GREENHOUSE CLIMATE CONTROL: A TWO TIME-SCALE APPROACH

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Keywords: optimal control, singular perturbed systems. greenhouse climate control, lettuce cultivation

Abstract

Based on differences in dynamic response times in the crop production process, a decomposition of optimal greenhouse climate management is proposed and evaluated in simulations. Using the favourable results of this decomposition, a hierarchical concept for optimal greenhouse climate management is derived and discussed in view of application in horticultural practice.

1. Introduction

In the literature, optimal greenhouse climate management systems are commonly presented and analysed as hierarchical systems (Udink ten Cate *et al* ., 1978; Tantau, 1991; Challa and Van Straten, 1991). One reason for the hierarchical decomposition of greenhouse climate management is the inherent complexity of the crop production process in which both physical and physiological phenomena take place. Another reason for the decomposition is the fact that in the crop production process, significant differences in response times do exist. For instance crop dry matter production responds rather slowly to changes in the environmental conditions compared with the relatively fast dynamic response of the greenhouse climate to changes in the control inputs and weather conditions.

Using the multi time-scale framework of singular perturbed systems, control of systems containing widely different dynamic response times has received considerable attention in the literature (see e.g. Kokotovic *et al.,* 1986). The multi time-scale approach to optimal control of greenhouse climate when the process is driven by slowly varying external inputs has been addressed by Van Henten and Bontsema (1992). Further to the previous study, a decomposition of the optimal greenhouse climate management problem, including rapid fluctuations in the external inputs (i.e. weather), is proposed here. The decomposition will be presented and discussed in rather general terms. For more details, refer to Van Henten (1994).

2. The optimal control problem

In the 'full' optimal greenhouse climate control problem, both greenhouse climate and crop growth dynamics are considered. The process is described by the following model:

$$\dot{x} = f(x,z,u,v,t), \quad x(t_0) = x_0 \tag{1}$$

$$\varepsilon\dot{z} = g(x,z,u,v,t), \quad z(t_0) = z_0 \tag{2}$$

Proc. Math. and Contr. Applic.
in Agric. and Hortic.
Ed. W. Day, P.C. Young
Acta Hort. 406. ISHS 1996

in which x denotes the slow state variables such as crop dry weight and z denotes the fast state variables including e.g. greenhouse air temperature, carbon dioxide concentration and humidity. The control inputs, u, are e.g. the energy input by the heating system, carbon dioxide supply rate and ventilation rate through the vents. The external inputs, v, are the outside air temperature, humidity, carbon dioxide concentration, wind speed and solar radiation. Here, t denotes time, t_o is the planting date and x_o and z_o are the initial states of the process. The parameter ε is a so-called time-scaling parameter, which expresses the ratio between the slow and fast system responses. As suggested by Shridar and Gupta (1980), in the present analysis, ε is given a value equal to 1 to circumvent a rather cumbersome determination of its exact value.

The performance of the controlled crop production process is evaluated with the criterion:

$$J = \Phi(x(t_1), t_1) - \int_{t_0}^{t_1} L(x, z, u, v, t)dt \tag{3}$$

where $\Phi(x(t_1),t_1)$ represents the value of the crop at harvest, $L(x,z,u,v,t)$ expresses the operating costs of the climate conditioning equipment and t_1 is the harvest time.

Physical limitations of the actuators are represented by simple bound constraints:

$$u_{min}(t) \leq u(t) \leq u_{max}(t) \tag{4}$$

with $u_{min}(t)$ and $u_{max}(t)$ denoting the lower and the upper bound on the control inputs respectively.

To deal with unmodelled effects, such as these of humidity on crop growth and development, simple bound constraints are also imposed on the greenhouse climate states:

$$z_{min}(t) \leq z(t) \leq z_{max}(t) \tag{5}$$

where $z_{min}(t)$ and $z_{max}(t)$ denote the lower and upper bound on the state variables respectively.

With these preliminaries, the control problem is to find $u^*(t)$ for $t \in [t_o, t_1]$ which maximizes $J(u)$ subject to eqns. (1), (2), (4) and (5).

