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Synthesis of an Optimal Dynamic Regulator Based on Linear Quadratic Gaussian (LQG) for the Control of the Relative Humidity Under Experimental Greenhouse

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ABSTRACT

This paper describes one practical approach that suggests a model based technique to control in real time the relative humidity under greenhouse. The humidity level is one of the most difficult environmental factors to be regulated in greenhouse. Moreover, maintaining and correcting for more or less humidity can be a challenge for even the most sophisticated monitoring and control equipment. For these raisons, a Linear Quadratic Gaussian (LQG) controller for relative humidity regulation under greenhouse turns out to be useful. Indeed a LQG controller is proposed for a relative humidity under a greenhouse control task. So, the state space model, which is best fitting the acquired data, was identified using the Numerical Subspace State Space System IDentification (N4SID) algorithm. The mathematical model that is obtained will be used for evaluating the parameters of LQG strategy. The proposed controller is implemented in two steps, in one hand, Kalman filter (KF) is used to develop an observer that estimates the state of relative humidity under greenhouse. In the other hand, the state feedback controller gain is estimated using a linear quadratic criterion function. The suggested optimal implemented controller using Matlab/Simulink environment is applied to an experimental greenhouse. We found, according to the results, that the controller is able to lead the inside relative humidity to the desired value with high accuracy, regardless of the external disturbances.

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1. INTRODUCTION

The greenhouse environment control problem is consisted to create a favorable environment for the crop in order to reach predetermined results for high yield, high quality and low costs [1],[2]. Real-time monitoring of the greenhouse environment with sensors and advanced software can greatly improves yields and economic performance by optimizing plant growth [3]. In control context, it is a very difficult task to implement in practice due to the complexity of the phenomena involved inside greenhouse during the plant growth process such as the dynamical behavior of greenhouse climate and control requirements, which present strong interactions among variables, nonlinearity and non-stationary[4],[5]. Internal temperature and relative humidity which are very sensitive to the outside weather, are closely linked together in a greenhouse, and are the two important variables for photosynthesis and photo morphogenesis of the plant [6]-[8].

However, the tuning of several controllers in the complex greenhouse environment is a challenge to process engineers and operators. It is important to maintain the proper relative humidity since the humidity inside the greenhouse has a close relation to crops growth, because the high level of humidity leads to create a suitable environment to the emergence and development of some kind of diseases [9],[10]. To achieve these goals, the temperature and relative humidity must be controlled optimally by given certain criteria through actuators like heater, humidifier and ventilator [11]. In order to reach a good performance of the controller, we need to have a mathematical model which is capable to describe correctly as much as possible the dynamical behaviour of the process parameters.

Control strategies have been recognized as an efficient and consistent way to improve greenhouse process automation. The design of such system will enable us to modify the behaviour of the plant to suit our needs in term of specified stability, performance, and robustness objectives [12]. In recent years, large amounts of studies have been conducted for controlling the climatic parameters of greenhouse system, where various basic and advanced control strategies, like predictive control, adaptive control, robust control and fuzzy control have been employed and tested in practice for the controlled greenhouse [13],[14].

In this paper, the problem of regulating the relative humidity under an expiremental greenhouse to a fouvaroble level is addressed. To achieve this goals, we use LQG technique that is one of the most popular model based control strategies in modern control theories and its applications [15].

The LQG controller synthesis is an approach of designing a proper regulator by combining the LQR and Kalman observer into an output feedback compensator. As all system states usually are not available, the system state variables are estimated using a KF, forming the LQG controller. The purpose of the studying theory of current controller is to synthesize their control laws with specified proprieties which permit to optimize a performance index and to reduce as well the noises encountered system [16],[17].

We report herein, the results of the developped mathematical modelling to control the relative humidity using N4SID algorithm. For that purpose, we make use of the state space model whose validation was carried out, and then we have elaborated an optimal control based on LQG approach permitting to assure the closed-loop stability and maintain the variations of internal relative humidity under an experimental greenhouse.

