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A multi-model with control increments for a nonlinear passive air-conditioning unit modeling

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ABSTRACT

This paper defines a discrete time dynamic model of a passive air-conditioning unit with respect of environmental conditions, for micro-climate in growth chambers and greenhouses, where temperature and relative humidity evolve and should be controlled independently. As the analytical model developed turned out to be complex, highly nonlinear and difficult to use for control objectives, especially with respect to relative humidity, a Takagi–Sugeno MIMO structure was used to model nonlinearities of the unit. Two structures (a global and two levels) identification algorithms were implemented. Pseudo-Random Multi-level Signals were used as excitation input in order to capture the dynamics and nonlinearities and to cover a wide range of inputs in which the air-conditioning unit will operate. The consequent parts of the relative humidity contained additional inputs composed of the increments values of the control inputs. Identification and validation results using the two levels showed good prediction performance for the temperature and the relative humidity outputs despite their strong coupling.

1. Introduction

Temperature and relative humidity in greenhouses and growth chambers play an important role on the growth and development of ornamental plants. For instance, very high and very low temperatures are lethal for most crops. Some crops also become sensitive to fungal diseases when grown under high relative humidity. Relative humidity also acts on flowering of some ornamental plants (Codarin, Galopin, & Chassériaux, 2006; Galopin, 1995).

Unfortunately, temperature and relative humidity are highly coupled through nonlinear thermodynamics laws. Their accurate modeling is an essential step of controller design in order to control crop growth and production, qualitatively and quantitatively, since it is possible to control temperature and relative humidity independently. Such objectives can be reached by incorporating new technologies for crop growth chambers and small-size greenhouses such as Heating Ventilation and Air-Conditioning (HVAC).

Various climate control technologies have been used for commercial and experimental greenhouses and growth chambers. There exists a consequent review on temperature control, and on relative humidity modeling control to a lesser extent (Bennis, Duplaix, Enea, Haloua, & Youlal, 2008; Herrero, Blasco, Martinez, Ramos, & Sanchis, 2008). The main cooling technologies routinely used in greenhouses are ventilation, evaporative cooling, and composite systems. A simple way to reduce the difference between inside and outside air temperature is to improve ventilation (Boaventura cunha, Couto, & Ruano, 1997; Gruber et al., 2011). Natural ventilation uses very little external energy, but whether it is natural or forced, ventilation is of limited efficiency and unsatisfactory on sunny days, and in addition it does not act massively on relative humidity values. Evaporative cooling using fan-pads (Kittas, Bartzanas, & Jaffarin, 2003) or fog/mist (Montero, Anton, Beil, & Franquet, 1994; Salgado & Boaventura Cunha, 2005) inside greenhouses and roof-cooling systems (Willis & Peet, 2000) represent an efficient means of greenhouse cooling that can significantly lower inner air temperature below that of ambient air, but the range of relative humidity variation remains limited. Mist or fog systems can provide more uniform temperature distribution than fan-pad systems, in addition to ensuring almost uniform high humidity levels. One of the drawbacks of fog/mist is that the compressor uses large amounts of energy, which increases the cost for operating the system. This method also uses expensive foggers or nozzles, which are often blocked due to insoluble and soluble

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Nomenclature

A_{pad}	pad exchange area (m^2)
AH_{ai}	absolute humidity of air intake (kg water/kg dry air)
AH_{mix}	absolute humidity in the mixer (kg water/kg dry air)
AH_{OHD}	absolute humidity after the humidified duct (kg water/kg dry air)
$AH_{sat}(T_{wi})$	saturated absolute humidity at T_{wi}(kg of water/kg of dry air)
AP	atmospheric pressure (N/m^2)
C_a	air specific heat (J/kg °C)
C_w	water specific heat (J/kg °C)
h	convective heat coefficient ($J/m^2 s$ °C)
h_{cc}	mass transfer coefficient relative to concentration (m^3 water/m^2s)
J	moment of inertia of the motor and the aperture (kg m^2)
k_M	proportional constant of DC motor (V/rad s^{-1})
k_{RDD}	dry duct heating power coefficient (J/sV)
k_{RHD}	humidified duct heating power coefficient (J/sV)
$L_V(T_{wi})$	latent heat at water intake temperature (J/kg of water)
POS_{aper}	aperture position (cm)
Q_{Va}	total volumetric air flow (m^3/s)
R	armature resistance of the DC motor (Ω)
RH_{mix}	air relative humidity in the mixer (%)
SPE_{aper}	aperture speed (cm/s)
T_{ai}	intake air temperature (°C)
T_{ODD}	air temperature after the dry duct (°C)
T_{OHD}	air temperature after the humidified duct (°C)
T_{mix}	air temperature in the mixer (°C)
T_{RHD}	air temperature after the heater of the humidified duct (°C)
T_{wi}	intake water temperature in the pads of the humidified duct (°C)
$\boldsymbol{u}$	control vector
U_{DD}	voltage on the dry duct resistor (V)
U_M	voltage on DC motor (V)
U_{HD}	voltage on the humidified duct resistor (V)
V_{DD}	dry duct volume (m^3)
V_{mix}	volume of the air mixing zone (m^3)
V_{pad}	pad volume (m^3)
V_{RHD}	heater chamber volume of the humidified duct (m^3)
$\mathbf{w}$	disturbance vector
$\boldsymbol{y}$	output vector
$\alpha(.)$	air flow percentage in the dry duct (%)
ε_r	pad porosity coefficient (%).
ρ_a	air density (kg/m^3)
ρ_w	water intake density (kg/m^3)

