Zheng, Y. 2016. *Distributed Model Predictive Control for Plant-wide Systems*. John Wiley & Sons.

Lightbody, G. and Irwin, G. W. 1997. Nonlinear control structures based on embedded neural system models. *IEEE Transactions on Neural Networks* 8 (3): 553–567.

Limon, D., Alamo, T., Salas, F. and Camacho, E. 2006. On the stability of constrained MPC without terminal constraint. *IEEE transactions on automatic control* 51 (5): 832.

Limon, D., Alvarado, I., Alamo, T. and Camacho, E. 2008. MPC for tracking piecewise constant references for constrained linear systems. *Automatica* 44 (9): 2382 – 2387.

Limon, D., Alvarado, I., Alamo, T. and Camacho, E. 2010. Robust tube-based MPC for tracking of constrained linear systems with additive disturbances. *Journal of Process Control* 20 (3): 248 – 260.

Limon, D.and Pereira, M., Muñoz de la Peña, D., Alamo, T., Jones, C. N. and Zeilinger, M. N. 2016. MPC for Tracking Periodic References. *IEEE Transactions on Automatic Control* 61 (4): 1123–1128.

Liu, J. 2013. Moving horizon state estimation for nonlinear systems with bounded uncertainties. *Chemical Engineering Science* 93: 376–386.

Löfberg, J. 2004. YALMIP: A toolbox for modeling and optimization in MATLAB. In *Computer Aided Control Systems Design, 2004 IEEE International Symposium on*, 284–289. IEEE.

Løvaas, C., Seron, M. and Goodwin, G. 2008. Robust output-feedback model predictive control for systems with unstructured uncertainty. *Automatica* 44 (8): 1933–1943.

Løvaas, C., Seron, M. and Goodwin, G. 2010. Robust output-feedback MPC with integral action. *Automatic Control, IEEE Transactions on* 55 (7): 1531–1543.

Love, J. 2007. *Process Automation Handbook: A Guide to Theory and Practice*. 1st edn. Springer Publishing Company, Incorporated.

Lu, Y. and Arkun, Y. 2000a. A quasi-min-max MPC algorithm for linear parameter varying systems with bounded rate of change of parameters. In *American Control Conference, 2000. Proceedings of the 2000*, 3234–3238. IEEE.

Lu, Y. and Arkun, Y. 2000b. Quasi-min-max MPC algorithms for LPV systems. *Automatica* 36 (4): 527–540.

Luedeking, R. and Piret, E. 1959. A kinetic study of the lactic acid fermentation. Batch process at controlled pH. *Biotechnology and Bioengineering* 1 (4): 393–412.

Maciejowski, J. 2002. *Predictive control with constraints*. Prentice Hall, Englewood Cliffs, NJ.

Maeder, U., Borrelli, F. and Morari, M. 2009. Linear offset-free model predictive control. *Automatica* 45 (10): 2214–2222.

Maeder, U. and Morari, M. 2010. Offset-free reference tracking with model predictive control. *Automatica* 46 (9): 1469 – 1476.

Maestre, J. and Negenborn, R. 2013. *Distributed model predictive control made easy*. , vol. 69. Springer Science & Business Media.

Magni, L., De Nicolao, G., Scattolini, R. and Allgöwer, F. 2003. Robust model predictive control for nonlinear discrete-time systems. *International Journal of Robust and Nonlinear Control* 13 (3-4): 229–246.

Magni, L., Raimondo, D. and Allgöwer, F. 2009. *Nonlinear model predictive control*. Springer.

Magni, L., Raimondo, D. and Scattolini, R. 2006. Regional input-to-state stability for nonlinear model predictive control. *IEEE Transactions on automatic control* 51 (9): 1548–1553.

Magni, L. and Scattolini, R. 2007. *Robustness and Robust Design of MPC for Nonlinear Discrete-Time Systems*, 239–254. Berlin, Heidelberg: Springer Berlin Heidelberg.