2. MATERIALS AND METHODS

2.1. Experimental Greenhouse Prototype

The experimental greenhouse used in these experimentation is equipped with a control system that allows both the acquisition and automatic control of greenhouse climate parameters (Figure 1) [18]. The internal climate is defined by the internal temperature, the internal relative humidity and CO_2 content which constitutes the outputs of the greenhouse, while the external climate is composed of the temperature, the relative humidity, and the solar radiation that acts directly on the operation of the greenhouse. The external climate parameters are uncontrollable inputs and they are considered as disturbances.

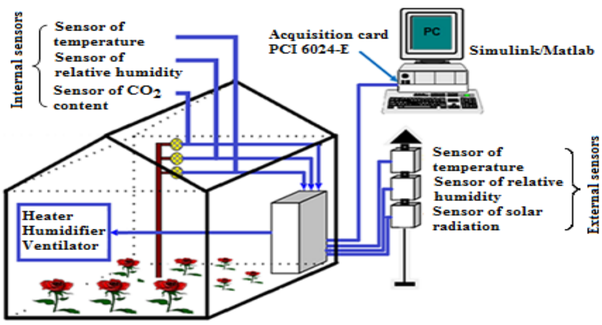

Figure 1. Experimental greenhouse set-up

The air temperature, relative humidity, solar radiation and carbon dioxide concentration of greenhouse are measured every 5 seconds by their respective sensors. The low-level signals delivered from sensors are conditioned, amplified and then transmitted to computer system through the PCI-6024E board (from National Instruments®) as a data acquisition (DAQ) device. The control and operating software was designed in the Matlab/Simulink environment.

2.2. Mathematical Modelling with State-Space Approach

This section is devoted to the mathematical modelling of the relative humidity under greenhouse. Modelling is an essential precursor in the parameter estimation process. The internal climate model of greenhouse is essential for improving environmental performance and control efficiency. The synthesis of regulators requires a very precise modelling for the process under regulation.

In the synthesis of the LQG controller, a state space model is identified using the N4SID. Subspace identification methods offer an alternative to the classic recursive prediction error minimization methods (e.g. AutoRegresive model with eXternal input (ARX)). The subspace identification methods are used to identify parameters (matrices) of a linear time-invariant state space model from the input/output data [19].

A state-space model has been derived to understand the dynamic behaviour of the relative humidity under greenhouse by using subspace N4SID algorithm. For this we excite the system by sending a voltage step to heater and then to the humidifier, and we collect measurements of relative humidity until a steady state is reached.

Linear subspace identification methods are concerned with systems and models of the form [20]:

$$\begin{cases} x(t+1) = Ax(t) + Bu(t) + Fw(t) \\ y(t) = Cx(t) + Du(t) + v(t) \end{cases} \tag{1}$$

Where:

x(t) is the state vector,

u(t) is the vector of input,

y(t) is the vector of output measurements,

w(t) and v(t) are the process and the output measurement noises vectors, respectively,A, B, C, D and F are the system matrices of appropriate dimensions to be estimated.

Once the data have been collected, it can be analysed by assuming a state space representation with the N4SID algorithm and fitting the model to the process data.

The percentage of the output that the model reproduces (Best Fit metric) [21], defined as:

$$Best\ Fit = \left(\frac{1 - |y - \hat{y}|}{|y - \bar{y}|} \right) * 100\% \tag{2}$$

In this equation, y is the measured output, $\hat{y}$ is the simulated model output, and $\bar{y}$ is the mean of y.

The first step for an advanced control design is the development of a dynamic model. Model quality is an essential aspect to achieve satisfactory control performances. The main objective in this part is to come up with a valid model that can be used as a basis for the relative humidity under greenhouse control design.

2.2.1. Relative humidity response to a step of humidifier

To decribe the evolution of the relative humidity under greenhouse, we excite the system by sending a step input to the humidifier in order to humidify the air under greenhouse until reaching a steady state. The collected data and the N4SID algorithm in Matlab are used to develop the model.

