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SENSITIVITY OF ON-LINE RHOC OF GREENHOUSE CLIMATE TO ADJOINT VARIABLES FOR THE CROP

G. van Straten, R.F. Tap, L.G. van Willigenburg

Wageningen Agricultural University, Systems and Control Group
Bomenweg 4, 6703 HD Wageningen, The Netherlands
e-mail: gerrit.vanstraten@user.aenf.wau.nl

Abstract: The optimal control of greenhouse climate and crop cultivation is performed by two-time-scale decomposition. First the slow sub-problem is solved leading to a seasonal pattern for the crop adjoint variables associated to the assimilate buffer, and the fruit and leaf weights. The adjoint variables or co-states are then used to represent the marginal price of a unit of buffer, leaf and fruit in an on-line receding horizon control of the greenhouse climate. Comparing simulations using the dynamic co-states to experimental results obtained with fixed co-states reveals that the on-line control is sensitive to the co-state trajectory. This suggests that it is advantageous to repeat the seasonal optimization from time to time to adjust to past weather and realized crop state.

Keywords: Dynamic optimization, receding horizon optimal control, greenhouse climate control, crop cultivation control.

NOTATION

greenhouse states z:

T_g	greenhouse air temperature
T_s	virtual greenhouse soil temperature
T_p	heating pipe temperature
V_i	air moisture content
C_i	CO_2 concentration in the air

crop states x:

D	development stage
B	assimilate buffer
W_L	leaf dry weight
W_F	fruit dry weight

co-states λ_s:

λ_B, λ_{WB}, λ_{WF}	co-states for assimilate buffer, leaf dw and fruit dw, respectively.

controls u:

r_{wi}, r_{ww}	window opening on lee-side and windward side, respectively
r_h	relative heating valve opening
φ_{inj}	CO_2-dosage flux

exogenous inputs v:

G	global radiation
T_o	outside temperature
w	wind speed
C_o	outside CO_2-concentration
RH_o	outside relative humidity

other variables:

RH_i	inside relative humidity
P_C, P_T, P_V	penalty functions for CO_2, temperature and humidity
J	goal function
H_u	heat input
p_F, p_H, p_C	price values for fruits (auction tomato price), heat input, CO_2 input, respectively.

1. INTRODUCTION

The scientific knowledge on plant and greenhouse behaviour can be exploited in the most economical way by applying the methods of optimal control. Optimal control is based on a dynamic model describing the system behaviour and a criterion to be optimized. (Bryson and Ho, 1975; Lewis, 1986). The grower's overall objective to obtain maximum profit can be implemented directly through a proper choice of the criterion (e.g. Seginer and Sher, 1993).

Direct application of optimal control is hampered by the lack of knowledge of the exogenous variables, which, in contrast to many other control problems, do not just constitute a disturbance but are, in any case with respect to the solar irradiance, essential resources for crop growth. In addition, feed-back is needed to cope with the actual weather and unavoidable errors in the models.

In the approach on which this paper is based this problem is solved by first calculating a seasonal pattern of the crop adjoint variables, assuming a pseudo-static greenhouse and a selected weather pattern, and then using this information in a short term receding horizon controller. In this way, a link is provided between the relatively slow crop behaviour and the on-line control, exploiting the weather variability as much as possible.

The problem addressed in this paper is to see to what extent the crop adjoint variables, which act as marginal values for increment in crop biomass during the on-line control, influence the behaviour of optimal controller algorithm.

2. THE IDEALISED OPTIMAL CONTROL PROBLEM

The system can be described by the following set of differential equations:

$$\frac{dx}{dt} = f(x,z,u,v,t)$$
$$\frac{dz}{dt} = g(x,z,u,v,t) \tag{1}$$

where z represent the greenhouse states, x the crop states, u the controls, v the measurable exogenous inputs, and t the time. The models are described in detail by Tap (1999).

If the models were exact, and the exogenous inputs from the weather were perfectly known in advance, then the optimal control policy would be obtained by finding the control sequence that minimizes the difference between the costs for heating and CO_2 dosage, and the benefits obtained by selling the harvested tomatoes. The crop model used describes the increase of the assimilate buffer by photosynthesis under influence of light, and the use of assimilates for growth and maintenance respiration, and the distribution over fruits and leafs under influence of the temperature. However, other developmental effects such as leaf stretching, bud formation, etc. are not described explicitly, nor the risks of diseases due to e.g. condensation. Consequently, it is necessary to modify the criterion function to give the grower the possibility to abate adverse effects that might occur in practice. So, the optimal control problem can be formulated as

$$u^* = \arg\min J$$
$$J = \int_{t_o}^{t_f} \left(-p_F \frac{dW_{HF}}{dt} + p_C \Phi_{inj} + p_H H_u + P_C + P_T + P_V \right) dt \tag{2}$$

were t_o is the beginning and t_f the end of the growing season, and where for brevity of the notation the dependancy on u of the right hand side variables is implied. The term dW_{HF}/dt represents the harvest rate of fruits. The harvest process is part of the model and is described as a function of the total fruit weight. The penalties are zero within the ranges specified, and simple linearly increasing functions outside.

