# Multivariable control of nighttime temperature and humidity in greenhouses combining heating and dehumidification ⋆

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**Abstract:** This work presents a multivariable control strategy to regulate nighttime temperature and relative humidity inside a greenhouse, using a pipe heating system and a dehumidification system. The greenhouse is modeled as a two-input two-output (TITO) process with a system identification methodology to calculate low-order linear models. Proportional-integral (PI) controllers with anti-windup are used, and an inverted decoupling scheme is adopted. The strategy was tested in simulation with real data. Results suggest that it is attractive for real implementation and show for the first time that the use of dehumidification systems can be applied as part of a combined control strategy.

*Keywords:* Agriculture, process control, TITO system, PID control, multivariable control, decoupling, system identification

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## 1. INTRODUCTION

Temperature and humidity are among the most important variables affecting the growth and health of a greenhouse crop, respectively. To ensure proper fruit formation and favor the physiological processes of the plants, the air temperature and humidity inside a greenhouse should be maintained between adequate values, which vary for daytime and nighttime, when plants have different needs. Specifically, in the nighttime, high temperature values are not required since the crop does not photosynthesize, but it is necessary to prevent excessively low values, especially in cold seasons, to prevent damage to the plants. For the relative humidity, it is important to avoid high values because of the risk of saturation of water vapor and condensation on the leaves of the plants, which reduces transpiration and may lead to the appearance of diseases (Rodríguez et al., 2015).

In the nighttime, temperature control in greenhouses is usually achieved through the use of heating systems. There are several types, but pipe heating systems and forced-air heaters are the most commonly used. The main methods to reduce humidity in greenhouses are ventilation, supplemental heating, adsorption by hygroscopic materials, and condensation of water vapor on a cold surface (Amani et al., 2020). The latter is usually performed by means of heat-pump dehumidifiers (Cámara-Zapata et al., 2019).

Despite the availability of actuators, it is still a challenge to control nighttime temperature and humidity due to the complexity of the phenomena occurring in a greenhouse. During the last hours of the afternoon, the vents of a greenhouse are normally closed to avoid a fast decrease of the inside temperature due to the reduction of solar radiation. If the vents remain closed, there is not exchange of water vapor with the outside air, so respiration of plants induces the increase of humidity. If the vents are opened, humidity can decrease if the outside air is drier, which means that ventilation to control nighttime humidity is only effective for certain external weather conditions. In contrast, to control nighttime temperature, the vents should be closed to avoid the heat loss due to a lower outside temperature. Although heating can be used to increase temperature and decrease relative humidity, without ventilation, the total amount of water vapor would remain enclosed inside the greenhouse, which can be an issue during the first and last hours of the nighttime, when heating systems are deactivated and the risk of condensation is higher.

Due to the presence of coupled dynamics, multivariable control can be a reasonable method to be applied to this problem. It allows to design controllers for multiple actuators while taking into account the interactions between control loops. This idea is of interest for greenhouses. For instance, as mentioned by Chantoiseau et al. (2016), the use of a heating system and a dehumidification system can be an efficient combination, but further research is needed, especially due to the lack of studies addressing automatic control with dehumidification systems. In the literature, multivariable control of temperature and humidity in greenhouses has been approached in a reduced number of

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studies, using advanced control methods such as model predictive control (MPC) (Song et al., 2013), feedback-feedforward linearization (Gurban and Andreescu, 2012), dynamic output feedback (Paraforos and Griepentrog, 2013), fuzzy logic (Azaza et al., 2015), and filtered Smith predictor (Giraldo et al., 2016). Most of the above techniques were applied only to daytime control and tested in simulation. Therefore, there is a need to study the development of control strategies for the nighttime, focusing also on a regulatory level to reduce the complexity of the design and facilitate their inclusion in commercial greenhouses.