3. Decomposition

3.1. The slow sub-problem

In the slow sub-problem, ε is set equal to zero which results in the reduced order system description:

$$\dot{x}_s(t) = f(x_s, z_s, u_s, v, t), \qquad x_s(t_0) = x_0 \tag{6}$$

$$0 = g(x_s, z_s, u_s, v, t) \tag{7}$$

where subscript s indicates that in this sub-problem the system response of the slow sub-process is emphasized. The objective of the slow subproblem is efficient control of the slow system dynamics. The performance criterion used in the slow sub-problem resembles the performance criterion originally used in the full control problem (eqn.(3)):

$$J_s(u_s) = \Phi(x_s(t_1), t_1) - \int_{t_0}^{t_1} L(x_s, z_s, u_s, v, t)dt \tag{8}$$

The control problem is then to find $u_s{}^*(t)$, $t \in [t_0, t_1]$, which maximizes J_s subject to eqns. (6) and (7) and the state and control constraints of eqns. (4) and (5).

3.2. The fast sub-problem

In the fast sub-problem, efficient control of the fast system dynamics, denoted by subscript f, is emphasized. The dynamics of the slow state variables x are neglected and the optimal state and costate trajectories $x_s{}^*$ and $\lambda_s{}^*$ obtained in the solution of the slow sub-problem are used as a kind of reference trajectories in the fast sub-problem. The dynamics of the fast state variables are described by

$$\dot{z}_f(t) = g(x_s^*, z_f, u_f, v, t), \qquad z_f(t_0) = z_0 \tag{9}$$

The performance criterion is defined as:

$$J_f(u_f) = \int_{t_0}^{t_1} -L(x_s^*, z_f, u_f, v, t) + \lambda_s^{*T} f(x_s^*, z_f, u_f, v, t)dt \tag{10}$$

where $x_s{}^*$ and $\lambda_s{}^*$ are the optimal state and costate trajectories obtained in the slow sub-problem, respectively. The costate λ, expresses the marginal value of the state of the crop, and so the performance criterion, J_f, expresses a trade-off between the cost of operating the climate conditioning equipment, $-L(x_s{}^*, z_f, u_f, v, t)$, and the benefits of greenhouse climate control valued at the marginal value of a unit crop growth, $\lambda_s{}^{*T} f(x_s{}^*, z_f, u_f, v, t)$ (Van Henten, 1994). The control problem is then to find $u_f{}^*(t)$, $t \in [t_0, t_1]$, which maximizes J_f, subject to eqn. (9) and the state and control constraints of eqns. (4) and (5).

4. Simulations

The simulation runs consider a cultivation period of lettuce of 50 days. In the simulations, measured data of the outside climatic conditions, obtained in a greenhouse experiment with lettuce in early 1992, were used (Van Henten, 1994). These data consisted of two minute measurements of the solar radiation, wind speed, temperature and humidity. To evaluate the decomposition, the full problem (in which greenhouse climate and crop growth dynamics are considered simultaneously (eqns. (1) to (5))), the slow sub-problem (eqns. (6) to (8)) and the fast sub-problem (eqns. (9) and (10)) were solved.

In fig. 1 it is shown that the crop growth trajectory obtained in the slow sub-problem agrees well with the evolution of the crop state obtained in the solution of the full problem. though an underestimation can be observed

Fig. 2 shows the variation of solar radiation over two days during the 50 days production cycle.

Figs. 3a and 3b clearly illustrate, for the same two days period, the difference between the carbon dioxide supply rate calculated in the slow sub-problem, ignoring the greenhouse climate dynamics, and the supply rate calculated in the full problem. The carbon dioxide supply rate calculated in the full control problem and the fast sub-problem, however, show a remarkable similarity. Because the greenhouse climate dynamics were neglected in the slow sub-problem, the supply rate responds immediately to rapid fluctuations in the solar radiation. These fluctuations are filtered out when the greenhouse climate dynamics are considered explicitly.

The control trajectories obtained in the fast sub-problem, using the state and costate trajectories obtained in the slow sub-problem, were used in a simulation of the full system including both slow and fast dynamics (eqns. (1) and (2)). The simulated dry matter production, also shown in fig. 1, closely approximates dry matter production simulated in the full problem. Evaluation of the performance criterion J using eqns. (1) to (3) and the control obtained in the fast sub-problem yielded a reduction of only 2% compared with the performance obtained in the solution of the full problem.

Overall, these results prove that, for the problem considered, the decomposition produces a fairly accurate approximation of the full control problem

5. A hierarchical concept for greenhouse climate management

Fig. 4 shows a hierarchical scheme for greenhouse climate control based on the previously described decomposition of optimal greenhouse climate management. The hierarchical control scheme contains two control loops, an outer loop controlling the (slow) crop growth dynamics and an inner loop controlling the (fast) greenhouse climate dynamics.

