CONTROL SOLUTIONS FOR GREENHOUSE CLIMATE SYSTEMS

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Cuvinte cheie: Greenhouse climate control, integrator plus dead time, linearization and decoupling, PID, Smith predictor, genetic algorithms, Hardware-in-the-Loop, SCADA.

Rezumat**,**

The PhD thesis develops solutions for greenhouse climate control systems (temperature and humidity control). This is an actual subject included in the more larger domain of application of control system in agriculture. The climate control system using a nonlinear-coupled model, with important influence of external disturbances, is implemented employing linearization and decoupling module and mainly PID controllers tuned by different methods.

The feedback-feedforward linearization and decoupling procedure applied to the greenhouse climate model requires the estimation of the output vector without delay, which is estimated by employing a state observer proposed by the author. An integrator plus dead time (IPDT) behavior is obtained for the greenhouse climate process with linearization and decoupling. There are developed greenhouse climate control solutions, using the equivalent IPDT decoupled, linearized model, by employing PID controllers tuned by: five conventional methods, three two degree of freedom (2DoF) methods, and genetic algorithms with proposed specific cost functions. The control system performances employing the previously mentioned controllers are analyzed and compared using the simulation results. A modified Smith predictor using a proposed state observer is also developed and tested by simulation. Finally, the thesis focuses on the development and the implementation of a Hardware-in-the-Loop (HIL) - SCADA platform for greenhouse climate control using NI LabVIEW and Siemens industrial automation software package and Siemens hardware technology. SCADA specific modules, i.e., two Human Machine Interfaces (HMI), and a generic GSM Ethernet Telematics System have been also developed.

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Abbreviations

2DoF	Two Degree of Freedom
CAN	Controller Area Network
GE-TS	GSM/Ethernet Telematics System
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HMI	Human-Machine Interface
IPDT	Integrator Plus Dead Time
LED	Light-Emitting Diode
MIMO	Multiple Input Multiple output
OPC Server	Ole for Process Control Server
PC	Personal Computer
PD	Proportional Derivative
PI	Proportional Integral
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
SIM	Subscriber Identification Module
TCP/IP	Transmission Control Protocol / Internet Protocol
USB	Universal Serial Bus
WSN	Wireless Sensor Network
GCC	Greenhouse Climate Control

1. INTRODUCTION

The increase in population, corroborated with the improvement of living standards, leaded to increased demand of fresh vegetable and fruits all year long. In order to fulfill this demand, the greenhouses are proving to be a viable solution. The greenhouse facilities provide a closed, controllable environment allowing intensive culture of plants.

For optimizing plant growth, the inter connection of plant development factors and their optimal values have to be taken in consideration: soil micro and macro nutrients concentration, temperature and humidity of soil and air, CO_2 concentration and light intensity.

The state of the art of greenhouse automation systems, presented in chapter two, shows that the greenhouses automation systems offer vast field of exploration.

In this context, the PhD thesis develops solutions for greenhouse climate control systems.

PhD thesis objectives

The PhD thesis objectives are the following:

- Development of *greenhouse climate control solutions* by employing a *simplified greenhouse climate model* which synthetizes the main factors affecting the greenhouse microclimate.
- Utilization of different *control algorithms to optimize* the greenhouse climate control, including: conventional PID tuning methods, 2DoF tuning methods, genetic algorithms, Smith predictor.
- Development of *comparative studies* considering different implementation of the previously presented control algorithms.
- Analysis of system behavior and *robustness* in case of modeling uncertainties or wrong disturbance estimation.
- Improving the control solution by employing *state observers*.
- Development of a *"hardware-in-the-loop"* (HIL) platform to implement the control structure and to validate the control algorithm by experimental test results. The HIL contains: PLCs to implement the control algorithms and PC running LabVIEW or MATLAB to simulate the greenhouse climate model.
- Development of HMI SCADA solutions for greenhouse remote monitoring and command.
- Development of remote monitoring and command human machine interface (HMI) solutions as part of SCADA for greenhouse.

Thesis Structure and short description

The thesis is structured in six chapters.

The 2nd chapter presents a state of the art and the current trends concerning the main parts of the greenhouse environment automation: greenhouse climate models, wireless sensor networks, remote monitoring/command and SCADA systems and image processing. For a better understanding of the greenhouse automation systems currently used in the field, the greenhouses of Banat University of Agronomical Sciences and Veterinary Medicine are examined. Another topic discussed in this chapter is the usage of central and distributed greenhouse climate control.

The 3rd chapter describes the greenhouse climate model and solution to obtain simplified models. The state space 2nd order model, which describes the greenhouse microclimate evolution (temperature and humidity), is nonlinear, coupled with variable parameters. This model has two state variables - the greenhouse air temperature and humidity (the two output variables are the delayed state variables), it considers three disturbances - solar radiation, air temperature and humidity outside the greenhouse, and uses two control variables - corresponding to the two actuators (fan and humidifier). A linearization and decoupling method leads to an equivalent integrator plus dead time (IPDT) behavior for the decoupled temperature and humidity loops. Two solutions for estimating the state variables without time delay, required by the feedback-feedforward linearization and decoupling method, are proposed.

The 4th chapter compares by simulation several control strategies for IPDT equivalent processes from 3rd chapter. Solutions for improving the greenhouse climate control are proposed and tested by simulations.

A first comparison study of PI/PID controllers for IPDT process, employing five conventional tuning techniques, is performed by simulation. A second comparative study for robustness is performed considering modeling and measurement uncertainty. In addition to conventional PI/PID tuning methods, robust 2DoF PI tuning methods are adopted. Also, a solution which optimizes the climate control by using genetic algorithms (GA) is developed. Finally, a modified Smith predictor structure, which uses a state observer, is proposed.

The 5th chapter mainly focuses on the implementation of SCADA elements for greenhouse climate control. A "hardware-in-the-loop" (HIL) system is developed, with the process model implemented in NI LabVIEW, and the control algorithms and decoupling module running on a Siemens PLC. Two types of human machine interfaces (HMI) for remote monitoring and command where developed. The first type of HMI has a web based monitoring and command implementation, and is developed by: i) LabVIEW Web UI Builder, ii) NI LabVIEW Remote Front Panels which allows the user to access remotely the monitoring and command VI front panel within a Web browser. The second HMI type is a part of a SCADA system which uses GPRS data transmission. This solution was developed for the cases when greenhouses are remotely distributed on a large area where physical data connections are not possible or feasible.

This chapter designs and develops an embedded, generic telematics system that allows remote monitoring and command using: Short Message Service (SMS) / phone calling or by using the web page hosted by the PIC microcontroller.

The 6th chapter summarizes the final conclusions and the main contributions of the thesis.

The results of the doctoral research including theoretical aspects, comparative simulation results and practical implementation have been disseminated in seven scientific papers: four papers published in proceedings of international conferences (indexed- IEEE Xplore, Scopus, INSPEC), one scientific paper sent to an international conference and two articles sent to ISI journals still being in reviewing process. (see the list of author's papers related to the PhD thesis, pg. 132)

2. GREENHOUSE AUTOMATION SYSTEMS - STATE OF THE ART

This chapter aims to present a review - state of the art in greenhouse environment monitoring and control and also looks at current trends in this particular domain, while exploring some of the solutions with a potential impact in the further development of greenhouse control systems. This chapter describes some of the available systems with specific configurations, and recent progress in many application examples. The analysis and classification of their characteristics and contributions in suitable categories offers ideas for new applications and relevant research opportunities, including for the present PhD thesis.

The main parts of the greenhouse environment automation are brought into discussion: greenhouse climate models, wireless sensor networks, remote monitoring/command and supervisory control and data acquisition (SCADA) systems, image processing.

On a more practical note, the greenhouse system of Banat University of Agronomical Sciences and Veterinary Medicine was the subject of study for evaluating one of the currently used greenhouse automation systems. At last, this chapter also takes a look at the usage of central and distributed greenhouse climate control.

2.1. Thematic Introduction

Greenhouses are part of our history for more than 2000 years. The first mention of enclosed environment usage to facilitate plant production comes from the times of the Roman Empire when Emperor Tiberius [CAS'13] demanded to have cucumbers all year long. For these reason, a new type of construction was firstly built by employing mica transparent walls.

Greenhouses are closed microclimate environments for plant growth in controlled conditions. The greenhouse microclimate is mainly controlled by adjusting temperature, humidity, CO_2 concentration and micro/macro nutrient concentrations.

The high demand of greenhouse products leads to an increased interest in developing greenhouse enclosed environments. China has secured the first place for largest greenhouse area, with total area of 4.6 million ha covered by greenhouses [CHE'13]. In Europe, the country with the highest surface covered by greenhouse is Spain, where more than 53,800 ha were reported in 2005 [AZN'11]. The highest density of greenhouse is observed in El Poniente region of Spain, where the greenhouse establishments counted for 16,000 ha from total area of 27,000 ha, being one of few manmade structures visible from space [GAL'11].

