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ON-LINE ESTIMATION OF THE TRANSPIRATION IN GREENHOUSE HORTICULTURE

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Abstract: Using a so-called unknown input observer (UIO) the transpiration of a crop in a greenhouse is on-line estimated. In this way a useful tool for the horticultural practice is developed, giving the grower instantaneous insight in the status of his crop. The design, implementation and performance in practice will be shown. *Copyright © 2007 IFAC*

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1. INTRODUCTION

In modern greenhouse horticulture the climate is controlled by a sophisticated greenhouse climate computer. The role of the grower is to define among others temperature trajectories, carbon dioxide set points and relative humidity boundaries, in such a way that during the growing season the crop in the greenhouse is maintained in an optimal condition and crop production is maximised. The climate computer will then realise the climate desired by the grower. The grower observes his crop and decides if the realised climate is good for the crop. A major parameter for the crop status is the transpiration. A good transpiration of the crop means that the plants are not stressed and are developing well. Although transpiration gauges (gullies) are commercially available for high-wire crops, in most cases the grower has to do a visual inspection, which will not always give a direct insight into the actual transpiration.

In this paper a new method is proposed which estimates on-line the transpiration of a crop in a greenhouse, by using only climate variables, already measured by the grower's climate computer. The method is based on an observer technique for estimating unknown input of a system, a so-called unknown input observer (UIO).

2. OBSERVER DESIGN

It is assumed that the original process has the following form:

$$\dot{x} = Ax + Bu + Ed, \ y = Cx,$$
$$x(0) = x_0, x \in \mathbb{R}^n, u \in \mathbb{R}^m, d \in \mathbb{R}^q, y \in \mathbb{R}^p \quad (1)$$

Where x is the state of the system, u is the control input and d is disturbance input acting on the system and y is the output of the system. Here it assumed that $d(t)$ is a measurable disturbance. In greenhouse production, most of the disturbances acting on the process are related to the outdoor weather, which is measured. An observer, the so-called Luenberger observer, named after his inventor has then the following form (Luenberger, 1966; Luenberger, 1971):

$$\dot{\hat{x}} = A\hat{x} + Bu + Ed + L(y - \hat{y}),$$
$$\hat{y} = C\hat{x}, \hat{x}(0) = \hat{x}_0 \quad (2)$$

Where $\hat{x}$ and $\hat{y}$ are the estimated state and output and L is called the observer gain. The observer is actually a copy of the model of the original system, but since the initial conditions of the system and observer are in general different, the outputs will be different. The observer is therefore driven by the difference of the outputs of the system and the observer. If finally $\hat{y}(t) \approx y(t)$ then, under the assumption that (C,A) is observable, $\hat{x}(t) \approx x(t)$.

The question is how to determine L. For this we consider the error between the state of the system and the state of the observer, $e(t) = x(t) - \hat{x}(t)$, using (1) and (2) it follows that:

$$\dot{e}(t) = (A - LC)e(t)$$
$$e(t_0) = x_0 - \hat{x}_0 \tag{3}$$

If L is chosen in such a way that the matrix A-LC has all its eigenvalues in the left half complex plane, then independent from $x_0 - \hat{x}_0$, $e(t) \rightarrow 0$. The eigenvalues of A-LC can be chosen arbitrarily, provided that (C,A) is observable.

Observers can also be defined for non-linear systems, the observer gain will then in general depend on the state (Dochain, 2003).

3. UNKNOWN INPUT OBSERVER

Observers originally were designed to estimate the non measured states. In recent years observer design is also used to estimate unknown inputs of a system. For simplicity we consider a scalar system:

$$\dot{x}(t) = ax(t) + bu(t) + ed(t)$$
$$y(t) = x(t) \tag{4}$$

Where $u(t)$ is an unknown input and $d(t)$ is a measured disturbance. Furthermore it is assumed that $u(t)$ is a slowly varying signal, so $\dot{u}(t) \approx 0$. Defining $z_1 = x$ and $z_2 = u$, the system can be written as:

$$\frac{d}{dt}\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{pmatrix} a & b \\ 0 & 0 \end{pmatrix}\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{pmatrix} e \\ 0 \end{pmatrix}d \tag{5}$$

This system is similar to the one described by eqn. (1). Using an observer, with observer gain $L = \begin{bmatrix} l_1 \\ l_2 \end{bmatrix}$ it is easy to calculate that the transfer function from the unknown u (z_1) to the estimated $\hat{u}$ ($\hat{z}_1$) is given by:

$$G(s) = \frac{bl_2}{s^2 + (-a + l_1)s + bl_2} \tag{6}$$

Defining:

$$\omega_0 = \sqrt{bl_2} \ , \ \xi = \frac{-a + l_1}{2\omega_0} \tag{7}$$

the transfer function is in standard second order form. We can therefore give a good recipe for tuning the observer. For a good estimate of the unknown input signal, which we assumed to be slowly varying, the transfer function, for low frequencies should have a gain close to 1 and a phase lag close to zero. One can

obtain such a result by choosing $\xi = 0.707$ and ω_0 5 to 10 times the dominant frequency in the signal to be estimated.