This paper proposes as a main contribution a simple but effective multivariable control strategy that can be understood and implemented by farm technicians with less mathematical background. The greenhouse nighttime control problem is addressed to control the inside air temperature and relative humidity using a pipe heating system and a heat-pump dehumidifier. Automatic control with a dehumidification system is also a novel aspect of this work. The greenhouse dynamics are reduced to low-order transfer functions through a system identification methodology, which is based on measured climatic data and open-loop testing of the actuators. The advantage of this procedure is that it also simplifies the calculation of controllers, because inverted decoupling (Garrido et al., 2011), proportional-integral-derivative (PID) controllers, and well-known tuning methods can be used (Åström and Hägglund, 2006).

## 2. DESCRIPTION OF THE GREENHOUSE

A traditional Almería-type greenhouse has been used in this work (see Fig. 1). It is located at "Las Palmerillas" Experimental Station of the Cajamar Foundation, in El Ejido, Almería, Spain. It has an area of 877 $m^2$, and is equipped with auxiliary actuators to regulate the climate inside. For the nighttime control problem, only a pipe heating system and a dehumidification system were considered.

The pipe heating system consists of a biomass boiler (see Fig. 1c) that heats water, which is pumped and circulates through pipes installed close to the crop rows, so the air temperature inside the greenhouse increases by convection. The system has a limitation on the maximum temperature of the water, set as 80 °C. Also, the minimum temperature of the pipes is assumed to be equal to the inside air temperature of the greenhouse.

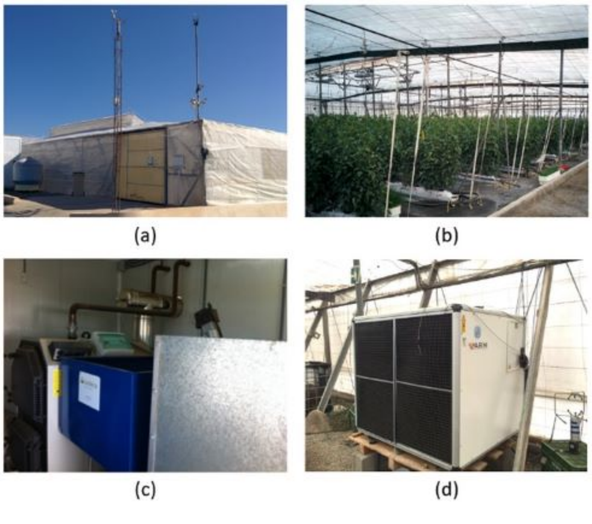

Fig. 1. Greenhouse facilities: (a) Exterior view, (b) Interior view, (c) Biomass boiler for the pipe heating system, (d) Dehumidification system

As for the dehumidification system, it is an electrical heat-pump dehumidifier installed inside the greenhouse (see Fig. 1d). This machine sucks out an air flow and removes the water vapor contained in it by means of condensation. Its operating limitation ranges from 0% to 100% of power.

## 3. SYSTEM IDENTIFICATION

The dynamics of the greenhouse temperature and humidity are commonly modeled with nonlinear differential equations that makes the design of controllers a difficult task, requiring analytical calculations (Rodríguez et al., 2015). Since one of the main objectives of this work is to offer a simple procedure to calculate the controllers, a system identification methodology has been applied to obtain linear models. This methodology is principally needed to model the effect of the disturbances on the controlled variables, due to the impossibility to perform step changes in the external weather variables.

The methodology has been successfully tested in previous works (García-Mañas et al., 2021). It can be accomplished using the System Identification Toolbox of MATLAB (The MathWorks, MA, US), and consists of the following steps:

1. Selection of adequate experimental data.
2. Identification and validation of Auto-Regressive with eXogenous input (ARX) models.
3. Reduction of the ARX models to first-order plus dead time (FODT) models.

For the first step, experimental data from January 2022 were selected. From December to March, cold nights can occur in the region where the greenhouse is located, so the data are representative of the type of climate that may cause the use of heating and dehumidification systems. Although this work is focused on the nighttime, ARX models were identified for complete days, so that daytime control could be applied in future works.