The enclosed controlled environment from greenhouses reduces the risk of diseases and protects the crops from extreme weather (winds, acid rain/fog, storms, extreme temperatures) and offer optimal growth conditions for plants.

Traditionally, the greenhouse plant cultivation involves close monitoring of environmental parameters and manual actuator commands. There are three main associated activities: the preparation of nutrient mixture, irrigation and ensuring proper climate condition specific to the cultivated plants. Nutrient mixture preparations are based on the measurement of the grooving substrate pH and the electrical conductivity (EC), which ensures proper micro/macronutrients balances for the considered crop development stages. Irrigation is usually based on a daily manual irrigation schedule, with the humidity in the growing substrate determined by the soil tension measurement. The temperature and the relative humidity are controlled by using heaters, ventilation and humidifiers manually operated. The next natural step is the automation of the previously described activities in greenhouses.

Advances in IT over the last decades, translated in high computation power at low prices, are making possible high scale automation of greenhouse facilities in order to reduce the human labor and to improve the production of greenhouse facilities.

Greenhouse growing systems are composed of two distinct, but highly coupled nonlinear parts: the physical part and the biological part. The greenhouse environment can be characterized as being a highly complex process with numerous parameters which can affect the crops. The control for this type of environment is based on the mathematical models of physical and biological process while the physical part of the greenhouse consists of the environmental parameters inside and outside of the greenhouse. Also the physical part has a high influence on the biological one, and also the biological process highly influences the greenhouse physical environment, both parts being strong coupled.

Several greenhouse climate models and biological models where developed, with different levels of complexity, varying from 2 to 300 state variables in the case of biological models. Control solutions for development and testing have benefited from the increasing number of greenhouse models. A high number of control structures have been proposed to control the greenhouse environment [SOT'11].

The communication infrastructure is one important part of the greenhouse automation. Greenhouse facilities mainly rely on cabled communication. The main disadvantages are the relative high cost and vulnerability to mechanical stress, and also sensor relocations employ difficulties. One solution is the usage of Wireless Sensor Network (WSN) [AHO'08]. The ratification of ZigBee specification, and high adoption rate of the ZigBee protocol for WSN modules, corroborated with cost decreasing, have leaded to the development of high number of greenhouse monitoring solutions using ZigBee WSN [ZHA'11].

Remote monitoring/command and supervisory control and data acquisition (SCADA) systems for greenhouses add more benefits. This type of centralized system offers online visualization of the process data, access to all process set-points, database data recording and alarm management [BHU'05].

The identification, classification and harvesting of fruits is another development direction in greenhouse automation. Robots with included image processing module are able to identify and harvest the fruits [COR'09]. Satisfactory results have been obtained also in pest control by employing robots to identify different types of pests. Image processing algorithms have been used also for chlorophyll content estimations [ALI'12b].

2.2. History of Greenhouses

As presented earlier the first written mention of a greenhouse structure comes from the times of Emperor Tiberius (the second emperor of Rome 14-37 A.D.) when an enclosed structure was built at his orders from translucent walls made from thin mica sheets. Philosopher Seneca condemned these practice considering them unnatural [CAS’13].

With the decline of Roman Empire these enclosed environment growing structures have perished with no mention in the Middle Ages [DAR’73]. The early history of greenhouses resumes in the 15 century, when in Spain and Italy, we find mentions of special constructions built for hosting the orange trees during the winter. Also the first mention of an “active” greenhouse appeared in the earliest records of the Annals of Joseon Dynasty (Korea) in 1438 which contained descriptions of a greenhouse designed to control the temperature and humidity [YOO’07]. It was used to grow mandarin trees. The Renaissance was a period which welcomed the early systematic approach to plant growth. It is a time marked by discoveries of unexplored parts of the globe and implicitly its vegetation. It was considered a source of pride to own exotic plants and thus ways of maintaining the plants alive all year emerged. The basic strategy was to design the orangery with a north facing wall made out of bricks and have the light source coming from south - the wall with windows. It was a structure that was hosting orange trees, pineapples and laurels.

The 18th century introduced more improvements in this domain by focusing on the medicinal plants and ways to grow them indoor. The French botanist Charles Lucien Bonaparte was credited with building the first modern and practical greenhouse in Leiden, Holland. The Royal Society financed a great number of experiments related to heating systems, lighting and insulating materials to be used in enclosed environments [HIX’05].

At the beginning of 19th century, favored by the industrial development in England, new techniques for producing cast-iron were discovered. Together with innovations in producing plate glass lead to the construction of large botanical gardens like Crystal Palace in London built in 1850 and many others [BAK’95]. Although they were built as showcases with no real commercial purposes they were statements that greenhouse development was of future interest as many problems implied by greenhouse construction like lighting, heating, ventilation, water supply and condensation had to be dealt with, studied and resolved. But in order for greenhouses to have a commercial value social wealth should be high enough, a market capable of absorbing costs associated with indoor plant growth had to be present. This happened first in England later in the 19th century due to early and rapid industrial revolution [BAK’95].

Meanwhile a similar growth in interest is reported in north eastern part of US, where several hundred hectares are covered in modern glass structures. It is estimated that at the beginning of 20th century there were about 200 ha in England and 900 ha in US of glass covered areas.

2.3. Greenhouses in Romania

Before 1989 Romania had the second largest area of greenhouses in Europe surpassed only by the Netherlands [EVD’09]. The surface covered by greenhouse was roughly 3000 ha, 2500 ha reported by [EVD’09] and 3500 ha reported by [JEN’95]. The biggest greenhouse complex in Romania was in Işalniţa, Dolj county, constructed in 1969, documented as the largest greenhouse complex in the world at that time.

The greenhouse complexes constructed under the communist regime where constructed near city power plants using steam for heating. Following the restructuring of the energy sector, preferential prices for the energy had been interrupted. Due to the lack of founding, the greenhouse could not be modernized and became unprofitable and ended up being sold by the state. Unfortunately a high number of investors have found it more profitable to take advantage of the real estate value of the land rather than invest in their modernizations and so the number of greenhouses has been dramatically reduced.

Since Romania joined the European Union (2007), EU funding has been accessed through 2007-2013 National Rural Development Plan by large companies and small farmers for modernizing the old greenhouses and also for constructing new ones. In 2007 Romanian Ministry of Agriculture and Rural Development (MADR) estimated a total greenhouse area of 420 ha [EVD'09] and 490 ha in 2012. An increase of investments in this sector is expected in the interval 2014- 2020, when a new batch of EU structural and cohesion funds is scheduled[VEE'13]. MAFRD estimated that Romania would need 2000 ha of greenhouses just for filling the internal demand [EVD'09].

2.4. Greenhouse Climate Models

In order to optimize the control of the greenhouse environment, complex mathematical models are employed: the greenhouse climate models and the plant growth biological models, with strong interconnections, nonlinearities and parameter variations. Also, these models are very important to test and primary validate diverse control structures and optimization methods before implementation in real greenhouse environments. Even if the greenhouse is a closed environment, it is highly influenced by disturbances as wind speed/direction, outside temperature/humidity/CO_2 air content, solar radiation and also by strong parameter variations of plant growths (Fig. 2.1).

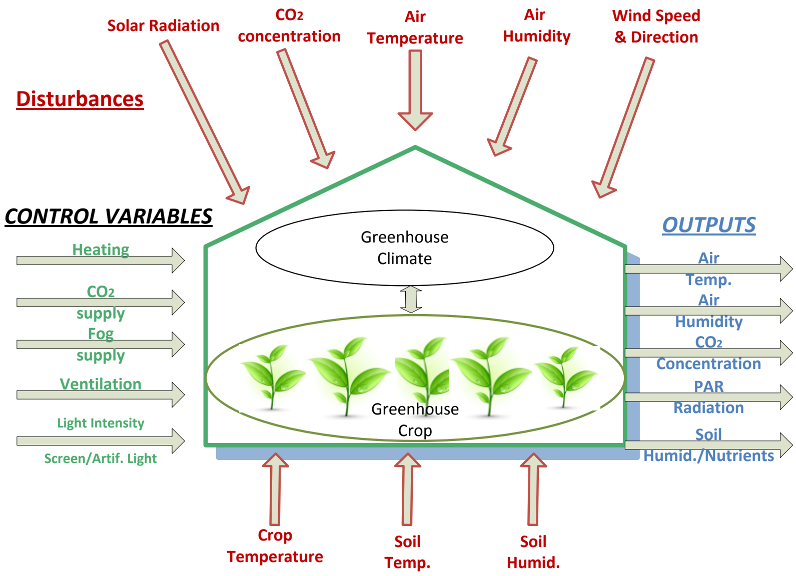


Fig. 2.1. Simplified greenhouse climate control schematic

The greenhouse climate model can predict the inside climate (temperature, humidity) by knowing the initial state and the outside climate parameters. The greenhouse dynamic climate model can be expressed by employing two entirely different approaches. The first approach describes the process trough energy and mass flow equations, while the second is based on system identification by analyzing the process input-output data. Due to diversity of greenhouse structures and various solutions for ventilation, humidification, cooling and heating, particular greenhouse system models have evolved. There are structures with natural ventilation [DAY'04], forced ventilation [WIL'03], evaporative cooling [BOU'00], or heating using pipes/air heaters [BAR'05].

