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A hybrid-controlled approach for maintaining nocturnal greenhouse temperature: Simulation study

A.P. Montoya [a,*], J.L. Guzmán [b], F. Rodríguez [b], J.A. Sánchez-Molina [b]

[a] Universidad Nacional de Colombia sede Medellín, Calle 49 N°59A-63 Bloque 21-115, Medellín, Colombia
[b] Departamento de Informática, Universidad de Almería, Carretera Sacramento s/n, Edificio CITE III, CP-04120 Almería, Spain

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ABSTRACT

Forced-air heaters and aerial pipe systems are the most common heating equipment used in greenhouses to control the nocturnal temperature in Mediterranean areas. These heating systems are often used separately and they are seldom combined in the same greenhouse for temperature control purposes. The main reasons are that the advantage of combining both heating systems has not been thoroughly analysed in literature, and that, the complexity of the problem increases from a control point of view due to the mixing of different dynamics. The combination of these two heating systems can be useful in some situations, obtaining a reasonable trade-off between thermal gain and running costs. Thus, this paper proposes to analyse the combination of these two heating systems and provide a solution to the problem of switching two different heating systems to control the nocturnal temperature in a greenhouse by using a hybrid controller. The proposed controller counteracts the switching disadvantages presented by commercial systems based on heuristic rules. To achieve this solution, the system dynamics are represented through a hybrid model, where weather variables act as logical conditions to switch between the different process dynamics. This approach allows considering the greenhouse dynamics as a hybrid system with continuous and discrete components. A Model Predictive Hybrid Controller is used to regulate the inner temperature during the night and calculates optimal control signals based on power consumption and commutation minimisation. The performance of this controller is studied, comparing its reference deviation, number of commutations, and running costs against commercial controllers. The final results show that the adequate combination of these heating systems can contribute to a much better control performance with a minor cost increment.

1. Introduction

Greenhouse climatic conditions directly affect crop productivity (Ramírez-Arias et al., 2012). Radiative and/or convective techniques are employed in order to keep an adequate climatic environment for the crop, as: hot pipes localised near the crop or forced air heaters (Teitel et al., 1999), ground floor heating (Reiss et al., 2007), and infrared heating (Kavga et al., 2015), among others. Forced-air heaters (FAH) in combination with aerial pipe heating systems (APH) are used to increase the greenhouse air temperature during overnight-wintertime in Mediterranean areas (Tadj et al., 2010). Despite their low energy efficiency, forced-air heaters (FAH) are the most commonly used in this areas, due to their low-cost installation, with high and fast thermal gain (Teitel et al., 1999). This system could be used along or merge with aerial pipe heating systems (APH) near the crop, which are more energy efficient, have more thermic inertia and could have a less running cost than the FAH (Bartzanas et al., 2005). There are some situations where the combination of these two heating systems can be useful, improving the thermal gain, temperature regulation, microclimate heterogeneity and condensation reduction, than using these heating system separately (Tadj et al., 2010; Bartzanas et al., 2005). The use of the combined heating systems controlled by and on off control strategy increases the energy consumption 19% (Bartzanas et al., 2005). Sometimes when the night is too cold, only one heating system is not able to supply enough heat to achieve the desired reference temperature, and an

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Abbreviations: FAH, forced-air heaters; APH, PVC aerial-pipe heating systems; HMPC, Hybrid Model Predictive Control strategy; MAE, mean absolute error; MDL, Mixed Logical Dynamic Model.

[*] Corresponding author. Tel.: +57 44309088.

E-mail addresses: apmontoy@unal.edu.co (A.P. Montoya), joseluis.guzman@ual.es (J.L. Guzmán), frrodrig@ual.es (F. Rodríguez), jorgesanchez@ual.es (J.A. Sánchez-Molina).

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additional heating system could be used to complement the required thermal increase (Teitel et al., 1999). Hence, the combination of two heating systems may resolve this issue, neutralising their individual disadvantages.

From a control point of view, the energy consumption of the combined system could be minimised, using an optimised control technique. When the two different heating systems are combined, the dynamics of the greenhouse temperature changes, notice that the APH presents a continuous dynamic and the FAH a discrete one, and both are subject to different operational restrictions. For that reason, heuristic control rules are commonly used (Kamp and Timmerman, 2003). The main problem of the heuristic tuning rules is that performance and cost requirements cannot be always be fulfilled since they cannot be explicitly included in the control design process. Therefore, the problem that needs to be solved is how to regulate the greenhouse inner temperature by switching these two heating systems, reaching a trade-off between performance and running costs, which are related to the operational usage of the heaters and their commutations.