For different days of January 2022, separate ARX models were obtained for temperature and humidity. Each ARX model was identified by using the minimum number of variables that affect the evolution of either temperature or humidity. Those variables are the external weather conditions and the state of the actuators, all assumed to be inputs of the ARX models. Hence, the inside air temperature was modeled considering the external solar radiation, the external air temperature, and the external wind velocity. For the inside humidity, the external relative humidity was considered, as well as the external solar radiation and wind velocity. In addition, the natural ventilation effect on both temperature and humidity was taken into account because it is the most frequently used actuator in Mediterranean greenhouses. Since the rest of the actuators are used sporadically, their effect was individually modeled and subsequently added to the rest of transfer functions calculated in the third step of the methodology.

Fig. 2 shows an example of identification results for the best ARX models (both of fourth order). Notice that the inputs of experimental data contain sufficient excitation, especially for natural ventilation as a manipulable variable, which is an important requirement for a successful system identification. Fig. 3 presents the results obtained for a validation test, in which the mean absolute error (MAE) is 0.91 °C for the temperature ARX, and 3% for humidity ARX. The fit to the real data is satisfactory, however, it is important to remark the difficulty to obtain linear models for a greenhouse due to the change of weather conditions that can occur every few weeks.

After the validation of the ARX models, the third step of the methodology can be accomplished. It can be seen in Fig. 2 and Fig. 3 that the obtained transfer functions (*TF model* in legends) are valid for nighttime and daytime, since they reproduce the dynamics captured by the ARX models (notice that the responses are overlapped). For reasons of limited space, only the transfer functions affecting during the nighttime are shown in (1), where $G_{\text{T-Text}}(s)$ in °C/°C relates inside temperature to external temperature, $G_{\text{T-Wind}}(s)$ in °C/(m/s) relates inside temperature to external wind velocity, $G_{\text{H-Hext}}(s)$ in %/% relates inside humidity to external humidity, and $G_{\text{H-Wind}}(s)$ in %/(m/s) relates inside humidity to external wind velocity. Time constants and dead times are in seconds.

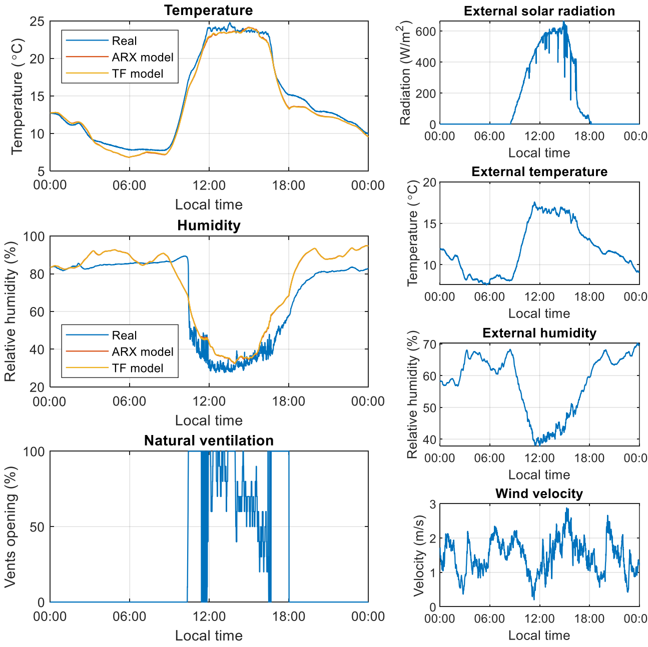

Fig. 2. Identification of ARX models and transfer function models with real data from 20 January 2022