One of the heavily used greenhouse climate model was proposed by Albright et al. [ALB'01], is a complex nonlinear coupled MIMO state-space model. The model is simplified by considering only the primary disturbance variables: the outside temperature, outside humidity and solar radiation.

The differential equations for coupled energy and water vapor mass balances are given below:

$$\frac{dT_{in}(t)}{dt} = \frac{1}{\rho C_p V}[Q_{heater}(t) + S_i(t) - \lambda Q_{fog}] - \frac{V_r(t)}{V}[T_{in}(t) - T_{out}(t)] - \frac{UA}{\rho C_p V}[T_{in}(t) - T_{out}(t)] \quad (2.1)$$

$$\frac{dw_{in}(t)}{dt} = \frac{1}{\rho V}Q_{fog}(t) + \frac{1}{\rho V}E(S_i(t), w_{in}(t)) - \frac{V_r(t)}{V}[w_{in}(t) - w_{out}(t)] \quad (2.2)$$

where: T_{in}, T_{out} are the indoor, outdoor air temperature (°C), V is the greenhouse volume (m^3), UA is the heat transfer coefficient (W/K), ρ is the air density (1.2 kg/m^3), C_p is the specific heat of air (1006 J/(kgK)), Q_{heater} is the heat provided by the greenhouse heater (W), S_i is the intercepted solar radiant energy (W), Q_{fog} is the water capacity of the fog system (g H_2O/s), λ is the latent heat of vaporization (2257 J/g), V_r is the ventilation rate (m^3/s), w_{in}, w_{out} are the interior and exterior humidity ratios (g H_2O/kg), $E(Si, w_{in})$ is the evapotranspiration rate of the plants (g H_2O/s) [ALB'01] . The model presented by Albright can be used as a multi-season model. In the case of summer, Q_{heater} in eqn. (2.1) is set to zero. The main factors that determine the evapotranspiration rate of the plants $E(S_i, w_{in})$ are the intercepted solar radiation S_i and the interior humidity ratio w_{in}, being expressed through the following simplified relation:

$$E(S_i(t), w_{in}(t)) = \alpha \frac{S_i(t)}{\lambda} - \beta_T w_{in}(t) \quad (2.3)$$

where α is an overall coefficient to account for shading and leaf area index and β_T is an overall coefficient to account for thermodynamic constants and other factors affecting evapotranspiration [ALB'01]. The state variables, which are also the output variables, are composed by the greenhouse inside temperature (T_{in}) and the interior humidity ratio (w_{in}). The input variables are the fan ventilation rate (V_r) and the water capacity of fog system (Q_{fog}). The disturbances are represented by the intercepted solar radiant energy (S_i), the outside temperature (T_{out}) and the outside humidity ratio (w_{out}).

A feedback-feedforward linearization and decoupling technique based on [SLO'91], [ISI'95] method is applied by van Straten et al. [STR'11] to the complex greenhouse climate model (2.1-2.3) with measurable disturbances. Finally, two decoupled Integral Plus Dead Time (IPDT) equivalent simplified processes are obtained with isolated disturbances, basically used in control systems for the greenhouse temperature and humidity regulations.

2.5. Biological Growth Models

The greenhouse model cannot be complete without including the biological growth model. The biological growth process is very complex, with parameters that need to be particularized for each culture type. TOMGRO model [JON'91], describing the tomato culture evolution, has 71 state variables (69 plant state variables) and 50 parameters. A more detailed tomato model is described by de Konig [KON'94] having more than 300 state variables. A simplified one and two state lettuce growth model, to present the dry matter evolution, is shown in [HEN'94], [STR'11].

Furthermore, Van Straten et al. [STR'11] present a tomato model that describes the evolution of leaf and fruit biomass after anthesis of the first fruit. The main state variables can be categorized based on biomass type into nonstructural and structural states. The model has three main states: the structural biomass in leaves and fruits, and the nonstructural biomass that can be seen as an assimilator buffer.

Vanthoor et al. [VAN'11] present a tomato model with the plant development stage divided in two phases, i.e., vegetative and generative phase. The model is based on the carbohydrates flow in the leaves, steams, roots and fruits for both development stages.

A generalized greenhouse model, where the greenhouse states variables are categorized into the plant state variables and the climate state variable, is described by the following generalized differential equations [CHA'93]:

$$\frac{dX_p}{dt} = g(X_p, X_c, U_e), \tag{2.4}$$

$$\frac{dX_c}{dt} = f(X_p, X_c, U_e, U_c), \tag{2.5}$$

where X_p are the plant state variables (biomass distribution in the plant constituent parts: root/strain/leaf biomass), X_c are the climate state variables (greenhouse air temperature, humidity and carbon dioxide concentration), U_e are the external inputs (outside greenhouse temperature, humidity, carbon dioxide concentration, solar radiation and wind speed and direction) and U_c are the control inputs (ventilation rate, fogger debit, supplemental light intensity).

Van Henten [HEN'94] proposed a lettuce growth model considering structural and non-structural biomass accumulations, described by the following differential equations:

$$\frac{dX_n}{dt} = c_\alpha \Phi_{phot} - r_{gr} X_s - \Phi_{resp} - \frac{1-c_\beta}{c_\beta} r_{gr} X_s \tag{2.6}$$

$$\frac{dX_n}{dt} = c_\alpha \Phi_{phot} - r_{gr} X_s - \Phi_{resp} - \frac{1-c_\beta}{c_\beta} r_{gr} X_s \quad (2.7)$$

where X_s and X_n are the structural and nonstructural biomass, Φ_{pho}t is the plant CO_2 uptake considering the photosynthesis process, r_{gr} is the conversion rate from nonstructural to structural biomass, Φ_{resp} is the amount of biomass (carbohydrates) used during respiratory process, c_β coefficient accounts for nonstructural biomass losses due to nonstructural to structural conversion process.

The gross carbon dioxide uptake due to photosynthesis of the canopy can be expressed as [GOU'90]:

$$\Phi_{phot} = \Phi_{phot,max}[1 - exp(-c_k c_{lar,s}(1 - c_t)X_s)] \quad (2.8)$$

where Φ_{phot} is the gross CO_2 assimilation, $c_{lar,s}$ is the leaf area to strain structural biomass ration, (1-cт) is the green dry mass to total crop dry mass ratio and c_k is the canopy extinction coefficient.
The methane is a greenhouse gas with a high capacity of heat trapping, which also results from wastewater treatment plants [MAN'11]. The usage of treated-wastewater for greenhouse crops was studied and short term usage is feasible with the remark that a strict heavy metal monitoring is necessary [MAR'13].

2.6. Wireless Sensor Network Usage in Greenhouse Monitoring and Control

Sensors and actuators play a crucial role in the greenhouse environment control. Over the last period, a great number of greenhouse environment control systems benefit from Wireless Sensor Network (WSN) usage. A WSN system contains sensors, controllers, radio frequency transceivers and power sources. Recent improvements for WSN translates in high computation power at low prices with reduced power consumption, with integrated multifunctional sensor nodes being able to measure and process a great amount of environment parameters, capable of networking and exchanging data with other sensor [SOH'07].

2.6.1. Wireless Transmission Protocols: ZigBee and Bluetooth

Two protocols are primarily used for wireless transmission of information from sensors: ZigBee and Bluetooth. Although Bluetooth was designed for high data rates, the higher power consumption of nodes discourages its usage in monitoring of greenhouse environment.

ZigBee is based on the IEEE 802.15.4 standard with added network and application layer functionality. ZigBee allows the usage of different topologies (tree, star, mesh), and it also supports a high number of nodes (65.536). ZigBee has the lowest current consumption, typically of 30 mA in RX mode, compared with Bluetooth devices with a consumption of 65-170 mA. In most cases, the ZigBee nodes are powered by batteries, thus special attention have been taken for the power consumption in sleep mode, at this point current consumption below 1uA is achieved. A feature of the ZigBee WSN is the ability to move, add or remove sensor nodes without disrupting the communication due to its auto configuring capability

[RUI'09]. Taking into consideration all these aspects, the usage of ZigBee has been imposed in large applications of greenhouse monitoring and control.

Modifying the type of cultivation, or moving the cultivated plants to a different lot, is difficult when employing a wired system. Usage of wireless sensor networks in greenhouse environments adds the flexibility of wireless data transmission.

2.6.2. WSN Greenhouse Applications

One of the first usages of WSN in greenhouse monitoring and control system is presented by Liu and Ying [LIU'03] and is based on the Bluetooth protocol.

