ON-LINE ESTIMATION OF THE VENTILATION RATE OF GREENHOUSES

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Abstract: Using an unknown input observer, with an output linearising feedback, an on-line estimator for the ventilation flow or rate is developed for natural ventilated greenhouses. The paper shows how to design, implement and tune such an estimator in practice and shows that it performs well. Furthermore the practical value for the grower is discussed.

Keywords: greenhouse climate, observer, ventilation rate, unknown input observer.

1. INTRODUCTION

In modern greenhouse horticulture the climate in the greenhouse is controlled by a sophisticated greenhouse climate computer. The role of the grower is to define among others temperature trajectories, carbon dioxide setpoints and relative humidity bounds, in such a way that during the growing season the crop is maintained in an optimal condition and the crop production is maximised. The climate computer will then realise the by the grower desired climate. Beside the heat supply and the carbon dioxide supply, a main variable to control the inside climate in a greenhouse is the natural ventilation through the windows in the roof of the greenhouse. However the ventilation is controlled by adjusting the window openings and is heavily depending on the outside wind conditions and the difference between inside and outside temperature. An easy method to estimate on-line the ventilation would give the grower valuable insight in the process of his greenhouse climate.

A model can describe ventilation in a greenhouse, see f.i. (Jong, 1990). These models are based on f.i. hourly averages of measurements of greenhouse climate variables, but these models are however applied on a timescale of minutes. Another approach is to calculate ventilation from static mass or energy balances. Since in practice the greenhouse climate is never in steady state, due to the external disturbances, the error is large due to neglecting the dynamic storage term. If one uses a dynamic mass or energy balance, this problem is solved, but on the other hand one is differentiating a measured variable, introducing amplification of the measurement noise. For off-line measurement one uses so-called tracer gas methods, see (Sherman, 1990), however these methods can hardly be used in practice during crop production.

The objective of this paper is to show how to estimate the ventilation rate in a greenhouse production system, using an observer technique for estimating unknown inputs of a system. Using a non-linear transformation, similar to output feedback linearisation, the non-linear system is transformed into a linear one, which makes it possible to use a linear observer design technique. After designing the linear observer, the inverse transformation is used to achieve the final non-linear observer.

In section 2 the observer theory is recapitulated, in section 3 an unknown input observer is designed for a scalar system, in section 4 an observer is designed for a bilinear system using an output feedback linearisation. In section 5 the greenhouse dynamics is described and compared with measurements from a real greenhouse. In section 6 the proposed method is applied to the greenhouse system and in section 7 the results of new method are compared with the outcome of a tracer gas experiment. In section 8 the practical use of the method is discussed and in section 9 some conclusions are drawn.

2. OBSERVER DESIGN

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

$$\begin{aligned} &\dot{x} = Ax + Bu, y = Cx, \\ &x(0) = x_0, x \in \mathbb{R}^n, u \in \mathbb{R}^m, y \in \mathbb{R}^p \end{aligned} \tag{1}$$

An observer, the so-called Luenberger observer, mentioned after his inventor has then the following form (Luenberger, 1966; Luenberger, 1971):

$$\begin{aligned} &\dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y}), \\ &\hat{y} = C\hat{x}, \hat{x}(0) = \hat{x}_0 \end{aligned} \tag{2}$$

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 diiferent. 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 $\hat{x}(t) \approx x(t)$. 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:

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

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 $x_0 - \hat{x}_0$, $e(t) \to 0$.

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:

$$\begin{aligned} &\dot{x}(t) = ax(t) + bu(t) \\ &y(t) = x(t) \end{aligned} \tag{4}$$

where $u(t)$ is an unknown input. 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:

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

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. OBSERVER FOR BILINEAR SYSTEMS

A special class of non-linear systems are the so-called bilinear systems, which have in the equations a product between the states and inputs. Consider the following scalar system:

$$\begin{aligned} &\dot{x}(t) = ax(t) + bx(t)u(t) \\ &y(t) = x(t) \end{aligned} \tag{8}$$

Defining a new input $v(t) = x(t)u(t)$, eqn. (8) is transformed, by a non-linear transformation into a linear system with the new input $v(t)$. This non-linear transformation is actually an output feedback linearisation. For this transformed system the standard observer as described in section 3 can be used for the unknown input $v(t)$, giving an estimation $\hat{v}(t)$ of $v(t)$. The estimation $\hat{u}$ is then given by the back transformation $\hat{u} = \frac{\hat{v}}{\hat{x}}$.