3. SEASONAL OPTIMIZATION

The optimal control problem defined by Eqn.(2) requires knowledge of the exogenous variables v. Over the season this knowledge is not available. Therefore the problem is separated into two sub-problems. First, using an assumed weather pattern v' and the assumption that the greenhouse is in quasi-steady state, i.e.

$$f(x,z,u,v',t) = 0, \quad \rightarrow \quad z = h(x,u,v',t) \tag{3}$$

the quasi-optimal trajectories of the crop states are computed. This problem is solved by forming the Hamiltonian:

$$H = -L + \lambda_s f(x,z,u,v',t) \tag{4}$$

and calculating u^*,x^* and the co-states λ_s^* that fulfil the necessary conditions. In this expression L is the part under the integral of Eqn. (2), and z follows from Eqn.(3). The co-states λ_s represent the marginal values of the accompanying crop states x:

$$\lambda_s(t) = \frac{dJ}{dx_s(t)} \tag{5}$$

i.e. they represent the marginal costs of producing an additional unit of assimilate buffer, leaf and fruit.

Problem (4) was solved by taking the observed hourly averaged weather inputs of the experiment year 1995. The starting time of the calculation was when the plant had matured and started to produce fruits. Figure 1 shows the result for the co-state of the assimilate buffer. Since the assimilate buffer is filled during day, and drawn during night, the co-state also shows a clear daily pattern. As expected, initially the marginal value of assimilates is negative at night (positive costs), and positive during the day. The marginal value of the leafs is negative in the beginning of the harvesting period (Figure 2). In stead, it makes sense to put as much as

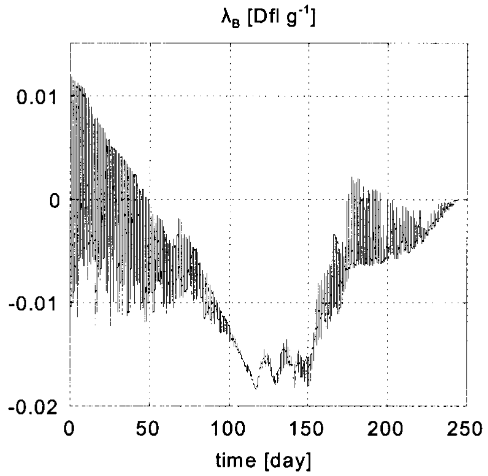

Fig. 1. Co-state pattern over the harvesting season (1 March till 31 October) for the assimilate buffer (λ_B) assuming 1995 weather. Fruit auction price p_F=0.02 Dfl/g.

possible of the assimilates into fruits. Between day 80 and 160 leaf production is profitable, because leaf area is needed to guarantee enough assimilate production in autumn when the global radiation is decreasing. At the end of the season it is a waste to invest in leafs since there is not enough time to pay back. Both co-states go to zero at the end.

4. ON-LINE OPTIMAL CONTROL

Once the marginal values of the crop (crop co-states) are known, they can be used to link the long term optimization to short term optimal control, in order to accommodate fast changes in the weather. This is done by formulating a receding horizon problem over one hour, using the measured weather as hourly forecast, and the measured greenhouse states as initial conditions. A piece-wise constant control sequence is sought according to

$$\{u^*(t),T\}_{t_k}^{t_k+t_h} = \arg\min J_f$$
$$J_f = \int_{t_k}^{t_k+t_h} \left(-L+\lambda_s^T f\right) dt \qquad (6)$$

where $-L$ is the term under the integral of Eqn. (2), and the second term represents the costs (negative value) of an additional increment of assimilate buffer, leaf and fruits. The control horizon is denoted by t_h, and the notation $\{u(t),T\}_{tk}^{tk+th}$ is used to represent the sequence $\{u(t_k), u(t_k+T), ..., u(t_k+t_h)\}$. Only the first control is applied to the system, and a new optimization problem is solved at the next sampling interval. Further details of the procedure are described by Tap (1999).

5. EXPERIMENTAL RESULTS WITH FIXED CROP CO-STATES

At the time the experiments were performed the slow sub-problem had not yet been solved. Therefore fixed marginal values had been assumed, being $\lambda_B=p_B=0$, $\lambda_{WF}=\lambda_{WL}=p_F=p_L=-0.02$ Dfl/g. The marginal values were set equal to the auction price of tomatoes. The leafs were given the same value, in order to make sure that the short term optimal controller does not ignore the production of leafs. Figure 3 top shows the exogenous variables, the important greenhouse states and the controls for 1 September 1995.