A greenhouse monitoring system based on ZigBee nodes, used for collecting the environment and crop information, is presented by Lee et al. [LEE'10]. By using WSN, the following parameters are monitored: fruit temperature, leaf temperature, leaf wetness, greenhouse inside temperature, humidity luminance, root zone environment information (pH and electrical conductivity), wind velocity and direction, precipitations. The proposed solution (Fig. 2.2) is composed of three layers: physical, middle and application. Physical layer is composed of sensors, actuators and PLC devices. The following actuators are used: window openers, fans and heaters. Also LED lamps are used to provide artificial light. The middle layer is composed of the following modules: data management, artificial light manager, PLC control, data analysis, database and sensor management. The data filtering module processes the raw data from the sensors, correcting the overlapping and incorrect data and writing all information in the database. The environment control module transmits the control signal to the PLC. The artificial light control module transmits the control signal to the artificial light controller. The third layer, application layer is the web based HMI.

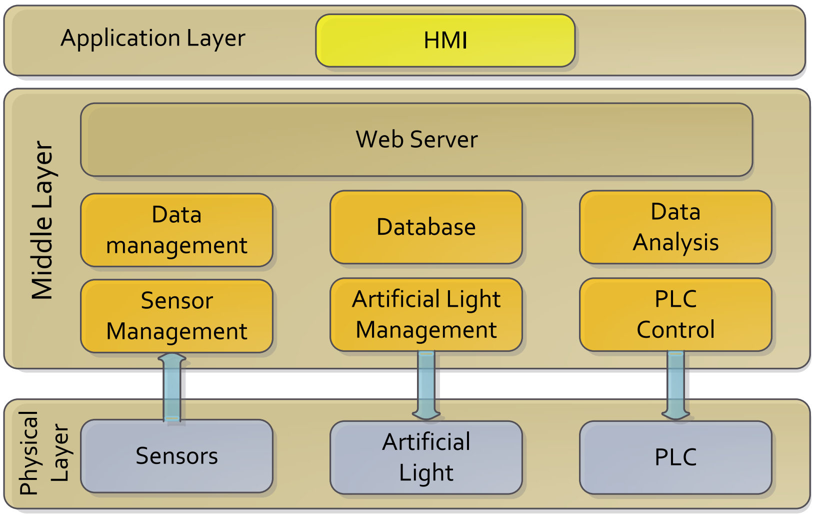


Fig. 2.2. Greenhouse System Structure [LEE'10]

A diurnal and nocturnal temperature control system is presented by Matijevics [MAT'09]. Sun SPOT WSN modules are used to acquire temperature and humidity information. By day, the natural ventilation is employed to control the inside greenhouse temperature, primary, and secondly to vary the inside humidity. The ventilation is controlled by proper adjustment of the greenhouse vent openings. Under diurnal conditions, a heating system is designed with a control algorithm using gain scheduling PI controller. The tuning parameter adjustments are based on the external disturbances: wind speed and outside temperature. For nocturnal conditions, an on/off hysteresis controller is used to command the forced air heaters.

A greenhouse modular irrigation system using ZigBee nodes is presented by Beckmann and Gupta [BEC'07]. Mica2 sensor nodes are used for monitoring the environment (soil moisture, air temperature and humidity) and for controlling the irrigation cycle. The greenhouse cultivated area is split into different irrigation sections, each section having its own irrigation control implemented on a ZigBee node that collects data from the adjacent wireless sensors. One important aspect is the option of relocating the sensor node, in which case the WSN node will be automatically reconfigured to communicate to the proper irrigation node.

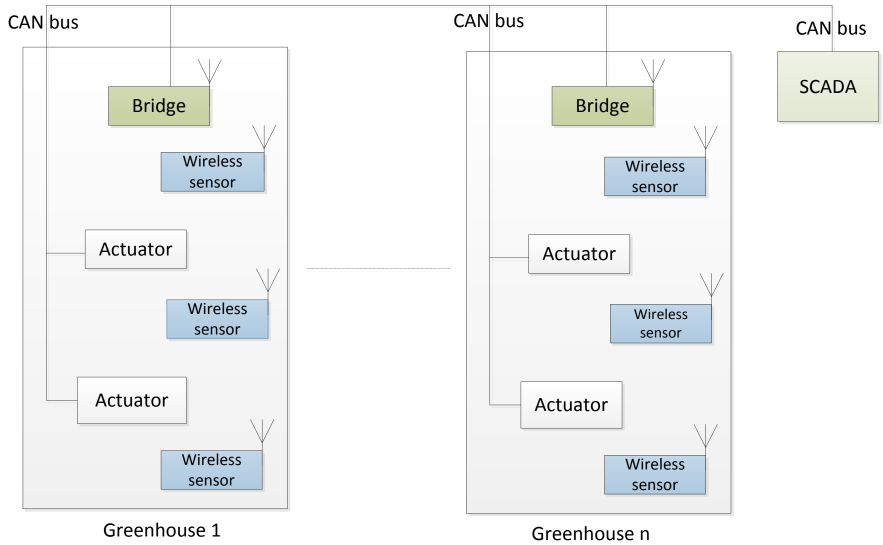


Fig. 2.3. CAN/WSN hybrid infrastructure for greenhouse farms

Monitoring of multiple greenhouses in farms employing WSN and Controller Area Network (CAN) bus is studied by Mirabella and Brischetto [MIR'11]. In each greenhouse, the monitored parameters are transmitted to the supervisory and control unit located near the greenhouse (Fig. 2.3.). The Supervisory Control and Data Acquisition (SCADA) system processes the environmental information and sends commands to the actuators in each greenhouse. This solution is based on a CAN type network backbone, which connects the supervisory and control system to sensors and actuators by the CAN/ZigBee bridge. The Smart Distributed System (SDS) application layer, defined by Honeywell, is chosen due to its implementation simplicity and good suitability for small resources devices. It offers all the necessary services for greenhouse automation. In order to provide a uniform service set, the SDS-CAN application layer is ported to ZigBee which bears the name ZSDS. In doing this, the device physical network independence is guaranteed, making possible for all devices to access both CAN and ZigBee network resources regardless of the physical network connectivity.

A low cost acquisition system for greenhouse environmental parameters using ZigBee WSN is developed by Zhang [ZHA'11]. A simple system structure is adopted; the system core is a SPCE3200 microcontroller for monitoring the terminals and data processing with capabilities of receiving commands from a supervisory PC, and locally, of storing data records. The sensor nodes are based on CC2420 ZigBee transceiver modules.

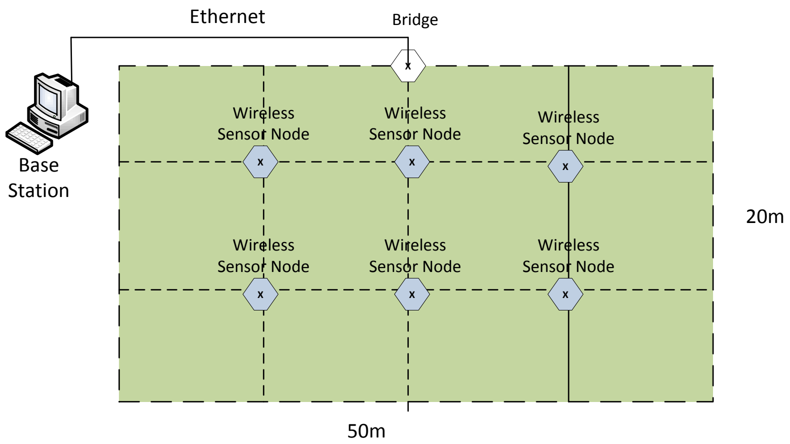


Fig. 2.4. WSN architecture by Mancuso and Bustaff (2006)

A large scale tomato greenhouse based on WSN solution (Fig. 2.4.) for monitoring the environmental variables is presented by Mancuso and Bustaff [MAN'06]. The workload implied for the installation and maintenance of a wired infrastructure in a large greenhouse is very high. The proposed system uses Sensicast RTD204 nodes which measures air temperature, relative humidity and soil temperature. The used protocol is SensiNet, which is based on IEEE 802.15.4 with frequency hopping modulation technique. A bridge node acquires the monitored information from sensors and transmits it through LAN to the base station that has a data acquisition system developed in LabVIEW.

A self-configuration multi-hop WSN for a greenhouse environment monitoring system is developed by Lea-Cox et al. [LEA'07] and monitors the temperature, electrical conductivity, measure substrate water, daily photosynthetic radiation and leaf wetness,. Other WSN system for monitoring the solar radiation is proposed by Cotfas et al. [COT'11].

A two-part framework based WSN prototype is proposed by Liu et al. [LIU'07]. The first level contains wireless sensors for measuring the temperature, light intensity and the soil moisture, plus a sync node that is connected to a Global System for Mobile Communications (GSM) module. The second level contains GSM modules for transmitting the information from sensors, and management software running on a remote PC.

An autonomous wireless sensor network for monitoring the temperature and soil humidity in a greenhouse was proposed by Pekoslawski [PEW'13]. The system uses Zigee sensor nodes powered by small-size solar cells. A DC/DC converter has been designed to regulate the output voltage generated by the solar cells alongside a super capacitor used to store electric energy for cases of peak power consumption. The central node (network coordinator) is connected to a PC using the USB interface. Two sensors are connected to each node: a 1-wire temperature sensor and an analog humidity sensor. The sensors where placed in aluminum tubes for avoiding the influences of soil conditions.