The model of the humidifier is given by the following state-space representation:

$$\begin{cases} x(t+1) = A_b x(t) + B_b u(t) + F_b w(t) \\ y(t) = C_b x(t) + D_b u(t) + v(t) \end{cases} \tag{3}$$

Where y(t) is the output vector, u(t) is the input vector and x(t) is a state vector of three dimensional. A_b, B_b, C_b and F_b, are the matrices given by:

$$A_b = \begin{bmatrix} 0.98427 & 0.10002 & -0.02704 \\ -0.03097 & 0.09140 & -0.62512 \\ -0.00244 & -1.0358 & -0.10883 \end{bmatrix} \tag{4}$$

$$B_b = [-0.00033 \quad -0.00511 \quad -0.03481]^T \tag{5}$$

$$C_b = [117.43 \quad -0.5049 \quad 4.4587] \tag{6}$$

$$D_b = 0 \tag{7}$$

$$F_b = [0.00359 \quad 0.01092 \quad -0.01327]^T \tag{8}$$

And the initial state was,

$$x_{b0} = [0.35479 \quad 0.20056 \quad -0.2002]^T \tag{9}$$

The index ‘b’ of the matrices described above refers to the humidifier (brume) actuator as the considered system input. Poles values of the identified model indicate open-loop stable, controllable, and observable system.

Figure 2 shows the comparison of the obtained model with real data, where it can be observed that the subspace model captures the system dynamics properly.

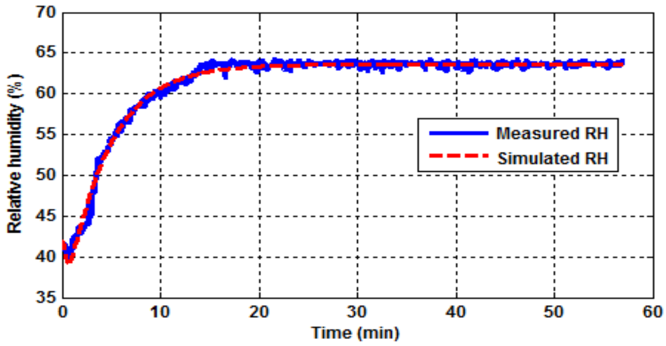

Figure 2. Comparison of system model for humidifier, simulated step-response with the experimental measurement

The inside relative humidity is stabilized at 63.95 % and the initial value is 39.76 %. The model best fit metric at about 90.55 %, and then the state space model describes 90.55 % of the variance in the process output. Results indicate that the simulation and experimental results follow very closely each other.

2.2.2. Relative humidity response to a step of heater

In this case, we excite the system by a step input of 2.2 V to the heater. Figure 3 shows the evolution of the measured and simulated relative humidity by using the N4SID algorithm.

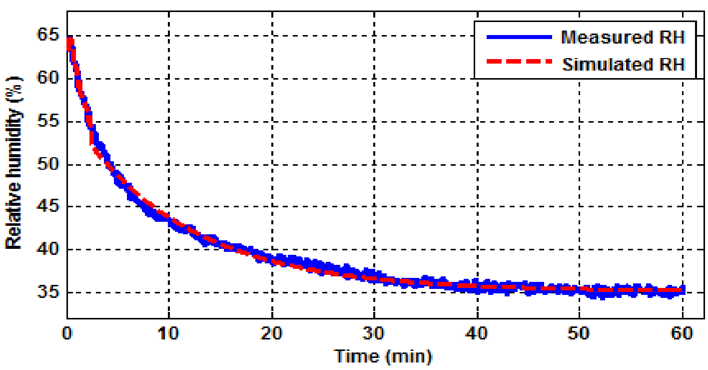

Figure 3. Comparison of system model for heater, simulated step-response with the experimental measurement

The results indicate that the proposed identification method can capture the dynamic behaviour of the experimental relative humidity successfully with a good accuracy. The best fit metric about 85.93 % of the obtained model, assert this outcome.

Then, the state-space model is described by:

$$A_h = \begin{bmatrix} 0.98876 & 0.0124 & 0.00192 & 0.0125 \\ 0.01185 & 0.09063 & 0.21045 & 1.2175 \\ 0.00246 & -0.6191 & -0.09386 & 0.3705 \\ 0.00079 & 0.1697 & -0.89485 & 0.22029 \end{bmatrix} \quad (10)$$

