Crop Model-Based Greenhouse Optimal Control System: Survey and Perspectives

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Abstract. A survey is presented of the developments in scientific literature on the greenhouse optimal control. The related problems to optimal control were discussed, and the schematic diagram of optimal control system, combined crop models and optimization algorithm were covered focusing on issues such as: model simplification and validation, definition of objective function, input or output constraints and dynamic optimization, and especially structure-function Greenlab model was made s a first exploration for the optimal control application. Not only the above research issues were listed in the paper, the perspectives and the solutions are presented as well. It is pointed out that only the crop growth model is integrated into the greenhouse climate optimal control, the best economical result and energy-saving can be warranted.

Keywords: Greenhouse optimal control; Crop growth model; Greenlab model; Dynamic optimization; Energy saving

1 Introduction

The operation cost of current modern greenhouse is usually high due to the complexity of greenhouse-crop production system, so many efforts have been made to develop optimal management and control strategy which aims to reduce the energy consumption, thus to improve the efficiency of greenhouse production[1,2,3,4,7,10]. Simulation and experimental work were also carried out to support the effectives of optimal control system. For instance, Van Ooteghem found that through the simulation of a optimal closed loop controls, the boiler use was reduced, thereby reducing fossil energy use, and gas use was decreased by 77% compared to a conventional greenhouse[5]; Van Henten made a experimental comparison of the performance between optimal control approach with the traditional control system, and the results showed that with optimal control , energy and carbon dioxide are used more efficiently[3].

However, it is still not an easy task to apply the optimal control concepts into greenhouse production practice , because the current models for greenhouse and crop are usually too complex to be incorporated into the optimal control. But crop models

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are essential, and without the support of crop models, it will be difficult for optimal control system to achieve the appropriate results, because the dynamic greenhouse-crop models output the state variables required by objective function[5,13]. The quality of crop models will affect the preformance of the optimal control , so for application of optimal control, accurate and simplified models are required , i.e. Only if to build an optimal control system combined appropriate crop growth model, energy efficient operation can be implemented[1]. In this paper, we will give a brief description about such optimal control system, and its recent advances about related optimal control problem will be presented in detail in order to exploit the possibilities for practical application.

2 The System Structure of Crop Model-Based Optimal Control

In order to understand the system structure of optimal control, in this section we will illustrate it by first comparing with the conventional climate control system in current practice (Fig.1). In conventional control of the greenhouse climate, the grower defines the set-points of the greenhouse climate variables such as temperature, humidity and carbon dioxide concentration , and the climate control computer works to achieve the desired climate using measurements and feed-back control techniques. During the growth season, the grower may modify the setting trajectory based on the observation of crop growth state and their experience.

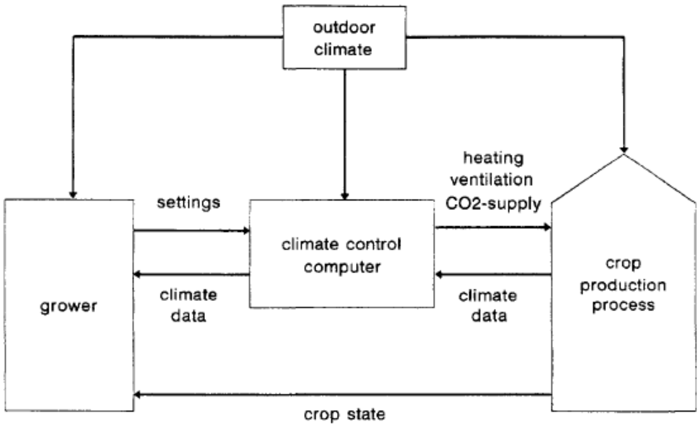

Fig. 1. A schematic diagram of the conventional climate control procedure [3]

In the above traditional system, trajectory settings were determined by the grower according to heuristic rules, which will have a definite effect upon the consumption of energy and other resources, as well as on growth and development of the crop, but the exact effect is unknown to the grower, and can at present only be inferred from experience [1].

We can see that the traditional control system of greenhouse climate don't take into account the costs in an explicit manner, and provide the control actions by focusing almost always on the performance. So the costs for keeping that performance might be unacceptable[10].

The optimal control strategy provide an alternative method to consider energy consumption [7,10]. It consists of models for the greenhouse as well as for the crop, a suitable objective function and an optimization algorithm(Fig.2), which will be introduced in the following.