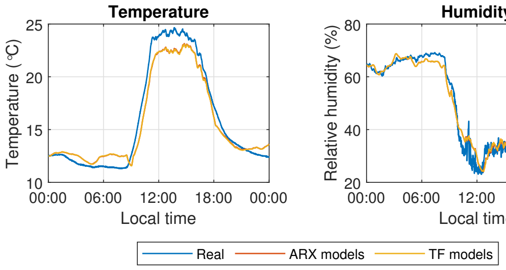

Fig. 3. Validation of ARX models and transfer function models with real data from 28 January 2022

$$
\begin{aligned}
G_{\text{T-Text}}(s) &= \frac{1.503}{2111\,s+1} \qquad G_{\text{T-Wind}}(s) = \frac{-0.4831}{2231\,s+1} \\
G_{\text{H-Hext}}(s) &= \frac{0.8142}{1191\,s+1} \qquad G_{\text{H-Wind}}(s) = \frac{-4.198}{1520\,s+1}\,e^{-21.2\,s}
\end{aligned}
\tag{1}
$$

The model for the nighttime is then reduced to the scheme presented in Fig. 4. Notice that, although external weather variables were treated as inputs for the identification of ARX models, in fact they are measurable disturbances. Natural ventilation effect is not included since the vents are closed during night. Instead, the effects of the nighttime actuators have been added. Transfer functions for the pipe heating system and the dehumidification system were obtained by applying the reaction curve method to data measured during open-loop tests, as shown in Fig. 5. The data were selected for days when external weather disturbances did not present variations that could affect inside temperature and humidity, so that exclusively the effect of the actuators can be modeled. The transfer functions were calculated according to the following considerations:

- For the pipe heating system, a cascade control structure was working in the real system to regulate the opening of a three-way valve to achieve a desired temperature for the water inside the pipes. The transfer functions calculated for this actuator include the dynamics of this inner loop.
- The dehumidification system was activated with steps from 0% to 100% in every period of use. For better humidity control, it has been assumed that two dehumidifiers were available, so the gains of the transfer functions for this actuator were multiplied by two. Notice that the approach followed in this work also helps to size actuators for design purposes.

The tests were performed during winter nights of different years, and the effect of the actuators was found to be diverse depending on the weather conditions. Equation (2) shows the average transfer functions that were calculated as a manner to take into account the variability in gains,

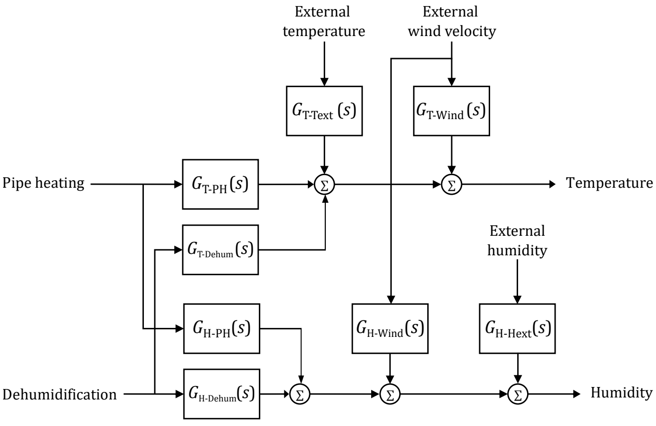

Fig. 4. Scheme of transfer functions for temperature and humidity in the nighttime