$$B_h = [0.00169 \quad -0.04205 \quad -0.07627 \quad -0.0217]^T \quad (11)$$

$$C_h = [123.19 \quad -5.6062 \quad 0.17959 \quad -0.71594] \quad (12)$$

$$D_h = 0 \quad (13)$$

$$F_h = [0.00206 \quad 0.00410 \quad 0.00598 \quad 0.00685]^T \quad (14)$$

And the initial state was,

$$x_{h0} = [0.53038 \quad 0.14132 \quad 0.01486 \quad -0.0906]^T \quad (15)$$

The index ‘h’ of the matrices above refers to the heater actuator as the considered system input. Poles values of the identified model indicate open-loop stable, controllable, and observable system. Accordingly, after having the system’s model on state space form, an optimal LQG controller will be implemented so as to control the relative humidity under an experimental greenhouse.

2.3. Design of Linear Quadratic Gaussian Controller

The focus of this section is to design an optimal LQG controller in order to regulate the relative humidity under greenhouse at desired state. Indeed, the LQG controller is the modern state-space control technique for the design of optimal dynamic regulators, which requires a state-space model of the plant and combines multivariate function such as Linear Quadratic Regulator (LQR) and Kalman Filter (KF) [22].

The purpose of the concept of a model based optimal controller is to enhance the regulation performance, while minimizing the cost of control effort as well as reducing the disturbance effect. To approach this problem, LQG controller can be implemented in two steps [23]:

1. Designing of a Kalman filter to estimate the desired states that are needed to be controled;
2. Calculation of state feedback controller gain to minimize the cost function based on linear quadratic criterion function.

The controllers, which provide input signals for the plant based on the estimated state-vector, are called compensators [24]. KF is one of the state estimation that can estimate the state variable with the measurement including noise.

The control method LQG consists of an LQR with the observer states of the system via the method of the KF. In the case where the system state is a linear one or linear around an operating point, the system is represented by equation (1) in which w(t) and v(t) represent white gaussian noise with zero as mean value, independent, respectively [25]-[27].

The estimate error covariance is defined as following:

$$P_f = \lim_{t\to\infty} E(\{x(t) - \hat{x}(t)\}\{x(t) - \hat{x}(t)\}^T) \quad (16)$$

The state estimator $\hat{x}(t)$ is derived from:

$$\dot{\hat{x}}(t) = A\hat{x} + Bu + K_e(y - C\hat{x} - Du) \quad (17)$$

The estimating gain K_e of Kalman is established by the following relation [28]:

$$K_e = PC^T (CPC^T + R_f)^{-1} \tag{18}$$

Where P is the solution matrix of Riccati equation:

$$\dot{P} = AP + PA^T - PC^T R_f^{-1} CP + Q_f \tag{19}$$

In Equations (18) and (19), R_f and Q_f are weighting matrices, or design parameters of KF.

The synthesis of the LQR controller is revealed through finding a matrix with gain L in which the optimal feedback control is given by [29]:

$$u = -L.x(t) \tag{20}$$

The minimizing quadratic criterion for obtaining the control law is:

$$J_{LQR} = \int_0^{\infty} (x^T Qx + u^T Ru)dt \tag{21}$$

Where the matrix Q and R are positive definite and positive semi definite matrix, respectively. They are weighting parameters that penalize the states and the control effort, respectively.

The minimal solution of the cost function gives the state feedback law which is introduced in equation (20), where L is obtained by solving the Control Algebraic Riccati Equation (CARE):

$$SA + A^T S - SBR^{-1} B^T S + Q = 0 \tag{22}$$

The optimal gain matrix L is then calculated by:

$$L = R^{-1} B^T S \tag{23}$$

Figure 4 shows the schematic diagram of the LQG control technique, where the term N is calculated in steady state to eliminate the static error by the following equation [30]:

$$N = \left[C \left[I - A + BL \right]^{-1} B \right]^{-1} \tag{24}$$

And where K_e is the KF gain and L is the LQR gain.