4. HUMIDITY IN A GREENHOUSE

The humidity balance, expressed per m^2 soil, for a greenhouse, is given by (Henten, 1994, Stanghellini 1987, Stanghellini and de Jong,1995):

$$h\frac{d\chi_a}{dt} = E - V - C \tag{6}$$

Where h is the average height of the greenhouse (m), χ_a is the vapour concentration of the greenhouse air (gm^{-3}), E is the crop transpiration, C is the condensation on the greenhouse cover and V is the moisture loss through the ventilation windows, all in gm^{-2}s^{-1}.
The loss caused by ventilation is given by

$$V = g_V(\chi_a - \chi_{out}) \tag{7}$$

Where χ_{out} is the vapour concentration in the outdoor air and g_V is the ventilation flux (m^{3}m^{-2}s^{-1} $\rightarrow$ ms^{-1}).
The loss through condensation is calculated by

$$C = g_c[0.2522e^{0.0485T_a}(T_a - T_{out}) - (\chi_a^* - \chi_a)] \tag{8}$$

Where χ_a^* is the saturated vapour concentration that can be approximated (10-40 °C) by:

$$\chi_a^* = 5.5638e^{0.0572T_a} \tag{9}$$

And g_C is given by:

$$g_C = \max[0, 1.8 \times 10^{-3}(T_a - T_{cover})^{1/3}] \tag{10}$$

which is derived from the mass transfer theory on horizontal plates, since (Papadakis et al., 1992) showed that the small slope (26°) of a Venlo type greenhouse did not play a role. The term between square brackets in eqn. 8 is derived by applying the "rule of thumb" for Dutch conditions that T_{cover}, the temperature of the cover of the greenhouse, can be calculated as follows:

$$T_{cover} = \frac{2T_{out} + T_a}{3} \tag{11}$$

By linearization of eqn. 9 in the interval T_a-T_{out} the result follows.
The unknown term in the humidity balance is the transpiration E.
In the next section we first discuss a model for the transpiration, which will be used for comparison with the new approach.

5. TRANSPIRATION MODEL

The transpiration of a tomato crop in a greenhouse can be modelled by (Stanghellini, 1987, Stanghelllini and De Jong, 1995):

$$E = \frac{2LAI}{(1+\varepsilon)r_b + r_s}\left[\chi_a^* - \chi_a + \frac{\varepsilon r_b}{2LAI}\frac{R_n}{L}\right] \quad (12)$$

Where LAI is the leaf area index of the crop, ε is the ratio of the latent to sensible heat content of saturated air for a change of 1 $^\circ$C in temperature. In the range of greenhouse air temperatures ε can be approximated by:

$$\varepsilon = 0.7584 e^{0.0518 T_a} \quad (13)$$

R_n (Wm^{-2}) is the net radiation of the crop, that is the balance of intercepted and reflected sun radiation plus the balance of incoming and outgoing long-wave radiation. The relation between R_n and the global radiation I_n (Wm^{-2}) is given by:

$$R_n = 0.86(1 - e^{-0.7 LAI})I_n \quad (14)$$

Which is a simplification of the formula give by (Stanghellini, 1987). r_b (sm^{-1}) is the resistance to heat transfer of the leaf boundary layer and (Stanghellini, 1987) calculated that $r_b = 200$ for a greenhouse tomato crop. r_s (sm^{-1}) is the stomatal resistance and is according to (Stanghellini, 1987, Stanghellini and De Jong., 1995), given by:

$$r_s = 82\frac{\frac{R_n}{2LAI} + 4.30}{\frac{R_n}{2LAI} + 0.54}\left(1 + 0.023(T_a - 24.5)^2\right) \quad (15)$$

This model is considered as one of the best to describe transpiration in a greenhouse (Jolliet and Bailey, 1992).