Remote control, distant monitoring and distant diagnosis are crucial features for greenhouse automation. János and Martinović [JAN'09] present a WSN integrated solution for distant monitoring and command based on a microcontroller with embedded Ethernet controller running a web server. The environmental parameters are monitored by using Sun SPOT WSN; this information, completed by a log of the monitored information and the live video stream from the greenhouse, are displayed on the web page. The same authors propose a mobile climate measuring station based on Waspmote ZigBee WSN implemented on a Boe-Bot robot kit [JAN'11].

An event-based control system for greenhouse climate using a ZigBee WSN is proposed by Pawlowski et al. [PAW'09]. Due to nonlinearity of the climate model, a PI gain scheduling technique is employed with the PI tuning parameters dynamically modified based on external disturbances. The management of level crossing sampling is based on the testing of control performance using 3% and 5% difference between the last transmitted measurement and the new one. Comparing with the time-based sampling, this event-based sapling ensures 90% traffic decrease on WSN, and 80% reduction of control output signals, which have a positive effect on the actuator lifetime. The performance comparison of the classical control and the event based control system (using different levels crossing sampling) leads to the conclusion: the best compromise between performance and state changes is obtained for delta of 3%.

2.6.3 Plant Diseases, Insects Monitoring and Prevention

One important problem in greenhouse environment is the dew condensation on the leaves, which creates a perfect habitat for fungus or bacteria, leading to various plant diseases. A solution to solve this problem is a WSN based control system for dew condensation prevention proposed by Park et al. [PAR'10]. This solution uses WSN for collecting environmental data, processes data, commands the actuators, and also employs a server for data storage and processing. The dew point is calculated by applying the Barenbrug formula, with the system using five sensors for air and leaf temperature and humidity. A scale down greenhouse model is used to test the automatic control system for dew condensation prevention, showing good results.

Insect monitoring is an important aspect of greenhouse management, because the insect pests are developed often more rapidly in greenhouses than in filed cultures, due to high levels of humidity and lack of natural enemies. Adhesive traps for monitoring insect evolution are used, with the downside of being a time consuming task, as the inspection has to be done periodically. Tirelli et al. [TIR'11] present a solution based on distributed imaging devices of traps using WSN that are able to acquire and send the trap images to a remote host station. This master station evaluates the insect density and activates an alarm when a certain threshold is reached. The proposed solution for insect monitoring was tested during a four weeks period inside a greenhouse, showing very good results.

2.6.4. Factors Affecting Communication Quality

One issue encountered while using the WSN in the greenhouse environment is the drop in communication range due to dense flora cultures and high humidity. A tomato greenhouse culture was monitored by using Sensinode sensor platform achieving just a 10 meters communication range, representing one third of the communication range for open spaces [AHO'08]. Pollen sedimentation on sensors is another common problem in greenhouse systems with negative impact on measurements. The relative humidity influence is studied also by Haneveld [HAN'07]: if the relative humidity is high, then the gateway receives around 60% of the expected messages, growing back to more than 70% when the relative humidity is low.

2.7. Greenhouse Remote Monitoring and SCADA Implementations

The remote monitoring, remote command and system alarm handling play an important role for greenhouse management. A high number of control systems are used in greenhouse automation, but a more unified approach is achieved by using supervisory control and data acquisition (SCADA) systems. This type of systems can also benefit from integrating remote monitoring and command telematics systems for alarm notifications, process data visualizations, and setpoint modifications.

2.7.1. Remote Monitoring and Command

A remote monitoring system for greenhouse environment is proposed by Li et al. [LI'06]. This is based on a microcontroller system that sends the greenhouse monitored parameters to a remote server by using a General Packet Radio Service (GPRS) and Code Division Multiple Access (CDMA) wireless module. The remote server employs a (Structured Query Language) SQL server for data recordings, and a web server for hosting a web page, that displays real-time data and together with history evolution information.

The Short Message Service (SMS) can also be used for remote command and monitoring. Research regarding the SMS usage for greenhouse parameters remote monitoring indicates the remote system shows good performance and reliability [AZI'09]. The SMS based on GPRS or GSM can meet the communication requirements taking into consideration the distance and the coverage, but on the other hand, it fails to do so after considering costs, possible delays in transmission, and small and often insufficient transmitted data frames (just 140 characters / SMS).

Android based devices show good characteristics for implementing human machine interfaces for a variety of processes due to high resolution screens, increased processing power and unified user interface. The significant increased popularity of Smartphones with Android operating system offers a viable option for greenhouse remote monitoring and command. Gao et al. [GAO'13] implemented an environment remote monitoring system using an Android Smartphone as terminal; the graphical user interface (GUI) provides information from temperature, humidity and light intensity sensors, relay states, and also displays a video stream from a wireless camera placed at the process location.

2.7.2. SCADA Systems

A hybrid SCADA telematics system implementation based on the GSM and Ethernet is developed by [GUR'11]. The microcontroller-based telematics system hosts a web server and a GSM hardware modem with AT command capabilities. The remote commands and monitoring are accomplished by using the GSM/3G Short Message Service (SMS) / phone calling, or using the web page hosted by the microcontroller.

A hierarchic NI LabVIEW SCADA system implementation for greenhouse environment is proposed by Bhutada et al. [BHU'05]. The supervisory and control is implemented by using a three hierarchic level model. The 1st level contains sensors and actuators, the 2nd one contains field point modules, and the 3rd one is represented by the main host computer. The benefit of using a hierarchic approach is the lack of disturbance in the field point modules for process control operations in case of main host computer failure. This implementation is based on NI LabVIEW VIs which is running on the main host computer and on the field point modules. The SCADA system is responsible for temperature, humidity, lighting and irrigation controls.

A SCADA system for three control subsystems, i.e., temperature and humidity, irrigation and fertilization, lighting and CO2 is proposed by Mirinejad et al. [MIR'08]. The process control and the Human Machine Interfaces (HMI) are implemented by using NI LabVIEW. A microcontroller is employed for acquiring data from sensors by monitoring the soil nitrate, phosphate, sulphate, calcium levels, and also the soil moisture, CO_2 concentration, light intensity, air temperature and humidity. The microcontroller is connected to a PC which hosts the NI LabVIEW application by using the RS-232 serial communication. The LabVIEW application processes the measurement data, and takes regulatory actions by using on/off dead-band control. The control actions are sent to the microcontroller which in turn, commands the actuators.

An irrigation control system (Fig. 2.5.) is proposed by Dumitrascu[DUM'13]. Here the wireless sensors collect the data from the process and transmit them to be stored on a database server. The collected data is sent using ModbusTCP communication protocol to the control device represented by a Siemens S7-1200 PLC. A Memsic eKo Pro wireless sensor network is used. Six wireless sensor nodes have been connected, each wireless eko node allowing four sensor connections. The data from the sensors is gathered by using a radio base station connected to the eKo server using the USB interface. The eKo server provides sensor network management, data visualization and recording functionalities. All the data from the sensors is stored using a SQLite database. The central device of the control system is a Siemens S7-1200 PLC which communicates with the eKo server using SiriusTCP communication protocol. The S7-1200 PLC is also connected to a LOGO BA7 PLC, and to a KTP600 touch panel. LOGO BA7 PLC is connected to the irrigation system actuators: one water pump and three on/off valves.

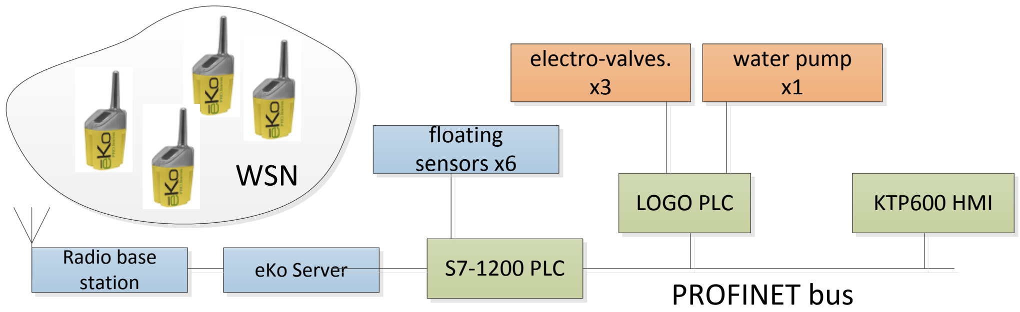


Fig. 2.5. SCADA irrigation control system

A low cost telematics system (Fig. 2.6.) was introduced by Moga et al. [MOG'12]. The telematics system was developed with intended purpose of achieving the following attributes: flexibility, scalability, low cost and easiness in deployment. A hybrid wired/wireless network was put into place. The WSN was implemented using Wireless USB communication protocol. For the wired section of the proposed platform the RS485 communication protocol was used. Several RS485 nodes where considered for each greenhouse: smart sensors, smart actuators and controllers. The whole system is composed of: wireless temperature sensors, wireless light sensors, wired relative humidity sensors, wired wind speed and direction sensors, controllers and smart actuators, wired and wireless gateways, local PC for data acquisition and archiving. Also a HMI software package was put together. This was installed on a remote machine and made possible the monitoring of greenhouse environment parameters, and also the adjustment of controller's setpoint and network parameters. On each greenhouse two gateway devices are used. One to interface the Wireless USB network to the RS485 interbus and one for interfacing the RS485 inter-bus to the intra-bus. The proposed platform was implemented for monitoring and controlling three greenhouses. A total of 18 sensor nodes, 5 controllers and 4 actuators where used. One problem mentioned by the authors is the network latency when using more than 20 nodes: the interval between controller to sensor request can go up to 10 seconds.