5. GREENHOUSE DYNAMICS

The energy balance for a Venlo-type greenhouse is given by (Henten, 1994)

$$C_{cap,q}\frac{dT_{air}}{dt} = Q_{pipe} - Q_{vent} - Q_{trans} + Q_{rad} \tag{9}$$

where T_{air} is the temperature inside the greenhouse, Q_{pipe}, Q_{vent}, Q_{trans} and Q_{rad} are respectively the heat supply by the heating pipes, the energy loss due to natural ventilation, energy loss through the greenhouse cover and the heat load due to the global radiation of the sun. $C_{cap,q}$ is the combined heat capacity of the greenhouse air, the crop and the construction of the greenhouse.
The heat supply is described by:

$$Q_{pipe} = c_{pipe,air}(T_{pipe} - T_{air}) \tag{10}$$

with $c_{pipe,air}$ the heat transfer coefficient between the heating pipes and the greenhouse air. T_{pipe} is the temperature of the heating pipes.
The energy loss due to the ventilation is:

$$Q_{vent} = c_{air}\phi_{vent}(T_{air} - T_{out}) \tag{11}$$

with c_{air} the heat capacity of air, ϕ_{vent} is the ventilation flux and T_{out} is the outdoor temperature.
The energy loss through the greenhouse cover is given by:

$$Q_{trans} = c_{cov}(T_{air} - T_{out}) \tag{12}$$

where c_{cov} is the heat transfer coefficient of the greenhouse cover.
Finally the heat load due to global radiation is:

$$Q_{rad} = c_{rad}I \tag{13}$$

with c_{rad} is the fraction of the global radiation, responsible for the heat load on the greenhouse. I is the global radiation.

This energy balance is simulated using measured data for the control and external disturbances. These data were recorded on a commercial greenhouse in the western part of the Netherlands. The crop was a fully producing tomato crop.

For the ventilation flux a model of (Jong, 1990) is used. In this model the ventilation flux is function of the wind speed and direction, the inside and outside temperature, the window opening and the configuration of the ventilation windows. Furthermore this ventilation model is only valid for greenhouses of Venlo-type.

The controls on day 71 (March 12th, 2004) are shown in figure 1.

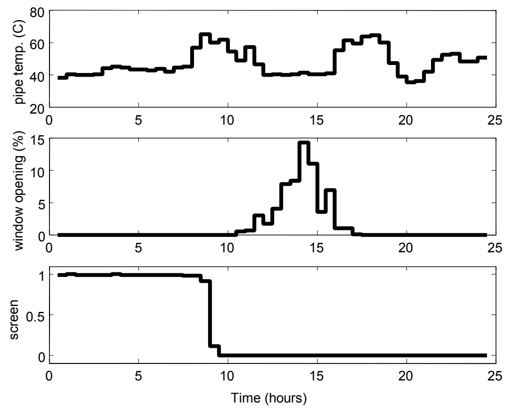

Fig. 1. The external disturbances acting on the greenhouse on day 71.

The external disturbances are shown in figure 2.

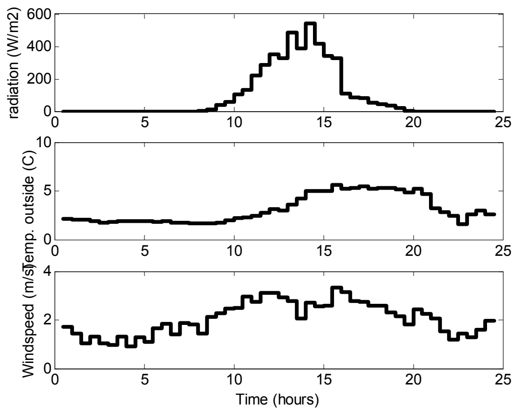

Fig. 2. The external disturbances action on the greenhouse on day 71.

The results of the simulated air temperature in the greenhouse are shown in figure 3. The opening of the so-called energy saving screen, which is not well modelled, causes the large deviation between simulated and measured temperature around 10 o'clock in the morning. However in our research we did not focus on a perfect fit of the model on the measured data, also for the reason that we don't want that the model is too much accommodated to the ventilation model of (Jong, 1990).

