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Soil moisture regulation of agro-hydrological systems using zone model predictive control

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ABSTRACT

In this paper, we consider input-output model identification and zone model predictive control of agro-hydrological systems. Specifically, we consider an agro-hydrological system with homogeneous soil layers to illustrate the proposed model identification and predictive control methods. The primary control objective is to maintain the soil moisture at the center of the root zone within a target zone. A secondary control objective is to reduce the total amount of water used in irrigation. First, a linear parameter varying (LPV) model for controller design purpose is identified. Then, based on the LPV model, a zone model predictive control (MPC) is designed, which uses asymmetric zone tracking penalties to reduce irrigation amount under weather uncertainties while maintaining the soil moisture within the target zone. The simulation results show that the LPV model provides satisfactory approximation of the process dynamics, and the designed zone MPC is suitable for irrigation of the agro-hydrological system.

1. Introduction

The increasing population and adverse climate change are escalating fresh water scarcity globally. Since irrigated agriculture consumes a large portion of fresh water (70% approximately), increasing the efficiency of water use in irrigation practice is important for ensuring the sustainable development of agriculture (Guan and Hubacek, 2007; Mubako et al., 2013; Wang et al., 2017). It is well recognized that if irrigators made more efficient use of water then there would be more water for environmental uses and for cities (Ward and Pulido-Velazquez, 2008). In the current practice, irrigations worldwide are mostly based on empirical or heuristic knowledge. Typically, the irrigation plans are made and carried out in total ignorance of the actual soil water content. Such strategies are called open-loop irrigation strategy. The main drawback of open-loop irrigation is the difficulty in delivering the precise irrigation amount, which could lead to either a waste of irrigation water or insufficient irrigation. Due to the inefficiency of open-loop irrigation and the emerging water crisis, there has been an increasing interest in the research of closed-loop irrigation. Many control systems, which are based on real-time feedback signals such as soil moisture measurement, evapotranspiration rate and other on-line sensors, have been proposed. In Goodchild (2015), a constrained integral proportional-integral-derivative (PID) controller was proposed. In Kim et al. (2009), an automated closed-loop irrigation control system was developed and tested with a self-propelled lateral-move sprinkler irrigation system that was set up for site-specific variable-rate water applications. In Bahat (2000), an irrigation controller based on the fuzzy-logic methodology was presented to decide on how far to open the water valve and how much water to be added to the soil, by considering the temperature, air humidity, wind speed and water budget as the fuzzy variables. In Cid-Garcia et al. (2014), a new methodology based on mathematical models of linear programming and site-specific management zones was presented to determine the crop pattern and the use of water in agricultural fields considering the crop requirements in real-time. Besides the above results, closed-loop irrigation were also reported in Kim et al. (2008), Pawlowski et al. (2017) and Navarro-Hellín et al. (2016).

Recently, model predictive control (MPC) has also been used in the control of irrigation systems. MPC is a very flexible optimal control framework based on solving constrained optimal control problem online repeatedly, and has been widely used in modern manufacturing industries due to its abilities to handle multivariate processes and to address state and input constraints (Mayne et al., 2000; Qin and Badgwell, 2003). In the MPC-based studies, due to the use of a prediction model, it is possible to incorporate weather forecast along with other environmental and crop factors. Hence the irrigation amount can be controlled accurately without hampering crop yields. In Park et al. (2009) and Park and Harmon (2011), Park et al. used MPC to incorporate sensor measurements, predictive models and optimization algorithms to drive field conditions to a desired environmental state (e.g. soil moisture, salt levels or contaminant propagation). In McCarthy et al. (2014), McCarthy et al. implemented MPC to determine

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irrigation timing and site-specific irrigation volumes based on crop production models. In Delgoda et al. (2016), Delgoda et al. proposed to use MPC to minimize root zone soil moisture deficit and irrigation amount under limited water supply. In these studies, the MPCs are all designed to keep the root zone soil moisture at some pre-determined set-point. However, these set-point tracking MPCs can be overly conservative. In fact, to ensure adequate root water extraction, it usually suffices to keep the soil moisture within a zone instead of at a specific setpoint (see Section 2.1.2 for details). This implies that zone control is a more natural choice than set-point control for irrigation systems. Model predictive control with zone objectives, or zone MPC, has seen applications in different areas such as diabetes treatment (Gondhalekar et al., 2013; Gondhalekar et al., 2016), building heating control system (Privara et al., 2011) and pressure management of water supply network (Liu and Li, 2016). More zone MPC designs and theoretical studies can be found in Ferramosca et al. (2010), Ferramosca et al. (2012), González and Odloak (2009).

In this work, we propose a systematic approach to system identification and zone MPC design for soil moisture regulation of agro-hydrological systems. In our study, the soil water dynamics of the field is simulated by an agro-hydrological model which consists of a nonlinear partial differential equation with source and sink terms characterizing the root water extraction, evaporation and transpiration, precipitation and irrigation. The agro-hydrological model is treated as the ‘real’ process and is unknown to the control system. A linear parameter varying (LPV) model is identified based on the input and output data of the agro-hydrological model, which is then used for zone MPC design. The main contributions of this paper include:

1. A method to identify a linear parameter varying model to describe the dynamics between the irrigation amount and the root zone soil moisture. The LPV model captures the nonlinear relation between the irrigation amount and the root zone soil moisture and is computationally efficient for zone MPC online optimization.
2. An approach to design state and disturbance observers based on the LPV model in state-space form.
3. A zone MPC design with asymmetric zone tracking cost to ensure root water extraction and save irrigation water.
4. Extensive simulations that demonstrate the applicability and efficacy of the proposed model identification and zone MPC algorithms. The results indicate that the proposed zone MPC leads to significant water conservation compared with existing methods, and is robust under model mismatch and weather uncertainty.

