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Multivariable control of temperature and humidity in greenhouses

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Multivariable control of temperature and humidity in greenhouses

Control multivariable de temperatura y humedad en invernaderos

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"Un sogno che fai da solo è solo un sogno, un sogno che vivi insieme a qualcuno è realtà"
(Proverbio Africano)

Condividere è la chiave

I miei genitori, le persone che ho avuto più vicino in questi cinque anni, mi hanno plasmato, hanno conferito al comportamento quelle particolarità che mi rendono la persona capace che sono. Mi hanno fornito l'armatura. Per questo li ringrazio.

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Cinque anni che mi han fatto crescere. Ed ora, se mi sentirò poeta.. Sarete la mia ispirazione. Se mi sentirò in guerra.. Sarete il mio esercito. Se mi sentirò indifeso, sarete il mio riparo. Se mi sentirò sull'orlo.. sarete la mia spinta.

Abstract

Since 1980, the small coastal plain, about 30 kilometers southwest of the city of Almeria, has developed the largest concentration of greenhouses in the world, covering more than 30000 hectares. Over 50% of the European fruit and vegetable demand comes from greenhouses. For this reason it is not difficult to understand why there is a need to concentrate energies to develop this field. In this work, in particular, effort was concentrated to control humidity and temperature inside the greenhouse, two of the variables that most influence the optimal growth of the crop. This work started from data collection in the field, through this data hundreds of models have been developed and then validated in order to select the best one. By menas of these models the controllers have been calibrated, which, in the final part of the work, have been implemented inside the real greenhouse.

The use of linear models to describe a strongly non-linear system has led to obtaining a fitting, during the validation phase, which does not exceed 80%. The desire to use a simplified model is justified by the fact that, through a Proportional-Integral (PI) and a feedback loop, satisfactory results can be achieved with less waste of resources. During the simulation phase temperature and humidity reach the set point and, although we are in the presence of a Multiple Input Multiple Output (MIMO) system, the transversal influence of the actuators does not lead the system to instability. The real tests carried out in the summer months have highlighted the impossibility of controlling the internal temperature through ventilation when the external temperature is too high.

It is therefore possible to conclude that if the objective was to control temperature and humidity within a sufficiently wide range (for example between $18 - 32°C$ of temperature and $30 - 70$ % humidity relative) and not during the summer months, then it is possible the developed use linear model togheter with PI controllers. If the specifications were more stringent, however linear models such as Auto Regressive models with eXternal input (ARX) and Auto Regressive Moving Average models with eXternal input (ARMAX) should be discarded and non-linear modeling and control methods should be employed.

Resumen

Desde 1980, la pequeña llanura costera, a unos 30 kilómetros al suroeste de la ciudad de Almería, ha desarrollado la mayor concentración de invernaderos en el mundo, que abarca 30000 hectáreas. Más del 50 % de la demanda europea de frutas y verduras proviene de invernaderos. Por esta razón, no es difícil entender por qué hay una necesidad de concentrar energías en este campo. En este trabajo en particular se ha tratado de concentrar los esfuerzos para controlar la humedad y la temperatura dentro del invernadero, dos de las variables que más influyen el excelente crecimiento del cultivo. Se comenza a partir de la recopilación de datos en el campo, a través de estos datos se han desarrollado mas de cien modelos que luego se han validado con el fin de mantener solo lo mejor. A través de estos modelos, han sido calibrados los controladores y, en la parte final del trabajo, se han implementado dentro del invernadero real.

El uso de modelos lineales para describir un sistema fuertemente no lineal ha llevado a obtener un ajuste, durante la fase de validación, que no supera los 80 %. El utilizar un modelo simplificado se justifica por el hecho de que, a través de un controlador PI y una realimentacion de la salida, todavía se pueden conseguir resultados satisfactorios con menos desperdicio de recursos. Durante la simulacion tanto la temeperatura como la humedad alcanzan el punto de ajuste y, aunque se encuentra en presencia de un sistema de MIMO, la influencia transversal de los actuadores no conduce a la inestabilidad del sistema. Las pruebas reales llevadas a cabo en los meses de verano han puesto de manifiesto la imposibilidad de controlar la temperatura interna a través de la ventilación cuando la temperatura exterior es demasiado alta. Por tanto, es posible concluir que, si el objetivo era controlar la temperatura y la humedad dentro de un range suficientemente amplio (por ejemplo, entre $18 - 32°C$ de temperatura y $30 - 80\,\%$ de humedad relativo) y no durante los meses de verano, entonces es posible seguir este trabajo y usar modelos lineales junto con los controladores PI. Si las especificaciones son rigurosas, sin embargo, no se obtienen resultados satisfactorios; entonces modelos tales como ARX y ARMAX deben ser desechados y se debe proceder con modelado y métodos de control que no sean lineales .

Sommario

Questo lavoro è stato sviluppato presso l'Università di Almeria (Spagna) ed in particolare presso un impianto situato a El Ejido. L'obiettivo è stato quello di sviluppare un progetto nell'ambito dell'automazione delle serre.

In particolare questa tesi si è occupata del controllo della temperatura e dell'umidità all'interno delle serre, che offrono, nel sud della Spagna, una delle più grandi fonti redditizie grazie all'abbondante esportazione dei prodotti coltivati al loro interno. Il motivo che ha portato l'Università di Almeria ad investire tempo e risorse in questa ricerca è dato dal fatto che il mondo delle serre ricopre un ruolo di fondamentale importanza all'interno dell'economia Andalusa: oltre il 50% della domanda di frutta e verdura europea proviene infatti da coltivazioni in serre e, la sola Almeria, ha una superficie di oltre 30000 ettari ricoperti da questo "mare di plastica".

Questa tesi si è posta come obiettivo quello di riuscire a controllare temperatura ed umidità relativa all'interno di una serra, nella quale è presente una coltivazione di pomodori (tipica della zona). Controllare queste due variabili è essenziale dal momento che bisogna ottenere una pianta forte, priva di malattie (che potrebbero insorgere in caso di umidità troppo bassa) e che non subisca forti sbalzi di temperatura (dati ad esempio dall'escursione termica tra il giorno e la notte). Per riuscire ad ottenere quindi valori di temperatura ed umidità che seguano un certo set-point all'interno di un range di valori accettabili, è necessario introdurre un sistema di controllo costituito da PI con anti-windup. All'interno della serra però, la presenza di umidificatore, deumidificatore, sistema di ventilazione e riscaldamento, hanno reso necessario lo sviluppo e lo studio di un sistema MIMO 4x2 in cui sono presenti quattro loop di controllo con altrettanti attuatori, utilizzati per controllare le due variabili interne sopracitate.

Il sistema di controllo implementato ha tenuto in conto, già in fase di modellizzazione, dell'influenza trasversale data, ad esempio, dal sistema di ventilazione rispetto all'umidità relativa, piuttosto che dall'umidificatore rispetto alla temperatura interna. A causa della presenza di quattro attuatori si è reso necessario inoltre l'utilizzo di altrettanti PI, ognuno

dei quali è tarato opportunamente sulla base del modello di riferimento.

Tenendo in considerazione non solo l'inseguimento del set-point, che viene reso estremamente complicato a causa della quantità di disturbi esterni molto elevata, ma anche le spese energetiche, si è dimostrato necessario l'utilizzo di una banda morta per ogni attuatore, in modo che entri in azione solamente quando l'errore generato dalla differenza tra set-point ed uscita è superiore ad un certo valore. In questo modo si riduce l'usura degli attuatori a discapito di un controllo più approssimativo, che permette comunque alle variabili controllate di rimanere all'interno di valori prefissati.

Grazie all'utilizzo di queste tecniche è stato ottenuto un controllo di temperatura ed umidità soddisfacente, mantenendo quindi all'interno della serra una temperatura che oscilla tra i 18 e 28 gradi ed un'umidità relativa che rimane tra il 50% ed il 90% circa. Durante la fase di simulazione e la fase sperimentale, gli attuatori utilizzati sono stati solamente due dei quattro disponibili. Questo perchè, sempre in un ottica di risparmio energetico, la giornata è stata suddivisa in due fasi: il dì e la notte. Lo sviluppo di questo lavoro è focalizzato solamente sul controllo applicato durante il dì, dal momento che durante la notte le variabili di temperatura ed umidità relativa non raggiungono valori così critici da mettere in pericolo il benessere del raccolto. Utilizzare quindi anche il riscaldamento ed il deumidificatore sarebbe solo uno spreco di risorse nell'ottica di mantenere un set-point oltremodo preciso.

Nel caso in cui le perturbazioni siano troppo elevate (per esempio in una giornata estiva con temperature estreme) il controllo è inefficiente a causa della limitatezza d'attuazione del sistema di ventilazione, esso infatti non può apportare un abbassamento della temperatura della serra superiore ai 7 gradi. In quel caso bisogna ricorrere anche all'utilizzo combinato (in modalità manuale) dell'umidificatore per potere diminuire ulteriormente la temperatura.

In conclusione si può considerare raggiunto l'obiettivo di mantenere entro i limiti di sicurezza le variabili interne della serra e potere contrastare gli effetti delle perturbazioni esterne tramite l'utilizzo degli attuatori presenti.

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Acronyms

ARM Automatic, Robotics and Mechatronics.
ARMA Auto Regressive Moving Average.
ARMAX Auto Regressive Moving Average models with eXternal input.
ARX Auto Regressive models with eXternal input.

CO2 Carbon Dioxine.

ERDF European Regional Development Fund.

FF FeedFoward.
FL Feedback Linearization.
FOPDT First Order Plus Dead Time.

GPC General Predictive Control.

IAE Integrated Absolute Error.

LTI Linear Invariant Time.

MIMO Multiple Input Multiple Output.
MPC Model Predictive Control.

NC Numerical Control.

PI Proportional-Integral.
PID Proportional-Integral-Derivative controller.

RGA Relative Gain Array.

SCADA Supervisory Control And Data Aquisition.

Preface

Modern agriculture is subject to the development of automatic control techniques that have increased during last few years. Due to the complexity process that are involved: chemical, physical and biological, is quite difficult to identify and characterize every single interaction taking place during experiments. The main object is to achieve, as much as possible, the best results for the grower inside greenhouses [1]. Crop growth is the most important process and is influenced by surrounding environmental climatic variables (photosyntetically Active Radiation, temperature, humidity, Carbon Dioxine (CO2) concentration, wind intensity and direction and others less important like ground's temperature).

Greenhouse is ideal for crop growing because it constituites a closed environment in which climate and fertigation can be controlled (with different control problem and objectives) [1]. Water and nutrients requirements of the different crop species are known and, in fact, the first automated systems were those that control these variables. On the other hand, the market price fluctuations and the environmental rules to improve water-use efficiency or to reduce fertilizer residues in the soil are the other aspects to be taken into account [1]. Therefore, the optimal production process in a greehouse agro system may be summarized as the problem of reaching:

- **optimal crop growth** (bigger production with better quality)
- **reduction of the costs** (fuel, electricity, fertilizers)
- **reduction of residues** (pesticides and ions)
- **improvement of water use efficiency**

Many of these objectives are addressed in this thesis, where the major topic is the modeling of different subsystems involved in the greenhouse crop grow control. It will describe different modeling techniques to show how models can be used for simulation or control. Furthemore, here can be seen the development of basic and andvanced control strategies to control the different variables of the climate problems.

Chapter 1

Introduction

In this chapter a brief summary will be made to clarify the reasons that led to the development of this work, the objectives to be achieved and the tools used. A contextualization of the problem will be useful for the reader to be able to immerse himself fully within the question and to be able to understand it in the depths of its difficulties.

1.1 Motivation

The Council for Agriculture, Fisheries and Rural Development of Andalusia continues to bet on improving and controlling horticultural production to ensure the protection of an ecological system of agricultural production. Almeria has over 2000 hectares of greenhouses dedicated to organic production and it is the first province among all the provinces of Spain in terms of agricultural production, with over $57,600$ hectares of greenhouse crops (50% with two crops a year) as well as fruits and vegetables in the open field. [6]

Andalusia is the leading producer of organic crops in the country, thanks to the promotion and environmental commitment of producers. Regarding the area dedicated to horticultural crops under plastic sheeting, in five years it has grown from 892 hectares to almost 2010 hectares, registering a growth of 44% [6].

Taking into account the employeers situation, the number of operators in Almeria, in relation to the whole of Andalusia, is also significant. In fact, it is the province with the highest number of operators, with a good 2969 (28% more than in 2015). 21% of Andalusian operators (agricultural producers, farmers, industries, etc.) are in Almeria. Moreover, during 2016 in Almeria more than 2000 hectares were dedicated to biologic production, 12% more than in 2015 [6]. Now Almeria has a total area of greenhouses equal to more than 30000 hectares [7].

It is worth noting that Almeria has 30% of all vegetable packaging and processing centers in Andalusia. Due to these several reasons it is easy to understand why we need to increase our knowledge and techniques in this area. It is necessary to improve the efficiency of cultivation, the waste of resources and the quality of the product.

The need for automation of crop growth in greenhouses

As mentioned in 1.1, a greenhouse is ideal for crop growing since it constitutes a closed environment where climate and fertigation variables can be controlled. Although working in a closed environment facilitates the environmental control task, adequate control strategies are required to keep the main variables within the required limits (see 4.3.1), besides the process disturbances.

Greenhouses should be equipped with sensors and actuators to be used by the control algorithms to interact with the process in order to fulfill the required control specifications.

Farmers can control the most important variables by the computer and they can adapt the control parameters in an automatic manner. Nowadays, most of the advanced control systems for climatic control include many parameters to be tuned. The main problems in such controllers are the following [1]:

- Setpoint temperature tracking problem is affected by interactions between different control loops and control devices [8].
- Setpoint values for the different climatic variables are not defined from a scientific point of view and thus the energy usage in greenhouses is usually inefficient [1].

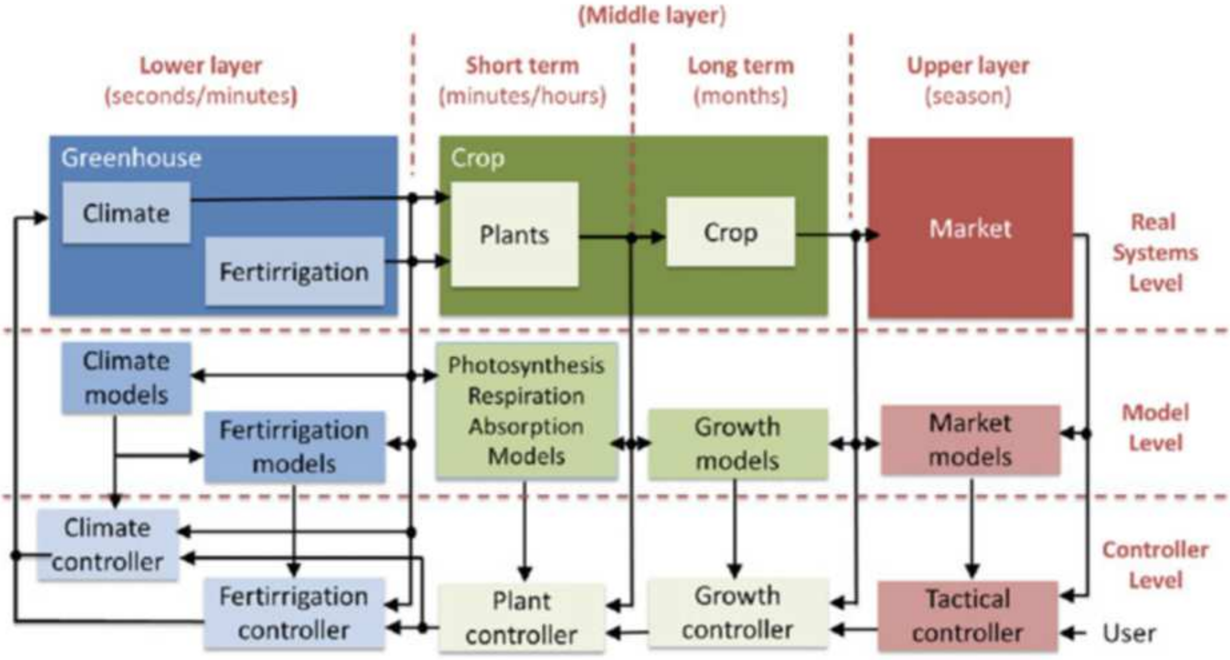


Figure 1.1: *Multilayer hierarchical control for greenhouse. Image taken from [1]*

- Energy efficiency and actuator performance are difficult to be evaluated because of the large number of parameteres and decision rules.

In this case it is going to be solved the first point seen before: interactions between different control loops can be solved (not totally) using a **multivariable control** [8]. For example, while temperature is controlling by ventilation, the effect that ventilation causes to humidity has to be taken into account. Surely simplifications are going to be formulated to face up this huge problem in an easy way.

Figure 1.1 shows multilayer hierarchical control for greenhouse and it will be put some focus only in the **lower layer**; here the controller compute the adequate control signals to be sent to the actuators. The control algorithms developed include a wide range from **proportional-integral (PI) control**. Derivative part is not included because of its related problems (increment of noise at high frequency for example).