Mahmoodi, S., Poshtan, J., Jahed-Motlagh, M. and Montazeri, A. 2009. Nonlinear model predictive control of a pH neutralization process based on Wiener–Laguerre model. *Chemical Engineering Journal* 146 (3): 328–337.

Maner, B., Doyle III, F., Ogunnaike, B. and Pearson, R. 1996. Nonlinear model predictive control of a simulated multivariable polymerization reactor using second-order Volterra models. *Automatica* 32 (9): 1285 – 1301.

Mao, W.-J. 2003. Robust stabilization of uncertain time-varying discrete systems and comments on an improved approach for constrained robust model predictive control. *Automatica* 39 (6): 1109–1112.

Marruedo, D., Alamo, T. and Camacho, E. 2002. Input-to-state stable MPC for constrained discrete-time nonlinear systems with bounded additive uncertainties. In *Decision and Control, 2002, Proceedings of the 41st IEEE Conference on*, 4619–4624. IEEE.

Mayne, D. 2001. Control of Constrained Dynamic Systems. *European Journal of Control* 7 (2): 87 – 99.

Mayne, D. 2014. Model predictive control: Recent developments and future promise. *Automatica* 50 (12): 2967–2986.

Mayne, D. 2015. Robust and Stochastic MPC: Are We Going In The Right Direction? *IFAC-PapersOnLine* 48 (23): 1 – 8. 5th IFAC Conference on Nonlinear Model Predictive Control NMPC 2015.

Mayne, D., Kerrigan, E., Van Wyk, E. and Falugi, P. 2011. Tube-based robust nonlinear model predictive control. *International Journal of Robust and Nonlinear Control* 21 (11): 1341–1353.

Mayne, D. and Langson, W. 2001. Robustifying model predictive control of constrained linear systems. *Electronics Letters* 37 (23): 1422–1423.

Mayne, D., Raković, S., Findeisen, R. and Allgöwer, F. 2006. Robust output feedback model predictive control of constrained linear systems. *Automatica* 42 (7): 1217 – 1222.

Mayne, D., Raković, S., Findeisen, R. and Allgöwer, F. 2009. Robust output feedback model predictive control of constrained linear systems: Time varying case. *Automatica* 45 (9): 2082–2087.

Mayne, D., Seron, M. and Raković, S. 2005. Robust model predictive control of constrained linear systems with bounded disturbances. *Automatica* 41 (2): 219 – 224.

McAvoy, T., Hsu, E. and Lowenthal, S. 1972. Dynamics of pH in controlled stirred tank reactor. *Industrial & Engineering Chemistry Process Design and Development* 11 (1): 68–70.

McAvoy, T. J. 1972. Dynamic Models for pH and Other Fast Equilibrium Systems. *Industrial & Engineering Chemistry Process Design and Development* 11 (4): 630–631.

McMillan, G. 2000. *Good Tuning: A Pocket Guide*. ISA.

McMillan, G. and Cameron, R. 2005. *Advanced pH measurement and control*. ISA.

Mirzaei, M., Poulsen, N. and Niemann, H. 2012. Robust Model Predictive Control of a Nonlinear System with Known Scheduling Variable and Uncertain Gain. *IFAC Proceedings Volumes* 45 (13): 616 – 621. 7th IFAC Symposium on Robust Control Design.

Mohammadkhani, M., Bayat, F. and Jalali, A. 2015. Two-stage observer based offset-free MPC. *ISA Transactions* 57: 136 – 143.

Mohammadkhani, M., Bayat, F. and Jalali, A. 2017. Robust output feedback model predictive control: A stochastic approach. *Asian Journal of Control* 19 (6): 2085–2096.

Mollov, S., Babuska, R., Abonyi, J. and Verbruggen, H. 2004. Effective optimization for fuzzy model predictive control. *Fuzzy Systems, IEEE Transactions on* 12 (5): 661–675.