Using a long term weather prediction, a prediction of the auction price and a measurement of the initial state of the crop, the slow subproblem is solved for the outer control loop. Due to modelling errors and errors in the weather prediction, the actual state and marginal value of the crop may deviate from the pre-calculated trajectories and state feedback is therefore required. Repeated solution of the control problem using new information about the state of the crop as well the weather is hence needed.

Using the state and costate trajectories calculated in the outer loop and a short term weather prediction, the fast sub-problem is solved for the inner control loop to control the greenhouse climate dynamics. This can be achieved using e.g. a receding horizon optimal control approach (Tap *et al.*, 1994). For that purpose, the performance criterion (10) has the favourable property that it does not have to be optimized over the whole growing period, but only over that time interval during which a control action affects the greenhouse climate. In horticultural practice this time interval will be approximately 1 hour.

6. Concluding remarks

In this paper it has been shown that the optimal greenhouse climate management problem can be decomposed into two sub-problems. One subproblem aims at economic efficient control of the slow crop growth dynamics. The second sub-problem has the objective of optimal control of the greenhouse climate dynamics.

Based on this decomposition, a hierarchical scheme for greenhouse climate management has been proposed. This scheme is characterized by the fact that (i) at each control level, control of the dynamic process responses is emphasized, (ii) at each control level, a performance criterion is used which has a clear and direct relationship with the main objective of economic optimal greenhouse climate management, and finally, (iii) the relation between the control levels is defined in terms of state and costate trajectories. The costate trajectories express the economic value of achieving the reference state trajectory at the lower level of control.

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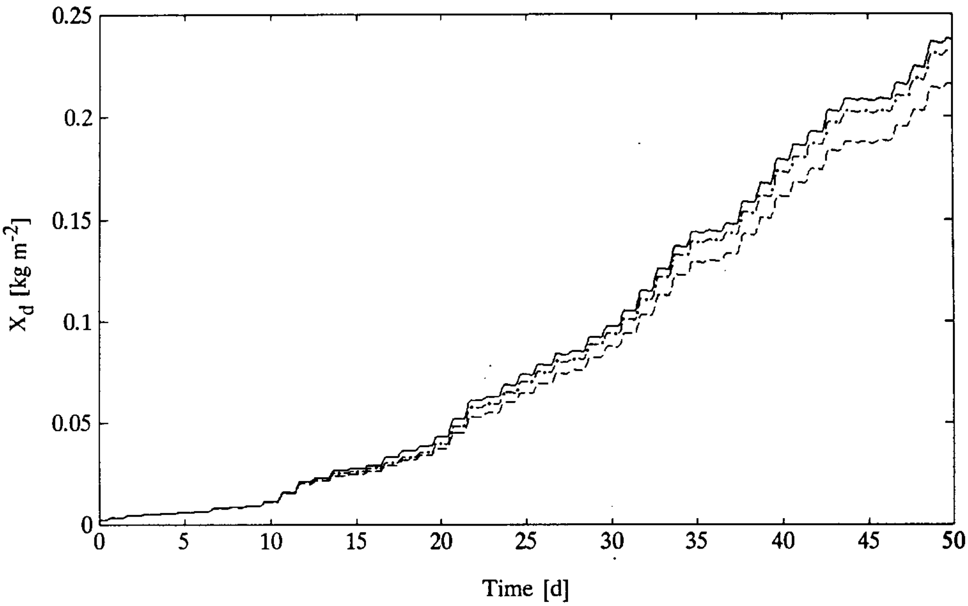

Fig. 1. Simulated crop dry weight obtained in the solution of the full control problem (-), the solution of the slow sub-problem (--) and a simulation of the full system dynamics using the optimal control trajectories obtained in the solution of the fast sub-problem (-•).