1.2 Context

This Master thesis was developed during time abroad in Almeria in 2018. This is one of the proposals offered by the Research Group TEP-197 (Automatic, Robotics and Mechatronics (ARM)), strategies for control and energy management in productive environments with the support of renewable energies, funded by the Ministry of Science and Innovation and the European Regional Development Fund (ERDF). This project deals with the analysis, design and application of modeling, control and optimization techniques to achieve an efficient management of energy in productive systems supported by renewable energies and storage systems. It is tried to demonstrate how the automatic control allows to obtain economic savings and to diminish the consumption of resources and consequent environmental impact of the human activity. The development of this work will take place in the greenhouse (figure 1.2) situated in the experimental station "Las Palmerillas" (EEP) latitude $36°48'$, longitude $2°43'W$ and altitude 155 meters, located in El Ejido, a small province of Almeria and belonging to the "Cajamar Foundation" [2]. This is a region with mild climatic conditions and, taking into account that Almeria produces more than a quarter of the total amount of tomatoes produced in Spain, this is why energies are concentrated on this system [9]. This research and its content will be partially supported by the work carried out during the final work of thesis developed between the months of March and August 2018.

Figure 1.3 shows the subsystems, processes, and variables in their relationship with crop. Inputs are variables that can be controlled, disturbances are those variables affecting crop growth directly or indirectly that cannot be manipulated but can be measured; in this way, their impact on the system can be accounted. The outputs are the variables to be controlled, divided into two types: those that are the target of production (fruits, leaves, flowers..) and pollutant waste ones. In this work only the variables that are able to influence the target of production will be considered , and just in a second moment, datas will be reviewed to understand the loss of money.

Figure 1.2: *View of greenhouse located in Las Palmerillas. Image taken from [2]*

1.3 Objectives

The objective of this project is to be able to follow the development of a control system from the initial phase to the end. More in detail the work begins with data collection and modeling, which will be subdivided into two sub-phases: estimation and validation. At this point it will be possible to design the most appropriate controller and end with real tests on the greenhouses of the controller.

The target of this work is to obtain a model of temperature better than the previous one and an acceptable model of humidty. With these two models it's possible to improve the current controller to better control internal temperature and humidity.

Models of dehumidification and heating system will be also calculated but, due to the period of the year during which we performed tests, it was not possible to verify the correctness of these two models.

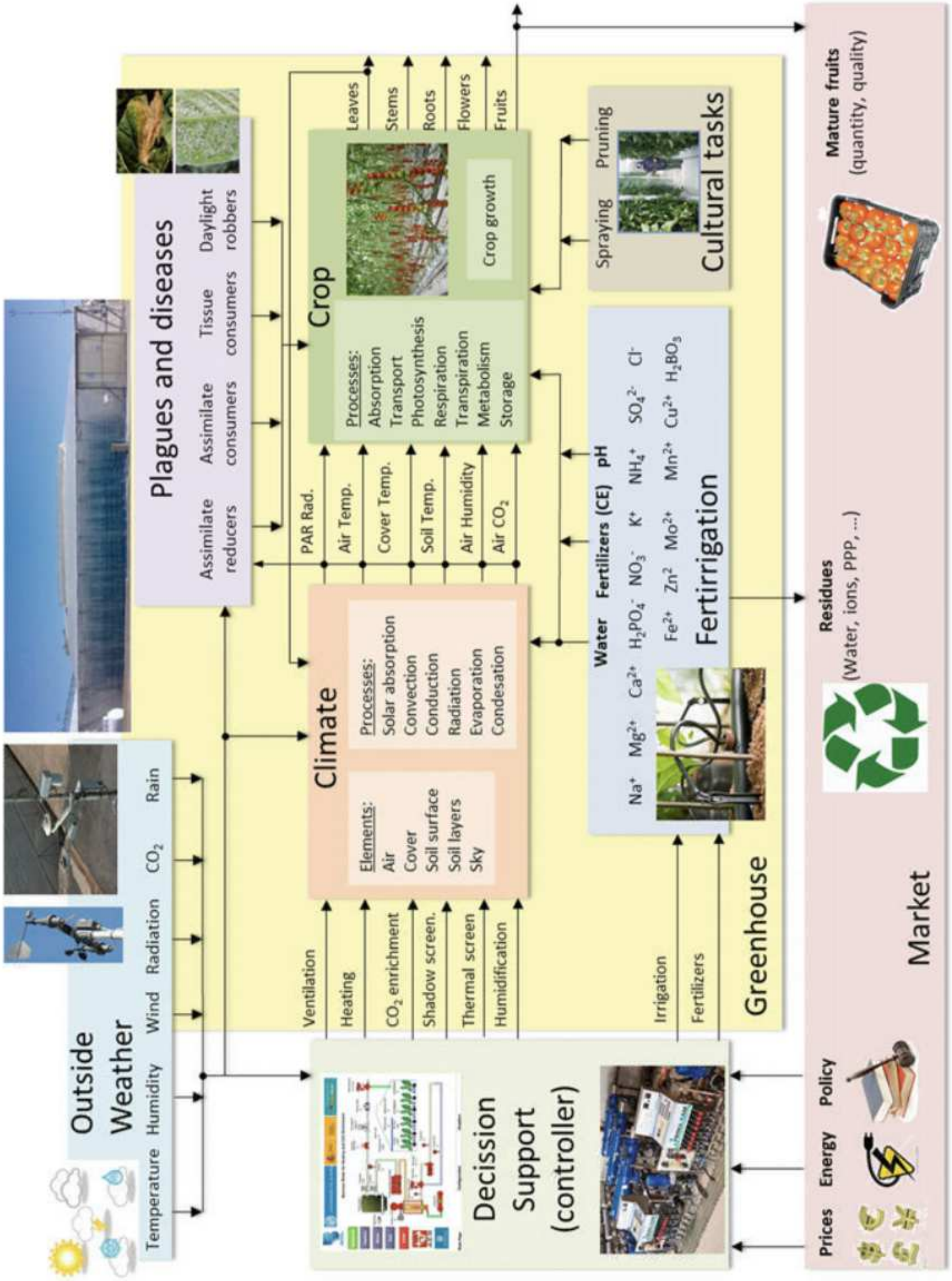


Figure 1.3: *Greenhouses complete scheme. Image taken from [1]*

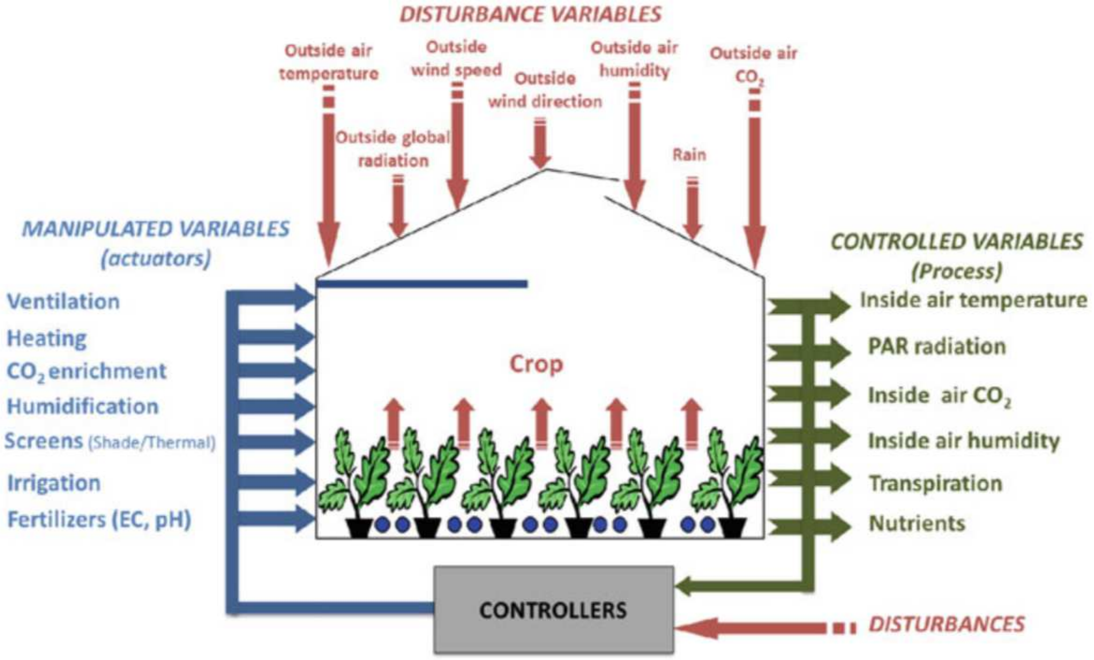


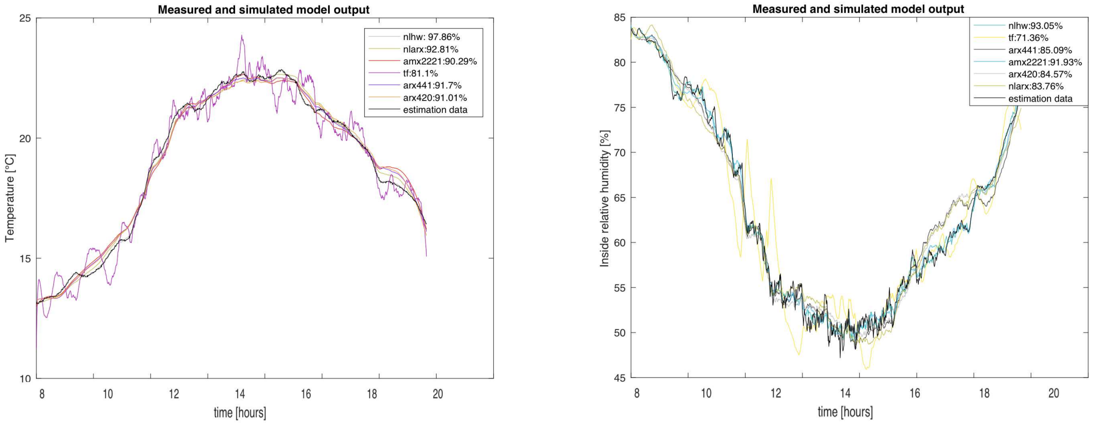
Figure 1.4: *Climate control scheme in a greenhouse.Image taken from [1]*

1.4 Summary of results

To find a model that represents in a correct way the dynamic of the system 9 inputs have been used; they are represented in figure 1.4 with all other disturbances and outputs.

With these datas different type of models have been improved: ARMAX, ARX, transfer function and two different non-linear models. A comparison between obtained results is represented in figures 1.5(a), 1.5(b) and in tables 1.1, 1.2 where:

- **tf** is a model based on transfer function;
- **nlhw** is non-linear model based on Hammerstein-Wiener method;
- **nlarx** is non-linear ARX model;
- **arx441** is the classical ARX model with 4 poles, 4 zeros and delay equal to 1 for every inputs;
- **arx420** is an ARX model with 2 zeros and delay equal to 0 for every inputs;
- **amx2221** is the classical ARMAX model.



(a) Comparison between different models for inside temperature

(b) Comparison between different models for inside relative humidity

Figure 1.5: *Inside Temperature and humidty models*

Temperature Model	$(\sum x1 - x2)^2$	**mean**	**st deviation**	**Err Max**	**IAE**
ARX441	861	0.1209	0.8434	1.877	836
ARX420	930	0.1529	0.8719	2.022	848
ARX421	951	0.1677	0.8790	2.216	839
AMX2221	938	0.1621	0.8738	2.193	827
transfer function	1022	0.2384	0.9402	2.523	912
lnarx (non-linear are)	563	0.1223	0.8110	1.854	822
nlhw (non-linear)	569	0.1102	0.8212	1.874	832

Table 1.1: *Numerical results of the temperature models*

After considering the above results, taking into account both precision and difficulty of implementation and control, the ARX420 model was chosen. Also a model based on Genetic Algorithm has been performed but, due to the bad result, it will be shown in chapter 3.1.5. Non-linear models are the best in this case but these types of models are not used here because of their complexity (more during the control phase than during the modeling one).

About control figure 1.6 shows the comparison between different PI tuning rules performed during simulation part.

Concerning simulation part, figure 1.7(a) and 1.7(b) show how control system works controlling temperature with a set point of $26°C$ and how works controlling humidity with

Humidity Model	$\sum(x1-x2)^2$	**mean**	**st deviation**	**Err Max**	**IAE**
ARX441	5895	-0.2625	7.039	17.247	684
ARX420	4830	-0.2363	6.372	17.163	603
ARX421	4887	-0.2541	6.409	17.630	599
AMX2221	9050	0.0188	8.728	14.895	892
transfer function	6574	0.3212	9.093	18.923	845
lnarx (non-linear arx)	4923	0.0222	5.676	16.543	543
nlhw (non-linear)	4750	0.0.132	5.876	15.246	532

Table 1.2: *Numerical results of the humidity models*

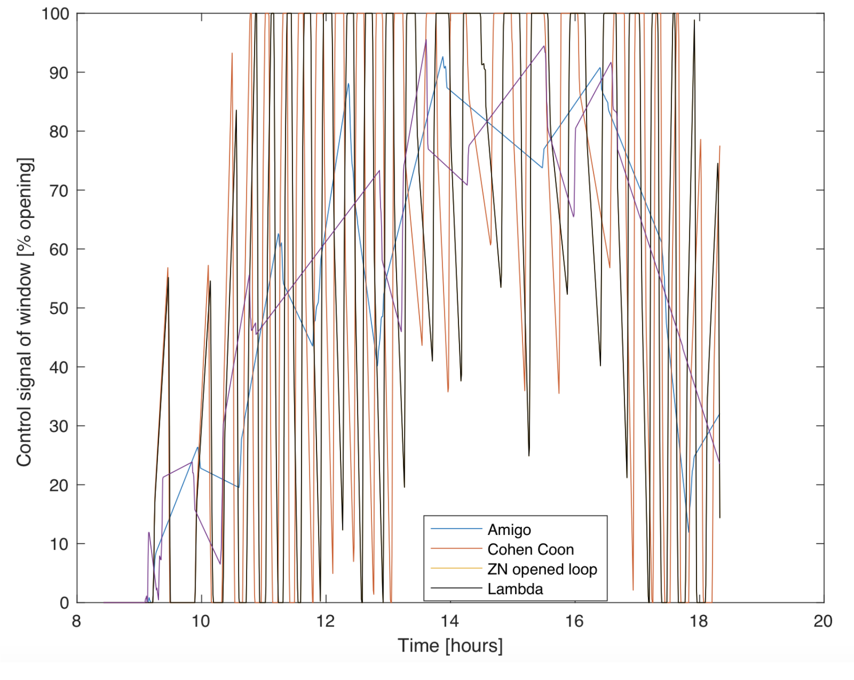
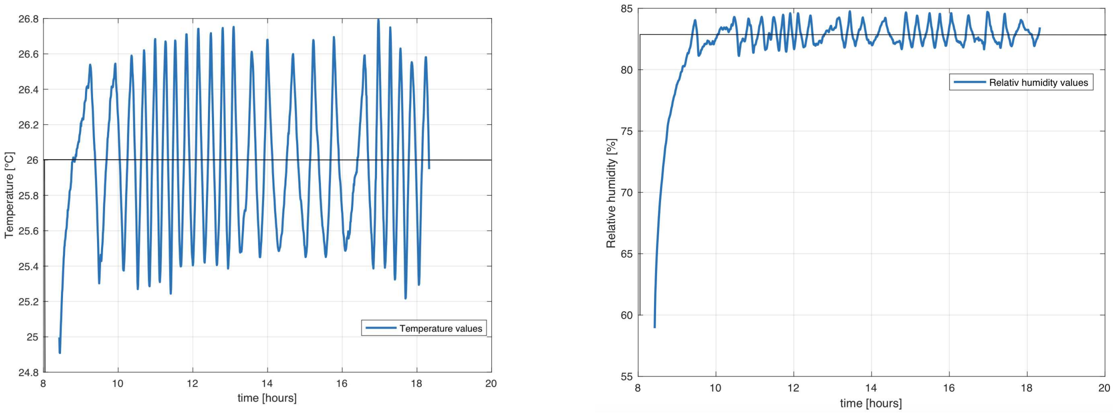


Figure 1.6: *Comparison between different PI tuning methods*



(a) Value of inside temperature with set-point of 26°C

(b) Interior relative humidty with set point of 83%

Figure 1.7: *Temperature and humidty controlled during simulation part*

a set point of 83%. The results shown in 1.5 oscillate because, in order not to overload the actuators, dead bands have been inserted.

1.5 Phases and development of work

The scheduling of the hours dedicated to the project is shown in Table 1.3. A project consisting of just over five months made at the University of Almeria (ES) in collaboration with the University of Brescia and the structure of greenhouse located in “Las Palmerillas” (El Ejido, Almeria).

Different stages of development that have been projected for the proposed Master thesis are detailed below, subsequently, a summary of the temporal planning for each activity is included in 1.3:

Bibliographic study (A). A review of the state of the art in terms of modeling temperature and humidity inside greenhouses, focusing on ARX and ARMAX model or, more in general, on linear model.

Analysis of the greehnouse building (B). Prior to the formulation of the problem, it is necessary a detailed study of the strategies and systems already implemented in the greenhouse and determine if it is necessary to include new systems or modify the existing ones (for example introduce an humidificator can be considered and avoid the use of heating system).

Analysis of variables (C). It is necessary to establish what is the objective to achieve and what variables take into account. Once known, it has been essential to collect or obtain models that relate these variables.

Proposal (D), implementation (E) and evaluation (F) of the control system and control strategies.

Validation of the strategy (G). Perform test inside a real greenhouse with the control strategies implemented in simulation phase.

Preparation of the memory for final degree work (H). Finally, a report was written to explain how each steps summarized above have been carried out, as well as the results obtained. Overall, 500 hours have been devoted to the realization of this final work of thesis.

1.6 Project structure

Chapter 1: Introduction

This chapter gives a brief summary of all the work done, giving the reader the main information regarding the development of a control system for the greenhouse. Results are shown with the phases nedeed to perform the simulation and validation part and to process the project in general.

