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Model predictive control and its application in agriculture: A review

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ABSTRACT

Agriculture plays a decisive role in the survival of humankind. The efficient and precise regulation of agriculture will ensure the welfare of people throughout the world. However, difficult and urgent agricultural challenges persist, and traditional agricultural production regulation methods are time consuming and laborious. Moreover, the application of intelligent algorithms to modern agricultural production requires the support of a database, which can be complex and difficult to use in practice and requires a large amount of computing. Fortunately, model predictive control (MPC) methods can achieve highly accurate control operations with moderate complexity and can also allow for rolling optimization in a limited time domain, which improves precision. Despite being a process control method that originated in industry, MPC is highly suited for application in agriculture because it can effectively address nonlinear and large time-delay systems. The aim of this review is to introduce MPC and describe its current application in agriculture. In this review, the development of MPC and various improved MPC schemes are described. The development of MPC is divided into three stages. In addition, applications and new technologies associated with MPC in irrigation systems, agricultural machinery, agricultural production, product processing and greenhouses are analyzed. Smart agriculture will have a promising future because of the implementation of MPC technologies derived from successful industrial applications. Finally, challenges and future perspectives of MPC technology use in agriculture are summarized and forecasted.

1. Introduction

Agriculture is the foundation of human existence, it is vital to the survival of humankind. Today, the total global population exceeds 7 billion, and by 2050, the urban population will increase by an additional 2.5 billion through population growth and urbanization, with nearly 90% of the population concentrated in Asia and Africa (Lloyd et al., 2017). However, the amount of available food is limited, especially in Africa, and the food scarcity problem has yet to be solved (Sanchez, 2002); additionally, Asia has a serious shortage of water (Pomeranz, 2009). The earth's water supply is rich, with 1.45 billion cubic kilometers in total, and 72% of the Earth's surface area is covered with water. However, less than 1% of the world's fresh water is easy to exploit for direct human use, accounting for approximately 0.007% of the total water on the planet. The total land area of the world exceeds 13 billion hectares; however, the area of potentially arable land throughout the world accounts for 22% of the total land area, at just 3031 million hectares (Lal, 1990). Moreover, traditional agriculture is time-consuming and labor-intensive, with low production efficiency. Considering the increasing population, water shortages, limited land resources, and low production efficiency, it is urgent to efficiently regulate agriculture.

Agricultural systems are complex, multivariate and unpredictable (Kamilaris et al., 2018). Classical control technologies such as those involving on/off, P, proportional integral (PI), and proportion-integration-differentiation (PID) control (Christofides et al., 2013; Afram and Janabi-Sharifi, 2014) are easy to implement but are unable to control moving processes with time delays; in addition, adjusting the controller is cumbersome and time consuming (Wang et al., 2001). Intelligent methods such as fuzzy logic (FL) control and artificial neural network (ANN) control involve not only deterministic mathematical models but also nonmathematical generalized models and mixed models (Afram and Janabi-Sharifi, 2014). However, these methods require learning and reasoning based on data-driven or embedded expert knowledge. Fortunately, the performance of MPC is superior to that of classical control and is easier to implement than intelligent computing algorithms. MPC can achieve high regulation accuracy with moderate complexity. Therefore, this method is highly suited for precision

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agricultural production.

MPC refers to a class of advanced computer-controlled algorithms that use an explicit process model to predict a plant's future response (Qin and Badgwell, 2003). A series of control inputs are computed at each sampling instant, but only the first computed input is implemented in the process (Bumroongsri and Kheawhom, 2014). The first input in the optimal sequence is then sent to the factory, and the entire calculation is repeated at subsequent control intervals (Mogal and Warke, 2013). The algorithm consists of three parts: prediction model, rolling optimization, and feedback adjustment (Zhang et al., 2017). MPC was developed in the early 1960s and has been used widely in process industries (Garriga and Soroush, 2010). The method allows for the introduction of constraints, predictive information, and nonlinear dynamics. Linear MPC (LMPC) is used to solve convex quadratic programming problems (QPs) online. Nonlinear MPC (NMPC) allows for the control of systems with nonlinear dynamics and involves significantly more calculation than does LMPC (Vukov et al., 2015). Early MPC theory incorporated dynamic matrix control (DMC) and model algorithm control (MAC), which are based on the linear quadratic Gaussian (LQG), which is a relatively simple parameter model. Internal model control (IMC) is defined for single-input/single-output, discrete-time systems (Garcia and Morari, 1982). DMC and MAC inspired the development of IMC but lacked stability. Thus, the generalized predictive control (GPC) model was developed; its theoretical basis is more complete than DMC and MAC, and it could also solve the robustness problem to a certain extent. Most industrial processes are highly complex, involve large amounts of interference and are strongly nonlinear; thus, adaptive MPC, robust MPC and NMPC have been developed. However, the calculation time for these MPCs is quite long and inefficient. To solve these problems, the distributed MPC, hybrid MPC, explicit MPC and other new MPC models were established (Lee, 2011). In addition, because actual production processes are random, stochastic MPCs have also been developed (Zhang et al., 2017).