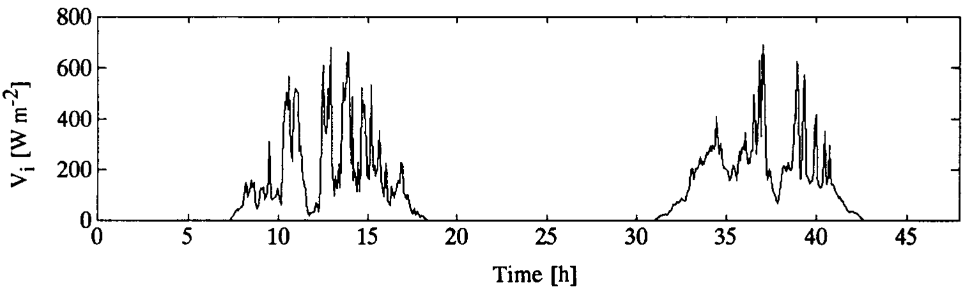

Fig. 2. Solar radiation during two days of the 50 days production cycle.

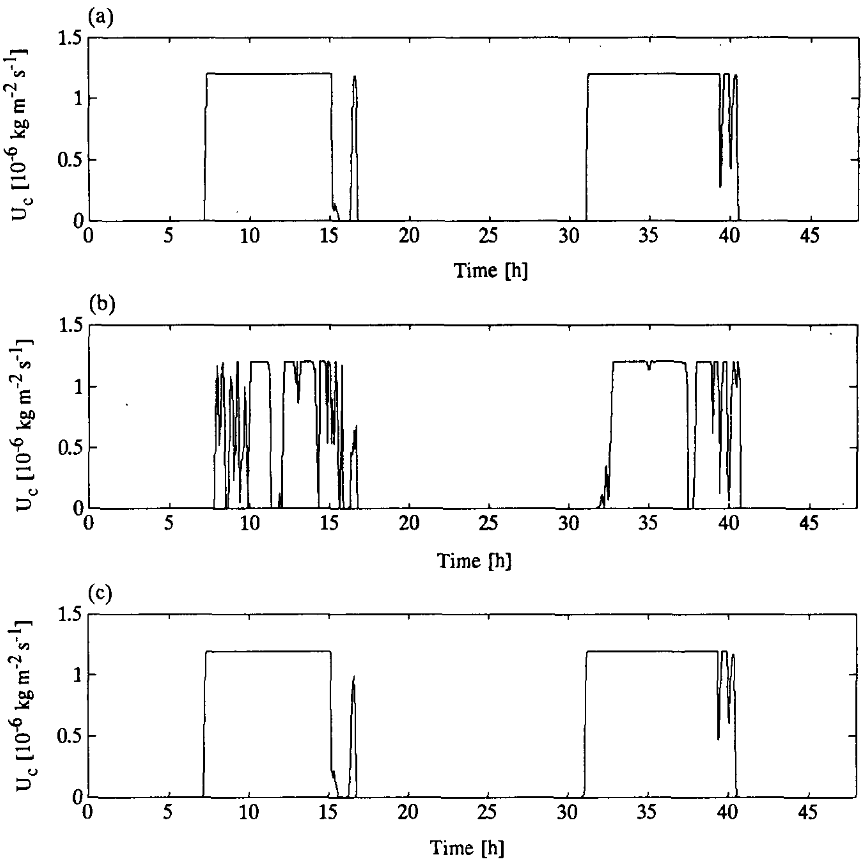

Fig. 3. Optimal carbon dioxide supply rate calculated in the full problem (a), slow sub-problem (b) and fast sub-problem (c).

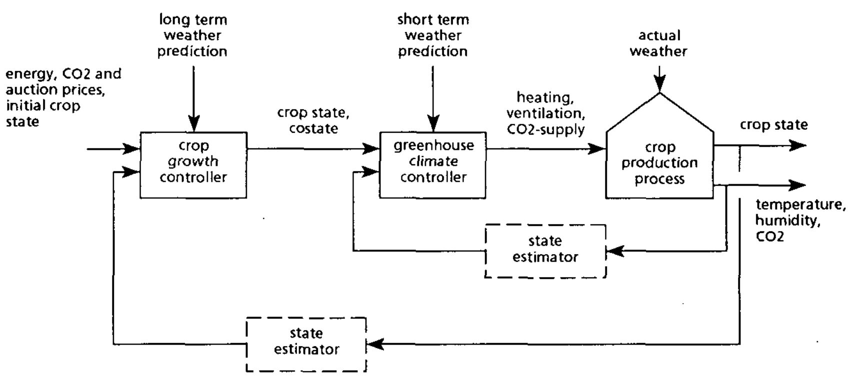

Fig. 4. Optimal greenhouse climate management: a hierarchical concept.