Chapter 2: Tools and methods

A brief summary about greenhouse of “Las Palmerillas” in El Ejido (Almeria) to explain the general features and characteristics of its sensors and actuators. Scada system designed to control the structure is explained with the general conditions to guarantee the best crop growth.

Chapter 3: Modeling

In this chapter will be explained different ways to model a complex system. Black box models like ARX or ARMAX will be taken into account and will be shown the comparison

Month	Week	A	B	C	D	E	F	G	H	Tot week	Tot month
March	1	20	10	-	-	-	-	-	-	30	140
	2	20	10	-	-	-	-	-	-	30	
	3	10	10	-	10	-	-	-	-	30	
	4	-	-	20	10	-	-	-	-	30	
	5	-	-	20	-	-	-	-	-	20	
Abril	6	-	-	30	-	-	-	-	-	30	105
	7	-	-	30	-	-	-	-	-	30	
	8	-	-	20	5	-	-	-	-	25	
	9	5	-	10	5	-	-	-	-	20	
May	10	-	-	-	-	20	-	-	-	20	80
	11	5	-	-	-	20	-	-	-	25	
	12	5	-	-	-	15	-	-	-	20	
	13	-	-	-	-	5	10	-	-	15	
July	14	-	-	-	-	10	-	-	5	15	130
	15	5	-	-	-	15	-	-	5	25	
	16	-	-	-	-	15	-	5	5	25	
	17	5	-	-	-	-	10	5	10	30	
	18	-	-	-	-	-	20	-	15	35	
August	19	-	-	-	-	-	-	5	20	25	45
	20	-	-	-	-	-	-	-	20	20	
Total	**By activity**	75	30	130	30	100	40	15	80	**Global**	**500**

Table 1.3: *Temporal planification and hours distribution*

between models to understand which is the best. The main objective of this chapter is to find transfer functions models of MIMO system. These models will be designed.

Chapter 4: Climate control

The problem of humidity and temperature control will be dealt with in detail. Different types of control will be taken into account and, to complete this part, a simulation of MIMO system will be implemented. Through the use of the Relative Gain Array (RGA) matrix, the coupling of the control loops for the MIMO system will be evaluated and then the Proportional-Integral-Derivative controller (PID) controllers will be calibrated with different techniques: Lambda method, Zieger-Nichols, Amigo, Cohen Coon and Chien-Hrones-Reswick. In the last part of this chapter real experiments will be performed to understand the real behaviour of the greenhouse.

Chapter 5: Conclusion and future improvments

In future it would be interesting to study the aspect concerning modeling, using non-linear methods. In addition, it would be possible to divide the day's arc into several parts and not just in two. In this way model can be changed several times during the day in order to increase accuracy and thus improve control. It would be appropriated to obtain data during a whole year so can be perceived and exploited climatic differences between different seasons.

Chapter 2

Materials and methods

In this chapter a summary of the software and hardware tools used in order to direct the reader within the physical structure of the greenhouse and beyond. Furthermore, the data collection methods used to obtain the models necessary for the development of this work will be explained.

2.1 Description of sensorial system

The greenhouse is composed of a series of sensors in order to obtain all the necessary data for the analysis of the operation of the various systems of action. Between the sensors it is possible to emphasize:

- **Sensor Pt100 WTR 280**: sensors used to obtain the temperature in different places of importance for obtaining data. This sensor at 0° C has a resistance of 100 Ohms and the increase in temperature will increase the electrical resistance [10].
- **Sensor of humidity and temperature HMP60**: they are sensors that measure the temperature, in addition to the relative humidity of the environment, these sensors are inside a capsule designed exclusively to measure temperature and humidity.
- **Anemometer**: an instrument that measures speed and instantaneous direction of the wind but the gusts of wind distort the measurement, so that the measure to

be used of said speed will be an average obtained in intervals of approximately 10 minutes. There are two types of anemometers to be used for obtaining measurements in the greenhouse:

  - **Anemometer of impulse**: this is an element that measures velocity and wind direction. It is composed by empty sphere whose position with respect to a point of suspension varies with the force of the wind.
  - **Ultrasonic anemometer**: It is a precision titlemeter that will control the speed and direction of the wind within a range of environmental temperature. Its behaviour is very easy. It sends ultrasonic pulses from North to South transducer (and from East to West of course) and, evaluating the time for every pulse, it can understand the direction of the wind. Temperature and humidity do not influence this measurement.

2.2 Actuators description

A detailed description of the actuator systems present in this greenhouse will be explained:

- **Heating system**: There are two types of heating systems in greenhouses: heating using hot air generators and hot water heating. In the heating by means of hot water, on the one hand they are systems of heating by water to high temperature, in which iron pipes located at ground level are used. On the other hand, low temperature water heating systems are used, in which polyethylene pipes located at ground level are used. In most heating installations in greenhouses the heating system with hot water is used because this system maintains the temperature uniformly in all rooms so that all the plants will receive the same temperature. For the correct functioning of this system, a control system is required, functioning as follows:

  - The mixing valves work by allowing more or less hot water to reach the required temperature at the outlet of the valve, which will be approximately the temperature that reaches the pipes in the plants. These valves are controlled by a temperature sensor or Pt 100 located approximately one meter from the outlet of the valve.

  - The controller is necessary to control the entire system. It begins by controlling the temperature of the boiler, when it exceeds a certain value, it gives the stopping order of the burner. Faced with a demand for temperature in the greenhouse, the controller acts by sending a start signal to the water pump, allowing a flow through the pipe circuit. The pump contains an all or nothing control, in some cases there is the possibility to choose between slow, fast or off depending on the temperature required at any time.

- **Ventilation system**: The ventilation system (represented in 2.1(a) and 2.1(b) Figures) is formed by side windows and overhead windows. The side windows usually in the greenhouses are around the perimeter of the greenhouse but in this specific one, windows are located on the north and south sides. The ventilation is formed by a control system that drives the motors of the windows. In the windows position sensors are not available, so to determine the opening the controller determines the time necessary to open a certain opening and sends that time to the motor. In this type of controller errors of operation take place due to the fact that time to close and open are different (due to the effect of gravity), and over time those small errors are increasing. Thanks to the exchange of air produced with the outside, ventilation is used to control the temperature, humidity and the concentration of CO2 in the greenhouse.
- **Deshumidification system**: In this section a description of the internal operation of the dehumidification system will be made, as well as its external sensors for the operation check and the scale system installed for the amount of water extracted from the system. A dehumidifying machine is a device used to solve problems caused by excess humidity. There are dehumidifiers of different sizes depending on their

(a) Lateral windows in greenhouse situated in Las Palmerillas

(b) Top windows in greenhouses situated in Las Palmerillas

Figure 2.1: *Top and lateral windows in greenhouse situated in Las Palmerillas. Images taken from [2]*

extraction capacity, which is the quantity of liters of condensed water coming from the humidity that they are capable of eliminating. This system is formed by a machine (see figure 2.2), which is used in industrial systems for the elimination of maximum possible humidity inside enclosed spaces where the amount of water vapor contained in the environment is high, as in the case of municipal swimming pools, industries or greenhouses as is our case. For an easy explanation about how this machine works, It is recommended to read [2]; here we are going to explain only why this machine has a big problem during its working. Indeed, with low ambient temperatures, the water condensed in the evaporator can freeze, which increases the resistance of the air flow in the exchanger. To prevent it from happening, an electronic control system periodically opens the electromagnetic valve. This operation redirects the hot refrigerant (in its gaseous state) to the evaporator. The ice then melts and water is collected in the condensate reservoir. This operation causes the machine to switch off for a few minutes and, for this reason, it is not possible to use all the time necessary to dehumidify the greenhouse. This is a factor to take into account when

Figure 2.2: *Deshumidificator located inside greenhouse in Las Palmerillas. Image taken from [2]*

designing a controller.

- **Humidification system**: a humidifier is a device that increases humidity (moisture) in a single room or an entire building. The most common portable humidifier, an "evaporative" consists of just a few basic parts: a reservoir, wick and fan [2]. The wick is made of a porous material that absorbs water from the reservoir and provides a larger surface area for it to evaporate from. The fan is adjacent to the wick and blows air onto the wick to aid in the evaporation of the water. Evaporation from the wick is dependent on relative humidity. A room with low humidity will have a higher evaporation rate compared to a room with high humidity. Therefore, this type of humidifier is partially self-regulating; as the humidity of the room increases, the water vapor output naturally decreases.

2.3 Software tools used: LabVIEW and Matlab/Simulink

The LabVIEW software belongs to the company "National Instruments", in the 80's they created this software and they call it Lab (laboratory) and VIEW (vision): vision laboratory, through which large processes can be automated in the industries from a single user interface controlling all the variables without having to be inside the factory in each of the systems. LabVIEW is a tool that offers integration to different measurement hardware. It is a development environment designed with a graphical programming syntax that facilitates visualizing, creating and coding engineering systems. The software LabVIEW has been used in the realization of the project to control the activation and deactivation of the ventilacion, heating, humidificacion and dehumidification system and the storage of data of the different variables such as the different measured temperatures, humidity or power consumption. In order to perform automatic process controls or data storage, Compact FieldPoint [1] must be used (this instrument ideated by *National Instrument* does not concern with this work).

It is a software developed by the company *MathWork*. It is a program that uses a high level language with an interactive environment for the numerical calculation, visualization and programming. When a high level language is used, the program includes mathematical functions, tools, being able to obtain different approaches and get the solution before compared to programming languages such as Java or C.

When making use of *MATLAB* it is allowed to make an analysis of the data to check in detail the functioning of the dehumidification system including variables such as humidity, temperatures or power consumed. Using *MATLAB* algorithms can be developed or models can be created in a simpler way. This program is used in applications such as control systems, signal processing and communications, as well as the simulation of models to check their operation before being actually installed in an industry.

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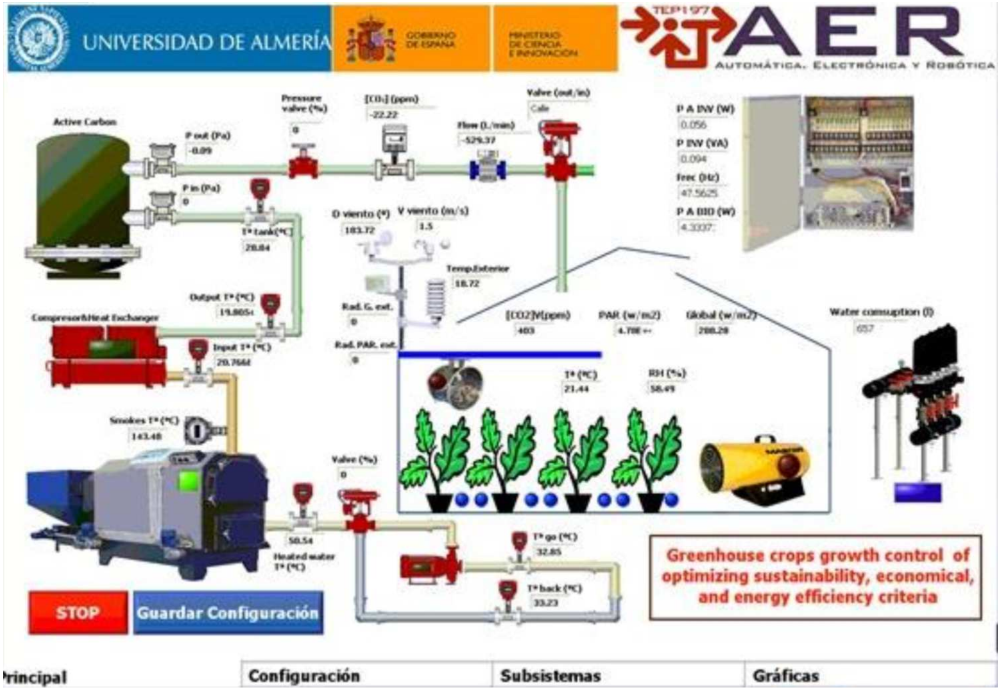
[1] is an easy-to-use, highly expandable programmable automation controller (PAC) composed of rugged I/O modules and intelligent communication interfaces



P out (Pa) -0.09
P in (Pa) 0
Pressure valve (%) 0
[CO₂] (ppm) -22.22
Flow (L/min) -529.37
Valve (out/in) Cale
Tª tank(ºC) 20.84
D viento (º) 103.72
V viento (m/s) 1.5
Temp.Exterior 18.72
Rad. G. ext. 0
Rad. PAR. ext. 0
Output Tª (ºC) 19.805
Input Tª (ºC) 20.7664
Smokes Tª (ºC) 143.48
Valve (%) 0
Heated water Tª (ºC) 50.54
Tª go (ºC) 32.85
Tª back (ºC) 33.23
[CO2]V(ppm) 403
PAR (w/m2) 4.78E
Global (w/m2) 208.28
Tª (ºC) 21.44
RH (%) 58.49
Water consumption (l) 657
P A INV (W) 0.056
P INV (VA) 0.094
frec (Hz) 47.5625
P A BIO (W) 4.3337

Greenhouse crops growth control of optimizing sustainability, economical, and energy efficiency criteria

Figure 2.3: *Labview interface of SCADA system situated in Las Palmerillas. Image taken from [3]*

2.3.1 Scada system designed

This Supervisory Control And Data Aquisition (SCADA) system represented in figure 2.3 is used to supervisory analysis of the system and the validation control algorithms, and the deviation analysis between the real and the simulated behavior of the greenhouse, derived from the assumed hypothesis in its disturbances and another uncertainties. The characteristics of this SCADA system are:

- **Data acquisition system**: Data are sampled in daily '.txt' files, and the different variables are separated in columns by tabulation, which is compatible with all of data mining software. The new data added when a new facility is installed remain after the last columns, in such way that the rest of the variables keep the preset order.
- **Sampling time setting up**: The presence of different system could require different sample time due to the different time constant of each.
- The system allows three types of users: **Researcher** (administrator), **supervisor** and **viewer**. The researcher/administrator has full access to modify the SCADA.

Supervisor can change the main configurations parameter and to use the manual control, but they cannot program control algorithms directly in the SCADA. The basic access is only for viewers, they cannot modify anything.

- Set up of the signal of different sensors and conversion of each sensor to a Matlab® variable to be share in all the systems: all the variables are name with Matlab® are included in a data cluster and shared by all the control algorithms and finally saved in a '.txt' file separated from the data to be able the recognition of the different data variables. This file has more than 200 variables (coming from each sensor), but only a small number will take into account for this work.
- Irrigation and climate systems integration, which allows to have available the use the climate or irrigation variables for decision making.
- **Hybrid control allowance**: the communication among systems is very important in control, and in classical SCADA is not implemented as options.
- All the control algorithm are implemented in Matlab/Simulink® environment, which makes the assay of new controllers an easy task . For the user is easy the introduction of new functionalities to the controllers or modifications. In particulary, this part will be very useful when we have to put our controller inside.
- Allows to configure **startup variables** that need to be running at the start: some controller can have the necessity of starting some variables only once per executions, to initialize some functions. The SCADA has a 'start-up' tab in which all that functions can be configure in a Matlab/Simulink® environment.

When systems are not static it means that their state evolves continuously during time; often this is due to: input signals, external perturbations or naturally. For example, inside a greenhouse, variables like temperature and humidity changes every second during all the day. The main object of this work, and of this chapter in particular, is modeling correctly the behaviour of these two variables. We want to formulate a mathematical representation of a system to be able, in a second phase, to control these behaviours with the lowest energy expenditure.

2.4 Modeling dataset

By approaching this type of problem, the first step that was performed to obtain an accurate model was collect as much data as possible that would reflect the behavior of the greenhouse. To reach this it was necessary to obtain whole days of data throughout the year. After obtaining numerous days of tests it was necessary to identify which of these days were suitable for obtaining a model of the greenhouse. Through various attempts it has been possible to understand that the days necessary to obtain a good result are those in which the following conditions occur:

- The sensors work correctly throughout the day (in figure 2.4 can be seen a problem on temperature sensor for instance),
- Actuator (windows) must operate in a correct way, moving themself not more than 38 degrees (when they are "all opened"),
- The day is a typical day of that period with standard temperatures and humidity. For example, there may be January days when the temperature exceeds 25 degrees or July days when, due to excessive rain, the humidity rises considerably.
- The sample time has to be setted equal to 30 seconds. Simulink scheme used to simulate the process proves that results can change simply modifing the sample time or working in continue mode.

Given these specifications, the only days available to get a good model have been the following: 10^{th} and 11^{th} November 2016, 25^{th} and 29^{th} January 2018, 13^{th} and 14^{th} July 2017. Taking into account that in November and in January there was plantation inside a the greenhouse, those days have been selected to be the days for estimation and evaluation of the ARX and ARMAX models in 3.1.4 and 3.1.4.

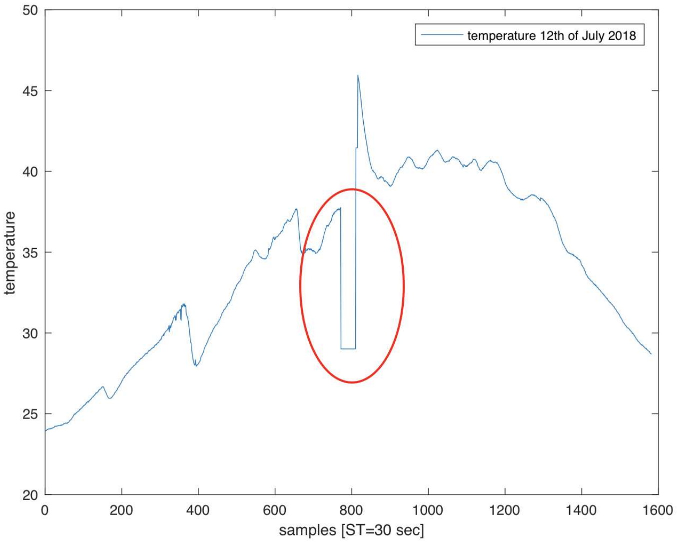


Figure 2.4: *Multilayer hierarchical control for greenhouse*

Chapter 3

Modeling with Black and White-Box models

The most fundamental concept in systems modeling is **abstraction**, which concerns hiding unimportant details in order to focus on essential characteristics. System like a greenhouse has too many details to reasonably be modeled. This system is very complex, to show the internal structure and to display every interactions that take place during the day is difficult.