In Fig.2 system, the control inputs are not the settings defined by the grower like above conventional system, because the incorporation of the heuristic control rules in the optimal control decreases the optimal control freedom. Therefore the greenhouse –crop model used in this research is based on actuator values as control inputs. But the input and output constraints are still need to be given by the grower. Other inputs include external weather data, and because the results of the optimal control strongly depend on the weather conditions, reliable forecasts are also needed in the optimal control system.

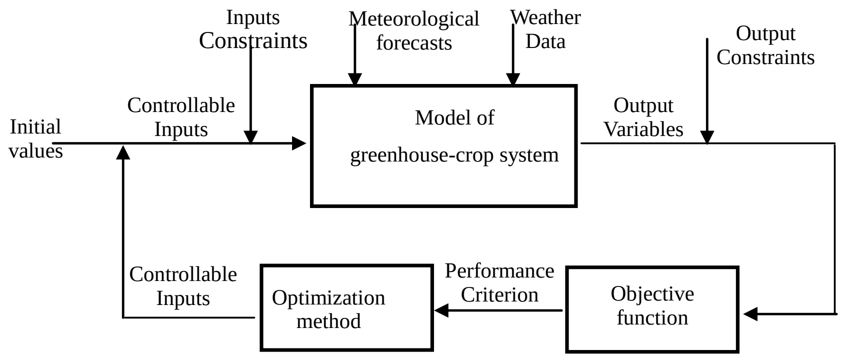

Fig. 2. The system structure of model-based optimal climate control

Optimal control approach is based on a mathematical model for calculating greenhouse energy consumption and on a mathematical method for minimizing total energy consumption, so the models for greenhouse climate as well as the crop are required. In a formal way, the model is usually represented by state equation[3],i.e.

$$\frac{dx}{dt} = f(x,u,v,t), \qquad x(t_b) = x_b \tag{1}$$

in which x are the state variables, u are the control inputs, v are the external inputs, t denotes time and dx/dt represents the rate of change of the state in time. The initial state of crop production process is denoted by $x(t_b)$ in which t_b represents the planting date. The state of production process is represented by variables relating to crop such as fresh weight, as well as to variables describing the indoor climate such as air temperature, humidity and carbon dioxide concentration.

The function $f(.)$ describes the dynamic behavior of greenhouse climate and crop, i.e. modeling methodology. In most literatures about optimal control strategy, the greenhouse climate model used is mainly based on energy and mass balance equations[4,5] , the details of which will not be explained in this paper, and the description about the energy balance can be found elsewhere[11,16,17]. While the crop growth model used in present optimal greenhouse control will be described in detail in section 3.

The objective function in the optimal system Fig.2 summarizes the output variables to one single performance criterion, which depends on the requirement of user, and it will affect the performance the optimal control. In general, the performance criterion can be summarized into two category: (1) economic performance criterion; (2) cost function. According, the definition of objective function is

$$J(u) = \Phi(x(t_f), t_f) - \int_{t_b}^{t_f} L(x, u, v, t)dt \tag{2}$$

Or

$$J(u) = -\Phi(x(t_f), t_f) + \int_{t_b}^{t_f} L(x, u, v, t)dt \tag{3}$$

Where $\Phi(.)$ is the term related with the expected crop economic value and $L(.)$ term related with the operation costs of the climate conditioning equipment. The optimal control problem defined by Eq. 2 is to determine the trajectory of the control inputs $u^*(t)$ over $[t_b, t_f]$ which maximize the economic revenue or production, while the performance criteria defined by Eq.3 aims to minimize the total energy consumption subjected to input and output constraints.

The optimization method is to find the solution of above optimal control problem defined by the objective function. In section 4, several commonly used optimization algorithm will be discussed and reviewed briefly.

3 Greenhouse Crop Model Oriented For Optimal Control

The Model quality is a fundamental aspect to achieve adequate control performances. Here some successful crop models in horticultural practice will be discussed in order to exploit their possibilities applied in the optimal control. At present, the main obstacles are that the current greenhouse crop models are too complex, or require too many data or too much calculation, which is not suitable for optimal control task, so simple or very compact models are required.