2. Methodology

In this work, we propose a control system engineering approach to the soil moisture regulation of agro-hydrological systems. The soil water dynamics of the field is simulated by an agro-hydrological model which consists of nonlinear partial differential equations with source and sink terms characterizing the root water extraction, evaporation and transpiration, precipitation and irrigation, etc (Section 2.1). The agro-hydrological model is treated as the ‘real’ process and is unknown to the control system. For control purpose, a linear parameter varying model is identified based on the input and output data generated by the agro-hydrological model (Section 2.2). The LPV model is augmented with a disturbance state which accounts for model mismatch, and the augmented LPV model is used in the observer and zone MPC design (Section 2.3).

A schematic of the proposed designs and implementation of the closed-loop control system is shown in Fig. 1. The LPV model is identified offline (lower half) before the closed-loop control system is implemented online (upper half). In the online closed-loop control implementation, at each sampling time, soil moisture measurements are taken from the agro-hydrological system and sent to the state and disturbance observer. The observer estimates the system state and disturbance state using an extended Kalman filter based on the augmented LPV model. The estimated state and disturbance are then sent to the zone MPC, which calculates the optimal irrigation amount based on the augmented LPV model, the weather forecast, and the desired soil moisture range. The calculated irrigation amount is then applied to the agro-hydrological system. At the next sampling time, the whole procedure is carried out again based on the updated soil moisture measurement.

2.1. Agro-hydrological model

We consider an agro-hydrological system that characterizes the hydrological cycle between the soil, the atmosphere and the crop. A schematic of the agro-hydrological system is shown in Fig. 2. In the agro-hydrological system, water transportation takes place by means of rain, drainage, evaporation, root water extraction and irrigation. The crop considered in this work is grass, which is irrigated by a sprinkler irrigation system. We assume that the irrigation water enters the ground in the same fashion as rain. Here, only vertical hydrological dynamics is considered and horizontal homogeneity is assumed.

2.1.1. Soil water dynamics

In this system, the soil water flux is computed using the Darcy’s law (Kroes et al., 2017)

$$q = -K(h)\frac{\partial(h+z)}{\partial z} \tag{1}$$

where q (cm/hour) is soil water flux density, $K(h)$ (cm/hour) is hydraulic conductivity, h (cm) is soil water pressure head, z (cm) is the vertical coordinate. Under the assumption of continuity and using Eq. (1), the soil water movement can be described by the following Richards’ equation (Kroes et al., 2017):

$$\frac{\partial \vartheta}{\partial t} = -\frac{\partial q}{\partial z} - S(h) = \frac{\partial\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z} - S(h) \tag{2}$$

where ϑ (cm^3/cm^3) is soil moisture content, S (cm^3/cm^3 *hour*) is a sink term which characterizes the root water extraction. Details on $S(h)$ will be provided in Section 2.1.2.

The hydraulic conductivity $K(h)$ can be calculated using the following relation (Ippisch et al., 2006):

$$K(h) = \begin{cases} K_{\text{sat}} S_e^{\lambda}\left(\dfrac{1-\left(1-(S_e S_c)^{\frac{1}{m}}\right)^m}{1-\left(1-S_c^{\frac{1}{m}}\right)^m}\right), & S_e < 1 \\ K_{\text{sat}}, & S_e \geqslant 1 \end{cases} \tag{3}$$

where S_e (cm/hour) is the relative saturation and can be computed as follows:

$$S_e = \frac{\vartheta - \vartheta_{\text{res}}}{\vartheta_{\text{sat}} - \vartheta_{\text{res}}} = \begin{cases} \frac{1}{S_c}(1+|\alpha h|^n)^{-m}, & h < h_e \\ 1, & h \geqslant h_e \end{cases} \tag{4}$$

S_c (cm/hour) is the relative saturation at the cut-off point h_e in the classical Van Genuchten model and defined by

$$S_c = (1+|\alpha h_e|^n)^{-m}$$

and ϑ_{sat} (cm^3/cm^3) is the saturated moisture content, ϑ_{res} (cm^3/cm^3) is the residual moisture content, K_{sat} (cm/hour) is the saturated conductivity, λ is a dimensionless shape parameter depending on $\frac{\partial K(h)}{\partial h}$, α (cm^{-1}), m and n are empirical shape factors.

Here, we consider $h_e = 0$ (i.e., $S_c = 1$). Then the relation between head pressure h and soil moisture content ϑ can be described as follows:

$$\vartheta = \vartheta_{\text{res}} + (\vartheta_{\text{sat}} - \vartheta_{\text{res}})(1+|\alpha h|^n)^{-m} \tag{5}$$

and the Richards’ equation in (2) can be expressed as