3.1 Black-Box Models

Inside a greenhouse there are many interations between outside climate variables and inside ones. Control internal humidity and temperature is not the only issue, is also difficult measure and understand the values and interactions with crop growth. For this reasons different types of modeling will be analyzed but everything is based on Black-Box Model, without pay attention to inside interactions. The White-Box (or clear-box) is useful when internal part can be viewed but usually not altered. Having access to the internal subsystem in general is easier to understand the processes and all the functionalities but it's impossible (or very difficult) to know interactions between every variable that is taking place during a control of the temperature in greenhouse. Surely it will be tried to write every physical relationship presents in the greenhouse, this has already been done in the book [1], but it is not the main object of this work.

The procedure to find a model with a Black-box is simple, there are 9 inputs:

- Exterior temperature;
- Solar radiation;
- Intensity of the wind;
- Opening side windows;
- Opening cenital windows;
- Direction of the wind;
- Relative humidity (exterior);
- Using of the umidifier;
- Using of the deshumidifer;

And the two outputs, for this reason is simple to understand that this is a MIMO system (9 inputs - 2 outputs):

- Interior temperature;
- Interior relative humidity;

Therefore, after having analyzed these data and made them usable for the identification of the model, can be investigated which model gives the best fitting. There are different types of models that can be used, however, only the most important has been analyzed for this type of work. It should be kept in mind that the use and effectiveness of any of the following models is guaranteed by a certain approximation. In this case all linear methods will be dealt with, but the environment considered consists of a multitude of non-linear interactions and, above all, of varying time. In fact, this system is not a Linear Invariant Time (LTI) and for this reason it has already been made aware that the results cannot be extremely satisfactory.

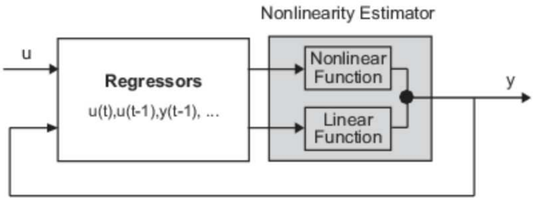


Figure 3.1: *Block system of non linear model estimator*

3.1.1 Transfer function model

Transfer function models describe the relationship between inputs and outputs of a system using a ratio of polynomials. A continuous-time representation of this model is shown in 3.1 and a better especifically explanation of this model will be in 3.3

$$Y(s) = \frac{num(s)}{den(s)}U(s) + E(s) \tag{3.1}$$

3.1.2 Non linear model

A nonlinear ARX model consists of model regressors and a nonlinearity estimator. The nonlinearity estimator comprises both linear and nonlinear functions that act on the model regressors to give the model output. The block diagram represented in 3.1 is a structure of a nonlinear ARX model in a simulation scenario.

The software computes the nonlinear ARX model output y in two stages:

- It computes regressor values from the current and past input values and past output data.
- It maps the regressors to the model output using the nonlinearity estimator block. The nonlinearity estimator block can include linear and nonlinear blocks in parallel.

3.1.3 ARMAX model

Based on the fact that the greenhouse is subject to the stochastic processes like climate changes (we cannot predict them), the behaviour of this system was studied using an ARMAX model. General Auto Regressive Moving Average (ARMA) model was described in the 1951 thesis of Peter Whittle [11], and it was popularized from 1970 on. Given a time series of data X_t , the ARMAX model is a tool for understanding and, perhaps, predicting future values in this series. The model consists of three parts, an autoregressive (AR) part, a moving average (MA) part and exogenous inputs (X). The AR part involves regressing the variable on its own lagged values. The MA part involves modeling the error term as a linear combination of error terms occurring contemporaneously and at various times in the past. X part is what needs to be considered exogenous inputs (in this case all the perturbations) Mathematically speaking the equation 3.2 represents the form of the ARMAX model

$$A(z)y(k) = B(z)u(k-n) + C(z)e(k) \tag{3.2}$$

3.1.4 ARX model: estimation and validation

Like in other cases is not necessary to achieve a deep mathematical knowledge of the system under study but it is sufficient to predict system's evolution. This is often the case in control applications, where satisfactory predictions of the system are collateralized by robustness of the parameter. In this study, the chosen method adopted for process modelling is based on a para- metric identification of an ARX model. The choice of this strategy is justified by the fact that it is simple to implement it. The aim in this case is to analyze the model orders, the time delay and the validation of the identified model. The ARX structure is represented by the equation 3.3 where $A(q)$ and $B(q)$ are estimated by least square identification:

- e(t) refers to the noise supposed to be Gaussian
- A(q) and B(q) are the matrix of model parameters
- n_k is the time delay between y(t) and u(t)

This first part is called **estimation**. The second one is the **evaluation** and here can be easily seen if the model folllows the dinamyc of the system or not.

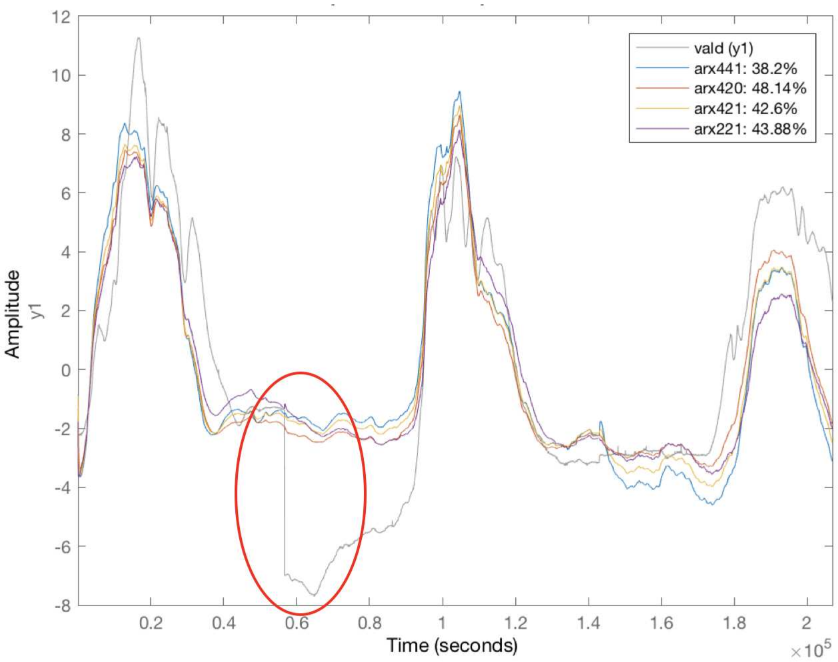


Figure 3.2: *ARX model estimation using three days*

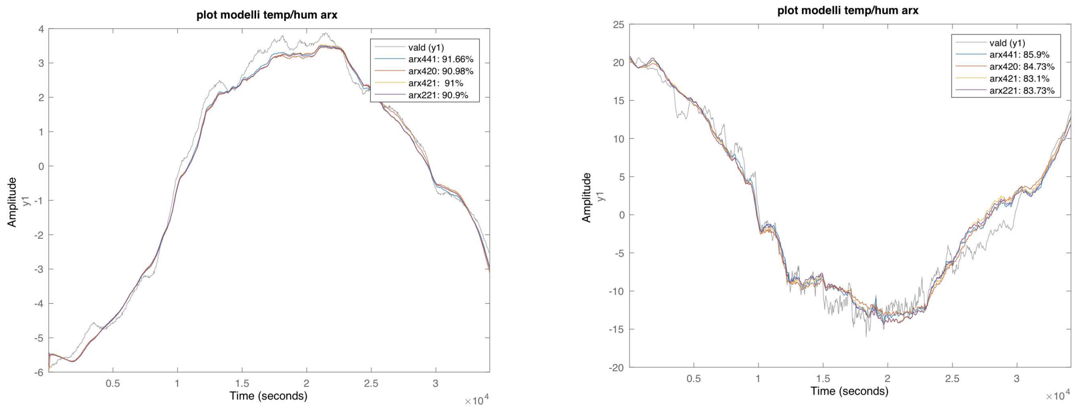
$$A(q)y(t) = B(q)u(t - n_k) + e(t) \tag{3.3}$$

ARX model estimation

In the first experiment more than one day for estimation and for evaluation have been used. Following this way the results are not satisfactory and it can be seen in the figure 3.2. Performing estimation part with different days (it means different perturbations, different temperature and humidity) can be noticed that the difference between one day and the follow one is too high and an ARX model cannot find correct values of parameters to obtain an accurate model.

Another big problem using this approach is caused by the difference between one day and the follow one if these two days are not one after the other; this problem can be seen inside the red circle in the figure 3.2.

These are the reasons why this model was used only one day at a time. Any day in which all the inputs have been used shows relationship between each of them and the



(a) ARX model for estimation of temperature

(b) ARX model for estimation of humidity

Figure 3.3: *Estimation of the model of temperature (a) and humidity (b)*

outputs of the MIMO system. In particular each day is divided into two parts: the day and the night [1], in this way it's easier to find a model that can estimate the process correctly. The day because is the most dangerous part; in fact during the night temperature and humidity are not so problematic for crop growth.

In Figure 3.3(a) and 3.3(b) there is a comparison between different types of ARX models that proved to be the best of all those presented in this section. More than one hundred of ARX models were tried with different numbers of poles, zeros and time delay to find the best one. Names of the model (in the legend of the figure) are presented with these characteristics:

- **First number**: is the number of poles for every input;
- **Second number**: is the number of zeros for every input;
- **Third number**: is the time delay for every input;

ARX model validation

For the evaluation, the fact that the days are so close to each other (temporally speaking) allows to obtain a better result since the disturbances had a more similar behavior (it

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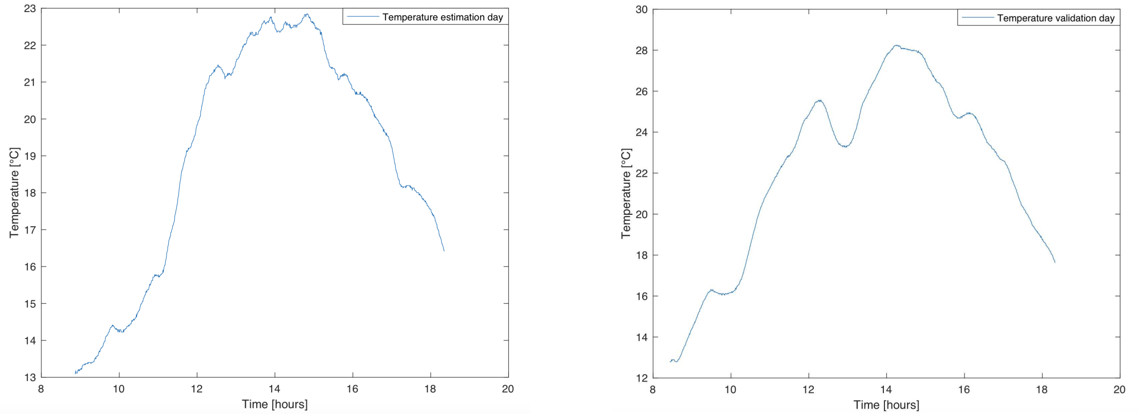
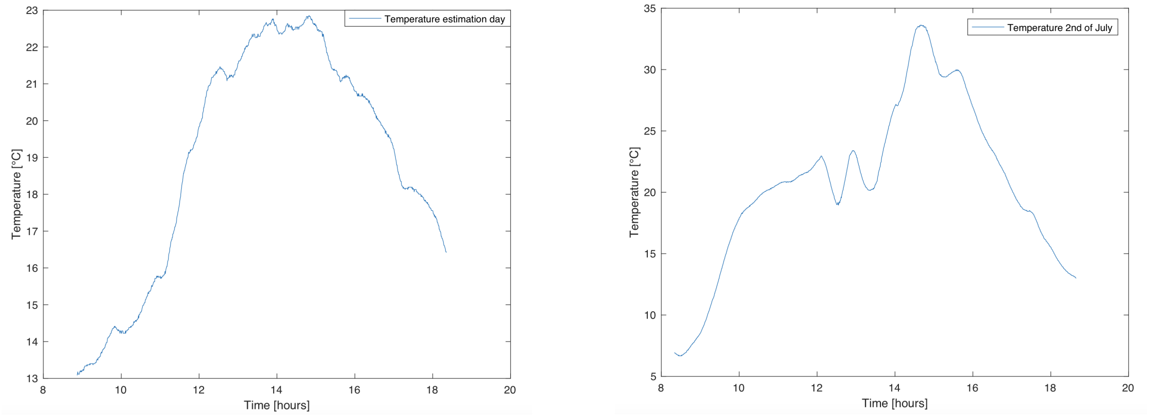
[1] It consider night when the solar radiation is less than $10\frac{W}{m^2}$



(a) Temperature 25^{th} of Janyary (b) Temperature 29^{th} of January

Figure 3.4: *Temperature of the estimation (a) and validation day (b)*

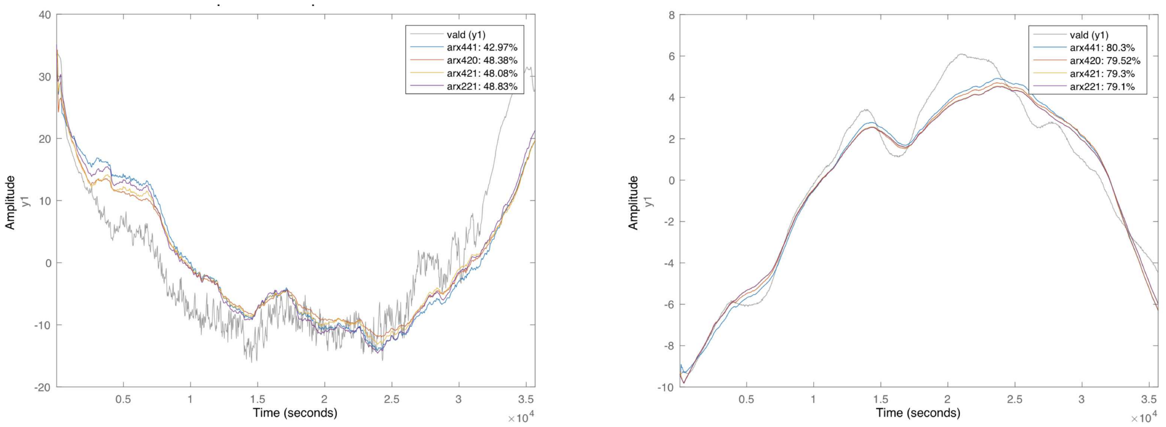


(a) Temperature 25^{th} of Janyary (b) Temperature 2^{nd} of July

Figure 3.5: *Temperature of the 25^{th} of January (a) and 2^{nd} of July (b)*

can be seen in 3.4), while very different days (for example one during the winter and the other during the summer like in figure 3.5) gave unsatisfactory results [12]. Figures 3.6(a) and 3.6(b) show the comparison between ARX model estimated with 25^{th} of January data and evaluated with the 29^{th} of January ones.

Surely the fitting is not good because of the difference of the disturbances when the day is different. In fact between one day and another there is a lot of difference in wind intensity or in solar radiation. Despite this, not having to perform simulations, but control actions, it is sufficient to have a model that is as accurate as possible, and then be able to compensate



(a) Lateral ventilation system

(b) ARX model for estimation of humidity

Figure 3.6: *Validation of the model of Temperature (a) and humidity (b)*

for any errors with the feedback effect and a controller more or less aggressive [13]. Another big problem is the fact that the system cannot be linearized around a particular operating point, because temperature changes a lot during the daytime for example. The question will be better explained in chapter 5.

3.1.5 Genetic algorithm

In this section it is necessary to identify a large number of parameters that minimize the error between the output obtained through the model and the real one. In this contest the genetic algorithms can be helpful to find heuristic solutions to best solve the problem. Genetic Algorithms (shortened in GA) is a global and stochastic research method inspired by the principle of natural selection and biological evolution theorized in 1859 by Charles Darwin.[2] They operate on a population of potential solutions applying the principle of survival of the best, thus evolving towards a solution that will hopefully approximate how much as much as possible to the real solution of the problem. With each new generation, a new set of solutions is created by the selection process that, based on the level of fitness,

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[2] Charles Darwin (12 Febbraio 1809 - London). He was a British naturalist, biologist and illustrator, famous for having formulated the **theory of evolution of animal and plant species by natural selection** acting on the variability of hereditary characters, and their diversification and multiplication by descent from a common ancestor.

selects the best members of the population and makes them evolve using a series of genetic operators derived from natural genetics. This process leads to a robust evolution towards individuals who are better suited to the environment, i.e. to the set of solutions that best respond to the problem placed in the beginning. In particular, the steps to describe how the genetic algorithms work are the following:

- **Initialization**: it begins with the creation of an initial population with random characteristics, but in any case limited within a certain pre-established range of values.
- **Evaluation**: in this step each member of the population is evaluated using a cost function that specifies the criterion useful for estimating the best element of the population. The criterion can be simple, to reduce the time of computation, or complex, if more references are to be taken into account.
- **Selection**: the cost function allows the elimination of the worst members from the populations, i.e. those that respect less the established criterion, preserving the best ones. This is what happens in nature with natural selection: the next generation will contain the best elements of the population.
- **Crossover**: the characteristics of the selected elements are mixed in order to create new individuals. By doing this, it increases the probability that new individuals inherit the best characteristics from the old generation.
- **Mutation**: it consists of a random behavior that is introduced into the new population. Usually this is achieved with small random variations to increase the chances of finding the optimal solution.
- **Repetition**: after obtaining a new population, another iteration is made by repeating the previous steps. To stop the algorithm, a tolerance threshold is introduced between successive solutions.

