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Design and Realization of Embedded Model Predictive Controller with Software Support

Introduction

In industry the industrial incineration power plants are very widespread. They have to provide process heat, steam and often electric energy for the production process. Due to fast unforeseeable changes in consumption e.g. rapid load changes, caused by disturbances in the production area, it is essential to provide a high dynamic reaction of the power plant. Using model predictive control, the power plant is able to react fast with high robustness and without instability. The highly dynamic behaviour of the steam consumption demands a high performance of the power plant control. The state of the art for combustion control is the utilization of PID-controllers. The constant set points for the controllers are given by the operator. Frequent manual inputs by the operators are necessary to keep within boundaries of e.g. pressures, temperatures and flows. Due to high coupling, time constants and delays of the process parameters, the PID-controllers have to be tuned relatively slow to achieve robustness and avoid oscillation. Therefore, a model based control is growing in the process industry [1]. In [23] an MPC is presented for the control of a waste incineration plant and in [12] for a biomass industrial incineration power plants. This paper tries to outline possible deployment of advanced model predictive control concept. This concept will be first simulated in MATLAB, implemented to the PLC and verified on the real power plant.

Literature Review and Research Opportunities

There are many resources describing how to design a model predictive control. One of the predictive control methods is called Generalized Predictive Control (GPC) and was developed as a part of adaptive control [7]. The second most famous method is called Receding Horizon Control (RHC) and was developed within the academic research. The stabilizing RHC method minimizes the quadratic criterion with end constraints and was described in the paper [11]. The issue of RHC is summarized in the monograph [18]. All of these predictive control methods were developed independently. There have been several attempts to clarify trends of MPC and create guidelines for its design [5]. The current predictive control methods are discussed in the monograph [6]. The main process of the optimal control calculation can be implemented either on-line (the repeated calculation of the optimization problem at each sampling period for a particular values of the initial conditions, see e.g. [7]) or off-line [4]. It should be noted that the design of optimal control is easier when it is possible to formulate the optimization problem as a problem of minimizing the cost function which is presented by integer variables. For these optimization problems the software packages (solvers) exist in the world, they solve the optimization tasks very efficiently [16, 17]. Currently there are tools of artificial intelligence also used with the MPC – neural networks [13, 2], genetic algorithms [20] and more. The promising area for future research can be a predictive control of nonlinear systems [31] or the approach of MPC based on multiple models (MM), where the work area is divided into several operating modes in which the system is represented by a local linear model [22]. The combination of these local models creates a global dynamic model system [30]. Theory and applications of MPC still have worldwide attention. The fact that the issue of MPC is not only the subject of research at academic institutions, but the theoretical results are successfully transferred into the industrial practice, is documented in an extensive review of industrial applications in the references [21, 24, 25] and Table 1 which describes a growing number of MPC applications in the industry. In the design of predictive control it is possible to include the measured disturbance variable, which is loaded into the controller before it could affect the output of the controlled system. This deal is presented in [32, 14, 27]. The predictive control with measured disturbance variables for processes with time delays deals [15] and for multi inputs multi outputs (MIMO) processes is discussed in [19].

Tab. 1. Number of MPC applications [8]

Branch	1995	1999	2005
Refineries	67,2%	55,7%	49,2%
Petrochemistry	13,0%	15,3%	9,9%
Chemistry	8,5%	4,6%	15,6%
Pulp and Paper	2,0%	1,9%	3,8%
Polymer Industry	–	1,1%	6,3%
Air and Gas Utilities	–	1,6%	5,9%
Food Industry	0,5%	1,5%	3,5%
Mining and Metallurgy	0,7%	1,0%	1,5%
Power Plants	–	–	0,2%
Machine Industry	1,9%	1,1%	–
Cement Industry	–	–	1,3%
Others	4,2%	16,1%	2,7%
Total number of applications	**2233**	**4635**	**9456**

It is possible to find a lot of commercial MPC controllers on the market with different limitations and presumed use in the hierarchical control structure like the functional block ModPreCon from the APC library for PLC Simatic or advanced process control (APC) engineering tools ABB Expert Optimizer, INCA or Matrikon. The biggest disadvantage is their price.