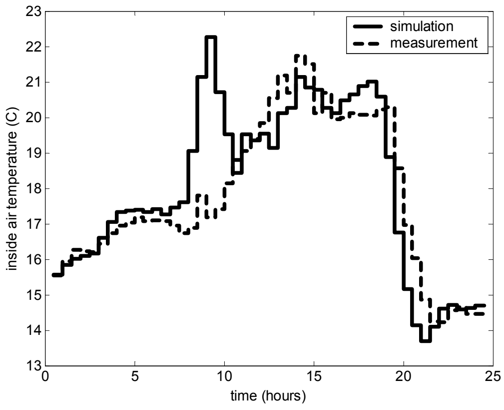

Fig. 3. Simulated and measured air temperature of the greenhouse on day 71.

6. OBSERVER FOR THE VENTILATION RATE

The model for the greenhouse temperature as defined in section 6 can be rewritten as:

$$\frac{dT_{air}}{dt} = -\frac{c_{pipe,air} + c_{cover}}{C_{cap,q}} T_{air} - \frac{c_{air}}{C_{cap,q}}(T_{air} - T_{out})\phi_{vent} + \frac{1}{C_{cap,q}}(c_{pipe,air}T_{pipe} + c_{cover}T_{out} + c_{rad}I) \quad (14)$$

Defining

$$d(t) = \frac{1}{C_{cap,q}}(c_{pipe,air}T_{pipe} + c_{cover}T_{out} + c_{rad}I)$$

$v(t) = c_{air}(T_{air} - T_{out})\phi_{vent}$, $a = -\dfrac{c_{pipe,air} + c_{cover}}{C_{cap,q}}$ and $b = -\dfrac{1}{C_{cap,q}}$, equation (14) can be rewritten as:

$$\frac{dT_{air}}{dt} = aT_{air} + bv(t) + d(t) \quad (15)$$

Note that $d(t)$ is a measured disturbance and the transformation $v(t) = c_{air}(T_{air} - T_{out})\phi_{vent}$ has the non-linear system of eqn. (14) transformed into the linear one of eqn. (15).

For the system of eqn. (15) the method of section 3 can be applied. The estimator for the ventilation flow or actually for the transformed ventilation flow is then given by:

$$\begin{aligned} \frac{d\hat{T}_{air}}{dt} &= a\hat{T}_{air} + b\hat{v} + d(t) + l_1(T_{air,meas} - \hat{T}_{air}) \\ \frac{d\hat{v}}{dt} &= l_2(T_{air,meas} - \hat{T}_{air}) \end{aligned} \quad (16)$$

where $T_{air,meas}$ is the measured inside air temperature, which is available form the greenhouse climate computer. From the measurements from the commercial greenhouse it turned out that a reasonable choice for the parameters a and b is:

$$a = -2.9 \times 10^{-4} \text{ and } b = -3.3 \times 10^{-5} \quad (17)$$

The gains of the estimator or observer are obtained according section 3 as

$$l_1 = 0.0239 \text{ and } l_2 = -8.3333 \quad (18)$$

From eqn. (17), which in practice will be calculated on-line according to the sample instants for the measurements in the greenhouse as defined on the climate computer, $\hat{\phi}$ can be calculated by transforming back $\hat{v}$:

$$\hat{\phi} = \frac{\hat{v}}{c_{air}(\hat{T}_{air} - T_{out})} \quad (19)$$

This procedure has been applied in a simulation, where the ventilation flow in the simulation model is calculated according (Jong, 1990), $T_{air,meas}$ is in this case of course the simulated air temperature. The results are given in figure 4.

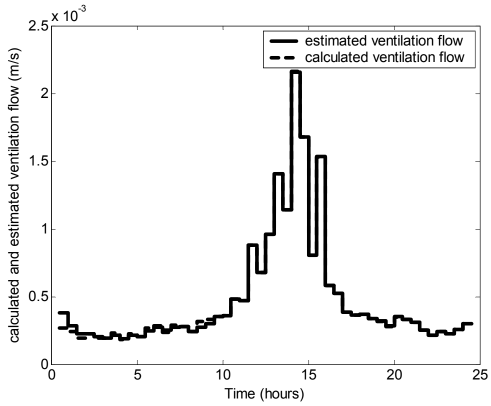

Fig. 4. The estimated and calculated ventilation flow of a greenhouse on day 71.

From the figure it follows that we have a perfect estimator, only in the beginning there is some deviation, mainly due to the fact that the observer starts at a different initial value than the simulation model.