In figure 3.7 an explanatory diagram of the functioning of genetic algorithms is represented.

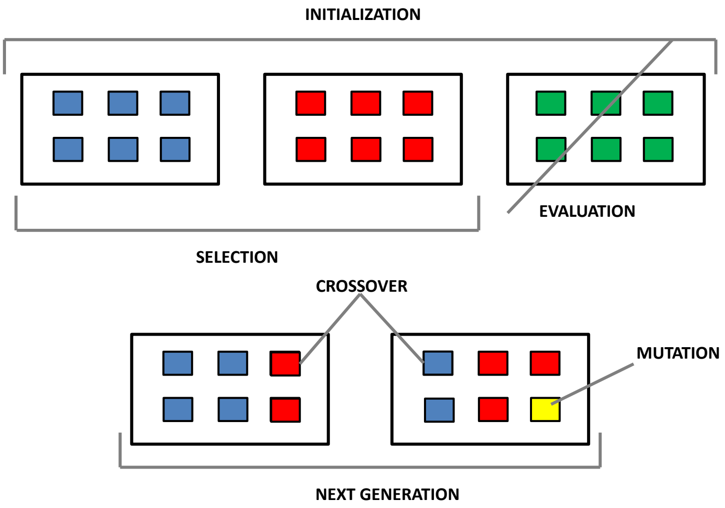


Figure 3.7: *Schematic of the operation principle of genetic algorithms. Image taken from [4]*

Genetic algorithms are often used in the field of artificial intelligence and computer science, as they are a simple but very powerful tool for finding solutions to research problems; however, they also present some drawbacks. First there is the problem of initialization of the population, since if the initial parameters are not set correctly, the result will be unreliable. The second problem concerns the final solution found: the genetic algorithms ensure to find an optimal local solution, relative to the considered environment, which in some cases may not coincide with the global one. Both of these problems could be solved by imposing very large initial bounds and increasing the population, but this would result in a considerable increase in computational time.

In order to evaluate the best elements of the population, a fitness function is used, which provides as an index of adequacy the value of the *Integrated Absolute Error* (IAE) between the model output and the real one:

$$IAE = \int_0^\infty |Temperaturemodel(t) - realTemperature(t)|\, dt \tag{3.4}$$

In this way the selection process prefers the parameters that provide the lowest Integrated Absolute Error (IAE). Just to give an example of the possible values of this index,

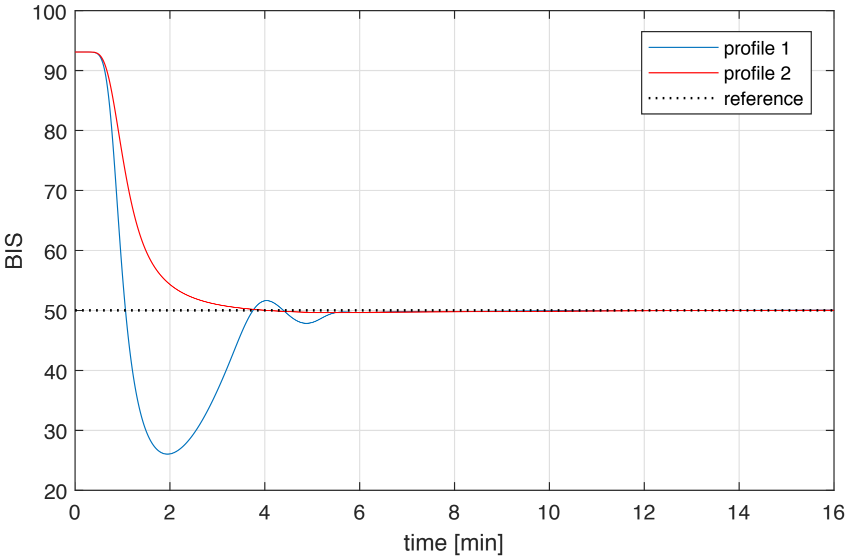


Figure 3.8: *Example of two different output-model profile.*

in figure 3.8 are reported two different “model-output” profile with the relative IAE. It can be noticed that the red profile has a better trend, in fact, numerically speaking, the blue has an IAE of $4871,4$ while the red one of $3340,5$.

Unfortunately, maybe due to the fact that there are too many parameters that need to be estimated, the result is not satisfactory (as can be seen in 3.9 where the final IAE is about 7000). In general this method is very useful when the cross correlation between parameters is not soo high like in a greenhouse, because, in this case, the most correct solution can be achieved in different ways and try to find it minimizing IAE it is not the correct way to follow. Therefore there is a problem connected with genetic algorithm itself, if it starts with a wrong set of parameter can terminate without satisfactory result.

3.2 Comparison between different models

In this section can be seen a comparison between the different models. The model that was found through the use of the genetic algorithm was not compared with the others because, as can be easily seen in the figure 3.9, it did not lead to any good results. The

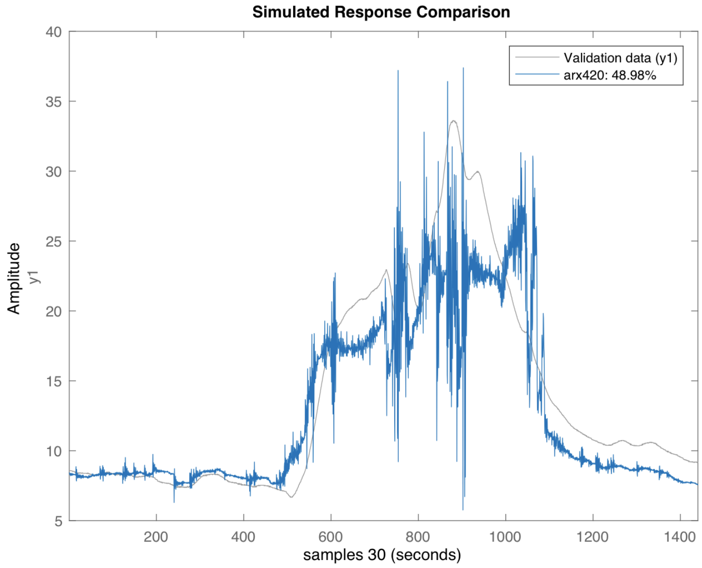


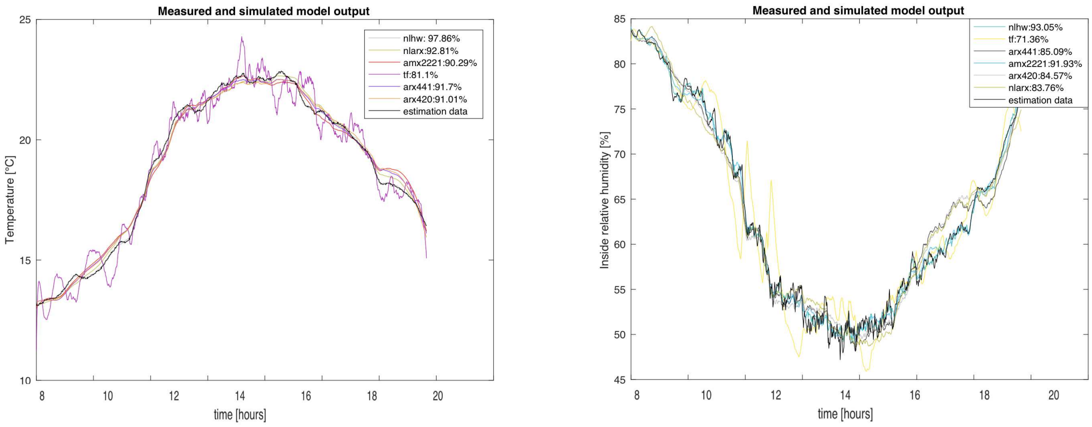
Figure 3.9: *Comparison between real output and model output found by Genetic Algorithm*

Temperature Model	$(x1 - x2)^2$	**mean**	**st deviation**	**Err Max**	**IAE**
ARX441	861	0.1209	0.8434	1.877	836
ARX420	930	0.1529	0.8719	2.022	848
ARX421	951	0.1677	0.8790	2.216	839
AMX2221	938	0.1621	0.8738	2.193	827
transfer function	1022	0.2384	0.9402	2.523	912
lnarx (non-linear are)	563	0.1223	0.8110	1.854	822
nlhw (non-linear)	569	0.1102	0.8212	1.874	832

Table 3.1: *Numerical results of the temperature models*

models represented in Figure 3.10(a) and 3.10(b) are the most significant, the result of over a hundred attempts. By means of the 3.1 and 3.2 tables, the characteristics of each model can be identified numerically, referring to the mean square deviation, the mean, the maximum error value and the IAE.

Taking into account the semplicity of the use of an ARX model with respect a non-linear one, a control scheme based on this type of model was implemented, in particulary, semplification of ARX model has been used. This simplification will be explain in 3.3 where a simple transfer function is obtained starting from a much more complex model, like the ARX in our case.



(a) Comparison between different models for inside temperature

(b) Comparison between different models for inside relative humidity

Figure 3.10: *Inside Temperature and humidty models*

Temperature Model	$\sum(x1 - x2)^2$	**mean**	**st deviation**	**Err Max**	**IAE**
ARX441	5895	-0.2625	7.039	17.247	684
ARX420	4830	-0.2363	6.372	17.163	603
ARX421	4887	-0.2541	6.409	17.630	599
AMX2221	9050	0.0188	8.728	14.895	892
transfer function	6574	0.3212	9.093	18.923	845
lnarx (non-linear arx)	4923	0.0222	5.676	16.543	543
nlhw (non-linear)	4750	0.0.132	5.876	15.246	532

Table 3.2: *Numerical results of the humidity models*

3.3 Modeling results

Through the use of a fourth order ARX model, the transfer functions obtained (by evaluating the step response) are all very complicated (they always contain 4 poles and at least 2 zeros). For this reason a comparison was made with two of the previous works carried out in the greenhouse ([14] and [8]). Thanks to these works it was possible to mediate transfer functions obtained, with those achieved previously, in this way the result was as reliable as possible. The transfer functions were made to be as simple as possible, giving them a first order (to the most significant transfer functions). This choice is the result of the fact that there is a problem in which it's okay to lose slightly in precision but, on the other hand, to have a great advantage in the simplified management of the controllers and of the control architecture. One of the most significant is undoubtedly the relationship (see 3.5 where the time-delay is expressed in seconds) between ventilation and temperature. In fact this is the most used actuator throughout the day:

$$P_{vent,T} = \frac{-0.07}{1000s+1}e^{-60s} \tag{3.5}$$

While, for example, transversal transfer function between ventilation and humidity is represented in 3.6 (composed by 3.7 and 3.8)

$$P_{vent,H} = \frac{N(s)}{D(s)}e^{-30s} \tag{3.6}$$

$$N(s) = 0.002365s^5 + 0.0004998s^4 + 6.949 \cdot 10^{-5}s^3 + 4.288 \cdot 10^{-6}s^2 + 1.478 \cdot 10^{-7}s + 1.866 \cdot 10^{-9} \tag{3.7}$$

$$D(s) = s^5 + 0.1763s^4 + 0.001017s^2 + 2.948 \cdot 10^{-5}s + 2.219 \cdot 10^{-8} \tag{3.8}$$

Other very important transfer functions are those that represent the relationship between humidifier and humidity (see 3.9) dehumidifier and humidity (see 3.10) and between the heating system and the temperature (see 3.11)

$$P_{hum,H} = \frac{29}{3650s+1}e^{-60s} \tag{3.9}$$

$$P_{desh,H} = \frac{-0.8}{400s+1}e^{-60s} \tag{3.10}$$

$$P_{cal,T} = \frac{0.0604}{4005s+1}e^{-30s} \tag{3.11}$$

All remaining transversal transfer functions (obtained in paragraph 3.1.4) are not simplified because they do not cause a major difficulty in implementing the controller. They are represented in the equations 3.12, 3.16 and 3.15 (this last one is composed by 3.13 and 3.14)

$$P_{hum,T} = \frac{-1.4}{275s+1}e^{-30s} \tag{3.12}$$

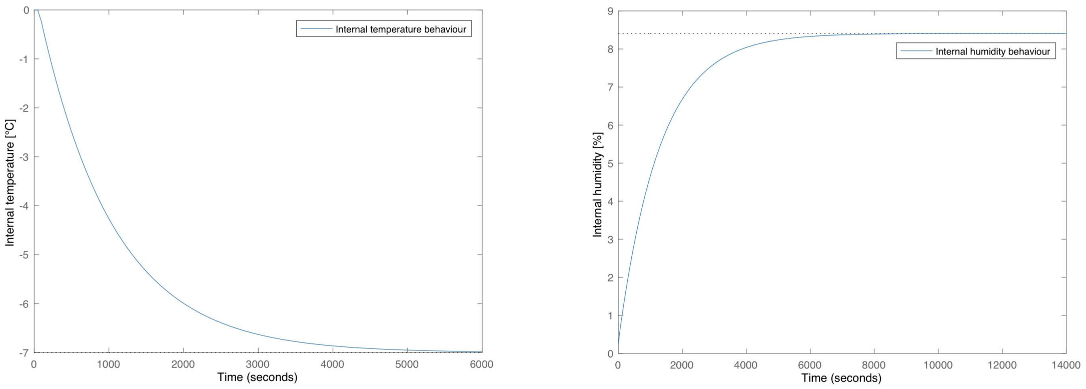
$$N(s) = s^5 + 0.1169s^4 + 0.0009108s^2 + 4.876 \cdot 10^{-5}s + 2.639 \cdot 10^{-8} \tag{3.13}$$

$$D(s) = -0.004936s^5 - 0.0001781s^4 - 2.15 \cdot 10^{-5}s^3 + 3.496 \cdot 10^{-6}s^2 + 2.77 \cdot 10^{-7}s + 9.089 \cdot 10^{-9} \tag{3.14}$$

$$P_{desh,T} = \frac{N(s)}{D(s)}e^{-30s} \tag{3.15}$$

$$P_{cal,H} = \frac{-0.0434}{1782s+1}e^{-30s} \tag{3.16}$$

In the final part of this chapter the transfer functions showed before will be presented grafically to get an idea of the main effect that the two actuators have on the two process variables: internal temperature and humidity. In this case only two actuators have been



(a) Interior temperature changing caused by a step of 100% on ventilation system

(b) Interior humidity changing caused by a step of 100% on ventilation system

Figure 3.11: *Direct and trasversal tansfer functions of the ventilation system working during the daytime*

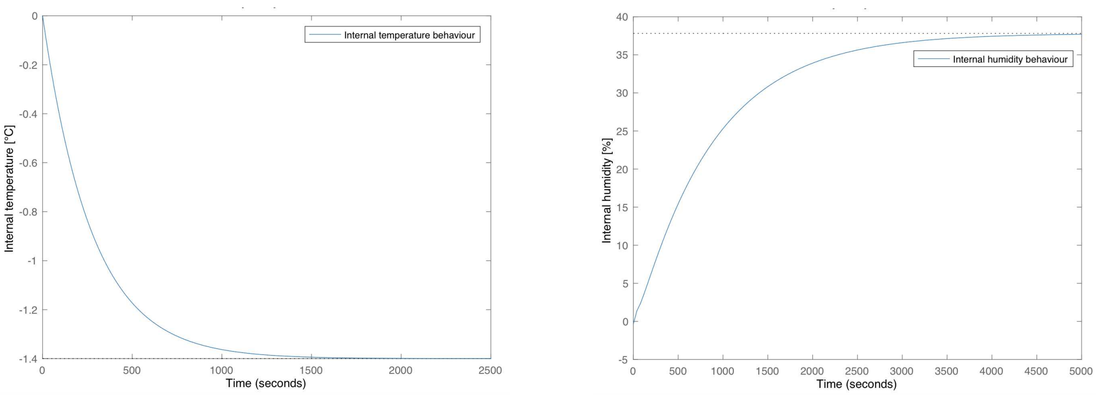
considered because the work is developed during the daytime, when humidifcator and ventilation system need to be used. If variables were controlled during the night, it would be necessary the use of deshumidificator and heating system.

In figure 3.11(a) and 3.11(b) can be clearly seen the effect that a step of 100% on the ventilation system produces in output on the internal temperature of the greenhouse. In particulary, in the figure 3.11(a) it can be seen that with the ventilation system the temperature can be lowered to a maximum of 7 degrees, this is one of the biggest limits present when controlling the internal temperature. It is always necessary to be careful not to lower too much temperature because, as it can be see from figure 3.11(b), the humidity tends to get up in the opposite direction.

This is another big problem present in this MIMO control system. There are two actuators that influence themselves at the same time, so it's not so easy to understand how to use them.

For example, taking into account figure 3.12(a) and 3.12(b), where are represented the effect of a step on humidificator system, it can be seen that trying to raise the internal humidity, the internal temperature begins to get low.

To conclude this chapter it will be showed the effect, on the internal temperature, of



(a) Interior temperature changing caused by a step of 100% on humidificator system

(b) Interior humidity changing caused by a step of 100% on humidificator system

Figure 3.12: *Direct and trasversal tansfer functions of the humidificator system working during the daytime*

two of the most important disturbances that have been taken into account during modeling phase: solar radiation and wind intensity.

