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A Test Environment to Evaluate the Integration of Operators in Nonlinear Model-Predictive Control of Chemical Processes[1]

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Abstract: In industrial process control, basic controllers such as linear PI(D) control and cascade controllers are widely accepted by the plant operators because they are easy to understand due to their clear *cause-and-effect* relation. When the control and performance objectives cannot be met by simple controllers and manual interventions, advanced process control (APC) solutions, usually MPC controllers are employed. The design of APC solutions requires a considerable understanding of the process and more mathematical background—but also during the operational phase (e.g. error diagnosis). Then the issue of the trust of the operators into such complex control solutions and in their ability to monitor their behavior during plant operation arises. It may happen that APC solutions are not accepted or are fully or partly switched off by the operators after a while, which means a wasted effort and lost opportunities for better plant performance. By providing carefully chosen information about the behavior of the controller and well-designed operator interfaces, the trust of the operators and their ability to monitor advanced controllers can be increased. In this contribution we present an environment to investigate trust in automation experimentally and to explore new opportunities for the user-interaction with APC methods. The test environment consists of a chemical process simulator which is controlled online by a NMPC scheme, an interface editor for the fast development of interface concepts as well as a control room simulation in order to evaluate the synergetic cooperation between the operator and the algorithmic control schemes.

Keywords: Human-Machine Interaction, Operator Interaction, Chemical Process Control, Nonlinear Model-predictive Control, Trust in Automation.

1. INTRODUCTION

In chemical and biochemical plants, the use of model predictive control (MPC) has increased considerably in the last decades with more than 9,500 applications in 2005 (Dittmar and Pfeiffer, 2009). Up to now, the majority of the applications is based on linear process models, while model predictive control based on nonlinear models (NMPC) is currently pushed ahead towards its industrial application (see e.g. Finkler et al., 2014).

A key challenge for a more widespread use of MPC in general and NMPC in particular is the interaction between the operators and the optimization techniques. The operators are responsible for monitoring and supervision of the MPC methods and have the authority to accept or to discard the proposed control moves if they consider them to be erroneous. The acceptance by the operators is crucial to the long-term success of APC solutions; they must be perceived as a useful and reliable support in their daily work.

Even for linear MPC, the underlying algorithms are complicated and difficult to understand for the operators. The tuning of the numerous parameters remains a task for specialized staff. For the operators it is nearly impossible to adjust these parameters based on their experience in controlling the plant in manual mode. In the case of NMPC, the monitoring and diagnosis of the underling algorithms is even more complicated than in the linear case, making it more difficult to operate such solutions in a collaborative manner.

In direct optimizing control an economic optimality criterion is directly incorporated into an NMPC scheme and other targets, e.g. purity constraints or plant limits, are implemented as contraints (Engell, 2007). It is not clear whether such formulations make it easier for the operators to understand the behaviour and the proposals of the controller.

We have developed a test environment for investigating the interaction between operators, NMPC solutions with a tracking or economic cost function and the process itself in an experimental setup of a realistic scale. It includes a real-time simulation of a polymerization process that is controlled by NMPC with an economically motivated cost criterion, tools for the rapid development of new interfaces and a control room simulator to perform behavioral experiments with test persons.

The paper is structured as follows: In section 2, we present a review on the interfaces that are currently employed in the chemical industry and a summary of the relevant aspects of trust in automation. In section 3, we give a short introduction to the NMPC algorithms which are used to control the plant and which have to be supervised by the operators, and in section 4, possible methods to increase the trust in NMPC

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algorithms are discussed. In section 5, the complete environment which will be used for testing the operator interaction is described. In section 6, we present a research concept for assessing the integration of operators regarding the monitoring and diagnosis of NMPC algorithms.