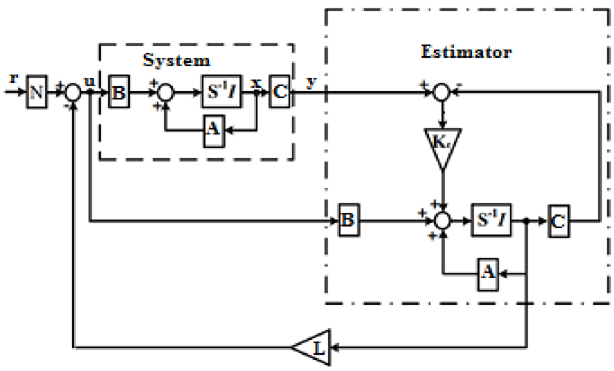

Figure 4. The LQG controller block diagram

The controller design and state estimation are treated separately in accordance with separation principle which allows to separate the estimation the state of the observer and the feedback gain controller together into two separated problems [31]. An estimator or observer according to equation (18) comes above to the block diagram in Figure 4. The observer gain matrix K_e determines the convergence speed of the estimated output $\hat{y}(t)$ to the measured output y(t). Moreover, an optimal feedback control law is determined based on linear quadratic optimal control theory as expressed in equation (20).

The fundamental objective of designing the KF observer is to estimate the state variables of the greenhouse including relative humidity level. These states can be used further to design LQG controller to drive the relative humidity under greenhouse at a desired state.

3. RESULTS AND DISCUSSION

The experiment was performed to examine the ability of the LQG controller for automatically adjusting the process of the output variation of relative humidity to new setpoints. To act on the greenhouse relative humidity, we used the actuators which are controlled according to the sign of the difference between the setpoint and the measured relative humidity (Figure 5) [32].

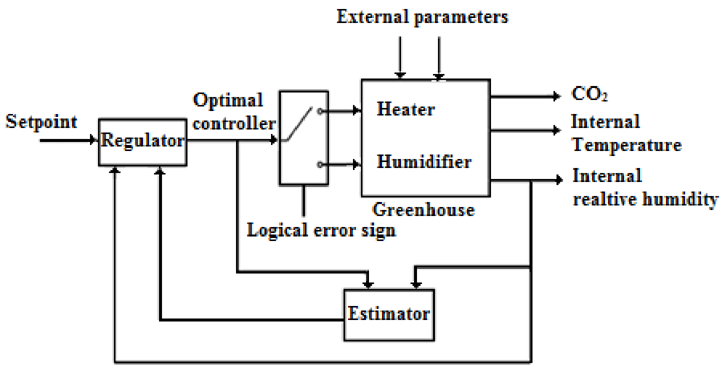

Figure 5. Structure of the control system

The LQG design method uses a state space model for the experimental greenhouse system as described above. As long as it is desirable to have a Kalman filter that removes as much noise as possible. This filter is tuned by adjusting the design parameters, which are Q_f and R_f matrices, for both system inputs which are the heater and the humidifier. After some trials and errors, the tuning matrices were set to:

$$Q_{fc} = 1.0393*10^{-4} \quad (25)$$

$$R_{fc} = 8.0602*10^{-5} \quad (26)$$

$$Q_{fb} = 3.0849*10^{-4} \quad (27)$$

$$N_b = -207.2780 \quad (28)$$

The computed Kalman gain matrix is given below:

$$K_{eb} = \begin{bmatrix} 0.0731 & 0.7264 & -0.8274 \end{bmatrix}^T \quad (29)$$

$$K_{ec} = \begin{bmatrix} 0.0861 & 1.0997 & -0.3904 & 0.7952 \end{bmatrix}^T \quad (30)$$

Likewise, and after some trials and errors, the optimal gain matrix is calculated in Matlab by using the selected matrices Q and R which are the design parameters of the LQR controller:

$$Q_b = \begin{bmatrix} 1379 & -5.9 & 52.4 \\ -5.9 & 0 & -0.2 \\ 52.4 & -0.2 & 2.0 \end{bmatrix} \tag{31}$$

$$R_b = 1 \tag{32}$$

$$Q_c = \begin{bmatrix} 1517.6 & -69.1 & 2.2 & -8.8 \\ -69.1 & 3.1 & -0.1 & 0.4 \\ 2.2 & -0.1 & 0 & 0 \\ -8.8 & 0.4 & 0 & 0.1 \end{bmatrix} \tag{33}$$

$$R_c = 1 \tag{34}$$

After calculating the gains of the LQR controller, we got the following results:

$$L_b = [8458.3 \;\; 164.3 \;\; -207.4] \tag{35}$$

$$N_b = -207.2780 \tag{36}$$

$$L_c = 10^4 * [3.0929 \;\; -1.2730 \;\; 1.2267 \;\; -1.62] \tag{37}$$

$$N_c = 3.0071 \tag{38}$$

When combining the LQR regulator-law design with the Kalman estimator design, we can get the LQG compensator that we will use for controlling the relative humidity under an experimental greenhouse.