The effect that these two quantities have on the controlled variable is intuitive; when solar radiation increases, internal temperature tends to increase (figure 3.13). Concerning intensity of the wind, however, due to the phenomenon of convection, the air passing reduces the temperature (Figure 3.14(a)). It is therefore clear that the lowering of the temperature is greatly influenced by the presence or absence of the wind. As regards the wind direction, however, this work was taken into consideration even if, as can be seen in figure 3.14(b), the temperature varies much less due to the direction not for the intensity. In particular, a unitary step in the direction causes a temperature change of 0.16°C, while because of the intensity more than 0.5°C. Considering also that the direction is a variable that changes throughout the day in a very casual and unpredictable way, we have come to the conclusion that we can neglect it during the simulation of the system.

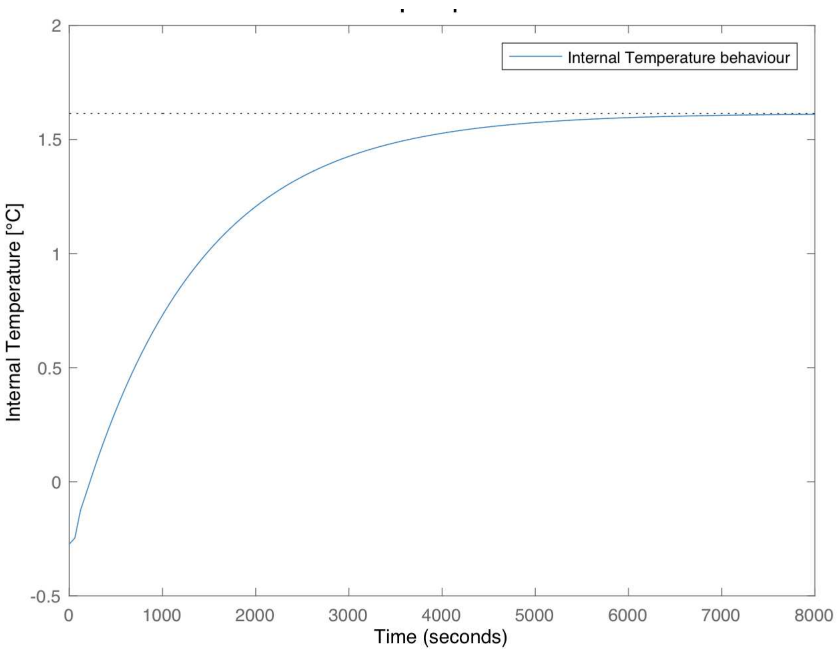
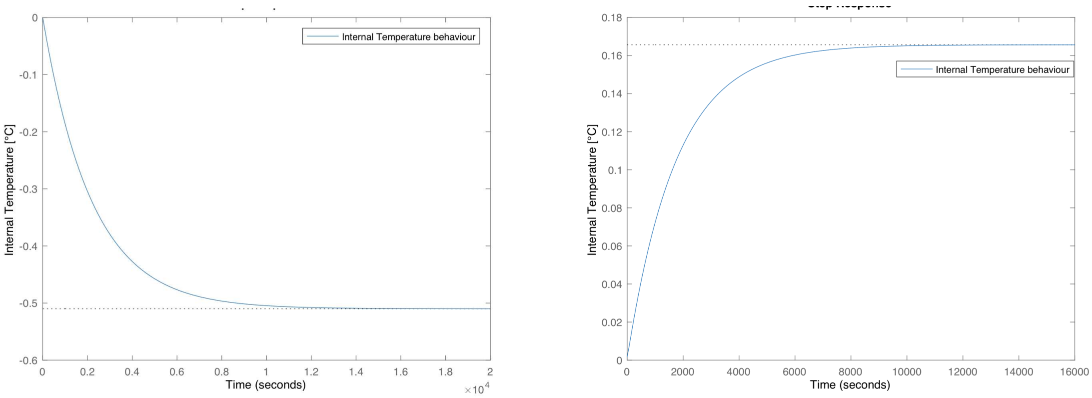


Figure 3.13: *Interior temperature changing because of an hipothetical step of* $100\frac{W}{m^2}$ *on solar radiation*



(a) Interior temperature changing because of an hipothetical step on wind intensity

(b) Interior temperature changing because of an hipothetical step on wind direction

Figure 3.14: *Effect on the internal temperature caused by wind intensity (3.14(a)) and wind ventilation (3.14(b)*

Chapter 4

Climate Control

Temperature and humidity control problem has the main following features [1]:

- Greenhouse climate is subject to strong disturbances, measurable and not
- There is a high correlation between different variables, for example crop growth and humidity or opening windows and wind intensity
- This system is strongly time-varying, this means that actuators (with the same input) may produce different effects (because of the presence of disturbances)
- Exist a lot of constraints in input of amplitude, slew rate and quantization type. For example windows can not achieve every degree of opening (they can not move between $+5$ and -5 degree), or temperature must evolve between a minimum and maximum value to promote growth and avoid stress or damage to plants.
- A lot of sensors are usually placed inside greenhouses, so it is considered that the greenhouse climate is represented by these measurements, not considering the distributed nature of the system, but just the punctual one.

Temperature is the climate variable that directly influences on crop growth and that is traditionally controlled inside greenhouses. The plants grow only under the influence of light, that is, when photosynthesize, thus requiring a relatively high tem- perature. During the night crop is not active (there is not growth), so it is not necessary to keep it at a high temperature. It is, therefore, desirable to have a higher temperature during the day than at night, so that different temperature set points are defined for these periods. [15]

Before explaining the PI control technique applied to the MIMO system we see other more advanced types of control. We are not going to use these tecniques because of their complexity. The main object of this work is use the simplest control with the more accurate results. It is sure that for a non-linear system like this one, non linear controller it would be perfect, but the implementation costs more and is more complex. Take a look of different type of advanced control that can be used in this case:

4.1 A review of temperature and humidity controllers

Natural ventilation provides an exchange of air between the interior and exterior of the greenhouse. Since the outside air is generally colder than the interior air, it is located in the lower layers of the greenhouse air volume and the hot air rises to the upper layers coming out through open ventilation. In this way the interior air temperature of the greenhouse decreases.

The problem of daytime temperature control using natural ventilation has the following characteristics:

- **Structurally**, the action system has two main drawbacks:
  - **Saturation**: the ventilation can be open between 0 and 100% ($0 - 38$ degrees).
  - **Resolution of the exit**: although it is a continuous action system, the positioning of the window is done using a rack whose teeth allow a minimum movement of 5% (2 degrees).
- The response of the indoor air temperature to steps in the ventilation behaves like a first order system with a delay of approximately one minute. In addition, there is a non-linear nature between ventilation and temperature.
- External disturbances significantly influence the effect of ventilation on temperature. When the ventilation is opened, the hot air of the greenhouse is replaced by the colder

air from the outside. The speed with which the hot air is extracted is a function of the size of the vents (greenhouse design constant), the difference between the indoor and outdoor temperature and the wind speed, so the perfect controller must take into account the weather conditions outside to calculate the opening of ventilation.

- For the same outdoor temperature, as the wind is higher, the gain of the system increases; the opposite occurs with the outside temperature, which decreases as the gain increases. After a thorough analysis of the data, it is observed that depending on the external climatic conditions and the interior temperature.

Having seen the amount of disturbances present, it would be natural to think that the best control system is able to compensate these disturbances. The problem with this approach, presented in section 4.2, is that in order to work well it would need very precise perturbation models. Having adopted a simplifying approach for this work, it is therefore impossible to guarantee sufficient correctness to the models so they can be used in the feedfoward control. Furthermore, the linear models found in section 3.1.4 are not suitable for modeling a strongly non-linear system such as a greenhouse. This problem will be explain in detail in chapter 5.

General problem of control of relative humidity: the content of water vapor in the indoor air of the greenhouse, measured for example by relative humidity, is not one of the climatic variables that directly affect the growth of the crop, although its control has a special interest. With high relative humidities, the appearance and development of cryptogamic diseases is favored, in addition to diminishing transpiration, which reduces the absorption of water and nutrients, being able to generate deficit of elements such as calcium. However, with low relative humidity, the rate of transpiration increases, which can lead to water stress, the closing of stomata and, therefore, the reduction of photosynthesis. Based on these facts, it is necessary to maintain the relative humidity of the air in a certain interval. The control of the relative humidity of the indoor air of the greenhouse has two main drawbacks:

- The air temperature and its relative humidity are highly related inversely (the correlation coefficient is higher than -0.9), so a variation in one of the two variables produces an inverse variation in the other. Generally, the higher the air temperature, the lower the relative humidity and vice versa, since the higher the temperature, the greater the amount of water vapor it needs to saturate.

- The action systems that are used to control the temperature modifies the value of the two variables (temperature and humidity)

As the main variable of the system is the temperature of the air since it directly affects the growth of the plants, it is considered to be the variable to control, trying to maintain the humidity in a range considered ideal, adapting the controller according to the effects of the ventilation and heating on humidity. For this reason, in order to mantain humidity in an ideal range, different set-points have been used in humidification system and, in practical, a MIMO control [8] is performed, where surely temperature continues to be the predominant variable.

4.2 A MIMO PID proposal

Thanks to the simplicity of managing and modifying the PID, this control method is the one that has been used in this context. For the PID controller, see the text [16] in which the three terms proportional, integrative and derivative are widely dealt with. In the 4.1 can be seen the form of parallel PI:

$$P(s) = P + \frac{I}{s} + D\frac{N}{1 + N\frac{1}{s}} \tag{4.1}$$

The PI is the most widely used controller in the industrial world [17], and as well as in greenhouses, this is due to its extreme simplicity of tuning and management. The derivative part has been deliberately excluded because it causes risky effects of high frequency noise amplification. The step forward that has been made in this paper is to use 4 different PID for each actuator (ventilation, heating, humidificator and deshumidificator system) and suppose that the environment was not made up of a single control loop but rather of two

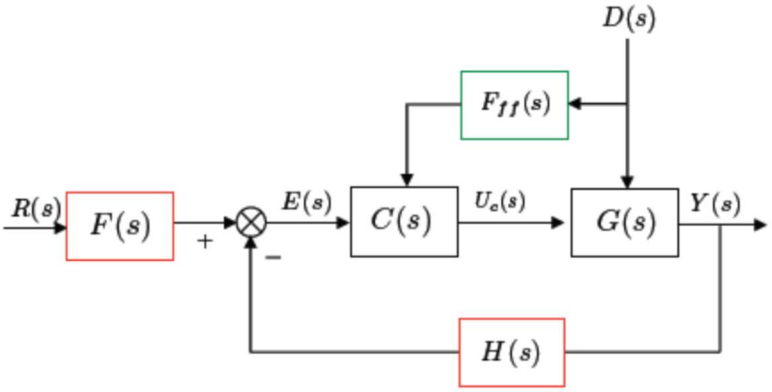


Figure 4.1: *Lateral ventilation system. Image taken from [1]*

interacting control loop, so a MIMO system was supposed to be used:

- **2 outputs**: interior temperature and humidity (relative one)
- **4 inptus**: they are the 4 set-points for ventilation, deshumidificator, humidificator and heating system

Some improvements that could be added to a regular PID controller are shown below:

Feedfoward control (proactive control)

Controllers with feedback do not take into account the influence of the disturbances that occur and affect the system. A means to correct the effect of disturbances is the feedforward control, which compensates for the effect of the disturbances before they produce error in the controlled variable. However, it must be borne in mind that this type of control is limited by the accuracy of the measurements, the calculations made and the unmeasured disturbances. Figure 4.1 shows a typical scheme of feedfoward control:

In this case the transfer function of the closed control loop is represented in 4.2

$$G_{closedloop} = \frac{P(s) - G(s)F_{ff}(s)}{1 + C(s)G(s)} \tag{4.2}$$

Feedback Linearization Control of Daytime Temperature

The Feedback Linearization (FL) method is an approach to Numerical Control (NC) design methods where the main idea is to transform a nonlinear system into a linear one, and thus obtaining a closed loop dynamics in linear form, so that any linear control method can be applied. Several authors have used this control approach within the field of greenhouse climate control ([18]) with different types of models.

For systems that can be represented in the form $X = f(X) + g(X)U$, a non linear mapping can be used to transform the system into a linear one:

$$U = \frac{\tilde{U} \; - f(X)}{g(X)} \tag{4.3}$$

Thus is possible to use any linear control method in order to obtain the virtual signal $\tilde{U}$, and from here can be obtained the real control signal with some algebrican trasformation.

Optimal Control

The problem of control temperature and humidity in a greenhouse using Optimal control has been treated in a good way in the book by van Straten et Al. [19] using the theory of optimal greehouse climate control, for this reason that method will not be used here. This method is quiet complicated to implement, surely more than simple PID controller. In fact this work tries to find the less complicated solution.

Model Predictive Control of Daytime Temperature

As the same as PI control, with Model Predictive Control (MPC) approaches the temperature is controlled using natural ventilation, while nighttime temperature control is obtained using heating system. To solve the actuators saturation problem (during the day this is the main problem) an MPC is combined with a FeedFoward (FF) compensator, in particulary they use an General Predictive Control (GPC) in series with the FF controller to regulate the greenhouse inside temperature during the daytime [1]. Figure 4.2 shows

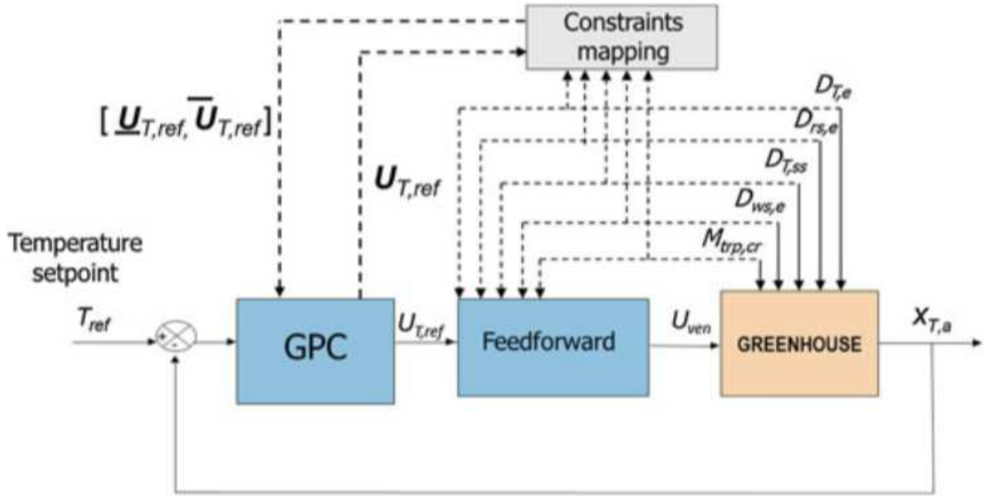


Figure 4.2: *Structure of model predictive control of daytime temperature. Image taken from [1]*

the combination of both system; moreover, as mentiond previously, adding FF controller to greenhouse in series makes it possible to obtain whole system linear models with nearly unitary gain and uncertainties will be compensated by feedback controller.

This control method will not be used because is needed a very accurate model of disturbances, because if not, FF controller can not work correctly and this situation could be worse.

4.2.1 Back-calculation Antiwindup for PI controller

All actuators have physical limitations: a motor has limited velocity for example or, in this case, windows can not be opened more than 100%. Due to this fact there is a very huge problem: the feedback loop will be broken when the actuator saturates because the output of the saturating element is then not influenced by its input. The unstable mode in the controller may then drift to very large values. When the actuator desaturates it may then take a long time for the system to recover. This work does not treat the problem of windup in a very detailled way, so reader can focus on [16] to find more informations about it. Here is painted out an easy solution to avoid the windup effect: anti windup technique called

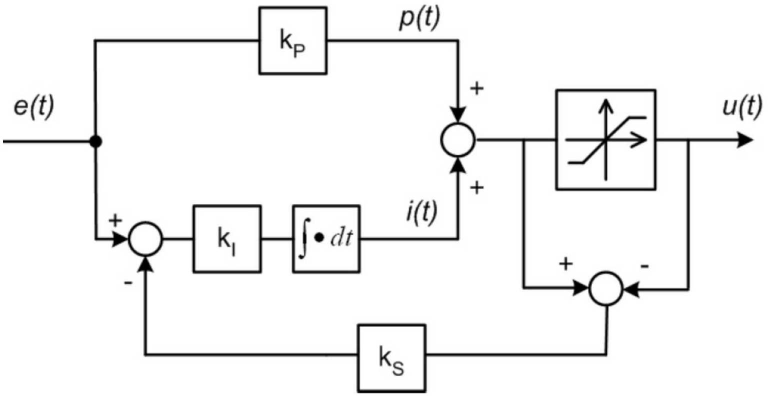


Figure 4.3: *Back-calculation Antiwindup. Image taken from [5]*

back-calculation. It's important to point out that there are several different solutions in the world of "antiwindup-scheme", but this is one of the easiest to use.

Windup is potentially destructive. It occurs when the control signal is in saturation and, at the same time, the controller variable is moving away from the set point. The natural behavior expected from the controller would be to get out of saturation when controlled variable is moving away from the desired value. The problem is that the integrative error accumulated up to that moment causes a desaturation of the integral term much slower and, for this reason, technique of back-calculation is necessary. This control scheme represented in Figure 4.3 allows to subtract area from the integral part, in this way, integral error can desaturate faster.

K_s value has been found with an empirical process, this is because in general, when in industrial automation is used a PID controller, that value is usually equal to $T_t = \sqrt{T_i T_d}$ where $K_s = 1/T_t$. In this case, there is not the T_d so, to deal with this problem, it is better to start from a practical point of view.