2. REVIEW OF THE CURRENT SITUATION

2.1 The role of operators in the process industry

Processing plants equipped with distributed control systems (DCS) can usually be operated by only a handful of operators. Their tasks are to monitor, diagnose and control the plant from a central control room that is placed at a distance to the actual process due to safety considerations. The main goals of plant operations are a stable and efficient operation while meeting safety and environmental regulations and constraints, product quality constraints, and minimizing the consumption of energy and resources and the degradation of the equipment. Regulation of the process variables such as pressures, temperatures and levels are done by SISO controllers that are realized in the DCS and more complex classical structures as e.g. cascade and split-range control.
In many units nowadays MPC (model predictive control) solutions have been installed. These are multivariable controllers that provide set-points to the basic instrumentation and replace engineered classical solutions and/or take over some of the tasks of the operators. The benefits of MPC were shown in many publications (see Qin and Badgwell, 2003). When MPC solutions have been installed, the tasks of the operators are changed: instead of controlling the process manually, they have to supervise the MPC solution and the process and to ensure its proper operation. They may also have the authority to change some of the settings of the MPC controller, e.g. ranges of variables, and can take parts of or the full controller out of operation. In the process industries where each plant and each controller is a specifically engineered individual piece of equipment and where numerous not fully understood external influences as well as not controllable internal processes (e.g. fouling) occur, full automation without operator interaction is usually not feasible. In certain situations, e.g. for large load changes, disturbances, or during start-up, the controllers have to be switched on and off manually and the plant is operated manually for certain periods of time. The challenges of designing and operating an MPC solution have been pointed out by Forbes et al. (2015). The authors describe two examples when the operators preferred to switch off the MPC solution. The reasons were simple: the operators did not understand the control moves that were conducted by the MPC and therefore returned to the manual process control which they knew from their experience.This way, quite a few MPC applications were either abandoned after a short period of operation or even never went into operation. Human factors that are often overlooked play an important role for the successful operation of MPC solutions (Forbes et al., 2015). This is even more true for the application of NMPC in industry.

2.2 Human factors and automation in the process industry

Several decades ago, Bainbridge (1983) coined the term “irony of automation”, which characterizes the erroneous assumption in the development of automation solutions that by means of an increased amount of automation, problems with human operators will automatically disappear. The opposite turned out to be true: with the growing complexity of the automation systems, the demands on the humans that have to deal with the automated systems stayed the same or even grew, essentially because of two reasons: 1) some tasks cannot be automated and 2) if the automated solution fails, the operators still have to be able to control the process manually. While automation is usually implemented with the intention of reducing workload and increasing performance, accumulating evidence suggests that underload resulting from low mental demands during normal operation is actually detrimental to the performance (Young and Stanton, 2002).
During the last decade, the process control industry has put significant efforts into the integration of human factors issues into control system development (Li et al., 2011).
The importance of trust for the operators’ decision between manual and automatic control has been shown several times (Schaefer, Chen, Szalma and Hancock, 2016). When operators trust an automatic solution that is more reliable than manual operation, they are likely to rely on the automation. Similarly, when operators distrust an automatic solution because it is less reliable than manual operation, they are likely to choose self-reliance (Dzindolet et al., 2003).
Distrusting a control algorithm that in fact is more reliable and performing better than manual operation may lead to disuse, which is according to Parasuraman and Riley (1997) defined as “underutilization of automation” and leads to suboptimal performance of the human-machine team (Hoff and Bashir, 2014). On the other hand, trusting a control algorithm that is less reliable and/or performing worse than manual operation may lead to misuse, which is defined as “overreliance on automation” (Parasuraman and Riley, 1997).
For the successful long-term operation of an integrated automation system, it is crucial that the following two points are fulfilled:

1) A sensible degree of automation has to be specified (for instance using the framework suggested by Parasumaran et al. (2000))
2) The operator has to trust the automation

2.3 The role of trust in automation

The effect of trust in automation has been studied in a series of experiments by Muir and Moray (1996), showing that the utilization of automatic or manual control modes of a process control system is directly linked to the trust of the operators in the automated solution. The authors conducted a series of experiments in a simulated milk pasteurization plant. The reliability of the pumps was manipulated using constant and variable errors of the flow rates. Furthermore, they introduced errors in the display of the pumps (with the pump actually working perfectly) and they changed the performance of the semi-automated pump controllers.
Muir and Moray then assessed operator trust using subjective and objective measures. Subjective ratings were acquired by