Morari, M. and Lee, J. 1999. Model Predictive Control: Past, Present and Future. *Computers & Chemical Engineering* 23: 667–682.

Morari, M. and Maeder, U. 2012. Nonlinear offset-free model predictive control. *Automatica* 48 (9): 2059–2067.

Muñoz-Carpintero, D., Cannon, M. and Kouvaritakis, B. 2013. Recursively feasible Robust MPC for linear systems with additive and multiplicative uncertainty using optimized polytopic dynamics. In *52nd IEEE Conference on Decision and Control*, 1101–1106.

Muñoz-Carpintero, D., Cannon, M. and Kouvaritakis, B. 2015. Robust MPC strategy with optimized polytopic dynamics for linear systems with additive and multiplicative uncertainty. *Systems & Control Letters* 81: 34 – 41.

Muñoz-Carpintero, D., Kouvaritakis, B. and Cannon, M. 2016. Striped parameterized tube model predictive control. *Automatica* 67: 303–309.

Muske, K. and Badgwell, T. 2002. Disturbance modeling for offset-free linear model predictive control. *Journal of Process Control* 12 (5): 617–632.

Muske, K. and Rawlings, J. 1993. Linear model predictive control of unstable processes. *Journal of Process Control* 3 (2): 85–96.

Mutha, R., Cluett, W. and Penlidis, A. 1997. Nonlinear model-based predictive control of control nonaffine systems. *Automatica* 33 (5): 907 – 913.

Norquay, S., Palazoglu, A. and Romagnoli, J. 1998. Model predictive control based on Wiener models. *Chemical Engineering Science* 53 (1): 75–84.

Norquay, S., Palazoglu, A. and Romagnoli, J. 1999. Application of Wiener model predictive control (WMPC) to a pH neutralization experiment. *Control Systems Technology, IEEE Transactions on* 7 (4): 437–445.

Novák, J. and Chalupa, P. 2013, In Nostradamus 2013: Prediction, Modeling and Analysis of Complex Systems, In *Nostradamus 2013: Prediction, Modeling and Analysis of Complex Systems*, 285–294, Springer, 285–294.

Novák, J., Chalupa, P. and Bobál, V. 2011. Multiple model modeling and predictive control of the pH neutralization process. *International Journal of Mathematical Models and Methods in Applied Sciences* 5 (7): 1170–1179.

Nyström, R., Sandström, K., Gustafsson, T. and Toivonen, H. 1998. Multimodel robust control applied to a pH neutralization process. *Computers & chemical engineering* 22: S467–S474.

Nyström, R., Sandström, K., Gustafsson, T. and Toivonen, H. 1999. Multimodel robust control of nonlinear plants: a case study. *Journal of Process Control* 9: 135–150.

Oblak, S. and Škrjanc, I. 2010. Continuous-time Wiener-model predictive control of a pH process based on a PWL approximation. *Chemical Engineering Science* 65 (5): 1720–1728.

Obut, S. and Özgen, C. 2008. Online identification and control of pH in a neutralization system. *Industrial & Engineering Chemistry Research* 47 (13): 4394–4404.

Ogawa, M. and Kano, M. 2008. Practice and Challenges in Chemical Process Control Applications in Japan. *IFAC Proceedings Volumes* 41 (2): 10608 – 10613. 17th IFAC World Congress.

Ojaghi, P., Bigdeli, N. and Rahmani, M. 2016. An LMI approach to robust model predictive control of nonlinear systems with state-dependent uncertainties. *Journal of Process Control* 47: 1 – 10.

Özkan, L., Kothare, M. and Georgakis, C. 2000. Model predictive control of nonlinear systems using piecewise linear models. *Computers & Chemical Engineering* 24 (2): 793–799.

Pannocchia, G. 2002. Robust Offset-Free Model Predictive Control. *IFAC Proceedings Volumes* 35 (1): 297 – 302. 15th IFAC World Congress.