Project Objectives

The main goal is to develop an open-source base MPC controller. Our project objectives can be divided into two phases.

Design and testing phase in laboratory

1. Design of MPC and algorithm for preprocessing of internal model:
   - studying MPC control theory,
   - definition of internal model and its mathematical form,
   - cost function definition,
   - choosing an open-source quadratic programming solver.
2. Creation of testing application in MATLAB:
   - MPC simulations,
   - only basic MATLAB functions.
3. Implementation to the PLC
4. Design and creation of controller parameterization interface
5. Controller verification with a laboratory model

Phase of real implementation at the plant

1. Definition of data collecting from the plant
2. Data mining:
   - internal model identification.
3. Simulation of control with testing application in MATLAB
4. Real implementation on the plant
5. Evaluation of control results:
   - comparison with PID control,
   - money and energy savings,
   - CO_2 reduction.

Model Predictive Control Algorithm

The presumed solution for PLC should consist of two functional blocks which can be used separately or together. Its more detailed description is presented further.

Functional Block for Internal Model Pre-processing

According to [29], the ideal candidate for mathematical description of internal model is a state space model. The reason is that it provides description of MIMO systems and another advantage is that it can also be used for the systems with integrators and unstable systems. But the most widespread mathematical description of systems in industry is transfer function and can be appropriate to use this form for entering the internal model specification by operator. Due to these requirements the functional block will have to solve the following steps:

1. Each transfer function from matrix of transfer functions must be transferred to the state space representation.
2. Must cooperate with transport delays.
3. Discretise each state space model.
4. Save and store each discrete state space models in memory.
5. Compose MIMO state space model of controlled system from the discrete state space models.

Functional Block of MPC Controller

These function block (FB) will calculate the optimal control actions and must be possible to connect feedback from the controlled system. The algorithm which will be realized in this FB will consist of three main parts which are shown in Figure 1. First, a cost function which will be transferred to the form which understands used quadratic programming (QP) solver must be defined. Like in the internal model, matrices from state space model pre-calculated in pre-processing internal model FB will be used.

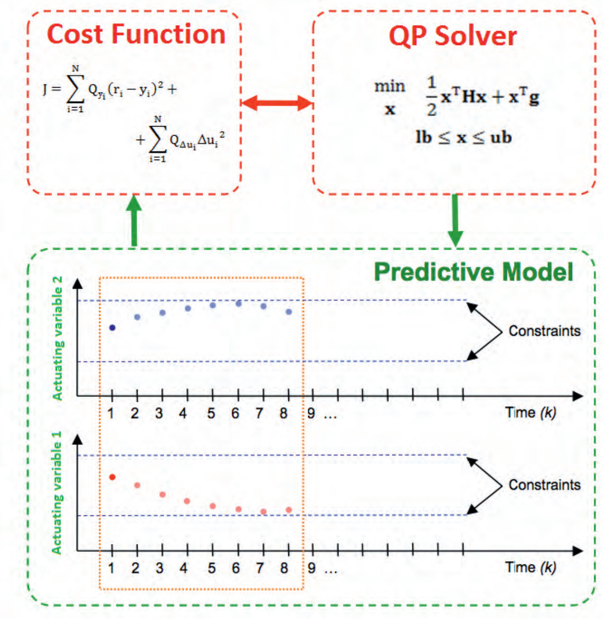

Fig. 1. Scheme of model predictive control algorithm

Development Environments and Tools

As was mentioned before, the main approach is to use open-source software packages and libraries. Our work will be determinated by keeping a low price of the final product. The most of the software packages are written for use with programming languages C or C++ and few of them also supports implementation to the MATLAB. The current high end PLCs with operation systems like, e. g. VxWorks, allow programmers to use C/C++ standards for writing programs for PLC without expansive PLC coders, e.g. Simulink PLC coder.

