Cairo University

DESIGN AND EXPERIMENTAL VALIDATION OF SUBSPACE PREDICTIVE CONTROL

By

Abdallah Fawzy Abd El-Fattah Hassan El Hamalawy

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Electrical Power and Machines Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Under the Supervision of

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Title of Thesis:

DESIGN AND EXPERIMENTAL VALIDATION OF SUBSPACE PREDICTIVE CONTROL.

Key Words:
Predictive Control; Subspace Identification; Data Driven Control; Process Control

Summary:

This Thesis studies different subspace identification techniques and its corporation with predictive control to introduce a subspace predictive controller (SPC). Furthermore, it investigates the combination of this controller with adaptation algorithm to develop an Adaptive version of Subspace Predictive Control which has the ability to deal with time varying and nonlinear processes. SPC is proved as a competitive replacement for conventional MPC as it avoids system's states measurement and hence avoids the need for state observer and its design. Instead, SPC predicts the output based on a bank of collected input and output data in a manner similar to Generalized Predictive Control (GPC) but can be extended to deal with MIMO systems based on a nonparametric model. Finally, the algorithm has been validated experimentally and applied to two benchmark systems Servomechanism and Level Control Process. The obtained results are promising.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institutes.

I further declare that I have appropriately acknowledge all sources used and have cited them in the references section.

Name: Date:

Signature:

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Dedication

To my inspiring parents, who never stop giving of themselves in countless ways

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Nomenclature

Symbols

General

u	System input
N_o	Prediction horizon
N_u	Control horizon
r_f	Reference trajectory
u_{min}	Minimum control action limit
u_{max}	Maximum control action limit
RR	Control action weight matrix
QQ	State weight matrix
n	System order

Model Predictive Control

A_m, B_m, C_m	Actual system state, input , and output matrices
$A_{aug}, B_{aug}, C_{aug}$	Augmented system state, input, and output matrices
x_m	Actual system states
y_m	Actual system output
x	Augmented system states
y	Augmented system output

Subspace Identification

A, B, C, D	Actual system state, input , output, and direct matrices
i	First estimation of system order
j	Number of identification data samples
O	Oblique projection
x^d	Deterministic system states
x^s	Stochastic system states
x	Combined deterministic – stochastic system states
y^d	Deterministic system output
y^s	Stochastic system output
y	Combined deterministic – stochastic system output
U_p	Block Hankel input past data matrix
U_f	Block Hankel input future data matrix
Y_p	Block Hankel output past data matrix
Y_f	Block Hankel output future data matrix
W_p	Block Hankel input and output past data matrix
X_p^d	Past deterministic state sequence

Subspace Identification Cont.

X_f^d	Future deterministic state sequence
$\tilde{X}$	Biased estimated state sequence
$\hat{X}$	Unbiased estimated state sequence
Γ	Extended observability matrix
H^d	Lower block triangular Toeplitz matrix
Δ^d	Reversed extended controllability matrix
$\bullet^\dagger$	Pseudo inverse operator

Subspace Predictive Control

$\widehat{Y_f}$	Estimated block Hankel output matrix
u_p	One column of past input block Hankel matrix
u_f	One column of future input block Hankel matrix
y_p	One column of past output block Hankel matrix
$\hat{y}_f$	One column of estimated future output block Hankel matrix
y_t	System output at time t
L_w	Past data prediction matrix
L_u	Future input prediction matrix
$\bar{L}_w$	Past data prediction matrix with inclusion of integral action
S_{ou}	Future input prediction matrix with inclusion of integral action
RQ	RQ factorization
ΦW_p	Added past input output column to block Hankel matrix
ΦU_f	Added future input column to block Hankel matrix
ΦY_f	Added future output column to block Hankel matrix

Abbreviations

MPC	Model Predictive Control
GPC	Generalized Predictive Control
SID	Subspace Identification
SIM	Subspace Identification Methods
SPC	Subspace Predictive Control
ASPC	Adaptive Subspace Predictive Control
GR	Givens Rotation

Abstract

This thesis aims to design and experimentally validate different approaches of Model Predictive Control (MPC) and focus on subspace based MPC or in other words Subspace Predictive Control (SPC). SPC provides a control technique that is based on predicting the output via nonparametric Subspace Identification (SID). Therefore, the thesis compares between different SID methods and also between conventional MPC and the proposed SPC techniques.

SPC is a competitive replacement for conventional MPC as it avoids system's states measurement and hence avoids the need for state observer and its design. Instead, SPC predicts the output based on a bank of collected input and output data in a manner similar to Generalized Predictive Control (GPC) but can be extended to deal with MIMO systems based on a nonparametric model. Hence, it is also called Data Driven Predictive Control. An adaptation technique is also provided to eliminate model mismatch and uncertainty. The adaptation technique is based on further identification under closed loop if the error between predicted output and measured output exceeded a predefined tolerance.

The different SID techniques are applied to two benchmark systems the first is an open loop unstable system (DC Servo system) which requires identification under closed loop. The second system is a level control setup associated with industrial actuators and sensors. SPC is also applied to both systems and presented promising performance. This thesis is one step forward towards validating the new predictive control techniques in subspace frame work experimentally so it can be provided as an industrial viable predictive control technique.