Pannocchia, G. 2015. Offset-free tracking MPC: A tutorial review and comparison of different formulations. In *2015 European Control Conference (ECC)*, 527–532.

Pannocchia, G. 2018. An economic MPC formulation with offset-free asymptotic performance. *IFAC-PapersOnLine* 51 (18): 393 – 398. 10th IFAC Symposium on Advanced Control of Chemical Processes ADCHEM 2018.

Pannocchia, G. and Bemporad, A. 2007. Combined design of disturbance model and observer for offset-free model predictive control. *Automatic Control, IEEE Transactions on* 52 (6): 1048–1053.

Pannocchia, G., Gabiccini, M. and A., A. 2015. Offset-free MPC explained: novelties, subtleties, and applications. *IFAC-PapersOnLine* 48 (23): 342 – 351. 5th {IFAC} Conference on Nonlinear Model Predictive Control {NMPC} 2015Seville, Spain, 1720 September 2015.

Pannocchia, G. and Rawlings, J. 2003. Disturbance models for offset-free model-predictive control. *AIChE journal* 49 (2): 426–437.

Patwardhan, R., Lakshminarayanan, S. and Shah, S. 1997, Nonlinear Model Predictive Control using PLS based Hammerstein and Wiener Models, Presented at the AIChe, Meeting, Los Angeles, Ca.

Patwardhan, R., Lakshminarayanan, S. and Shah, S. 1998. Constrained nonlinear MPC using Hammerstein and Wiener models: PLS framework. *AIChE Journal* 44 (7): 1611–1622.

Pawlowski, A., Fernández, I., Guzmán, J., Berenguel, M., Acién, F. and Normey-Rico, J. 2014a. Event-based predictive control of pH in tubular photobioreactors. *Computers & Chemical Engineering* 65: 28–39.

Pawlowski, A., Mendoza, J., Guzmán, J., Berenguel, M., Acién, F. and Dormido, S. 2014b. Effective utilization of flue gases in raceway reactor with event-based pH control for microalgae culture. *Bioresource Technology* 170: 1–9.

Pin, G., Raimondo, D., Magni, L. and Parisini, T. 2009. Robust model predictive control of nonlinear systems with bounded and state-dependent uncertainties. *Automatic Control, IEEE Transactions on* 54 (7): 1681–1687.

Ping, X. and Ding, B. 2013. Off-line approach to dynamic output feedback robust model predictive control. *Systems & Control Letters* 62 (11): 1038–1048.

Pluymers, B., Suykens, J. and De Moor, B. 2005. Min–max feedback MPC using a time-varying terminal constraint set and comments on Efficient robust constrained model predictive control with a time-varying terminal constraint set. *Systems & control letters* 54 (12): 1143–1148.

Poursafar, N., Taghirad, H. and Haeri, M. 2010. Model predictive control of non-linear discrete time systems: a linear matrix inequality approach. *Control Theory & Applications, IET* 4 (10): 1922–1932.

Pröll, T. and Nazmul Karim, M. 1994. Model-predictive pH control using real-time NARX approach. *AIChE Journal* 40 (2): 269–282.

Qin, S. and Badgwell, T. 1997. An overview of industrial model predictive control technology. In *AIChE Symposium Series*, 232–256. New York, NY: American Institute of Chemical Engineers, 1971-c2002.

Qin, S. and Badgwell, T. 2003. A survey of industrial model predictive control technology. *Control Engineering Practice* 11: 733–764.

Raković, S., Kouvaritakis, B., Cannon, M. and Panos, C. 2012a. Fully parameterized tube model predictive control. *International Journal of Robust and Nonlinear Control* 22 (12): 1330–1361.

Raković, S., Kouvaritakis, B., Cannon, M. and Panos, C. 2012b. Fully parameterized tube model predictive control. *International Journal of Robust and Nonlinear Control* 22 (12): 1330–1361.