During night time the heating is turned on in order to satisfy the lower temperature constraint (15 °C at night and 17°C during the day). During day time the heating is turned off, as the temperature stays above its lower boundary and the upper relative humidity constraint (set at 95%) is satisfied as well. During the night, when the humidity is expected to be no problem the windows are closed to save energy. During the day the temperature is adjusted by opening the windows in order to economise on respiration losses, which maximizes income as all biomass (fruits, leafs and harvested fruits) have the same assumed marginal value in the experiment. The windows stay closed until about 8 a.m. to benefit from the high CO_2-concentration at the end of the night. During a short time when the sun is shining and the windows are still closed, CO_2 is dosed. The dosage is suspended as soon as the windows open for humidity and temperature reasons.

Tap (1999) shows by simulation that the results are robust, i.e. deviations between model and true system are effectively counteracted by the feed-back provided by the receding horizon controller.

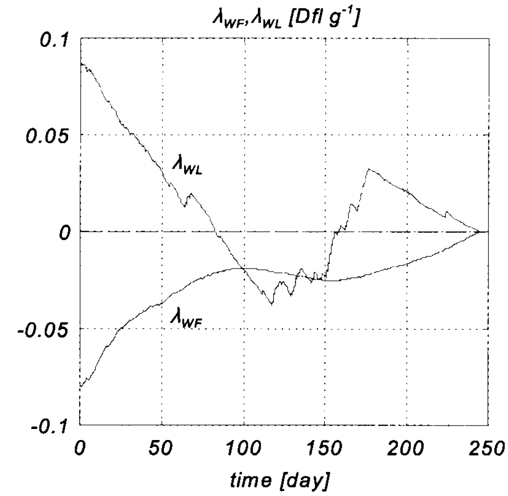

Fig. 2. Co-state pattern over the harvesting season (1 March till 31 October) for leafs (λ_{WL}) and fruits (λ_{WF}) assuming 1995 weather. Fruit auction price p_F=0.02 Dfl/g.