6. THE GREENHOUSE DYNAMICS

The absolute humidity defined by the humidity balance, eqn. 6, together with the transpiration model, eqn. 12, has been simulated with data from a real greenhouse (Green Q, Monster, The Netherlands) and compared with the measured absolute humidity. The results are given in fig. 1.
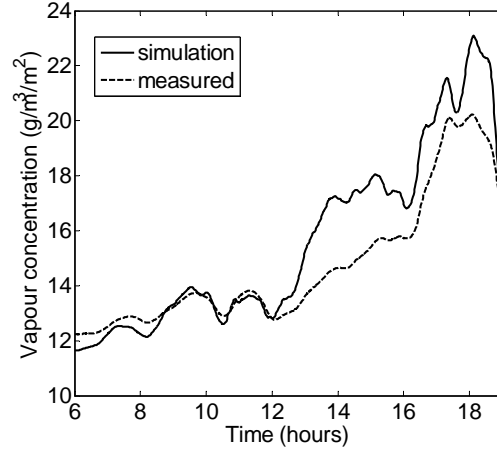

Fig. 1. The simulated and measured absolute humidity in a greenhouse on 19th September 2006.

Since there is a good resemblance between the measured and simulated value it can be concluded, that the model on which the unknown input observer is based, is good.

7. THE TRANSPIRATION MONITOR

The estimation of the transpiration using an unknown input observer, as described in section 3 goes as follows. Eqn. 6 is in the form of the system described by eqn. 4., where E is the unknown input to be estimated. The measured disturbances are the condensation C and the outside humidity. If eqn. 6 is rewritten in the form of eqn. 4, the parameters in eqn. 4 are as follows:

$$a = \frac{g_V}{h}, b = \frac{1}{h} \text{ and } ed(t) = \frac{g_V}{h}\chi_{out} - \frac{1}{h}C \quad (16)$$

The ventilation flux g_V is measured by the ventilation monitor, described in (Bontsema et al., 2005) The ventilation flux is time varying, and so will be a. The tuning of the observer can be done in a similar way as for time invariant parameters.

In the experiments with a commercial greenhouse tomato crop the ventilation rate and the transpiration were calculated with the ventilation monitor and the transpiration monitor, by means of the standard data of the inside and outside climate, as collected by the climate computer of the grower.

8. MEASUREMENT OF TRANSPIRATION

The new approach will not only be compared with the model from section 5, but also with the transpiration determined with the aid of a transpiration measurement gully, a Priva Groscale[®]. The measurement gully is shown in figure 2. The information available from the climate computer, is M the mass of the measurement gully, D the drain of the surplus water in the gully and S the supply of water

through the drips. The mass balance for the measurement gully is, with E the transpiration of the crop:

$$\frac{dM}{dt}(t) = S(t) - E(t) - D(t) \qquad (17)$$

From this balance of the measurement gully the transpiration of the crop can be calculated as:

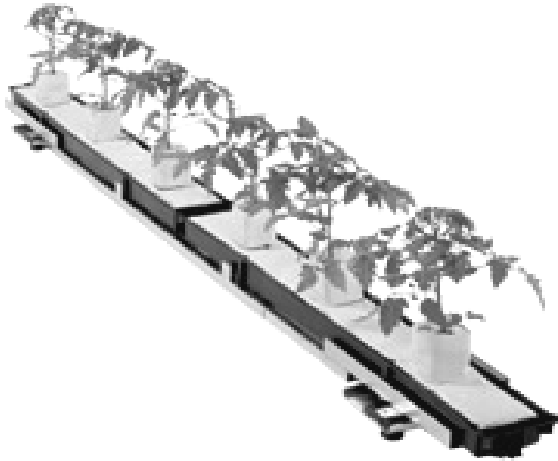$$E(t) = S(t) - D(t) - \frac{dM}{dt}(t) \qquad (18)$$

Fig. 2. The Priva Groscale.

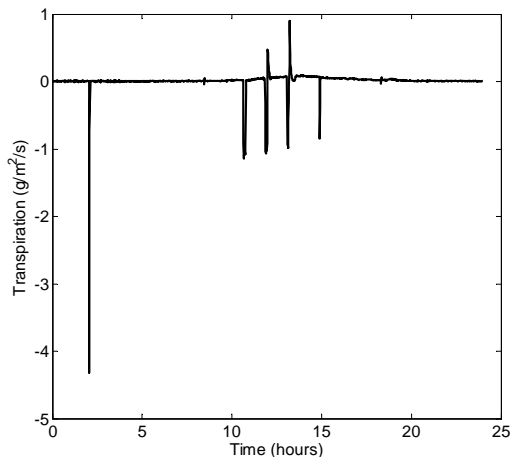Using equation (18) gives the following result for the transpiration on 19th September 2006.