Raković, S., Kouvaritakis, B., Cannon, M., Panos, C. and Findeisen, R. 2012c. Parameterized tube model predictive control. *IEEE Transactions on Automatic Control* 57 (11): 2746–2761.

Raković, S., Kouvaritakis, B., Findeisen, R. and Cannon, M. 2012d. Homothetic tube model predictive control. *Automatica* 48 (8): 1631–1638.

Raković, S. and Levine, W., eds. 2019. *Handbook of Model Predictive Control*. Springer.

Rankin, D. W. 2009, CRC handbook of chemistry and physics, edited by David R. Lide.

Rawlings, J. and Mayne, D. 2009. Model predictive control: theory and design. *Madison, WI: Nob Hill Publishing, LCC* .

Rawlings, J. and Muske, K. 1993. The Stability of Constrained Receeding Horizon Control. *IEEE Transactions on Automatic Control* 38 (10): 1513–1516.

Richalet, J. and O'Donovan, D. 2009. *Predictive functional control: principles and industrial applications*. Springer Science & Business Media.

Richalet, J., Rault, A., Testud, J. and Papon, J. 1978. Model predictive heuristic control: Applications to industrial processes. *Automatica* 14 (5): 413–428.

Rodrigues, M. and Odloak, D. 2003. MPC for stable linear systems with model uncertainty. *Automatica* 39 (4): 569–583.

Rohani, S., Haeri, M. and Wood, H. 1999. Modeling and control of a continuous crystallization process Part 2. Model predictive control. *Computers & Chemical Engineering* 23 (3): 279 – 286.

Rossiter, J. 2013. *Model-based predictive control: a practical approach*. CRC press.

Rubagotti, M., Raimondo, D., Ferrara, A. and Magni, L. 2011. Robust model predictive control with integral sliding mode in continuous-time sampled-data nonlinear systems. *IEEE Transactions on Automatic Control* 56 (3): 556–570.

Saadat, A., Alvanagh, A. and Rezaei, H. 2013. pH control in biological process using MMPC based on neuro-fuzzy model by LOLIMOT algorithm. In *Control Conference (ASCC), 2013 9th Asian*, 1–6. IEEE.

Saha, P., Krishnan, S., Rao, V. and Patwardhan, S. 2004. Modeling and predictive control of MIMO nonlinear systems using Wiener-Laguerre models. *Chemical Engineering Communications* 191 (8): 1083–1119.

Salhi, H., Kamoun, S., Essounbouli, N. and Hamzaoui, A. 2016. Adaptive discrete-time sliding-mode control of nonlinear systems described by Wiener models. *International Journal of Control* 89 (3): 611–622.

Sandström, K. and Gustafsson, T. 1994, A study of the dynamics of calcium-phosphate precipitation in pH-control systems, Tech. rep., Åbo Akademi University, Åbo, Finland.

Schuurmans, J. and Rossiter, A. 2000. Robust predictive control using tight sets of predicted states. *IEE Proceedings - Control Theory and Applications* 147 (1): 13–18.

Shafiee, G., Arefi, M., Jahed-Motlagh, M. and Jalali, A. 2006. Model predictive control of a highly nonlinear process based on piecewise linear Wiener models. In *E-Learning in Industrial Electronics, 2006 1ST IEEE International Conference on*, 113–118. IEEE.

Shaghaghi, D., MonirVaghefi, H. and Fatehi, A. 2013. Generalized predictive control of pH neutralization process based on fuzzy inverse model. In *Fuzzy Systems (IFSC), 2013 13th Iranian Conference on*, 1–6. IEEE.

Shamsaddinlou, A., Fatehi, A., Sedigh, A. and Karimi, M. 2013. Study of Multiple Model Predictive Control on a pH neutralization plant. In *Control Conference (ASCC), 2013 9th Asian*, 1–6. IEEE.

Shinskey, F. 1973. *pH and pION control in process and waste streams*. John Wiley & Sons, Inc.