4.2.2 MIMO control architecture

Figure 4.4 shows the correct MIMO Simulink scheme and some hypotesis have been made to understand how it works:

- Ventilation only works where the temperature set-point is higher than the interior

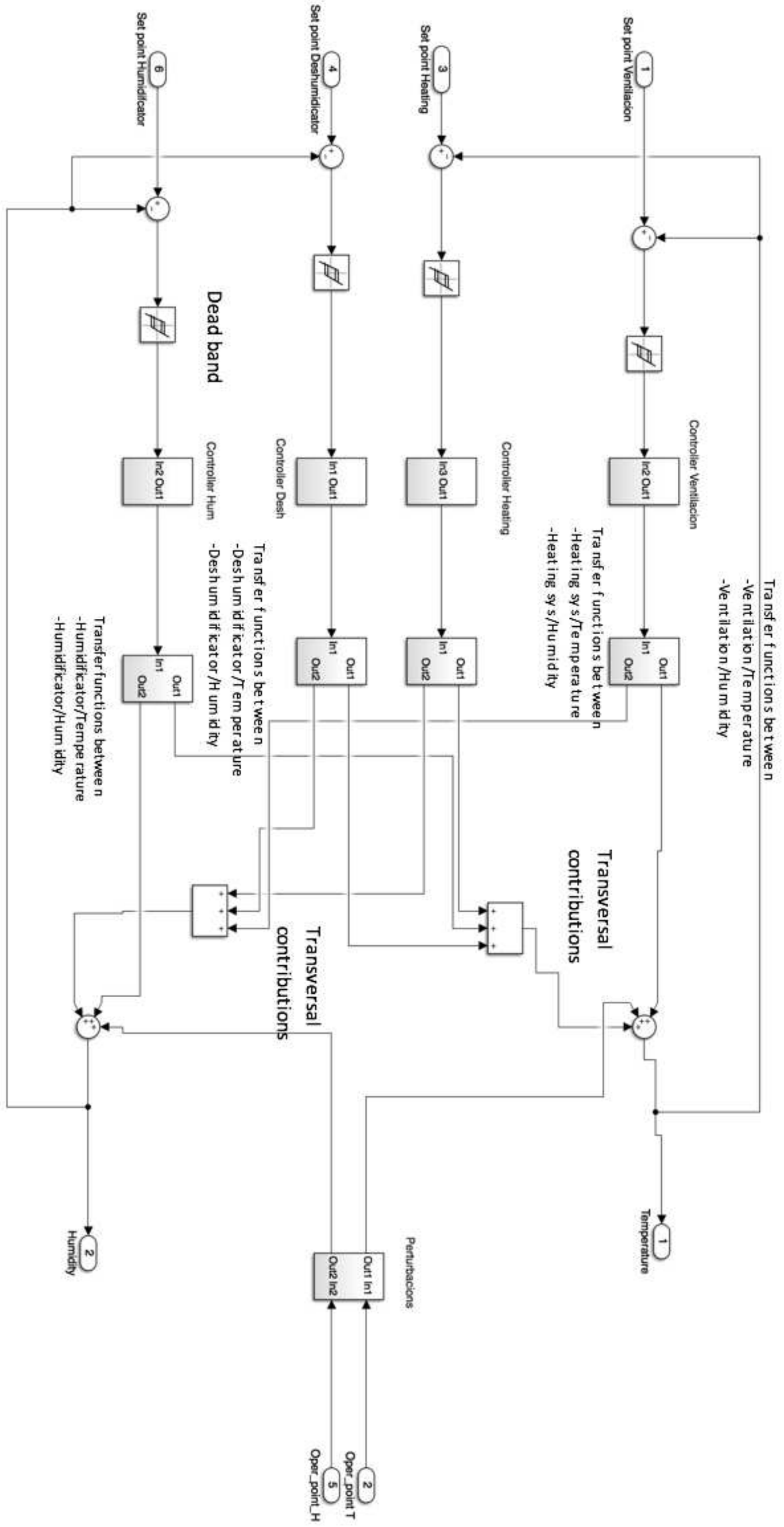


Figure 4.4: *Control system*

temperature, if is lower, heating system will work and ventilation will be stopped.

- Humidification system works only if the humidity is lower than the interior humidity, if is higher, deshumidification system will work and humidification will be stopped.
- Every loop affects indirectly the other ones. Transversal transfer functions have been found (for example how humidificator affects temperature).
- To understand how to tuning PI controller for MIMO system a RGA matrix has been performed (its explication is treated in section 4.2.4).

It's easy to understand the role of the blocks that appear in Figure 4.4:

- **Four dead bands**: in a greenhouse it's not nedeed to control temperature with only 0.1°C of error for example, it's best if the actuators start to work only when difference between the value of real temperature and the set-point is changing and it is more than 1°C. For humidificator and deshumidificator the dead bands allow the error to reach up to 2% relative humidity. In this way actuators do not work all the time. Surely this approach allow to achieve a better energy waste but worse temperature and humidity control.
- Block of perturbation allow to understand the effect that perturbations have inside a greenhouse.
- Two blocks of transfer functions for every control loop, the first one is the *direct transfer function* (ventilacion with temperature or humidificator with humidity for example) and the other one is the *transversal transfer function* (ventilation with humidity or humidificator with temperature for example).

4.2.3 RGA matrix

This section will explain the method of identifying RGA matrix and why it is extremely useful in this situation. RGA of a non singular square complex matrix G is a square complex matrix defined as:

$$RGA(G) = \Lambda(G) \triangleq G \times (G^{-1})^T \tag{4.4}$$

in this case × denotes element by element multiplication (Shur or Hadamard product). With Matlab:

$$RGA = G. * pinv(G).' \tag{4.5}$$

For a $2x2$ matrix with elements g_{ij} the RGA is:

$$\Lambda(G) = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} \tag{4.6}$$

and so can be found that:

$$\lambda_{11} = \frac{1}{1 - \frac{g_{12}g_{21}}{g_{11}g_{22}}} \tag{4.7}$$

The RGA is a very useful tool in practical applications, it allows to have an idea of the level of the interactions present between different control loop [20]. For example it's clear that ventilation (that is used to control temperature) influences more humidity that temperature, it would be a problem. More strictly, let $u_j andy_i$ denote a particular input-output pair for the multivariable plant G(s), and assume that our task is to use $u_j$to control y_i.[20] Here there are two extreme cases:

- All other loops open: $u_k = 0, \forall k \neq j$
- All other loops closed with perfect control $y_k = 0$, $\forall k \neq i$

Now gain $\partial y_i / \partial u_j$ has been evaluated for this two extremly cases:

Other loops open:

$$\left(\frac{\partial y_i}{\partial u_j} \right)_{u_k=0, k \neq j} = g_{ij} \tag{4.8}$$

Other loops closed:

$$\left(\frac{\partial y_i}{\partial u_j} \right)_{u_k=0, k \neq j} \triangleq \hat{g}_{ij} \tag{4.9}$$

Where $g_{ij} = [G]_{ij}$ is the ij'th element of G, whereas $\hat{g}_{ij}$ is the inverse of the ji'th element of G^{-1}.

Bristol argued that the ratio between the gains in 4.8 and 4.9 is a useful measure of interactions, and defined the ij'th "relative gain" as

$$\lambda_{ij} \triangleq \frac{g_{ij}}{\hat{g}_{ij}} = [G]_{ij} \left[G^{-1}\right]_{ij} \tag{4.10}$$

The RGA is the corresponding matrix of relative gains. From 4.10 we see that $\Lambda(G) = G \times (G^{-1})^T$ where × denotes element by element multiplication (the Schur product). This is identical to the previous definition of RGA matrix in 4.6.

Extension of RGA to non-square matrices

In our case, $4x2$ MIMO system is in use, so matrix G is a $4x2$ matrix and not a square one. For this reason 2 columns are chosen each time and another $\hat{G}$ matrix is found. With this new matrix the RGA is calculated with 4.10. In this way some information will be lost because only two inputs are considered at a time but a general idea about the interactions that take place between the control loops is still in mind. For example in 4.11 there is a gain matrix of the whole system :

$$K = \begin{bmatrix} -0.0700 & 0.0604 & -1.4000 & 0.3444 \\ 0.0841 & -0.0434 & 37.8142 & -0.8000 \end{bmatrix} \tag{4.11}$$

Taking two by two columns every different square matrix is found. The result is represented in 4.12 and 4.13 and surely it's not taken into account the matrix that represents deshumidificator with humidificator (because they never worked togheter) and for the same reason the ventilation and heating system are not considered. The 4 matrix are divided into 2 groups, in the first one there is the interaction between ventilation and deshumidificacion (4.12) and the interaction between heating system and humidification (4.13):

$$\begin{bmatrix} 1.0465 & -0.0465 \\ -0.0465 & 1.0465 \end{bmatrix} \tag{4.12}$$

$$\begin{bmatrix} 1.0273 & -0.0273 \\ -0.0273 & 1.0273 \end{bmatrix} \tag{4.13}$$

Then, there is the principal diagonal that is very near the unity, essentially the interaction between these two control loops don't affect each other a lot.

The second group represents the interaction between ventilation and deshumidification (4.14) and between heating system and deshumidification (4.15):

$$\begin{bmatrix} 2.0711 & -1.0711 \\ -1.0711 & 2.0711 \end{bmatrix} \tag{4.14}$$

$$\begin{bmatrix} 1.4479 & -0.4479 \\ -0.4479 & 1.4479 \end{bmatrix} \tag{4.15}$$

In the main diagonal the values are slightly greater than one. This, according to the RGA matrix theory [20] simply means that the control of this loop will be slower to get, but the interaction between the two loops, despite being present, should not lead the system to instability. Having seen these data, it is considered better not to insert any type of decoupler because, in the case of strongly non-linear systems, the effect of the decouplers would be strongly limited and potentially harmful. In terms of cost-benefits it would not be a smart operation.

4.2.4 PI tuning

In this section it will be tried to tune the PI controller with different method to understand which is the best one [21]. It will be simulated the control scheme and it will be found the best solution for the simulation one. In chapter 4.2.4 it will be compared this methods (for the simulated system) and we can appreciate the difference. For this tuning part, it will be considered **First Order Plus Dead Time (FOPDT)** system where:

- **T** is the time constant of the system;

- **L** is the time delay of the system;
- **K** is the gain of the system;

Tuning PI with opened loop Zieger-Nichols

With this techinque it will be put the focus on the value of **a** that is calculated by the values of the gain, the delay and the time costant of the system that is needed to be controlled. So in this case the table that is used is the follow one ([22]):

	K_p	T_i	T_d
P	1/a		
PI	0.9/a	3L	
PID	1.2/a	2L	L/2

Tuning PI with Chien-Hrones-Reswick-0%

The main purpose of this technique is to obtain good performance both for noise rejection and for the set point changing. In particular, to get the fastest response with 0% overshoot. The table to follow is represented in 4.2.4 and it is in particulary to noise rejections

	K_p	T_i	T_d
P	0.3a		
PI	0.6/a	4L	
PID	0.95/a	2.4L	0.42L

It easy to notice that, respect to Zieger-Nichols, this techinque is less agressive

Tuning PI with Chien-Hrones-Reswick-20%

This techinque, like the previous one, is focused on obtain the fastest response with 20% overshoot. The table is represented in 4.2.4

	K_p	T_i	T_d
P	0.7a		
PI	0.7/a	2.3L	
PID	1.2/a	2L	0.42L

Tuning PI with Cohen-Coon

This is the techinque that will be used in 4.7 to show results of the simulation. This is because Cohen-Coon is very good to noise rejection and load disturbance. The table represented in 4.2.4 is designed to have a factor decay of 0.25 [1]

	K_p	T_i	T_d
P	$\frac{T}{KL}(1+0.35L/T)$		
PI	$\frac{0.9T}{KL}(1+0.92L/T)$	$\frac{(0.3L+3.3T)L}{T+2.2L}$	
PD	$\frac{1.24T}{KL}(1+0.13L/T)$		$\frac{(-0.9L+0.27T)\tau}{T+0.13L}$
PID	$\frac{1.35T}{KL}(1+0.18L/T)$	$\frac{(0.5L+2.5T)L}{T+0.61L}$	$\frac{0.37TL}{T+0.19L}$

Tuning PI with Lambda method

Lambda method [24] is the variant or extension of the pole cancellation method for systems with delay and it is an analytical method. A transfer function like 4.16 is found (approximating the delay with the development of Taylor series) and is assumed that the time costant T_i of the zero of the controller is $T_i = \tau$, so it's simple to understand how it can pass from 4.17 (transfer function of open loop) to 4.18 (transfer function of closed loop). In this way can be set the λ parameter to find **K** of the controller (from 4.19)

$$G(s) = \frac{\kappa}{\tau s + 1} e^{-t_r s} \tag{4.16}$$

$$L(s) = \frac{K(T_i s + 1)}{T_i s} \frac{\kappa(1 - t_r s)}{\tau s + 1} \tag{4.17}$$

---

[1] The ratio by which the oscillation is reduced during one complete cycle, or the ratio of successive peak heights. A "one quarter" **Decay Ratio** is a traditional standard. The ratio can be calculated from $DR = \frac{c}{a}$ where "c" is the amplitude of the second peak and "a" is the peak of the first one [23]

$$T(s) = \frac{L(s)}{1 + L(s)} = \frac{(1 - t_r s)}{\frac{\tau - K\kappa t_r}{K\kappa} s + 1} \tag{4.18}$$

$$K = \frac{\tau}{\kappa(t_r + \lambda)} \tag{4.19}$$

Tuning PI with Amigo's method

This is a method developed by Karl Astrom and Tore Hagglund ([24]); they tried to obtain better performance between robustness and rejection to perturbations. In this way softer responses will be obtained for both problems. The process is the same of 4.2.4 and values of the PI controller are represented in 4.2.4

	K_p	T_i
PI	$\frac{0.15}{K_p} + (0.35 - \frac{LT}{(L+T)^2})\frac{T}{K_p L}$	$0.35L + \frac{13LT^2}{T^2+12LT+7L^2}$

Comparison between tuning methods

To understand which method is the best, several attempts have been made. Figure 4.5 shows the most significant methods compared, highlighting the control effort that is required of the actuators (in this case upper and lateral windows). No consideration was made regarding the waste of resources (to power the engines that move the windows), therefore the choice of method to be used is a simple matter of need to have a more or less aggressive controller. In this case the Cohen Coon method will be used in 4.3.1 for the simulation, as it appears to be one of the most aggressive but without constantly sending the actuators to saturation. Methods like **Lambda** and **Amigo** are instead used in case is necessary to have the mildest control actions, in fact, as shown in Figure 4.5, they do not even lead actuators to the saturation.

While Cohen Coon is used for simulation part, Lambda method is used for real tests in Las Palmerillas. This is due to the fact that Lambda method, with parameter λ, is more manageable and more easily modifiable in a short time. Through the simple modification of

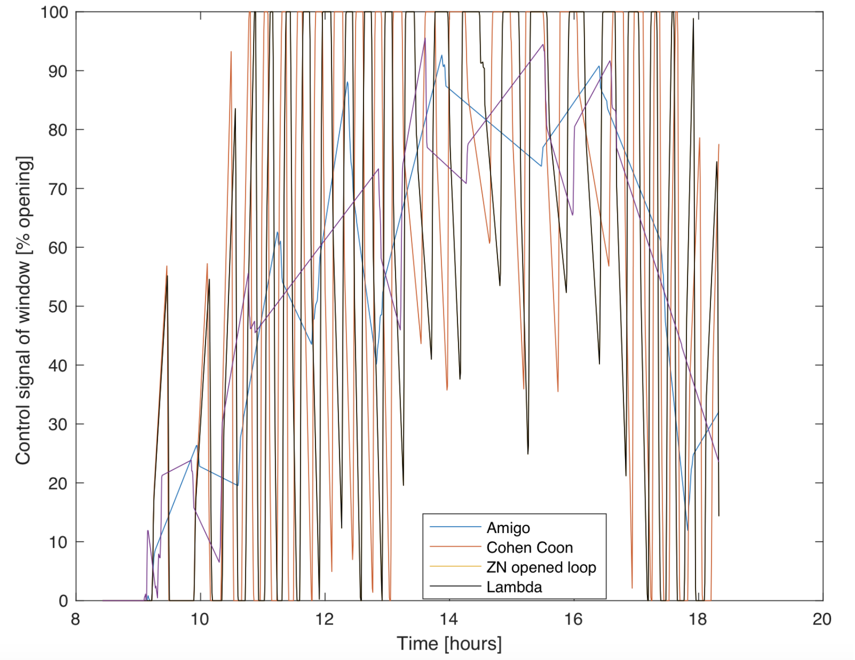


Figure 4.5: *Comparison between different PI tuning methods*

a parameter, Lambda method allows to obtain other methods and this makes it extremely versatile.

4.3 Results

In this section the results seen were obtained during simulation test and during real experiment performed in greenhouse. Is necessary to take into account that simulation test and real test were performed in different period of the year (this means with different external condition) and with different internal conditions (no presence of crop growth for example). For this reason there are differences between values of set-point. In chapter 5 it will be discussed more in detail this differences but is clear that the same results can not be achieved with this huge differences about "initial conditions".

4.3.1 Simulation result

Having seen in 4.2.3 that the decouplers aren't needed, in this section figures 4.6(a) and 4.6(b) show the result of temperature and humidity control with just PI's controllers. These results were obtained taking into account only the day [2] and not the night. This is because, as already explained in the aforementioned 3.1.4, the cult is subjected to strong stress (through high temperature for example) only during the day, while at night it remains, in general, a problem to keep under control, but not so relevant. It can easily seen that, thanks to the dead bands, output is not a constant signal but change a lot between two values. This is because the output was only controlled when it goes out of an estabilished range, not to overload the actuators too much.