As one of the most promising control strategies, MPC has been widely studied (Froisy, 1994; Morari and Lee, 1999; Qin and Badgwell, 2003; Rawlings and Mayne, 2009) and applied in industry (Qin, 1997; Seki et al., 2001; Han and Qiao, 2014). The application of MPC to agriculture can yield significant productivity and efficiency benefits. However, no review of MPC use in agricultural applications has been reported. MPC has been applied to agriculture, but it has not yet been applied in all respects. In this review, MPC development and current application in agriculture are described. The development of MPC can be divided into three stages: classical MPC, improved MPC, and the latest MPC. These MPCs are described in Chapter 2. Currently, MPC is used mainly in agricultural applications such as irrigation systems, machinery, production, product processing, and greenhouses. These applications are described in Chapter 3. The challenges and future perspectives of MPC are discussed in Chapter 4. Finally, conclusions are discussed.

2. The development of MPC

In the 1960s and 1970s, the concept of MPC appeared in the literature. However, MPC was not introduced into process industries until the 1980s (Froisy, 1994). In general, the evolution of this scheme can be divided into three stages according to the degree of technological development. The theoretical principle of MPC is shown in Fig. 1. The input is $\mathrm{r(k)}$, the initial output is $y_d(k+j)$, the output after optimization is $y_m(k+j)$, and the output after on-line correction is $\mathrm{y_p(k + j)}$; after a number of repeated cycles, the final output is y(k).

Fig. 2 shows the flow of a common MPC calculation for each control operation (Qin and Badgwell, 2003).

2.1. Classical MPC

The purpose of the first-generation MPC scheme was to solve typical multivariable constraint control problems in industry. Many algorithms emerged during this period. Herein, DMC, MAC, and GPC are introduced, which are relatively classical, and other algorithms established during this period are shown in Table 1.

2.1.1. Dynamic matrix control and model algorithm control

Early MPCs, such as LQG controllers (Kalman, 1960), were unable to handle constraints, process nonlinearity or uncertainty. Later, DMC and MAC systematically introduced input and output constraints to address some of the drawbacks of LQG (Garriga and Soroush, 2010).

DMC is a significant and classical predictive control method first proposed by Culter and Ramakar (Cutler and Ramakar, 1980). This method uses a step-response model (SRM) that is relatively easy to develop in practice (Moon and Lee, 2011). Studies have shown that DMC could sometimes be combined with PID to improve the performance of DMC (Guo et al., 2010; Wu et al., 2014). In addition, nonlinear systems with high efficiency are consistently described by many SRMs (Moon and Lee, 2011). Quadratic dynamic matrix control (QDMC) is also commonly used. This algorithm can reduce the cost of a given system (Li et al., 2012). Richalet et al. established the original concept of MAC in the late 1970s (Richalet et al., 1978). MAC essentially involves an impulse response model, a reference trajectory, an optimality criterion and state and control constraints (Xia et al., 1993). The purpose of MAC is to obtain an optimal control strategy for minimizing the relevant criterion, which reflects future deviations within a certain range (Zhang et al., 2009). The combination of MAC with PID can also improve the performance of MAC (Wei, 2015).

Regardless of model structure and order, the DMC and MAC schemes include fixed time-delay terms. The disadvantage is that these methods cannot describe unstable systems, are not applicable to unstable objects, and cannot easily perform online model identification.

2.1.2. Generalized predictive control

The GPC model was first developed in 1987 by Clarke et al. (1987a,1987b). The principle of GPC is to generate a series of control signals at each sample interval to optimize the control effort to track the reference trajectory accurately (Lu and Tsai, 2009). The core idea is to develop a control strategy that can adapt to dynamic changes in the sampling rate. (Pawlowski et al., 2012). The purpose of GPC is to replace the self-regulating regulator to solve robustness problems (Lee, 2011). GPC can be used with the CARIMA model to improve performance (Kiselev et al., 2016; Wang et al., 2016).

Predictive control (PC) can control simple to highly complex processes, including those involving large time delays, nonminimal phases, unstable and multivariable systems (Aguilar et al., 2016). GPC has the advantages of both self-tuning control and PC, and feedback correction is implemented in a self-tuning manner through online model identification and online control law correction. GPC can control open-loop instability, nonminimum phases, and time-varying delay objects and exhibits good robustness to time-delay and order-indeterminate systems. However, GPC is difficult to be deploy in multivariable systems. In addition, different companies using early MPC technologies have had unique sets of problems to address. Some technologies have become known by their commercial software product names, which are still used today. In general, these technologies are also known as MPCs and are briefly described in Table 1.

2.2. Improved MPC

The classical MPC schemes cannot meet complex industrial requirements. The purpose of the next generation of MPC, referred to as improved MPC, was to address the robustness and nonlinearity of control problems.

2.2.1. Adaptive MPC

Generally, control problems involve many unmeasurable