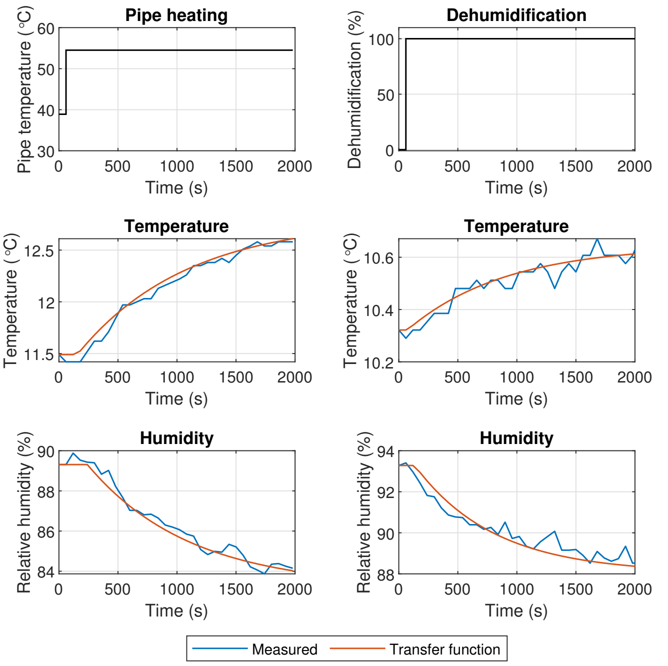

Fig. 5. Examples of open-loop tests to calculate transfer functions for the nighttime actuators

time constants and dead times, where $G_{\text{T-PH}}(s)$ in °C/°C and $G_{\text{H-PH}}(s)$ in %/°C, relate temperature and humidity to the temperature of the pipes of the heating system, respectively; $G_{\text{T-Dehum}}(s)$ in °C/% and $G_{\text{H-Dehum}}(s)$ in %/%, relate temperature and humidity to the power of the dehumidification system, respectively. Time units are in seconds.

$$\begin{aligned} G_{\text{T-PH}}(s) &= \frac{0.07455}{720\,s+1}\,e^{-180\,s} & G_{\text{T-Dehum}}(s) &= \frac{0.008886}{570\,s+1}\,e^{-330\,s} \\ G_{\text{H-PH}}(s) &= \frac{-0.3246}{660\,s+1}\,e^{-300\,s} & G_{\text{H-Dehum}}(s) &= \frac{-0.1202}{771.9\,s+1}\,e^{-198\,s} \end{aligned} \tag{2}$$

## 4. MULTIVARIABLE CONTROL DESIGN

The nighttime control problem of the greenhouse can be intended as the control problem of a two-input two-output (TITO) system, in which the outputs are the temperature, $y_1$, and the relative humidity, $y_2$, and the inputs are the temperature of the pipes of the heating system, $u_1$, and the power of the dehumidification system, $u_2$. The TITO system can be expressed as follows:

$$\begin{bmatrix} Y_1(s) \\ Y_2(s) \end{bmatrix} = \mathbf{G}(s) \begin{bmatrix} U_1(s) \\ U_2(s) \end{bmatrix} + \mathbf{G_d}(s)\,\mathbf{W}(s) \tag{3}$$

$$\mathbf{G}(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} = \begin{bmatrix} G_{\text{T-PH}}(s) & G_{\text{T-Dehum}}(s) \\ G_{\text{H-PH}}(s) & G_{\text{H-Dehum}}(s) \end{bmatrix} \tag{4}$$

where $\mathbf{G}(s)$ is the process model composed by the transfer functions shown in (2), and $\mathbf{G_d}(s)$ is the disturbances model for the set of external weather variables, $\mathbf{W}(s)$, that affect the outputs of the system, as presented in (1).

To develop a multivariable control strategy, the interactions between the inputs and outputs of the system described in (4) must be analyzed. The relative gain array (RGA) shown in (5) indicates that the recommended pairings are to control the air temperature with the pipe heating system and to control the air humidity with the dehumidification system (that seems the logical layout). The values in the secondary diagonal of the RGA indicate that undesired interactions will appear if the control loops are not connected properly.

$$\mathbf{RGA} = \begin{bmatrix} 1.4747 & -0.4747 \\ -0.4747 & 1.4747 \end{bmatrix} \tag{5}$$