The specifications during the day are as follows:

- the ventilation is activated only if the temperature exceeds $26°C$;
- the dehumidificator works only if the humidity exceeds 90%;
- the heating system is actived only if themperature is under $18°C$ degrees;
- the humidificator works only if the humidity is under 60%;

On this simulation day, for example, humidity does not exceed this value and therefore the humidity control signal is not taken into account. As far as the control signal of the ventilation is concerned, since a very aggressive controller has been used for the simulation, even in case of not very high errors, the output signal from the PID leads to the saturation of the actuators (which means having the totally open windows). This fact can be seen in figure 4.6(c).

To see the effects of the dehumidifier action, the set point is lower setted, so humidifier goes into action sooner than necessary. Figure 4.7(b) shows the relative humidity present inside the greenhouse and in Figure 4.7(c) the control action of the dehumidifier (remember that, in this case, the limits of the control action are 0 and 10).

In figure 4.7(a) can be seen that the value of the temperature, between 14.00 and 18.00 is not controlled at all; this is due to the fact that, during this period, the ventilation system

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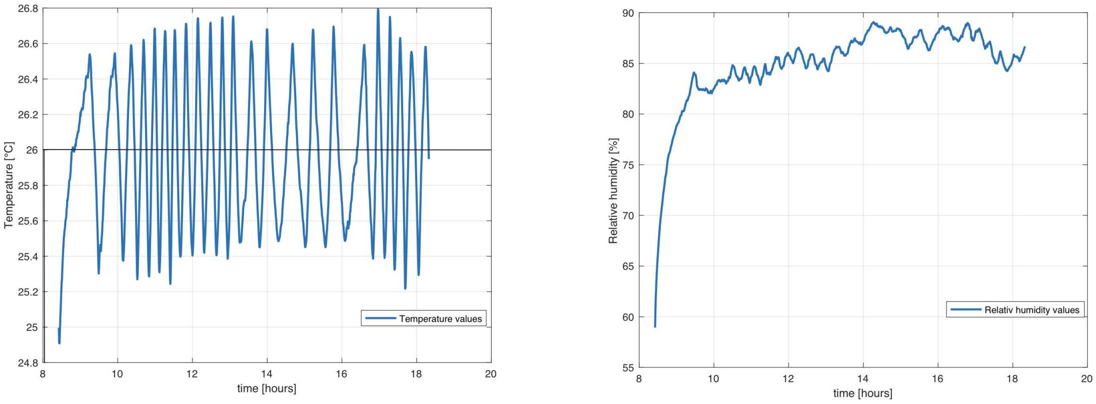
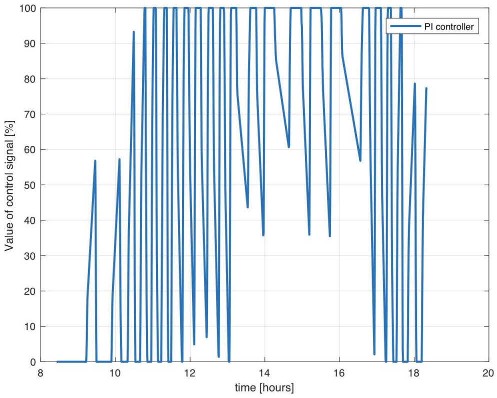
[2] when solar radiaton is greater than $10\frac{W}{m^2}$



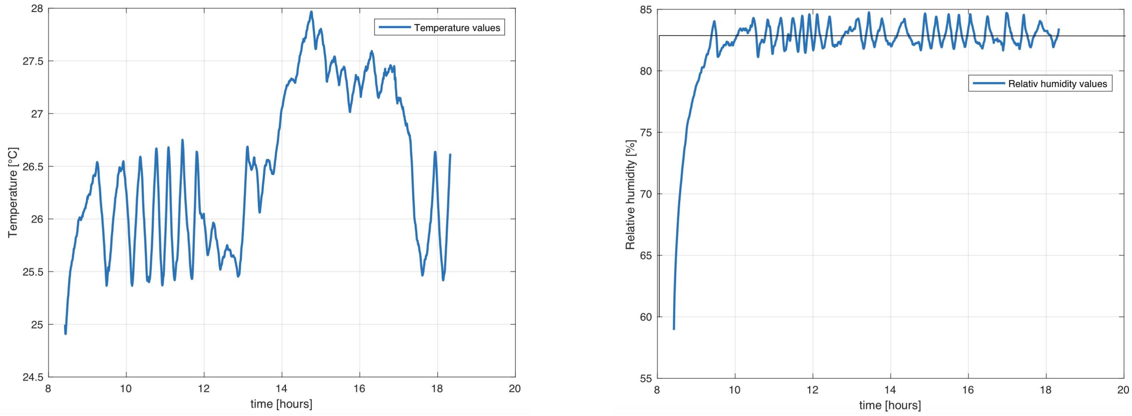
(a) Value of inside temperature with set-point of 26°C

(b) Interior relative humidty with set point of 90%



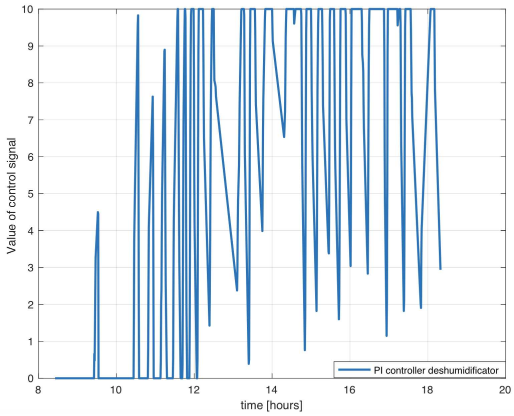
(c) Control signal of PI that controls temperature by windows

Figure 4.6: *Simulated MIMO control when set-point of humidity is 90%*



(a) Interior temperature while set-point of humidity is 83%

(b) Interior relative humidty with set point of 83%



(c) Control signal of PI that controls deshumidificator

Figure 4.7: *Simulated MIMO control when humidity set-point is 83%*

is saturating (because of the deshumidificator system). Figure 4.8 shows the saturation of the windows during the day when the set point for humdity is 83%.

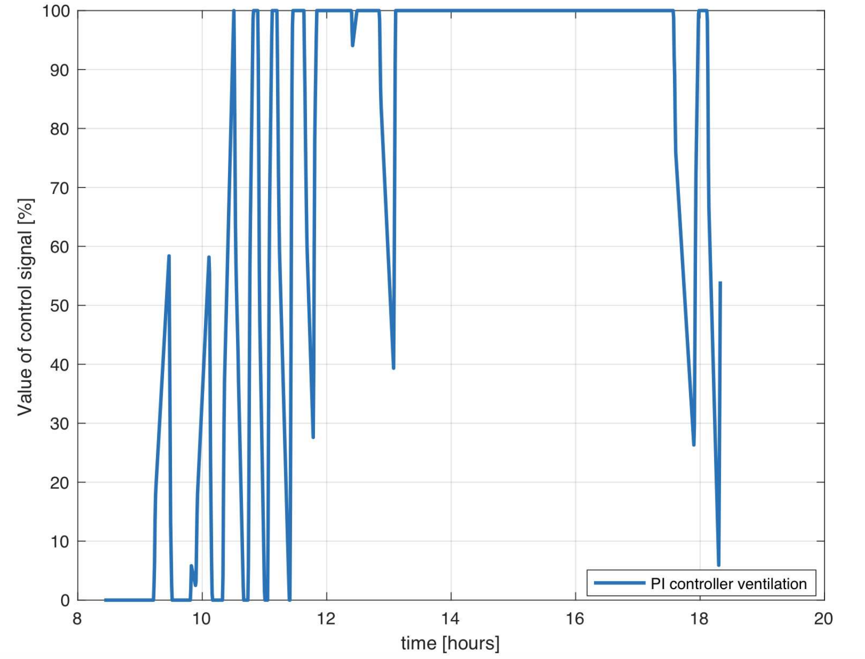
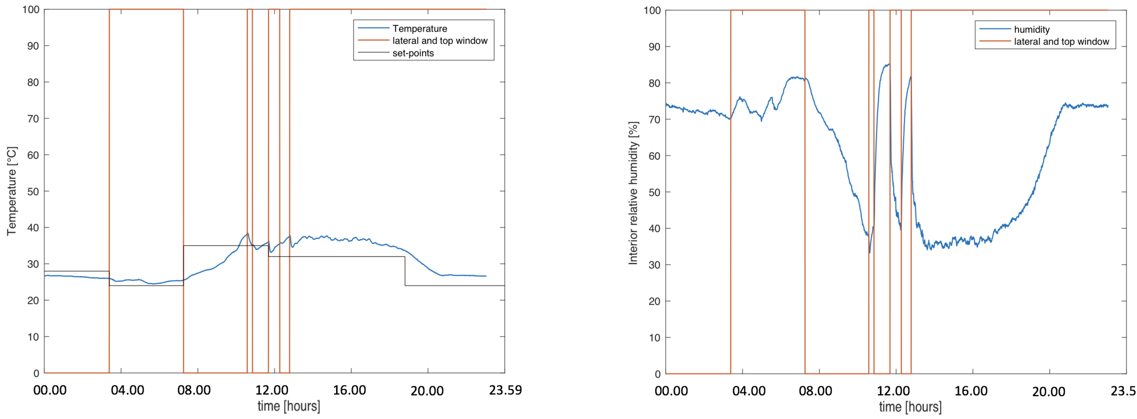


Figure 4.8: *Contorl signal of ventilation system while set-point of humidity is 83%*

4.3.2 Real results

In this section the real experiments will be performed in Las Palmerillas (for more details about this control station see 1.1). These experiments want to show that the temperature can be maintained in a certain range of values, as well as humidity. It will be started in 4.3.2 by controlling only the temperature through the windows and letting the humidity follow its dynamics without using the humidifier (as already explained in 4.3.1, in general during the day only the humidifier and ventilation are used). In a second phase, both the temperature (through the windows) and the humidity (through the humidifier) are controlled (4.3.2). The results obtained are very different from the simulation and this is easily understandable due to the strong non-linearity of the system, the ON-OFF use of the actuator apt to increase the humidity, and above all due to the fact that, during the period which it was possible to perform experimental tests, the plantation inside the



(a) Interior temperature controlled by ventilation

(b) Interior relative humidity controlled only by ventilation

Figure 4.9: *Real control of Temperature and humidity inside greenhouse using only ventilation*

greenhouse was absent. This absence causes a lowering of the humidity because, increasing the temperature during the day, the internal relative humidity tends to lower due to natural causes; if there were the plantation, on the contrary, it would heat up and start to transpire, increasing the relative humidity of the entire greenhouse.

Temperature control

The most important process variable to control is certainly the temperature. As already explained in 1.1, it is directly involved in the crop growth process, while humidity control plays an important but secondary role. This is the reason why it was decided to use a type of drives (windows) that works in a discrete mode and not in ON-OFF mode like humidificator. Figure 4.9 shows the control action applied on the top and lateral windows and the corrispective increasing or decreasing of the temperature related with every set-points changing (4.9(a)). Figure 4.9(b) shows the trend of humidity due only to changes made by the ventilation system, since the humidifier was not used in this phase. As expected, opening the windows influences the humidity itself, which is why MIMO system has been used.

It can be easily seen that after 12.00 it is not possible to control temperature even if the set point value is higher than necessary, in fact the saturation of the window is not avoidable during summer, due to the extremely high outdoor temperature and general low wind. It's best to focus only between 8.00 and 20.00 because this is the part of the day where model of temperature and humidity has been found. Control process variables during the night is not the main objective of this work. The only thing that can be done during the day is to use a control technique based on both humidificator and windows to increase humidity and, at the same time, decreasing internal temperature. This is very difficult to obtain due to the extreme accuracy required for both models. In 4.3.2 these types of experiments will be performed.

Temperature and humidity control - MIMO control

Unfortunately, due to the fact that the humidifcator stops to work during real test, It was not possible to continue experiments in this direction.

Chapter 5

Conclusions and future works

During the simulation phase, through the use of linear models and PI controllers, the result of following the set-point was widely satisfactory (see 4.6(a)). For real test it is easy to understand that, given the extremely unfavorable external conditions in summer (very high temperatures), the ventilation system is not sufficient to lower the internal temperature until reaching the set-point, especially during the hottest hours (4.9(a)). Despite this, the system reacts promptly to temperature changes and humidity remains, for almost all the time, within the desired range $30 - 80\%$ (4.9(b)).

Therefore it can be concluded that the ventilation system could work correctly only on days with outside temperatures not too high (not above 30 degrees). With regard to humidity, due to the failure of the humidification system during the experiments, it was not possible to test the real MIMO control. Despite this, the humidity, even only thanks to the action of ventilation, remains within the pre-set range while, during the simulation, it reaches the set-point perfectly. (4.7(b)) As far as the controller is concerned, PIs have proved suitable, taking the saturation control variable when necessary without overloading the actuators.

A more detailed control scheme, using feedfoward (4.1) or Model predictive control (4.2) could be implemented only if, previously, accurate models are obtained through the use of non-linear methods. Linear methods for models and controllers have been used in this work and this has generated a big limit. The problems connected to a non-linear system are many and in the following paragraph some methods will be proposed to be able to try to solve them through the use of more refined techniques.

Every problem that affected this work was related with the fact that it's working with a strongly non-linear system, but using linear techniques like transfer functions (linear-models) and PID's (linear controllers). To solve these problems and to improve significantly the results it would be better follow different survey methods explained below. It has been verified that being able to keep a temperature too low inside a greenhouse is not possible, the actuators (in particular the windows) reach saturation and this prevents a follow-up of the set-point at any hour of the day. Surely a limit of investigation in this project is due to the use of **linear tools** to analyze a system that was **strongly non-linear**. This approach was attempted to try to simplify the solution as much as possible, in order to keep the most complicated method as a last resort. For this reason the list below describes the problems related to the non-linearity of the system and how try to solve them.

- The behavior of the system variables is strongly influenced by external disturbances, moreover it is strongly non-linear. For this reason, the influence that each disturbance has on the variable to be controlled should be modeled through a model that is not linear but takes into account several other factors. An ARX model was used but, maybe, it would be better use a **non-linear ARX** or a **neuronal network** [25].
- One of the non-linearity of the system is precisely due to the values that the disorders take throughout the day. In this work the day has been divided from the night subdivisions could be made by dividing the day into parts of 6 hours each and also can be created more models for different periods of the year and varying them in running
- Using a non-linear model is also necessary to introduce a controller that is not linear. Initially it's thought of using a PI with simple gain scheduling as in our case (simply by varying the proportional gain) but, a more accurate work already on the models, could insert a FF that is reliable, so to obtain excellent noise rejection.

Not focusing the discussion on non-linearity but trying to investigate upstream of the problem, a much larger amount of data could be collected. Furthermore, an accurate work on the choice of data and their correlation could lead to the discovery of an extremely precise model. The data could therefore be collected daily for whole months and, in the meantime, further tests could be carried out on the ventilation system, but over all, on the humidification system (much more recent than the others).

Following the path of the genetic algorithm it could be tried to minimize a parameter that is not the IAE. Unfortunately, taking this path is very expensive on a computational level given the presence of numerous parameters (each simulation uses resources for about 1 full day). It is therefore suggested to first try to reduce the number of parameters as much as possible and then continue with the genetic algorithm method.

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Resumen

Desde 1980, la pequeña llanura costera, a unos 30 kilómetros al suroeste de la ciudad de Almería, ha desarrollado la mayor concentración de invernaderos en el mundo, que abarca 30000 hectáreas. Más del 50% de la demanda europea de frutas y verduras proviene de invernaderos. Por esta razón, no es difícil entender por qué hay una necesidad de concentrar energías en este campo. En este trabajo en particular se ha tratado de concentrar los esfuerzos para controlar la humedad y la temperatura dentro del invernadero, dos de las variables que más influyen el excelente crecimiento del cultivo. Se comenza a partir de la recopilación de datos en el campo, a través de estos datos se han desarrollado más de cien modelos que luego se han validado con el fin de mantener solo lo mejor. A través de estos modelos, han sido calibrados los controladores y, en la parte final del trabajo, se han implementado dentro del invernadero real.

El uso de modelos lineales para describir un sistema fuertemente no lineal ha llevado a obtener un ajuste, durante la fase de validación, que no supera los 80%. El utilizar un modelo simplificado se justifica por el hecho de que, a través de un controlador PI y una realimentación de la salida, todavía se pueden conseguir resultados satisfactorios con menos desperdicio de recursos. Durante la simulación tanto la temeperatura como la humedad alcanzan el punto de ajuste y, aunque se encuentra en presencia de un sistema de MIMO, la influencia transversal de los actuadores no conduce a la inestabilidad del sistema.

Las pruebas reales llevadas a cabo en los meses de verano han puesto de manifiesto la imposibilidad de controlar la temperatura interna a través de la ventilación cuando la temperatura exterior es demasiado alta. Por tanto, es posible concluir que, si el objetivo era controlar la temperatura y la humedad dentro de un range suficientemente amplio (por ejemplo, entre 18 − 32°C de temperatura y 30 − 80 % de humedad relativa) y no durante los meses de verano, entonces es posible seguir este trabajo y usar modelos lineales junto con los controladores PI. Si las especificaciones son rigurosas, sin embargo, no se obtienen resultados satisfactorios; entonces modelos tales como ARX y ARMAX deben ser desechados y se debe proceder con modelado y métodos de control que no sean lineales.

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