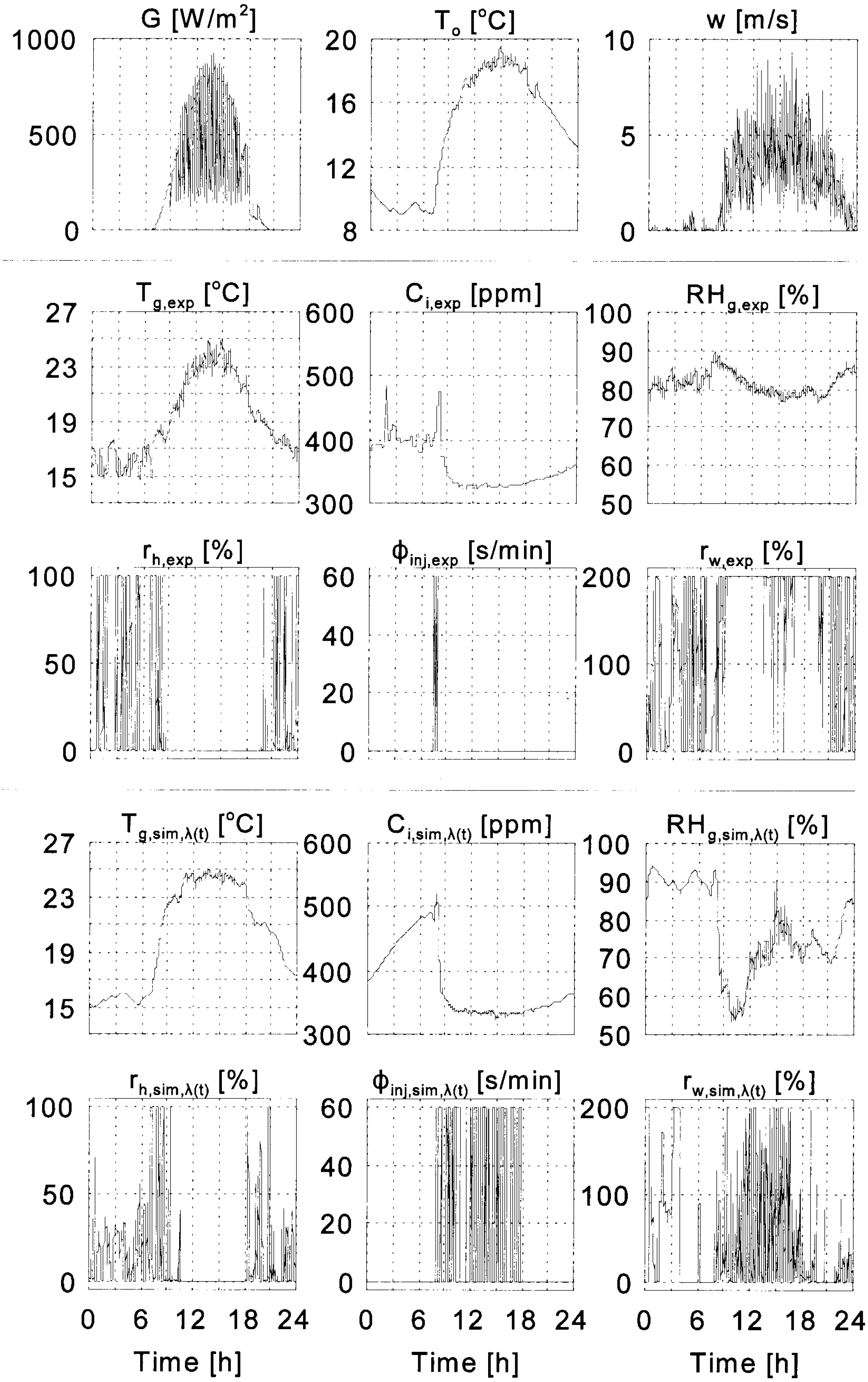

Fig. 3. Results for 1 September 1995. Top: exogenous inputs; Middle block: first row: state trajectories during the experiment, second row: controls during the experiment. Fixed co-state marginal values (see text). Bottom: first row: state trajectories simulated with the co-state trajectories of Figure 4, second row: associated controls.

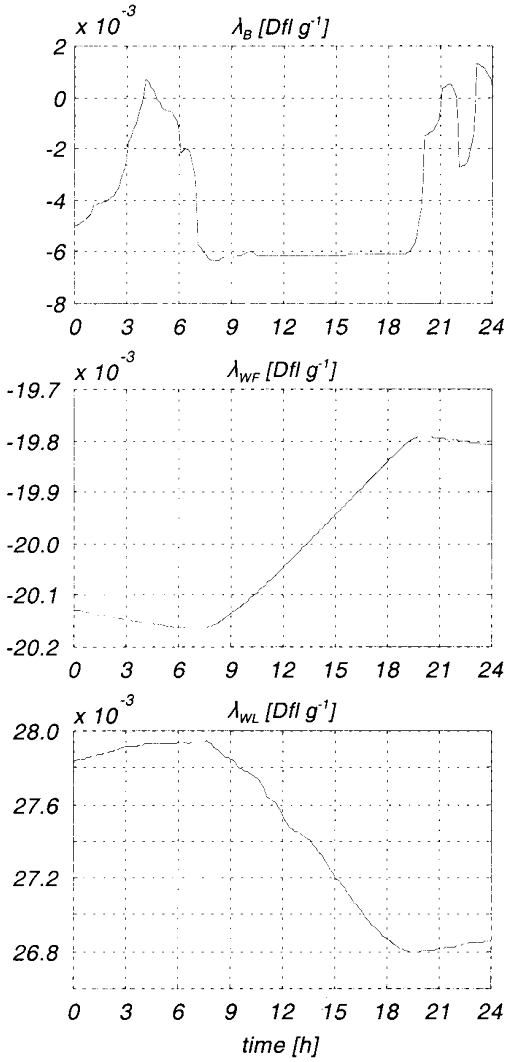

Fig. 4. Crop co-state patterns for 1 September 1995.

6. SIMULATION RESULTS WITH DYNAMIC CO-STATES

Knowing in retrospect the co-state trajectories, it is now possible to simulate the behaviour of the RHOC controller that would have been obtained had the co-state pattern been used rather than fixed values. Figure 4 shows the co-state pattern for 1 September 1995. The result of the RHOC simulation is shown in Figure 3 (bottom). The buffer co-state is fluctuating. In the simulation it makes more sense to invest in the assimilate buffer during the day, than in the experiment, but since the marginal values are small, the effect is probably limited. Since the marginal fruit price is practically the same as the fixed value in the experiment it will also have little effect. However, the leaf co-state at this day is positive, meaning that it is more costly to produce leafs in the simulation than assumed in the experiment. As a consequence, the temperature is increased in order to produce as few leafs and as much fruits as possible. This can be achieved by closing the windows as much as possible. Since the temperature is higher, the relative humidity does not reach its limits as fast as during the experiment. Apparently the ventilation rate, though lower, is still enough to prevent moisture problems. The optimal control algorithm immediately tries to take advantage of this situation and starts to dose CO_2 when the windows are closed or almost closed.

7. CONCLUSION

The separation of the optimal control problem of tomato cultivation in greenhouses into a long term and a short term optimization problem leads to a feasible optimal control algorithm. It was shown that the behaviour of on-line receding horizon control is influenced by the adjoint variables for the crop states obtained from a seasonal optimization. This suggests that it makes sense to repeat the seasonal optimization from time to time, in order to adjust to the past weather and the realized state of the crop.

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