Commercial control algorithms try to solve the problem of controlling inner greenhouse temperature during wintertime by using only one heating system. Proportional Integral (PI) controllers are commonly used for APH and On–Off controllers for FAH (Kamp and Timmerman, 2003). More elaborated control structures can be found in literature, where real-time control and predictive control approaches were used (Chalabi et al., 1996; Ramírez-Arias et al., 2005). However, from these works, it was possible to observe that there were periods of time with very cold weather where the proposed heating control system was not able to reach the required temperature reference, because the heating system was saturated. Furthermore, since the heating system was working at its maximum capacity, it consumed a large quantity of energy without reaching the required control performance. To solve this issue, Kamp and Timmerman (2003) proposed to control the greenhouse inner temperature using two heating systems at the same time, by employing a controller as the fusion of two classical control algorithms, a PI controller for APH plus an On–Off controller for FAH. This solution presented interesting results, but it does not address constraints or minimise the running costs and heating system commutations explicitly. The main problem was that the heating system dynamics were considered separately, and the commutation between both control systems was done by means of heuristic rules. Hence, the realisation of explicit performance and cost requirements for the whole heating control system was complicated to reach. To address these drawbacks, firstly a model including the dynamics of both heating systems should be developed. Then, this model including the dynamics commutations should be used to design the control algorithm in a systematic way in order to cope with the required problem specifications.

Therefore, this paper proposes to consider the greenhouse as a hybrid system to solve the nocturnal temperature regulation problem. Due to the discrete and continuous dynamics presented in the greenhouse, because of the combination of the two heating systems, hybrid-modelling and control techniques are used. These techniques have been successfully used in industrial applications during the past decade (Ding and Engell, 2007), and were first used in the greenhouse climatic control problem in Guzmán et al. (2007) and afterwards in Laribi and Mhiri (2008). A hybrid model that switches between ventilation and heating systems was developed Guzmán's, study (2007); while in Ding and Engell (2007), a hybrid model and controller to regulate temperature by FAH was presented. Based on these ideas, this paper proposes a novel approach to solve the problem of regulating the inner greenhouse temperature using two heating systems, modelling and controlling the temperature by a hybrid framework, where a Hybrid Model-based Predictive Controller (HMPC) handles logical variables and constraints. In this approach, a model predictive controller with receding horizon is formulated based on a hybrid model, and this framework incorporates the manipulation of analogue and discrete variables, allowing a formal representation of the hybrid control problem (Camacho et al., 2010).

Please note that experimental results are not included in this paper since the requirement is to have a greenhouse with both heating systems, which is unusual in classical greenhouses. For that reason, the main objective of this work is to present a simulation study to analyse the viability of this heating system combination and to see if this approach can be considered as a solution when a new heating system has be to implemented in a greenhouse.

2. Materials and methods

2.1. Greenhouse facilities

The systems identification experiments to obtain the greenhouse temperature model were carried out between December 2011 and February of 2012 in two identical Parral greenhouses located in "Las Palmerillas-Cajamar" Experimental Station, Almería, Spain (36°48′N, 2°43′W and 151 m above sea level). One of the facilities was equipped with an APH system, and the other one had a FAH system. Both greenhouses are identical in size and hardware, with the only difference being the included heating equipment. On both greenhouses were established identical test crops (Tomato, *Solanum Lycopersicum*). At the beginning of data collection the crops were 60 days after seeding.

The greenhouses are symmetrically-curved, oriented E-W, with a flat roof, 877 m^2 of covered surface (37.8×23.2 m) with a crop area of 616 m^2 and a height ranging from 2.8 m to 4.4 m. The framework is made of 114 mm galvanised structural steel tubing and 4.8 mm wire rope. The covering material is a 200-micron-thick multilayer PE film. Each greenhouse had natural-automated ventilation system with lateral windows in the northern and southern walls and mesh-protected anti-trip bionets 20×10 in thickness. The greenhouses are fully equipped to develop climatic control research (Ramírez-Arias et al., 2012).

A meteorological station was used to measure external variables. Air temperature and relative humidity (Vaisala HMW60Y), solar radiation (Campbell LP02L) wind speed and direction (Young 03002) were taken. Inside the greenhouses the air temperature, relative humidity, solar radiation (Delta Ohm LP PYRA02), soil temperature (PT100) at 40 cm, among others, were measure. Additional sensors were used to measure auxiliary variables like vents position and actuators states.

The APH system is composed of a boiler, a biomass burner, mixing valves, pumps and heating pipes. The boiler has an independent On–Off control to maintain a constant water temperature of 80 °C using a maximum power consumption of 174 KW. In this system, a pump of 2.5 HP is used to produce a constant flow of 25 $m^3\,h^{-1}$ and a continuous mixing valve is used to control the temperature of water flowing through the pipes. The valve position, the return, and the main pipe water temperature are measured for this system.

The FAH system is housed within the second greenhouse, with a discrete actuator of 95 KW, and is controlled via relays. It is composed of: a combustion camera – where a heat exchanger is located, a diesel tank of 500 L, a chimney to expulse the combustion gases outside the greenhouse and a 70 cm diameter fan with a flow capacity of 7000 $m^3\,h^{-1}$. This system generates faster temperature changes than the APH with an average diesel consumption of 10 $L\,h^{-1}$. The activation state, chimney gases temperature, and temperature of air flow are measured for this study.