In the following figure the estimated ventilation flow, based on the real measurements of day 71 is given and compared with the calculated ventilation flow according to (Jong, 1990).

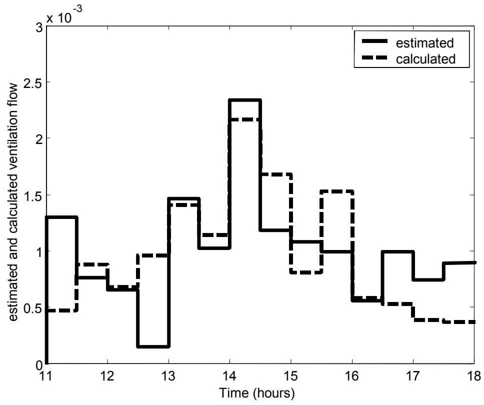

Fig. 5. The estimated and calculated ventilation flow of a greenhouse on day 71.

Although there is more difference between the estimated and calculated ventilation flow compared to the simulation, the order of magnitude is the same, which gives good confidence that the new method is correct. Note that the outcome of the new method need not to be the same as the calculations from (Jong, 1990), since the latter is also only a model and not reality.

The new method can be seen as a result of sensor fusion, since the measurements of a set of four sensors, respectively a radiation sensor and three temperature sensors (pipe, inside and outside) are used to calculate a new variable, namely the ventilation flow. On the other hand the new method can also be seen as an intelligent or soft sensor, besides measurements also knowledge in the form of the energy balance of the greenhouse is used.
In the next section the new method is compared to so-called tracer gas experiments.

7. TRACER GAS EXPERIMENTS

At the horticultural research station in Naaldwijk, the Netherlands, two classical tracer gas experiments with carbon dioxide were performed to evaluate the proposed method. For these experiments an empty greenhouse with a concrete floor was used in order not to have disturbing sources and sinks of carbon dioxide. With closed windows pure CO_2 was supplied up to a concentration of 1500 ppm or higher. Then the supply is stopped and the windows are opened. This has been repeated for several window openings. The measurements of the second experiments are shown in figure 6.

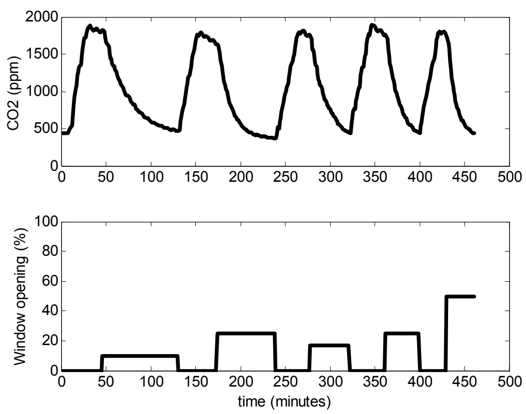

Fig. 6. The measured CO_2-concentration and the window openings at the leeward side.

For an empty greenhouse and no supply of carbon dioxide, the carbon dioxide balance is written as:

$$\frac{dCO_{2,in}}{dt} = -\frac{1}{c_{cap,c}}(CO_{2,in} - CO_{2,out})\phi_{vent} \quad (20)$$

Where $CO_{2,in}$ and $CO_{2,out}$ are the inside and outside carbon dioxide concentration and $c_{cap,c}$ is a constant. Assuming that $CO_{2,out}$ is constant, what is a reasonable assumption during the experiments, the differential equation for the difference between inside and outside carbon dioxide concentration, ΔCO_2, is:

$$\frac{d\Delta CO_2}{dt} = -\frac{1}{c_{cap,c}}\Delta CO_2 \phi_{vent} \quad (21)$$

The solution of this equation is:

$$\Delta CO_2(t) = \Delta CO_2(0)e^{-\frac{1}{c}\int_0^t \phi(v)dv} \quad (22)$$

The average ventilation flow on the ith sampling interval is then given by:

$$\overline{\phi}(t_i) = c\ln\Delta CO_2(t_{i-1}) - c\ln\Delta CO_2(t_i) \quad (23)$$

In figure 7 the estimated ventilation flux according to the new method and the calculated flux according to the tracer gas method are compared.