The inverted decoupling scheme presented in Fig. 6 can be used to solve the problem of interacting control loops. In comparison to conventional decoupling, inverted decoupling was selected because of its practical advantages (Garrido et al., 2011), such as the possibility of tuning the controllers $C_1(s)$ and $C_2(s)$ independently, or the simplicity to include the anti-windup mechanism since the decoupling is obtained as a feedforward input to each controller. For the TITO system studied in (3), it is necessary to calculate two decouplers as follows:

$$D_{12}(s) = \frac{-G_{12}(s)}{G_{11}(s)} = \frac{-0.1192\,(720\,s+1)}{570\,s+1}\,e^{-150\,s} \tag{6}$$

$$D_{21}(s) = \frac{-G_{21}(s)}{G_{22}(s)} = \frac{-2.7\,(771.9\,s+1)}{660\,s+1}\,e^{-102\,s} \tag{7}$$

Notice that there are not realizability issues to obtain the decouplers. Nonetheless, for this particular system, small peaks appear in the control signals, as shown in Fig. 7. To eliminate these peaks, first-order low-pass filters have been added to the decouplers, with $\tau_{\text{f}} = 0.05\,\tau_D$, where $\tau_{\text{f}}$ and $\tau_D$ are the time constant of each filter and decoupler, respectively.

For feedback control of each loop, proportional-integral (PI) controllers were calculated for $G_{11}(s)$ and $G_{22}(s)$ using the lambda method with $\lambda = 0.3\,\tau$, where $\tau$ is the open-loop time constant of each transfer function. The value for $\lambda$ was imposed for fast responses to setpoint changes and for compensation of disturbances. The resulting parameters are $K_{\text{p1}} = 24.39$ °C/°C, $T_{\text{i1}} = 720$ s,

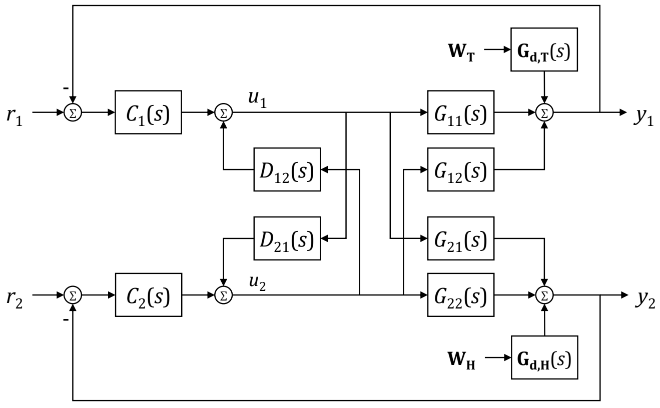

Fig. 6. Multivariable control scheme with inverted decoupling for the nighttime control problem

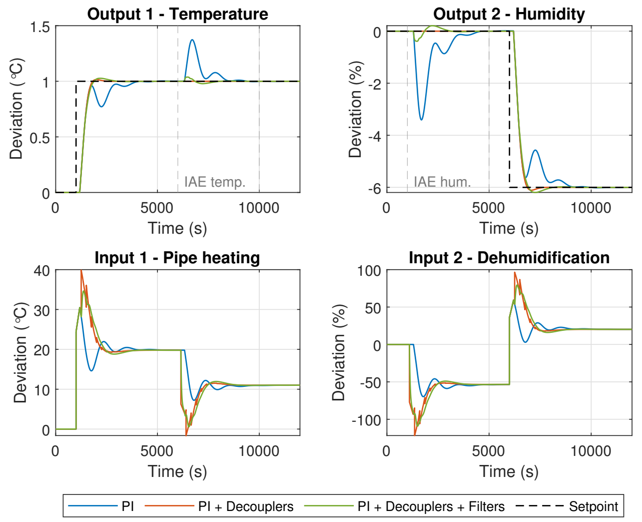

Fig. 7. Example of interaction between temperature and humidity control loops without and with decouplers

$K_{\mathrm{p}2} = -14.96$ %/%, and $T_{\mathrm{i}2} = 771.9$ s, where $K_{\mathrm{p}j}$ are the proportional gains and $T_{\mathrm{i}j}$ are the integral times, respectively. The controllers were implemented with an anti-windup scheme to deal with the operating limitations of the actuators, setting $T_{\mathrm{t}} = \sqrt{T_{\mathrm{i}}}$ as tracking constant (Åström and Hägglund, 2006). It is important to mention that feedforward controllers for measurable disturbances rejection were not considered in this study because the external weather variables normally present slow variations with less impact on the greenhouse dynamics during the nighttime, which can be well compensated by the feedback controllers.