Fig. 3. The transpiration calculated from the data from the measurement gully on 19th September 2006. The calculated transpiration is not corrected for outliers and is not filtered.

The large deviation at 2 o'clock in the morning is caused by an automatic reset on the signals for the drain and supply. The positive peaks are due to the drain and the negative peaks are due to the supply.

Since the uncorrected and unfiltered signal gives no insight into the transpiration the signal is firstly corrected for outliers. The result is shown in figure 4. Clearly already one can see what the transpiration will be, although the signal is still rather noisy. Therefore the signal of figure 4 is filter using a moving average over 1 hour. The result is shown in figure 5.
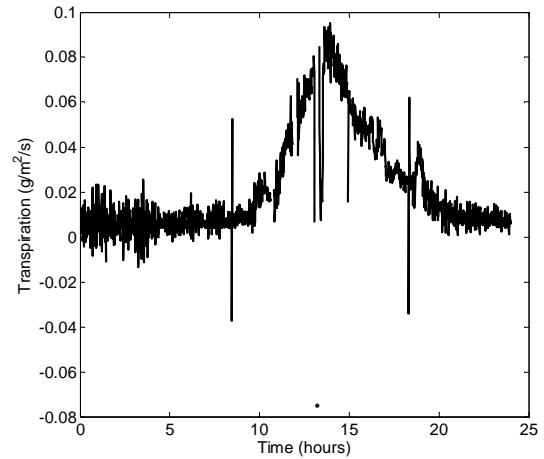

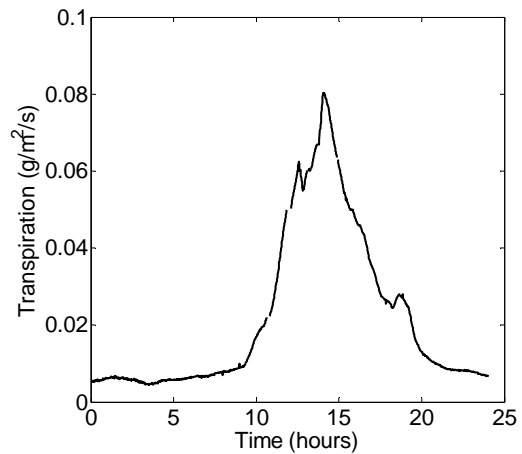Fig. 4. The transpiration on 19th September 2006, corrected for outliers.

Fig. 5. The transpiration on 19th September 2006 filtered by a moving average of 1 hour.

9. RESULTS

In fig 6. the model of section 5 is compared with the results of the measurement gully of section 8. In the greenhouse, were the measurements were performed, some leaf area measurements were done, on different days. On these different days the average leaf area of the crop was 1.7 and 2.2. With these two values the transpiration was calculated with the climate data on September 19th 2006. Clearly the LAI has a considerable influence on the outcome of the model. If we compare the outcome of the model with the reconstructed transpiration from the measurement gully, it can be concluded that the model and the

measurement gully give similar results. Notice that when the transpiration is decreasing, it seems that the measured transpiration from the gully is decreasing faster, than the calculated transpiration from the model.
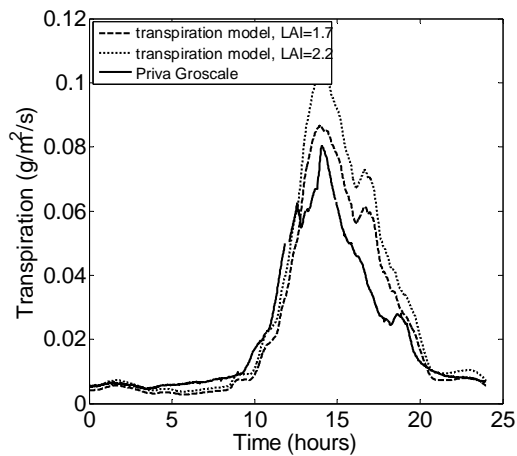

Fig. 6. The transpiration on 19th September 2006, calculated from the model of section 5 and measured by the Priva Groscale.