Current horticultural crop models are mostly based on a photosynthesis model and an evaporation model, and the typical instance is TOMGRO[12,18]. Although TOMGRO model has been validated and proved enough accurate , it has too many parameters to be directly involved into the optimal control method . So its simplified version is proposed in order to be suitable for the optimal application . For instance , Pucheta restricted TOMGRO model to two state variables : dry weight and number of leaves which are modeled by Eq.4. to implement the optimal greenhouse control of tomato-seedling crops[15].

$$\dot{W} = E[P_g(T, S_{PAR}, CO_2) - R_m(T)W], \qquad \dot{N} = r_m\, r(T) \tag{4}$$

Where W and N are the time-dependent state variables representing the total dry weight and the number of leaves, respectively. $P_g(.)$ is the photosynthesis rate which depends on the temperature , solar radiation and the concentration of CO_2; $R_m(.)$ is respiration rate of the leaves, which only depends on temperature.

van Straten also described a simplified model which has similar modeling mechanism with the description in Eq.5 , but it gives a fairly general representation of crop production[1].

$$\begin{aligned} \dot{x}_n &= q_P\{C, I, \cdot\} h\{x_n\} - (1+\theta) s\{x_n\} \sum_i q_{Gi}\{T, x_{si}, \cdot\} - \sum_i q_{Mi}\{T, x_{si}, \cdot\} \\ \dot{x}_{si} &= s\{x_n\} q_{Gi}\{T, x_{si}, \cdot\} \quad i = 1, \cdots, N \end{aligned} \tag{5}$$

Where $\dot{x}_n$ and $\dot{x}_{st}$ are two state variable representing not-structural biomass and structural biomass. C, I and T are the temperature , solar radiation and carbon dioxide concentration, respectively.

Above models is only a general description for optimal control-oriented application. Ioslovich fruther proposed a three-stage growth model for tomato named MBM-A[2], which is modelled in a more adequate and accurate way . In MBM-A model, two state variables namely accumulated vegetative dry mass x and the harvestable red fruits y are defined and they have different differential equations as described by Eq.6.

$$\begin{cases} \dfrac{dx}{dt} = M(t,U) f(x), \quad \dfrac{dy}{dt} = 0 \quad \textit{vegetative} \quad \textit{stage} \\ \dfrac{dx}{dt} = M(t,U)(1-\alpha) f(x), \quad \dfrac{dy}{dt} = M(t,U) g(y)/K_c \quad \textit{vegetative}-\textit{reproductive} \quad \textit{stage} \\ \dfrac{dx}{dt} = 0, \quad \dfrac{dy}{dt} = M(t,U) f(x)\eta \quad \textit{reproductive} \quad \textit{stage} \end{cases} \tag{6}$$

From Equation 6, the time-dependent state variables x and y relies on control variables U , including greenhouse heating, ventilation and CO2 enrichment, which will influence the greenhouse climate such as temperature and CO2 concentration. Further assumption is that the mean daily temperature is strongly correlated with the mean daily light, and light is strongly correlated with photosynthesis. In Eq.6, unknown coefficients are need to be calibrated, and the model was validated against TOMGRO.

The recently emerged plant structure-function model Greenlab also provides the possibilities to be introduced into the optimal control strategy [6]. Because it is an efficient dynamic process of balancing the simplicity and complexity. It consists of biomass production and allocation equations, and the plant produces biomass by leaf photosynthesis,i.e.

$$Q(i) = F(S(i), E(i), r1, g(r2, S(i), N(i)) = \frac{E(i)S(i)}{r1}[1 - \exp(-r2\frac{\sum_{j=1}^{N(i)} S_j(i)}{S(i)})] \tag{7}$$

where $Q(i)$ represents the dry biomass created at the growth cycle i and we define the growth cycle (GC) as the thermal time necessary for each plant axis to develop a new growth unit (GU); S_j is the blade area of the j th leaf, and $S(n)$ is a kind of ground projection area of the leaf surface; Parameter $r1$ sets the leaf-size effect on transpiration per unit leaf area, while $r2$ accounts for the effect of mutual shading of leaves according to the Lambert–Beer's law.; $N(i)$ is the number of leaves; $E(i)$ is the average biomass production potential depending on environmental factors, such as light, temperature and soil water content.