Sivakumaran, N. and Radhakrishnan, T. 2007. Predictive controller design for non-linear chemical processes. *Indian Journal of Chemical Technology* 14 (4): 341–349.

Sontag, E. and Wang, Y. 1995. On characterizations of the input-to-state stability property. *Systems & Control Letters* 24 (5): 351–359.

Su, Z., Kang, R.and Shi, S., Cong, W. and Cai, Z. 2008. An economical device for carbon supplement in large-scale micro-algae production. *Bioprocess and Biosystems Engineering* 31 (6): 641–645.

Sui, D., Feng, L. and Hovd, M. 2008. Robust output feedback model predictive control for linear systems via moving horizon estimation. In *American Control Conference, 2008*, 453–458. IEEE.

Tatjewski, P. 2014. Disturbance modeling and state estimation for offset-free predictive control with state-space process models. *International Journal of Applied Mathematics and Computer Science* 24 (2).

Tian, X., Wang, P., Huang, D. and Chen, S. 2014. Offset-free multistep nonlinear model predictive control under plant–model mismatch. *International Journal of Adaptive Control and Signal Processing* 28 (3-5): 444–463.

Todaro, C. and Vogel, H. 2014. *Fermentation and Biochemical Engineering Handbook*. William Andrew.

Vahid Naghavi, S., Safavi, A., Khooban, M., Pourdehi, S. and Ghaffari, V. 2016. A robust control strategy for a class of distributed network with transmission delays: LMI-based model predictive controller. *COMPEL-The international journal for computation and mathematics in electrical and electronic engineering* 35 (5): 1786–1813.

Vieira, W., Santos, V., Carvalho, F., Pereira, J. and Fileti, A. 2005. Identification and predictive control of a FCC unit using a MIMO neural model. *Chemical Engineering and Processing: Process Intensification* 44 (8): 855 – 868.

Villanueva Perales, A., Ollero, P., Gutierrez Ortiz, F. and Gómez-Barea, A. 2009. Model predictive control of a wet limestone flue gas desulfurization pilot plant. *Industrial & Engineering Chemistry Research* 48 (11): 5399–5405.

Waller, J. and Toivonen, H. 2002. A neuro–fuzzy model predictive controller applied to a pH Neutralization process. In *Proc. of the 15th International Federation of Automatic Control IFAC World Congress*.

Wan, Z. and Kothare, M. 2003. An efficient off-line formulation of robust model predictive control using linear matrix inequalities. *Automatica* 39 (5): 837–846.

Wang, L. 2009. *Model predictive control system design and implementation using MATLAB®*. Springer Science & Business Media.

Wang, L., Zhang, X. and Shu, Y. 2016. Tube-based robust model predictive control for constrained continuous-time nonlinear systems. In *Control and Decision Conference (CCDC), 2016 Chinese*, 554–559. IEEE.

Wang, Q. and Zhang, J. 2011. Wiener model identification and nonlinear model predictive control of a pH neutralization process based on Laguerre filters and least squares support vector machines. *Journal of Zhejiang University SCIENCE C* 12 (1): 25–35.

Wu, F. 2001. LMI-based robust model predictive control and its application to an industrial CSTR problem. *Journal of Process Control* 11 (6): 649–659.

Xie, S., Zhou, L., Ma, A. and Zhou, L. 2008. A new switching scheme for multi-model predictive control using clustering modeling. In *Fuzzy Systems and Knowledge Discovery, 2008. FSKD'08. Fifth International Conference on*, 484–488. IEEE.

Yan, Z., Le, X. and Wang, J. 2016. Tube-Based Robust Model Predictive Control of Nonlinear Systems via Collective Neurodynamic Optimization. *IEEE Transactions on Industrial Electronics* 63 (7): 4377–4386.

Yan, Z. and Wang, J. 2014. Robust model predictive control of nonlinear systems with unmodeled dynamics and bounded uncertainties based on neural networks. *Neural Networks and Learning Systems, IEEE Transactions on* 25 (3): 457–469.