An example of interactions occurring due to setpoint changes around an operating point is shown in Fig. 7. The linear model from Fig. 4 was used for this simulation, considering null weather disturbances and without saturation of the actuators. The inclusion of the decouplers improves the performance of both control loops by removing the effect of the interactions. This can be noticed for the integral absolute errors (IAE) presented in Table 1, which are calculated for the load disturbance responses caused by each setpoint change, and the last column shows the normalized values with respect to the responses of the PI controllers. Perfect cancellation of the interactions is achieved for PI+Decouplers. In comparison, if the filters for the decouplers are also included, the normalized IAE value increases but smoother control signals are obtained.

Table 1. IAE for disturbance responses in Fig. 7

| | **Temp.** | **Hum.** | **Normalized** |
|---|---|---|---|
| PI | 266.54 | $2.77{\cdot}10^3$ | 1 |
| PI+Decouplers | 0 | 0 | 0 |
| PI+Decouplers+Filters | 29.58 | 305.77 | 0.11 |

## 5. CONTROL RESULTS

The multivariable control strategy was tested in simulation using the linear model presented in Fig. 4, fed with real data measured in the greenhouse, and taking into account the saturation of the actuators. Fig. 8 shows a comparison of control results to analyze the performance of the multivariable control strategy. Three different simulations are compared: (i) using PI control only for temperature, (ii) using PI control only for humidity, and (iii) using multivariable control for temperature and humidity. In all the cases, the humidity setpoint starts at 80% and changes to 60% at 02:00, and the temperature setpoint starts at 14 °C and changes to 12 °C at 03:00. Setpoint changes can be performed, for example, to avoid saturation of the heating system when the external temperature is very low during the last hours of the nighttime, and thus reduce the consumption of biomass or fuel.

Attending to the results presented in Fig. 8, multivariable control performs better in comparison to individual control of temperature or humidity. This is confirmed by the IAE values in Table 2, calculated from 18:00 to 10:30, as a manner to compare the accumulated deviations from the setpoints. Some effects of the decouplers can be noticed in the control signals for the actuators. For instance, when the humidity setpoint changes at 02:00, the temperature of the pipes slightly decreases to compensate for the peak in the control signal for dehumidification, which is caused by the humidity controller to quickly reach a lower value of humidity. When the temperature setpoint changes at 03:00, the temperature of the pipes greatly decreases, so a decoupling effect can be seen in the control signal of the dehumidification system, which increases up to saturation, but the humidity does not deviate much from the setpoint. Also, notice that the IAE value for temperature is greater for multivariable control than for temperature control because saturation prevents the action of decoupler $D_{12}(s)$ from decreasing the pipe temperature at 18:20, when the dehumidification is activated. In this regard, although saturation of the control signals prevents a perfect cancellation of the undesired interactions, the best overall performance is still obtained with multivariable control.

Table 2. IAE for the results in Fig. 8

| **Control** | **IAE temperature** | **IAE humidity** | **IAE sum** |
|---|---|---|---|
| Temperature | $1.878{\cdot}10^4$ | $2.887{\cdot}10^5$ | $3.075{\cdot}10^5$ |
| Humidity | $1.558{\cdot}10^5$ | $3.429{\cdot}10^5$ | $4.987{\cdot}10^5$ |
| Multivariable | $2.193{\cdot}10^4$ | $1.375{\cdot}10^5$ | $\mathbf{1.594{\cdot}10^5}$ |