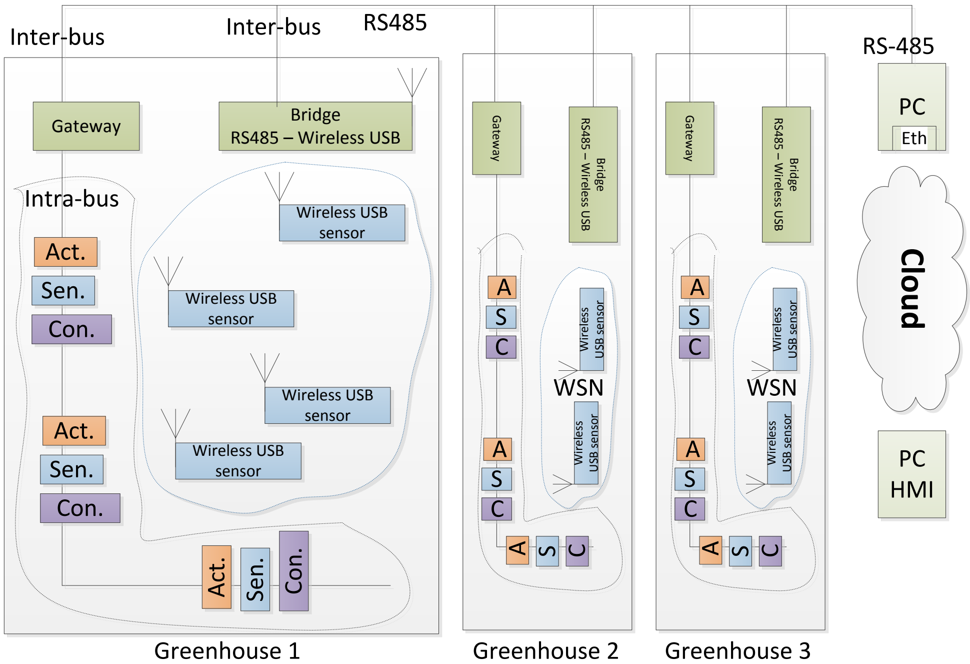


Fig. 2.6. SCADA architecture using ZigBee WSN and RS485 devices

A SCADA system implementation for temperature, humidity and illumination control is studied in [FAN'11]. ZigBee WSN is used to acquire temperature, humidity, CO2 and light intensity information which are later transmitted to a local PC. NI WSN-3202 along with four analog channels, WSN modules where used. The HMI was implemented using LabVIEW. Here the interface can be accessed on the local PC or remotely by using the LabVIEW Remote Front Panels functionality. LabVIEW offers the possibility to visualize and control the VI front panel remotely by using a web browser where the web based interface is in fact the main VI front panel. The information from the WSN is sent to a PLC. The data communication between LabVIEW and the PLC is established using NI OPC server. The OMRON CPM2AH PLC monitors the information provided by the WSN, the position of several limit switches. It commands several actuators as can be seen in fig. 2.7.

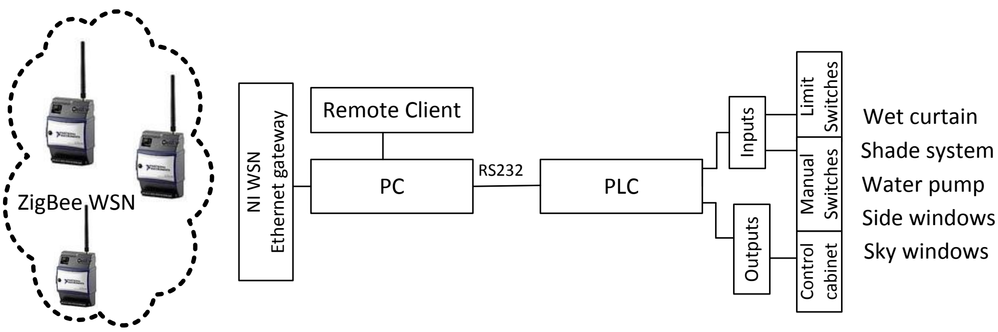


Fig. 2.7. SCADA system for greenhouse temperature, humidity and illumination control.

2.7.3. CAN bus Communication Systems

The Controller Area Network (CAN) communication protocol is gaining popularity in greenhouse communication infrastructures. This is a Carrier Sense Multiple Access with Collision Detection (CSMA/CD) communication protocol, communicating to the sender information about the activity on the bus. The protocol uses a logic that checks to see whether there is activity on the bus before sending a CAN frame. Multiple controllers can start sending frames, but after sending the identifier message only the controller with the highest priority will continue to transmit data. CAN bus uses differential data transmission allowing data transmission in high noise environments, and in most cases, the communication can continue even if one of the two bus wires is broken. Currently, there are two CAN specifications in use: 2.0A - low speed CAN with maximum data transfer rate of 125 Kbits/sec, and 2.0B - high speed CAN with maximum data transfer rate of 1 Mbit/sec.

An irrigation control system to cover multiple greenhouses using Programmable System on Chip (PSoC) and CAN bus is presented by Puri and Nayse [PUR'13]. The system implementation is based on a PC core that centralizes data from the field devices, offering a centralized way for the greenhouse monitoring. The PC is connected by a PSoC module to the CAN backbone bus, which connects all greenhouses by employing individual master modules responsible for setting the soil moisture setpoints. For each greenhouse, the own master module is connected to the local CAN bus linking the irrigation control modules. It uses two moisture sensors and a solid state relay to drive the solenoid valve. Each greenhouse has two irrigation control modules extended with temperature and humidity sensors for two climatic parameters used by the irrigation algorithm. By partitioning the greenhouse area in several blocks, a more precise irrigation is achieved by providing optimal soil moisture conditions for each zone. If one or both CAN buses are physically damaged, the irrigation modules continue to function with the remark that moisture setpoint changes and centralized monitoring of the greenhouses are not possible.

A greenhouse temperature and humidity control system based on CAN bus infrastructure was proposed [PEN'10]. The control system structure has two main layers: the coordination management and the distributed monitoring and control layer. The main control unit is an ARM STM32VBT6 (Fig. 2.8) with a built-in controller compatible with CAN 2.0B frames. The distributed monitoring and control layer consists of several STM32F103CBT6 MCU that monitor the temperature and humidity in their location proximity by using DS 18B20, 1-wire digital temperature sensors and SHT10 2-wire digital interface digital temperature and humidity integrated sensor. The main control unit interrogates the distributed monitoring for temperature and humidity measurements, apply linearization correction, and based on the implemented control strategy sends commands to the actuators.

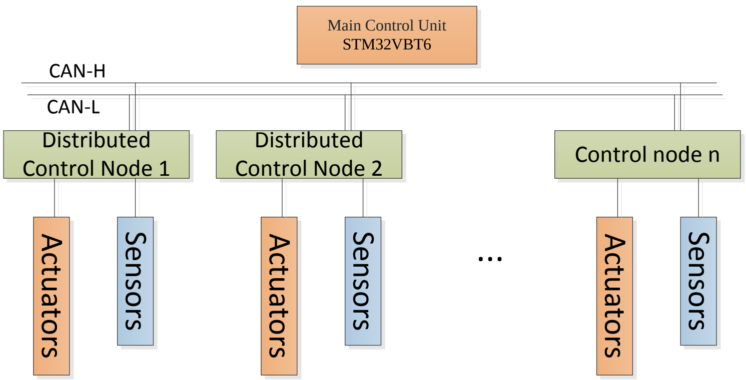


Fig. 2.8. Greenhouse temperature and humidity control system using CAN bus

A greenhouse temperature and humidity control system, using CAN bus to connect monitoring and control modules, is proposed by Song et al. [SON'12]. This is based on a three level hierarchical model. The supervisory 1st level consists on a PC that has HMI, database recording and remote monitoring using a web based interface. The 2nd level contains the monitoring and control modules connected to the PC by using CAN bus. The 3rd level consists on sensors and actuators connected to the monitoring and control modules. Because the greenhouse zone has assigned one monitoring and control module, it is very easy to extend/reduce the greenhouse cultivation area by adding/removing the CAN bus connected modules.

Data reliability, validity and availability

The measurement data reliability is one important aspect in acquisition systems. The eliminating of measurement noises, detecting and replacing invalid data, have to be fulfilled by implementing a data cleaning module. This plays a crucial role for the climate control and for the climate system black box modeling.