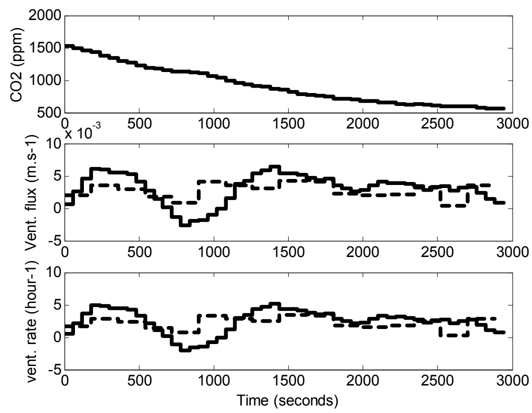

Fig. 7. The decay of the CO_2-concentration in case of a window opening of 10%, the estimated ventilation flux by an observer (—) and the estimated flux based on the CO_2 decay (---). The figure at the bottom shows the ventilation rate.

Both methods give similar results, which show that estimating the ventilation flux, or rate using the unknown input observer with output linearising feedback is a good method.

8. PRACTICAL USE OF THE ESTIMATION

The method gives an estimation of the ventilation flux, from which the ventilation rate easily can deduced. The ventilation rate says how often the inside air in a greenhouse is refreshed in one hour. Growers prefer to know the ventilation rate instead of the ventilation flux.

The method gives a good estimate for the ventilation rate, but this is not always interesting for the grower. He would also like to have insight in how much energy he loses by ventilation, how much carbon dioxide is lost by ventilation and how much moisture has been removed by ventilation. Once one has estimation for the ventilation flow, this is easily calculated. In figure 8 the estimated ventilation rate on June 19th 2004 is shown, together with the applied window openings.

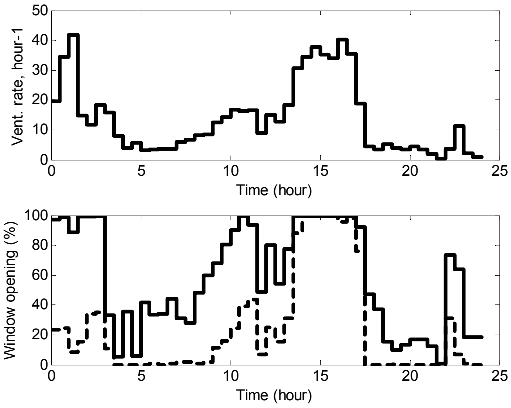

Fig. 8. The estimated ventilation rate (upper part) and the window openings at the east side (–) and at the west side (--) (lower part).

From figure 8 it can be seen that the windows were opened in the beginning of the night and when the sun starts to shine. When the solar radiation is at its maximum, the windows at both sides of the roof of the greenhouse are maximally opened. It is also clear that the ventilation rate is high at these moments.

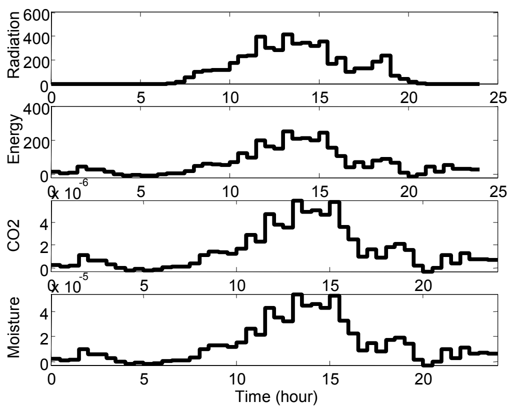

Fig. 9. The global radiation, loss of energy, loss of CO_2 and removed moisture on June 19th 2004.

From figure 9 it follows that the energy loss is large at moments when the ventilation rate is large. In case of high radiation this is necessary in order to reduce the heat load from the sun and also at this moment large ventilation has a good effect on removing the excess of moisture, so the crop will have a good transpiration. On the contrary the ventilation has a negative effect on CO_2 concentration, while at high radiation levels, a lot of CO_2 is needed for a good production of the crop.

Furthermore at night the ventilation was used to remove moisture, but as can be seen also energy will be lost.

9. CONCLUSIONS

An unknown input observer with an output feedback linearisation is a good and simple method for estimation the ventilation flow or rate in natural ventilated greenhouses.

The method does not depend on wind measurements (inaccurate, (Knoll, 2004)), window configuration and works for all types of greenhouses.

The method is easy to implement and to tune for the particular greenhouse. Furthermore the new method gives the grower valuable insight is the energy and mass flows caused by ventilation.

The new method for estimation the ventilation rate is an example of sensor fusion and also an example of an intelligent or soft sensor.

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