Yang, J.-F., Xiao, L.-F. and Qian, J.-X.and Li, H. 2012. Nonlinear model predictive control using parameter varying BP-ARX combination model. *International Journal of Systems Science* 43 (3): 475–490.

Yu, D. and Gomm, J. 2003. Implementation of neural network predictive control to a multivariable chemical reactor. *Control Engineering Practice* 11 (11): 1315 – 1323.

Yu, S., Böhm, C., Chen, H. and Allgöwer, F. 2012. Model predictive control of constrained LPV systems. *International Journal of Control* 85 (6): 671–683.

Yu, S., Maier, C., Chen, H. and Allgöwer, F. 2013. Tube MPC scheme based on robust control invariant set with application to lipschitz nonlinear systems. *Systems & Control Letters* 62 (2): 194–200.

Zhang, B. and Zhang, W. 2006. Adaptive predictive functional control of a class of nonlinear systems. *ISA transactions* 45 (2): 175–183.

Zhang, J., Chin, K.-S. and Ławryńczuk, M. 2018. Nonlinear model predictive control based on piecewise linear Hammerstein models. *Nonlinear Dynamics* 92 (3): 1001–1021.

Zhang, J. and Liu, J. 2013. Lyapunov-based MPC with robust moving horizon estimation and its triggered implementation. *AIChE Journal* 59 (11): 4273–4286.

Zhang, R., Xue, A. and Gao, F. 2019. *Model Predictive Control*. Springer.

Zhao, H., Guiver, J., Neelakantan, R. and Biegler, L. 2001. A nonlinear industrial model predictive controller using integrated PLS and neural net state-space model. *Control Engineering Practice* 9 (2): 125–133.

Zheng, P., Li, D., Xi, Y. and Zhang, J. 2013. Improved model prediction and RMPC design for LPV systems with bounded parameter changes. *Automatica* 49 (12): 3695–3699.

Zhou, F., Peng, H., Qin, Y., Zeng, X., Tian, X. and Xu, W. 2017. A RBF-ARX model-based robust MPC for tracking control without steady state knowledge. *Journal of Process Control* 51: 42 – 54.

Zhou, L. and Zhou, L. 2006, In Intelligent Control and Automation, In *Intelligent Control and Automation*, *Lecture Notes in Control and Information Sciences*, vol. 344, 559–564, Springer, 559–564.

Zou, Z., Yu, M., Wang, Z., Liu, X., Guo, Y., Zhang, F. and Guo, N. 2013. Nonlinear model algorithmic control of a pH neutralization process. *Chinese Journal of Chemical Engineering* 21 (4): 395–400.

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LIST OF PUBLICATIONS

A.W. Hermansson, S. Syafiie, and S.B. Mohd Noor. 2010. Multiple model predictive control of nonlinear pH neutralization system. In *Proceedings of the 2010 IEEE international conference on industrial engineering and engineering management (IEEM)*, 7–10 December 2010, Macau. pp. 301–304

A.W. Hermansson, and S. Syafiie. 2014. Control of pH neutralization system using nonlinear model predictive control with I-controller. In *Proceedings of the 2014 IEEE international conference on industrial engineering and engineering management (IEEM)*, 9–12 December 2014, Kuala Lumpur, Malaysia. pp. 853–857

A.W. Hermansson, and S. Syafiie. 2015. Nonlinear Model Predictive Control with I-controller using multiple models, Paper presented at the International Conference on Control, Optimization and Autonomous Vehicles 2015 (COAV 2015), 30–31 July 2015, Putrajaya, Malaysia.

A.W. Hermansson, and S. Syafiie. 2015. Model predictive control of pH neutralization processes: A review. *Control Engineering Practice.* 45: pp. 98–109

A.W. Hermansson, and S. Syafiie. 2019 An offset-free MPC formulation for nonlinear systems using adaptive integral controller. *ISA Transactions* In Press

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