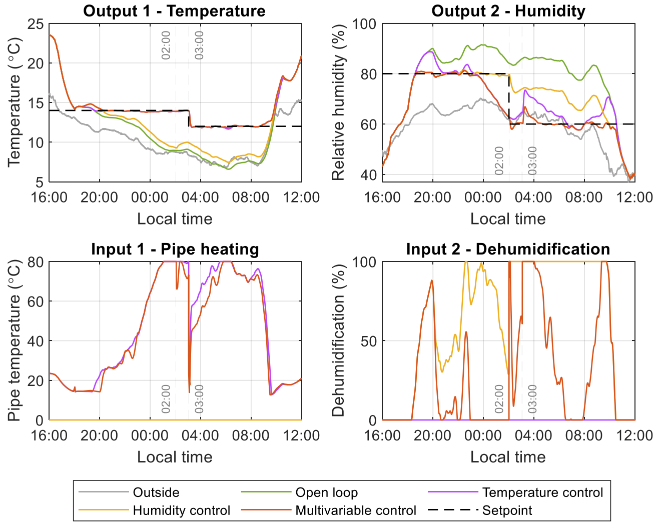

Fig. 8. Results for data from 20 and 21 January 2022

An additional simulation was performed to verify that multivariable control could be used for nights with high humidity values. The system identification methodology was repeated using data from November 2020 and the controllers were retuned accordingly. Fig. 9 shows that this strategy is also effective for these weather conditions. As occurred in Fig. 8, it is not necessary to keep the dehumidification system active throughout the night thanks to the heating supply. In this sense, the combination and automatic control of these two actuators is interesting from the point of view of energy saving.

## 6. CONCLUSION

This work constitutes a first approach to find a simple control strategy for the problem of controlling nighttime temperature and humidity in greenhouses. A multivariable control strategy using inverted decoupling has been tested in simulation and positive results have been achieved. The main advantage of using this strategy is that the procedure to obtain the models and controllers does not require complicated calculations, so it allows farm supervisors and technicians to easily understand the dynamics of the problem and tune the controllers. Additionally, compared to MPC strategies, multivariable control offers more flexibility, for example, to disconnect one of the controllers when required for maintenance tasks. As a disadvantage, the models have to be identified periodically, since the climatic conditions in the greenhouse may change every few weeks, which would affect also to the controller parameters.

Future works could be focus on simulating the proposed control strategy with a nonlinear model of the greenhouse before testing it on the real facilities, and to extend the proposal to address daytime control. Also, as mentioned above, the possibility of adding an adaptive control mechanism to tune the parameters of the controllers depending on the change of weather conditions may be studied. Moreover, multivariable control could be compared to other techniques, such as selective control (Liu et al., 2022), and integrated within a hierarchical control framework (Rodríguez et al., 2015).

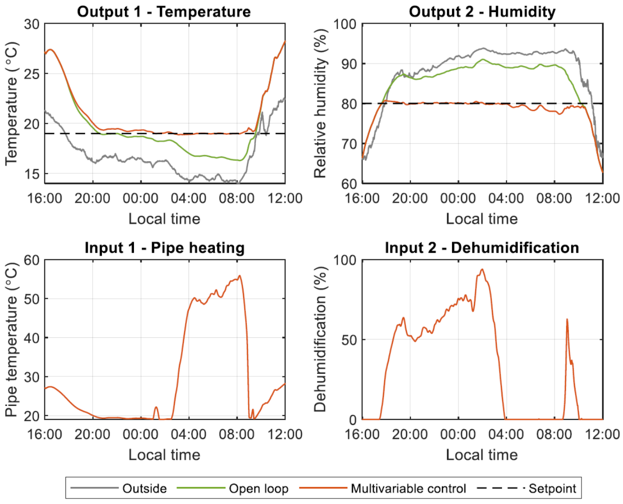

Fig. 9. Results for data from 15 and 16 November 2020

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