The biomass produced by photosynthesis is redistributed among all the organs according to their demands and sink strength:

$$\Delta q_o(i, j) = \frac{P_o \times f_o(j)}{D(i)} Q(i-1) \tag{8}$$

Where Δq_o is the biomass increment of o-type organ; P_o are the organ sink strengths and are model hidden parameters. f_o are normalized distribution functions characterizing the evolution of the sink strengths; $D(i)$ is the total biomass demand.

The Greenlab model provides an interaction interface with climate and an explicit definition about growth cycle(the duration of which can vary from several days(tomato) to one year), so it describes the evolution of the plant structure periodically. Furthermore, the validation study of this Greenlab model has been well made[8,22] , and the research work shows possible applications of GreenLab in optimization and control for agronomy.

4 Optimization Algorithm

The Effective optimization methods play an key role on finding the solution of optimal control problem. The above-stated control problems in section 2 belong to dynamic optimization problems which can be solved by choosing a dynamic programming technique, such as Hamilton-Jacobi-Bellman equation[2], Lagrange Multiplier technique [19], Genetic algorithm[21], Model-based Predictive control[10]and Receding Horizon Optimal Controller[5], and so on.

However, optimal control concepts and nonlinear dynamic programming (NDP) in particular have almost not been used in practice, due to the implementation complexity. Therefore the researchers try to improve the optimization techniques mentioned above to be capable of using crop growth models. For example, Luus proposed iterative dynamic programming(IDP)procedure to solve the optimal control problem[14]. IDP—a modified dynamic programming is a computational procedure that allows one to obtain the optimal control trajectories for time varying nonlinear processes, with any type of performance indices and with restrictions on both state and control variables. The application of this algorithm to a continuous system requires discretization of the differential equations that model the process, and quantification of the variables of state, decision, control and time. Ioslovich used the Hamilton-Jacobi-Bellman formalism in the form of Krotov-Bellman sufficient conditions and the optimal value of the constant seasonal control intensity can be approximately obtained from the MBM-A model by Eq.3 [2]. Because during each sampling period, the simulation of the associated optimal closed loop control system is very time consuming in general. to drastically limit the simulation time, the optimal control problems can be solved by the receding horizon optimal controller[5,21] used genetic algorithm combined with Greenlab model to achieve the simulation for greenhouse water supply optimization problem, which open the possibilities for Greenlab model to be applied to optimal greenhouse climate control .The advantage of genetic algorithm is to avoid local minima.

Optimal control problem based on non-linear and non-quadratic performance criteria, such as those discussed in this paper , are very difficult to solve analytically. Iterative schemes need to be used to achieve a numerical solution of the mathematical problem. Dynamic optimization problems can be numerically solved by direct or indirect methods. Over the last years, a number of numerical search methods have been developed. For instance, Van Henten proposed a modified steepest ascent algorithm and used a forth order Runge-Kutta integration algorithm to obtain the numerical solution for optimal control trajectories[3]. An indirect gradient method was proposed which has proven its effectiveness in optimal greenhouse control and many other fields[5,20]. The search procedure to find optimal value is described as the following:

- start the simulation model with initial values for a set of input variables;
- calculates the output variables by the simulation model and an objective function value;
- derives an improved set of controls the optimization procedure and starts a new simulation procedure

The above feedback loop is repeated until the objective function value converges on the optimum .Since the simulation model runs independently from the optimization algorithm, there are in principle no restrictions with respect to its structure. The drawback is ,there is no certainty finding the absolute minimum or maximum[13]. Besides this, the selection of initial values also need to paid more attention because it will affect the performance of optimal algorithms.

5. Discussion and Perspectives

This paper presented a framework of crop model-based optimal greenhouse control system and key factors, which shows optimal control of the greenhouse is feasible. However, even if some valuable research work has been made during the last decades, we can see that it is still a long way for the optimal control strategy to be applied into greenhouse practice, especially for China horticulture production. To solve above problem, current elaborate and complex horticultural crop models are needed to simplified to be suitable for optimal control, and only if are the simplified models calibrated and experimentally proven accuracy, they can be incorporated into the optimal algorithms; Efficient optimal algorithms are required to solve the time-consuming and stability problem, and time-scales problem induced by crop growth response and control actions are also the obstacles to hamper the application of optimal control. Despite the challenging list of issues that need further investigation, we are convinced that with the improvement of modeling technology and computer power, the optimal control methodology based on crop growth model must find its way for on-line production practice, and provide an effective tool to achieve the energy saving.

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