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A Survey on Advanced Control Approaches in Factory Automation

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Abstract: The goal of this paper consists in providing a survey of the main advanced control techniques currently adopted in factory automation. In particular, attention is devoted to model based control, model predictive control, intelligent and adaptive control, discrete event and event-triggered control. Open issues and challenges are pointed out, and the needs for further research efforts are discussed in detail.

Keywords: factory automation, advanced control, model based control, model predictive control, intelligent control, adaptive control, discrete event control, event-triggered control.

1. INTRODUCTION

Advanced control approaches are required to improve the efficiency of production sites. In particular, advanced control approaches may lead to production processes that are more competitive and autonomous from human action, but also have positive effects in terms of optimization of the production distribution and support decision-making. The term advanced control refers to a wide range of techniques applied in industrial plants and typically integrating tools from various disciplines. All these techniques are characterized by their ability to design high performance controllers that can be applied to high-order and multivariable processes or plants, which are typically nonlinear and subject to constraints. The five main classes of advanced control techniques may broadly be singled out as follows:

- Model based control techniques;
- Intelligent control techniques or control techniques based on computational intelligence;
- Adaptive control techniques;
- Discrete event/hybrid control techniques;
- Event-triggered and self-triggered control.

In this paper, for each of the above classes of advanced control techniques, we describe the main control techniques with their application areas, indicating the related emerging research trends in industrial control and factory automation.

2. MODEL BASED CONTROL TECHNIQUES

Model based control concerns with designing a control system and evaluating its performance in a simulation environment by way of mathematical model(s) of the plant (Åstrom and Kumar 2014).

2.1 Model predictive control approaches

At an industrial level, the recognized most widespread technique in this context is Model Predictive Control (MPC) (Camacho and Alba Bordons 2007). MPC provides an integrated solution for controlling systems with interacting variables, complex dynamics, and constraints. As such, it has become the standard approach for industry process control today (Jämsä-Jounela 2007, Darby *et al.* 2012). In MPC, a model of the process is used to predict its evolution over a future time horizon. These predicted output values are then used to compute a control signal that optimizes the future behaviour of the plant (Bemporad and Morari 1999). To determine the sequence of control moves, a dynamic model of the process, a history of past control moves and an optimization cost function are required over the receding prediction horizon.

After the early diffusion of numerous MPC linear techniques -e.g., model predictive heuristic control, dynamic matrix control, extended prediction self-adaptive control, and generalized predictive control- in the '90s the first applications of nonlinear MPC appeared. Subsequently, MPC techniques for hybrid systems were developed (Camacho and Alba Bordons 2007). Typical areas of industrial applications for the MPC strategy are chemical and petrochemical plants operation, together with refinery control (Jämsä-Jounela 2007). Emerging areas for applications are: mining/ore treatment, sheet

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processing, fuel cell, upstream oil production, power generation, and pulp and paper industry. Moreover, MPC is moving into pharmaceutical manufacturing, food processing and has even penetrated discrete manufacturing, most notably the automotive industry.

One of the limitations of MPC is that it relies on the solution of an online optimization problem, which had precluded its application to processes requiring high sample rates. Recently, the impact of faster and multi-core processors is being seen in MPC products. As a result, several research directions for improved MPC application in factories can be identified. First, the use of nonlinear models is increasingly being applied in MPC, and it would likely increase if the associated modelling costs could be reduced. This motivates the idea of model libraries, tailored to control, for important unit operations (Darby *et al.* 2012). In this context, applications of switched/hybrid MPC seem promising (Morari 2009), for instant in the area of batch distillation columns, fed-batch reactors and bioreactors profile control. Second, much remains to be done in terms of robust MPC that currently lacks a practically implementable method (Darby *et al.* 2012, Lee 2011). In this context, a further interesting application which needs advances both in terms of theoretical development and application is MPC for uncertain systems (Lee 2011). Indeed, to facilitate tuning in light of expected model errors, another area to consider is incorporating into simulation the characteristics of unmeasured (stochastic) disturbances that could be obtained from historical data, test data, and/or from the actual controller (Darby *et al.* 2012). Third, the application of adaptive MPC, mainly in terms of plant testing, is a natural area for further research (Morari 2009). Fourth, areas where improvements could be realized are in the identification and modelling for MPC, including enforcing model consistency and taking advantage of prior knowledge. Benefits would include better handling of ill-conditioning and time savings in model development (Darby *et al.* 2012). Fifth, an area where a clear space for further contributions is available regards detection and diagnosis of control performance deterioration. The problem is evidently a challenging one due to its multivariable aspect and the number of constraint combinations (Darby *et al.* 2012). Sixth, reducing complexity of online optimization and of explicit solutions (i.e., number of regions) are other interesting open research areas for MPC (Morari 2009). Finally, decentralized and distributed MPC are an obvious reply to address the control of large-scale systems in factory automation (Cristofides *et al.* 2013, Morari 2009).

2.2 Multivariable control approaches

Multivariable control refers to control problems where there are typically a number of process variables which must be controlled and a number of variables which can be manipulated (Skogestad *et al.* 2005). Multivariable feedback control systems include numerous approaches, e.g.: the so-called Relative Gain Array method, decoupling control schemes, multi-loop controllers (typically with PID regulators), optimal control methods such as the well-known Linear Quadratic Gaussian (LQG) control approach, and, in the case of uncertainty in the plant, robust control, including H_2 and H_∞ control (Skogestad *et al.* 2005).

In the industrial context, the following multivariable control applications are notable: robust nonlinear feedback control is being applied in pharmaceutical companies; optimal LQG is applied in milling industries; Kalman filtering is used for automatic gauge control; extended Kalman filters are used to construct observers for batch processes in chemical/petrochemical applications; state feedback linearization has been implemented in the glass and ceramic industries; LQG, robust, and $H\infty$ control trials have been performed in experimental fusion main plasma control; applications of multivariable decoupling control solutions have become standard in pulp and paper mills.

Future challenges in the use of multivariable feedback techniques in process industries are: improving energy efficiency in industrial processes by monitoring, optimization and control technologies; economic-performance optimizing approaches, also known as dynamic real time optimization approaches; and very large scale integrated process control, i.e., integrated hierarchical control approaches aiming at the combined control of the classical layers of a process enterprise.

3. INTELLIGENT CONTROL APPROACHES

Intelligent control methods are computational intelligence based approaches. They include a number of techniques based on reasoning from data, including the following three main classes and their integration: techniques based on fuzzy systems, Artificial Neural Networks (ANNs), evolutionary algorithms.

3.1 Fuzzy control techniques

Roughly speaking, fuzzy control algorithms consist of a set of heuristic control rules, and fuzzy sets and fuzzy logic are used, respectively, to represent linguistic terms and to evaluate the rules (Feng 2006). Since the first applications in the ‘70s, fuzzy logic control has attracted great attention from the industrial community. As regards factory automation, the main areas for application of fuzzy control are chemical and petrochemical processes, food processing industries, as well as nuclear reactors. The industrial applications of fuzzy control are characterized by the use of heuristic rules that can be a viable alternative to classical crisp (non-fuzzy) control for the control of ill-defined processes or systems with functional nonlinearities subject to difficult mathematical modelling (Precup and Hellendoorn 2011). Moreover, compared to conventional control, fuzzy control can be strongly based on the experience of a human operator, and a Fuzzy Controller (FC) can model this experience in a linguistic manner (Precup and Hellendoorn 2011).

In the majority of applications a FC is used either for direct feedback control or on the low level in hierarchical control system structures (Precup and Hellendoorn 2011). In the former case, the related literature traditionally