Quadratic Programming solver qpOASES

For solving quadratic optimisation problem which is described in fig. 1, the MPC algorithm uses parametric QP solver from an open-source software package qpOASES. This package was designed for online active set strategy which does not change much from one quadratic program to another and is suited for MPC applications. It has already been successfully used within industrial projects, e.g., for closed-loop control of a real-world Diesel engine [9]. The package contains several interfaces to third-party software like MATLAB, Simulink or Scilab. The qpOASES solves QPs which are described in the qpOASES manual [10] and they are given the following form.

$$\begin{aligned} &\min_{\boldsymbol{x}} \quad \tfrac{1}{2}\boldsymbol{x}^T\boldsymbol{H}\boldsymbol{x} + \boldsymbol{x}^T\boldsymbol{g} \\ &s.t. \;\; \boldsymbol{lbA} \leq \boldsymbol{Ax} \leq \boldsymbol{ubA} \\ &\qquad \boldsymbol{lb} \leq \boldsymbol{x} \leq \boldsymbol{ub} \end{aligned} \tag{1}$$

The Hessian matrix **H** is symmetric and positive (semi-)definite and **g** is the gradient vector and others are bound and constraint vectors. This is the same form which MATLAB uses in quadprog function.

Linear Algebra Library Armadillo

From [28], the Armadillo is a C++ linear algebra library aiming towards a good balance between speed and ease of use. The syntax (API) is deliberately similar to MATLAB and is useful for algorithm development directly in C++, or quick conversion of research code into production environments. It provides efficient classes for vectors, matrices cubes and functions for various matrix decompositions, which operate on the classes. An automatic expression evaluator combines several operations to increase efficiency and reduce temporaries. The library is open-source software, distributed under a license useful in both open-source and proprietary contexts.

Bachmann PLC

For future implementation of MPC algorithm to the PLC, the PLC from Bachmann Electronic GmbH was chosen. The processor modules of the MPC200 series are modules with Pentium Class III processors, based on PC technology with operational system VxWorks. More description can be found in [3].

Fig. 2. Processor module MPC240 [3]

- 2 serial interfaces,
- 2 Ethernet-interfaces 10/100 Mbit/s with status displays,
- 1 USB interface V1.1 functionality,
- real time clock, status displays for RUN, INT and ERROR,
- mass storage Compact Flash type I,
- RAM 128 MB DRAM,
- data memory 512 kB SRAM, battery backed,
- data memory 64 kB nvRAM,
- program memory 32/64 MB FLASH on PC card.

Bachmann SolutionCenter

Bachmann delivers with their PLC devices also the engineering tool SolutionCenter which allows to configure PLC, create visualizations in Java or program in C/C++, Java or in IEC 61131(CoDeSys) standards. The part of SolutionCenter which will be used for programming in C/C++ languages is called C/C++ Developer and allows to import external libraries.

Expected results

Many required goals have already been reached. The application for control simulations in MATLAB where finished and the designed algorithm based on qpOASES