Figure 6 (a) and (b) describe the evolution of external temperature and the relative humidity, respectively, in an interval of 20 hours of experimentation with testing the LQG controller in order to regulate the relative humidity under an experimental greenhouse.

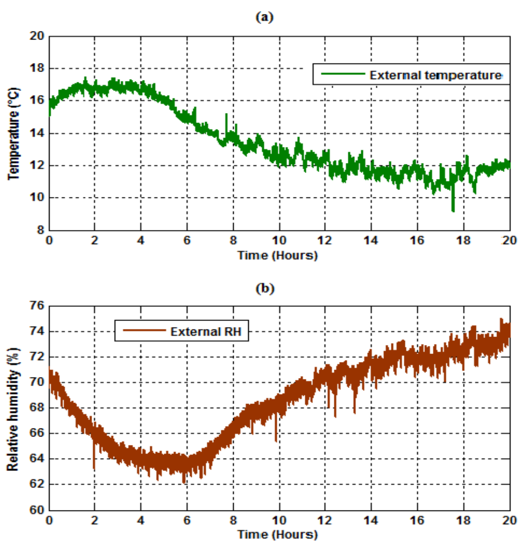

Figure 6. Control test on the greenhouse: (a) Measured external temperature and (b) Relative humidity in an interval time of 20 hours

In fact, for same types of plants, the ideal comfort relative humidity level is taken from 40 % to 60 % in winter months. Based on this reality, and as shown in Figure 7, the setpoints of the internal relative humidity are changed respectively at 20 hours of record by increasing and decreasing the step of reference trajectory in order to test the performance of the LQG controller.

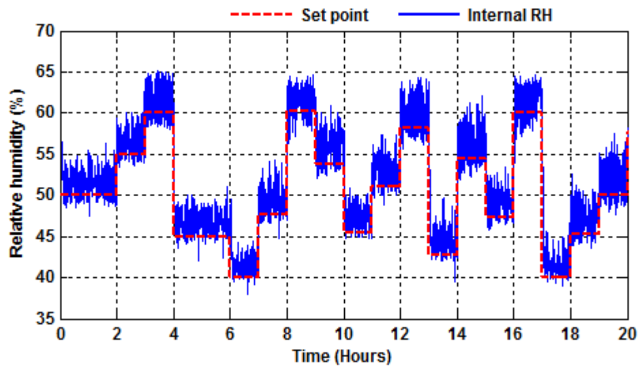

Figure 7. Experimental results for relative humidity regulating for several steps

The results are obtained within the model-based LQG controller strategy that is implemented on the Matlab/Simulink environments. From this Figure, it can be observed that the internal relative humidity reaches its set points in spite of disturbances that are the external meteorological conditions which are acting on greenhouse. However, the controller maintains the measured internal relative humidity with small deviations around the setpoint.

In order to get more visibility of the evolution of the internal relative humidity and different desired values of the set point, we present the behaviour of internal relative humidity for 3 hours as shown in Figure 8. Obviously, these results indicate that more time is required for the relative humidity to attain the setpoint when it decreases from an upper level to lower one. This means that the heater mode is solicited to decrease the level of relative humidity which takes more time in comparison the acting of the humidifier to increase due to the external factors.