salts present in the water, thereby reducing the working efficiency of the system.

Another class of refrigeration approach includes two primary composite systems, such as Earth-to-Air Heat Exchangers (EAHES) and Aquifer Coupled Cavity Flow Heat Exchangers (ACCFHES) (Sethi & Sharma, 2007a) can be used for heating as well as cooling greenhouses. The major disadvantage of EAHES is the cost of digging and laying the pipes. Deterioration of the pipes under soil pressure also makes this system less reliable for long-lasting projects. A substantial review of cooling technologies can be found in Sethi and Sharma (2007b). Air-conditioning units used in crop growth chambers are made up of heating and cooling system components with a compression cycle (Hanan, 1998; Hansen & Hoghs Schmidt, 1996; Jones, Jones, Allen, & Mishve, 1984). In addition to the energy cost and the high maintenance expenses for this type of system, they represent an ecological issue due to the pollutant emissions generated by the use of refrigerating gases.

An ecological approach for growth chamber and greenhouse climate control based on a passive principle was investigated. A similar approach is presented in Buchholz, Buchholz, Jochum, Zaragoza and Pérez-Parra (2006). The conditioning unit under study is a new design with innovative properties and offers various environmental advantages It does not use the more typical compression system or absorption-refrigeration cycle. It was designed to produce a microclimate with variable temperatures and variable relative humidity set point values inside growth chambers. The initial study (Tawegoum, Teixeira, & Chassériaux, 2006a) dealt with simulation of variable temperature and constant relative humidity set points control using a quadratic regulator, based on a linear state space model of the air-conditioning unit. A model using operating point dependent parameter-structure was presented in Riadi, Tawegoum, Rachid, and Chassériaux (2006). In Tawegoum, Bournet, Arnould, Riadi, and Chassériaux (2006b), numerical techniques based on computational fluid dynamics were implemented to analyze the flow characteristics of the mixed air produced by the device. Simulation disclosed a nonlinear relationship between the air flow rate and the aperture opening. Subsequently, Tawegoum, Riadi, Rachid, and Chassériaux (2008), focused on the one hand, on the comparison between the indirect (Riadi, Tawegoum, Rachid, & Chassériaux, 2007) and the direct adaptive generalized predictive control of the temperature of each duct of the conditioning unit using autoregressive linear models with exogenous input, and on the other hand, on the control of relative humidity based on aperture position control. In spite of rather satisfactory control of the temperature in ducts, the temperature in the mixture zone was less accurate than that of the ducts. Concerning the relative humidity output, the tracking performance was too slow. Nonlinear parametric modeling could therefore be an efficient approach to represent the air-conditioning unit.

Several methods have been developed for nonlinear system identification, including the Hammerstein, Wiener, Voltera and NARMAX models. Wiener and Hammerstein-type nonlinear models are suitable for static nonlinearities. Voltera series models require a large number of parameters to be optimized, thus it is difficult to apply such models to high order systems. NARMAX structures are one-step prediction models. In addition, it is often difficult to represent a system on a wide range of operating points using these structures. In the last decade, new approaches of system identification have been developed based on multiple model strategy, fuzzy logic, and neural networks.

The multiple model approach (Murray-Smith & Johansen, 1997) is an appealing mathematical framework for the modeling and analysis of complex systems. The basic principle of this modeling framework is to proceed to the approximation of a nonlinear process with a finite collection of linear models called local models or sub-models that are interpolated by the means of an interpolation mechanism. Each sub-model describes the behavior of the process within a limited operating range of the nonlinear process. The local validity of each sub-model is defined by a weighting function that specifies the contribution of the sub-model to the approximation of the global dynamics of the nonlinear process. A multiple model can be expressed in a state-space representation (Johansen & Babuska, 2003) or in a regression form (Abonyi, Babuska, & Szeifer, 2002; Gasso, Mourot, & Ragot, 2001; Takagi & Sugeno, 1985), the latter form being more suitable for identification purposes.

The Takagi–Sugeno (T-S) fuzzy model is a system described by fuzzy IF-THEN rules which can give local linear representation of