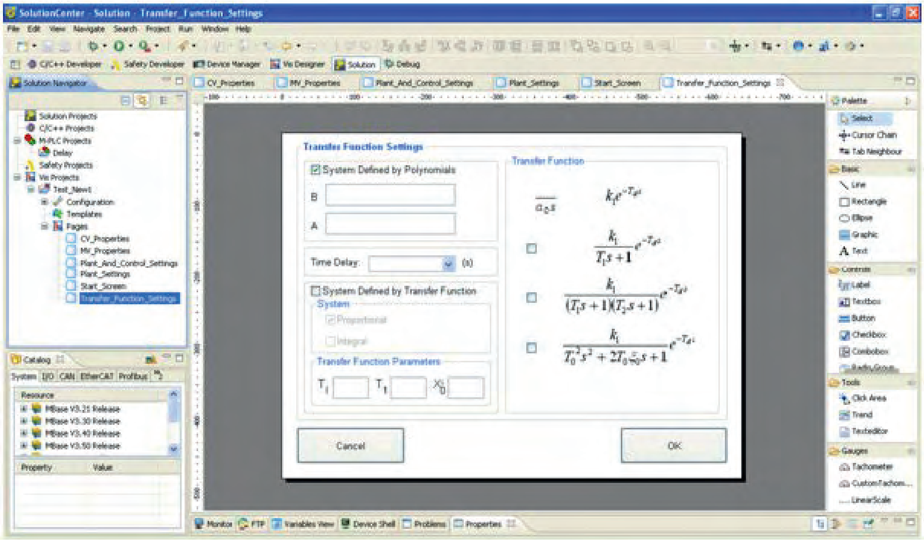

Fig. 3. Tool for creating Java visualizations

quadratic programming solver was tested online with the laboratory model in laboratories belonging to Department of Control Systems and Instrumentation, Faculty of Mechanical Engineering, VŠB-Technical University of Ostrava. The FB for internal model pre-processing has already been developed and the transfer functions are entered over the visualization created in Java. The future step is to implement MPC algorithm to the PLC and test it for control of any part of incineration power plant described in Figure 4. The visualization has been developed with emphasis on a simple, modern, comfortable and user-friendly interface. We hope that the future MPC controller will become commonplace not only in small and medium enterprises.

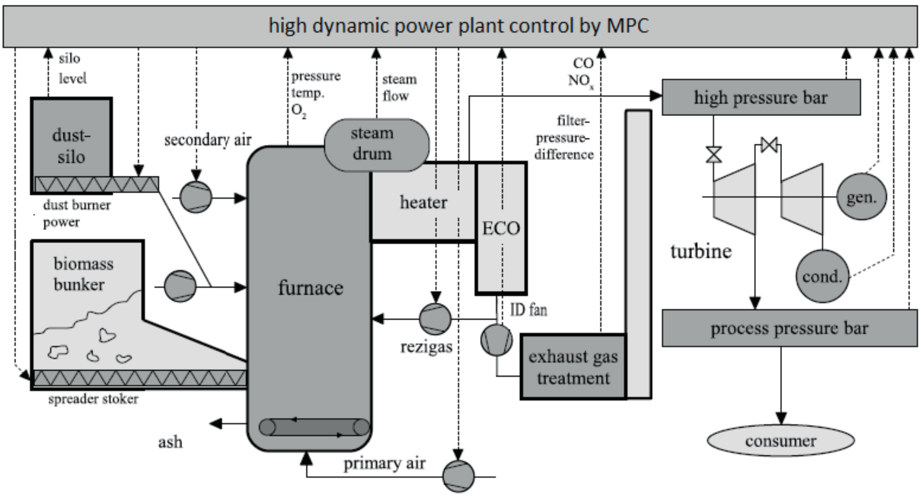

Fig. 4. Schematic of the plant [12]

Conclusion

This work aims at contributing to the research of model predictive control systems and brings its research outputs to the industry praxis. The designed solution provides advanced process control with a user-friendly interface. The application base can be extended in the future.

The MPC is one of the ways how to implement optimal control to the industrial praxis. It is currently one of the most emerging approaches in automatic control and one of the few theoretical approaches which are also massively applied to the industrial practice. It will find a use where the quality of control using PID controllers is not satisfying. The main advantage of our solution is the price, because of the use of an open source software packages. We hope that the use of predictive control method will reduce production of CO_2 and fuel consumption in incinerations power plants.

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Abstract

The aim of this paper is to describe the design and future realization of a new embedded model predictive controller (MPC) for a small and medium enterprise. This research was driven by a need of small and medium sized companies, because the professional commercial solutions of MPC controllers are very expensive and with limited use on the PLC. The goal of the work is to implement MPC to the PLC by using open source software packages, quadratic programming solver qpOASES and linear algebra library Armadillo. The second requirement is to create a simple, comfortable and user-friendly interface. The created solution will be tested and used for a control of a small industrial incineration power plant.

Key words: MPC, PLC, qpOASES, Armadillo

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