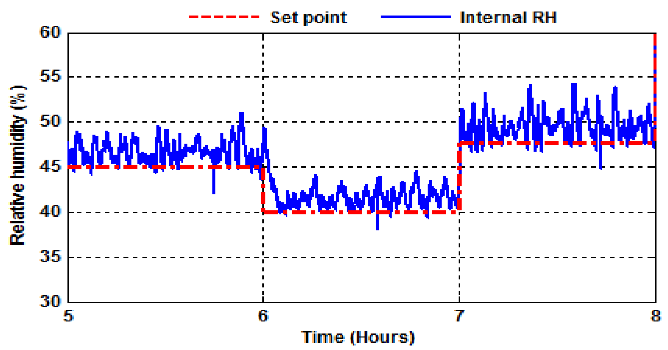

Figure 8. Control test on the greenhouse: controlled relative humidity with the proposed LQG controller in [5],[8] h

The LQG regulator is a powerful method for the control of linear systems in the state-space representation due to the LQR technique which generates controllers with guaranteed closed loop stability robustness property.

Figure 9 (a) and (b) illustrate clearly the comportment of the two command variables associated to the heater and the humidifier actuator, respectively, in order to maintain the internal relative humidity at its desired setpoint towards this regulation.

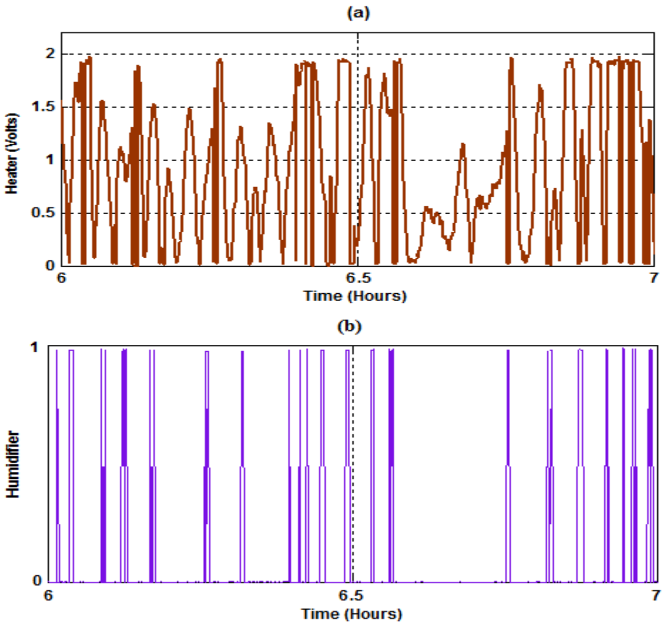

Figure 9. Control test on the greenhouse: control signals calculated by the proposed LQG controller associated to : (a) The heater and (b) The humidifier actuator in an interval time of [6],[7] h

The LQG controller turns on the heater when the relative humidity gets over the reference and it turns the humidifier if relative humidity gets under the reference.

Results of the test indicated that the time constant of the heater system was rather large in the purpose of reaching the desired relative humidity level. These results were probably due to long time constants of controller system including sensors and the disturbances, like external temperature and relative humidity, which affect the internal parameters. Based on the observation, the evolution of the internal relative humidity was adjusted.

The used controller is suitable but at the expanse of actuators frequent activity. This compensator permits a good performance where we keep the relative humidity under greenhouse for a long period of time and with a minimum power which is generated to the heater and humidifier actuators. The advantage of an observer-based controller is the possibility to optimise the state feedback gain matrix taking measurement noise and actuator saturation into account. In addition, the LQR-based controllers provide reliable closed-loop system performance despite of stochastic plant disturbance. These experimental results show the efficiency of the proposed strategy to control the relative humidity under an experimental greenhouse system regardless the possible mismatch between the real process and its identified model.

4. CONCLUSION

The automation and high efficiency on greenhouse environment monitoring and control are crucial for agricultural production. This paper describes the practical application of an optimal dynamic regulator using model based Linear Quadratic Gaussian (LQG) method of the relative humidity under greenhouse. The Numerical Subspace State Space System Identification (N4SID) is used to identify the basic model of the LQG regulator. The obtained model was validated with the experimental data. This LQG regulator consists of an optimal state-feedback LQR controller and Kalman filter. In this case, the separation principle allows designing a dynamic regulator based on Linear Quadratic Gaussian strategy, where a performance criterion is minimized in order to regulate the internal relative humidity of the greenhouse. An observer based on Kalman filter is used to estimate the relative humidity as a state variable in greenhouse process. Then, the use of LQG regulator demonstrates the significant advantages for tracking desired setpoints which is a good solution for the relative humidity under greenhouse control.

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