The data validity and availability is other important aspect in cases when black box system identification techniques are used, requiring large sets of data during the learning phase. Some solutions in case of measurement errors or missing values are presented in [ERE'11], [ERE'12]. In the case of a single incorrect value, a simple replacement with the previous value is performed. When blocks of missing measurement values are found, the proposed solutions are based on spatial interpolation or regression methods. These solutions increase the usable measurements records by 50%. The authors look at yet another solution based on Bayesian networks, showing good performance results for data cleaning.

2.7.4. Robotic Applications in Greenhouses

Another development direction in greenhouse automation is the identification, classification and harvesting of the fruits.

A complex distributed autonomous gardening system is presented by Correll et al. [COR'09]. The project was developed at MIT for determining the position of the plants, watering, identifying and harvesting of fruits. The system has two main components: the IRobot Create (mobile robot platform for developers) and the wireless sensors attached to each growing pot. IRobot Create is controlled by using a laptop, communicating through an USB to Serial connection. It is equipped with 4 degrees of freedom arm controlled by a servo board, a water pump/reservoir and a webcam. The wireless communication between the IRobot and plant sensor nodes is established using IEEE 802.11b Wi-Fi communications protocol. Each plant pot is equipped with a wireless sensor node which monitors the soil humidity, and makes request to the IRobot if the humidity is under a defined threshold. When the IRobot receives a request, it travels to the plant pot (that is unique identified by its IP address), waters the plant and makes a plant inventory by identifying the plant fruits. The identification procedure uses a filter based identification using color, shape, size and spectral highlights information. Finally, the location and color for each fruit are recorded and synched with the plant wireless sensor. Another developed feature is the fruit harvesting, implemented by using an image based algorithm.

A picking robot for sweet pepper cultures, where the main problem is the fruit identification by image processing, is developed by Kitamura et al. [KIT’08]. In the case of eggplant and tomato, the identification algorithm is based on the fruit color, but in the case of sweet peppers, the plant foliage and the fruits have the same color. Therefore, the image acquisition is based on a stereovision system using two CCD cameras and a capture board to compute the distance from camera to plant. White LED lighting is used also, providing similar brightness levels for all the acquired images. One identification step is established by processing of the HSI (Hue, Saturation and Intensity) histograms based on the differences that appear on the hue channel between foliage and fruits. Due to different texture of foliage and fruits, also an identification method based on reflection of LED lightning is used. It was determined that the fruits have an increase reflective behavior which translates to areas with high values for intensity, and low values for saturation. A 80% identification rate is obtained with no incorrect identification of leaves as fruits.

2.7.5. Image Processing in Greenhouse

Pesticides are highly used in agriculture to protect the crop from pests (bugs, fungi, bacteria etc.). On the other hand, the consumer demand for products, that are labeled organic or natural, has led to an increased interest for reducing of the pesticide usage, but in the same time, keeping high production levels. One solution would be an early identification of contaminated area and extermination of pests by using a minimum required dosage of pesticide.

An optimized solution for pesticide plant disease treatment using a spraying robot is proposed by Geng et al. [GEN’12]. The system consists of three modules: image acquisition and processing module, mechanical module (mobile platform, manipulator and nozzles), and motion control module. The system can identify the cucumber downy mildew based on leaf color and texture. The proposed classification algorithm was tested considering different illumination levels and proves a high accuracy of around 90%.

The plant health and nutrient assimilation can be monitored trough destructive and nondestructive methods. One important indicator of the plant health is the chlorophyll content. The foliar chlorophyll concentration can be measured in laboratory by organic extraction using mass spectrometry analysis.

The image processing algorithms for chlorophyll content estimation comprises another method. Vollmann et al. [VOL’11] use a commercial digital camera for capturing the leaves images. To ensure the equivalent illumination condition, incandescent lamps are used. After leaves selection against the background, the average green tones of the leaves are used to estimate the chlorophyll content. Inconsistent results can be obtained due to different illuminating conditions.

Other solution using a Pico Life hand-held digital scanner is proposed by Ali et al. [ALI'12a], [ALI'12b]. An algorithm is developed in MATLAB for measuring the following leaves dimensions: area, height, width and perimeter. The chlorophyll content is estimated by using a logarithmic sigmoid function with normalized values of green component with respect to red and blue components.

2.8. Case Study – Greenhouse of Banat University of Agronomical Sciences

For identifying new direction of development we visited one of the most modern greenhouses in the west part of Romania, the greenhouses of Banat University of Agronomical Sciences and Veterinary Medicine.

The university owns two greenhouse modules that are used for research and didactic purposes, growing different species of flowers and vegetables.

This are multi-span greenhouses each having an area of 1200 m^2 (24 m wide, 50m long) Fig. 2.9.

Each greenhouse has its own climate control modules and an external weather station. The greenhouse is covered with a double layer inflatable plastic film that reduces the heat loss.

Fig. 2.9. Greenhouse from Banat University of Agronomical Sciences and Veterinary Medicine.

Three automation subsystems are used for ensuring the proper greenhouse climate and soil nutrients concentration and humidity.

The greenhouse air temperature and humidity is controlled using the Ulma Agrícola climate controller. The greenhouse heating is done through steel heating pipes. The heating pipes are situated above the floor level.

Ridge (roof) vents are used for ventilation (Fig. 2.10.), the ridge vents are situated on the east side of the greenhouse roof. The ridge vents were constructed on every direction except the west side due to the high risk of being damaged by the strong winds, the regional dominant wind direction is west to east. The greenhouse air humidity can be increased by using a sprinkler system. Just one greenhouse air temperature/humidity sensor is used; the sensor is situated near the center of the construction.

The Ulma climate controller allows selecting different temperature and humidity during a day, a day being divided in 5 time slots.

For reducing the solar radiation once the light intensity is above a defined threshold the shade screen is expanded to cover the entire greenhouse soil. The shade screen control is assured by a Mikro Agro controller. Also for reducing the solar radiation the greenhouse lateral walls where opacified using a calcium-based product.

The rubberized shade/thermal screen is also used in the nights with low temperature by reducing the total space that has to be heated (3m above the soil level).

Fig. 2.10. Inside view of the greenhouse roof

One important aspect for the greenhouse plant cultivation is being able to control the CO_2 level for not exceeding the 1% concentration critical threshold.

In the morning the CO_2 concentration at plant level is high and it's possible to reach 1% in the plants foliage proximity. It can cause irremediable damages to plants. The CO_2 concentration level is decreased by turning on the ventilators and opening the ridge vents. The procedure has to be repeated on a daily basis by the human operator due to the lack of automation.

For fertirrigation a drip irrigation system is used.

A manually operated artificial light system is also installed in the greenhouse but has never been used in plant production due to the lack of funding.

Identified problems

The automation system is fragmented, the three existing automation subsystem are not interconnected.

Several greenhouse operations are still handled manually: ventilation for reducing the CO2 concentration, artificial lighting and thermal screen extending/retracting.

Desired features

Aggregation of all the existing control subsystems and automation of the manual operations.

Development of a control system that's able to import plant specific parameters from a database (expert system): air temperature, air humidity, light intensity, CO_2 concentration, soil humidity and micro/macronutrients (concentration) dosage.

Dynamic update of the setpoints based on the primary factors that affect the plant growth.

Recording of all the monitored environmental parameter in a database for further analysis of the plants evolution or for comparative studies.

2.9. Central and Distributed Greenhouse Climate Control

For greenhouses with a 1000 m^2 area, a centralized control system is more suitable. The whole greenhouse space is characterized by a single spatial point where the measurements for temperature, humidity, CO_2 are taken. This spatial point is usually relocated based on the canopy development.

One example is the greenhouses of Banat University of Agronomical Sciences and Veterinary Medicine, where the temperature and humidity control system receives the temperature and humidity information from a sensor situated in the center of the greenhouse and the height is adjusted based on the plant canopy. The actuators are distributed in the greenhouse to create a homogenous temperature and humidity distribution.

For greenhouses that cover a larger area than in the previous described case, it is difficult to use a control strategy and to locate the actuators in the greenhouse so that a homogenous climate is ensured. A solution for this situation is the usage of a distributed control systems.

The distributed control systems is developed by segmentation of the GH in several zone, each area having its own control device, sensors and actuators (Fig. 2.11).