In fig. 7 the results of the transpiration monitor, based on the UIO-approach are compared with the results from the measurement gully.
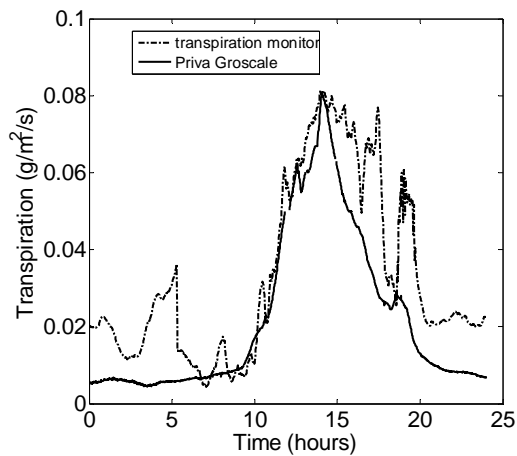

Fig. 7. The transpiration on 19th September 2006, determined with the transpiration monitor and measured by the Priva Groscale.

Again the resemblance between the two signals is good. Also here the signal of the monitor is slower than the signal of the measurement gully, when the transpiration is decreasing.

If we compare the three methods it can be said that all three methods (model, measurement gully and transpiration monitor) give similar results. The transpiration monitor is producing a positive transpiration during night, this is due to the fact that the transpiration monitor is based on the ventilation monitor (Bontsema et. al., 2005). This ventilation

monitor is not very accurate when the difference between inside and outside temperature is small. From fig. 6 it can be seen that the model of section 5 is rather sensitive for the leaf area index (LAI). This LAI is in normal practice in greenhouse not measured. So when using this model, one should take care of the fact that the LAI has to be estimated and this will influence the accuracy of the calculated transpiration.

In order to discuss the differences between the approaches some climate data on 19th September are given.
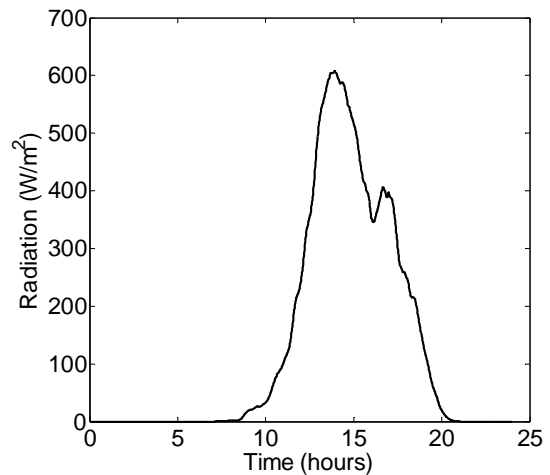

Fig. 8. The global radiation on 19th September 2006.

The sudden change in the radiation around 16.00 hours, results, according to the model of section 5, also in a change in transpiration. However the measurement gully is hardly detecting this change, see fig. 6. The transpiration monitor detects, just as the model, this change in transpiration.

The measurement gully detects a sudden change in transpiration, around 12.00 hours and a similar change around 19.00 hours. These changes are also detected by the transpiration monitor, but not by the model. The change is probably caused by rapidly opening and closing of the ventilation windows, as can be seen in figure 9. It seems that rapidly opening of the window causes a decrease in transpiration, probably caused by cooling of the leaves.
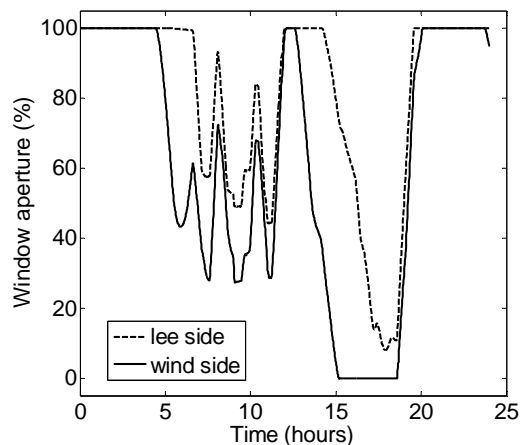
Fig. 9. The window apertures 19th September 2006.

10. CONCLUSIONS

An unknown input observer is a good and simple method for estimation of the transpiration of a greenhouse crop, the so-called transpiration monitor. The method uses only measurements which are already available in the climate computer of most growers, though not all growers measure the outside humidity, which is required here. Such sensors are commercially available for the horticulture practice. The transpiration monitor is a successful and useful expansion of the ventilation monitor, which is based on the same concept of an UIO.

The method is easily implemented and tuned for a particular greenhouse. Furthermore the new method gives the grower valuable insight into the status of his crop.

The transpiration monitor developed here is a good example of an intelligent or soft sensor.

ACKNOWLEDGEMENTS

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