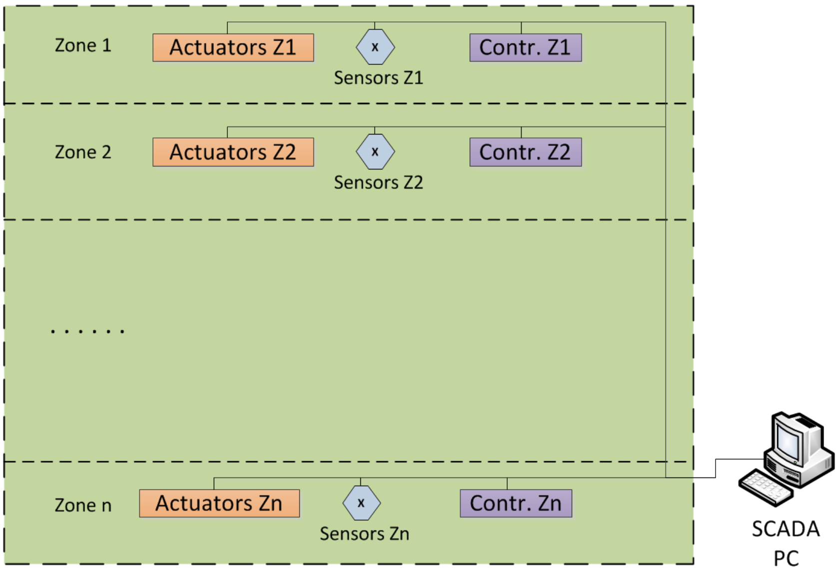


Fig. 2.11. Decentralized greenhouse climate control system

Following this idea, the same control algorithm can be implemented on each control device where an upper level SCADA PC should provide the global setpoints for all the greenhouse zones.

3. GREENHOUSE CLIMATE MODEL, LINARISATION AND DECOUPLING

Greenhouses are defined as structures which cover and protect the crop providing at least one way for changing the internal environment [STR'11]. This separation between the crop environment and the external environment protects the crop from strong winds, acid rain or pests and allows control over the main environmental factors affecting plant growth: temperature, humidity, CO_2 concentration, light intensity. All these variables should be maintained through control and managed automatically according to proper time programs. Due to their spatial distribution, the greenhouses are systems with distributed parameters, but currently, for the sake of simplicity and also for greenhouses under 1000 m^2, they are considered as MIMO systems with lumped parameters characterized by high coupling between the two main control variables: temperature and humidity.

There are several models for the greenhouse climate. Some of them use system identification approach based on the black box I/O analysis [TAP'00], [PAT'08], [HE'10] and others are based on energy and mass flow equations [ALB'01], [PAS'03], [IMP'07], [GEL'12], [JAV'08]. One of the most used greenhouse climate model is the one presented by Albright et al. [ALB'01] for controlling the temperature and humidity.

This chapter presents the nonlinear coupled MIMO model of greenhouse climate process proposed by Albright et al. [ALB'01], and also the feedback-feedforward linearization, decoupling and disturbance compensation procedure [SLO'91], [ISI'95] for this model. By employing this technique, an equivalent decoupled system is obtained. The equivalent model is reduced to integral plus dead time (IPDT) decoupled processes suitable for greenhouse climate (temperature and humidity) control. Simulation results validate the theoretical considerations.

The feedback-feedforward linearization and decoupling procedure applied to the greenhouse climate model requires the estimation of the output vector without delay. The author proposes two solutions for this estimation by using: i) an internal model or ii) a state observer.

3.1. Greenhouse Climate Model

From the control engineering point of view, a greenhouse is a distributed parameter system, based on energy and mass transfer processes (Fig. 3.1), whose modeling is a quit difficult task. Furthermore, the models obtained on this way, are not suited for design of the control systems. That is why, actually, simple models, with lumped parameters, as those developed by Albright et al., given through equations (3.1), are used [ALB'01].

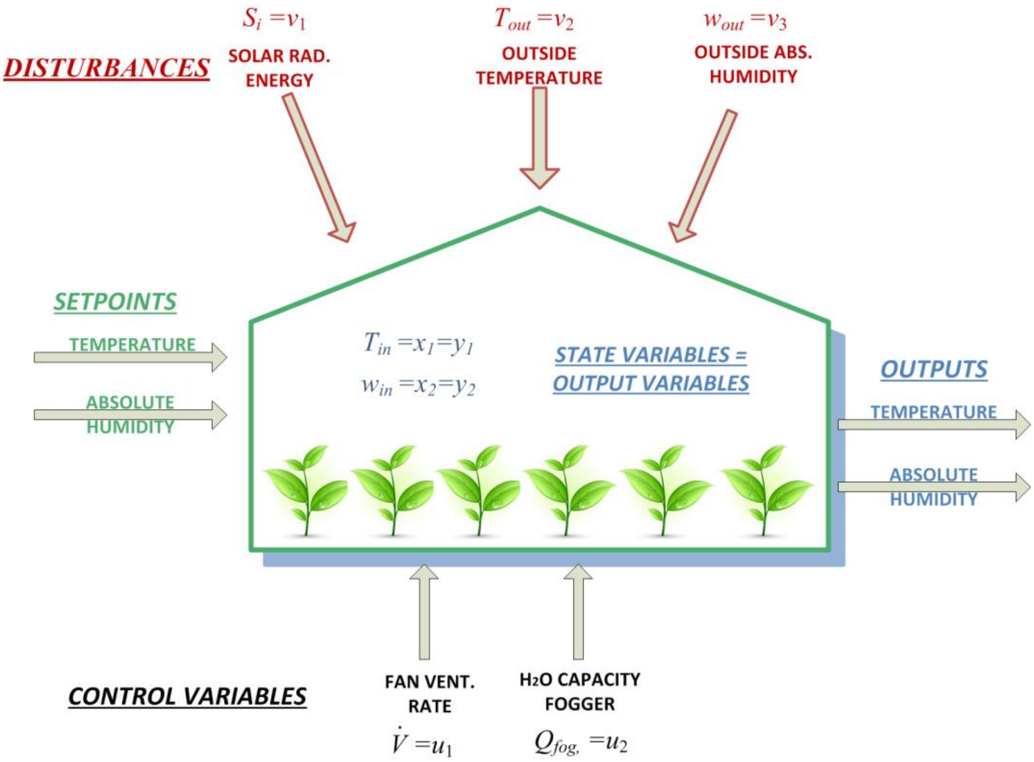


Fig. 3.1. Greenhouse - a schematic representation oriented on climate issues–suited for Control Approaches

$$\frac{dT_{in}}{dt} = \frac{1}{\rho C_p V}\left[Q_{heater}(t) + S_i(t) - \lambda Q_{fog}\right] - \frac{\dot{V}(t)}{V}\left[T_{in}(t) - T_{out}(t)\right] - \frac{U_A}{\rho C_p V}[T_{in}(t) - T_{out}(t)] \tag{3.1a}$$

$$\frac{dw_{in}}{dt} = \frac{1}{V}Q_{fog}(t) + \frac{1}{V}E(S_i(t), w_{in}(t)) - \frac{\dot{V}(t)}{V}\left[w_{in}(t) - w_{out}(t)\right] \tag{3.1b}$$

The first equation describes the temperature dynamics inside the greenhouse, while the second one describes the humidity dynamics inside the greenhouse, under the hypothesis that only the main disturbances are considered: outside temperature and humidity, and the solar radiation. The meaning of the notations is given in Table 3.1.

Table 3.1. Greenhouse Climate Model Parameters and Variables

C_p	specific heat of air (1006 J/(kgK))
$E(S_i, w_{in})$	plants evapotranspiration rate (g/s)
Q_{fog}, u_2	water capacity of the fog system (g /s)
Q_{heater}	heat flow provided by the greenhouse heater (W)
S_i, v_1	intercepted solar radiant energy (W)
T_{in} ,x_1,y_1	air temperature inside the greenhouse (°C)
T_{out}, v_2	air temperature outside the greenhouse (°C)
u	control variable
U_A	heat transfer coefficient (W/K)
v	external disturbance variable
V	greenhouse volume (m^3)
$\dot{V}$, u_1	ventilation rate (m^3/s)
w_{in} ,x_2,y_2	interior absolute humidity (g/ m^3)
w_{out}, v_3	exterior absolute humidity (g/ m^3)
x	state variable
y	output variable
α	coefficient accounting for shading and leaf area index
β_T	coefficient to accounting for thermodynamic constants and other factors affecting evapotranspiration
λ	latent heat of vaporization (2257 J/g)
ρ	air density (1.2 kg/m^3)

Because next only summer operations regimes are considered $Q_{heater} = 0$. According to [PAS'03] the plant evapotranspiration rate $E(S_i(t),w_{in}(t))$ can be expressed as:

$$E(S_i(t),w_{in}(t)) = \alpha \frac{S_i(t)}{\lambda} - \beta_T w_{in}(t), \tag{3.2}$$

Finally, from (3.1) and (3.2) the second order nonlinear state model (3.3) is obtained. Here, the equivalent symbols from Table 3.1 where used.

$$\begin{aligned}\dot{x}_1(t) = &-\frac{UA}{\rho C_p V} x_1(t) + \frac{1}{\rho C_p V} v_1(t) + \frac{UA}{\rho C_p V} v_2(t) + \frac{1}{V} v_2(t) u_1(t) \\ &- \frac{1}{V} x_1(t) u_1(t) - \frac{\lambda}{\rho C_p V} u_2(t)\end{aligned} \tag{3.3a}$$

$$\dot{x}_2(t) = -\frac{\beta_T}{V} x_2(t) + \frac{\alpha}{\lambda V} v_1(t) + \frac{1}{V}\left[v_3(t) - x_2(t)\right] u_1(t) + \frac{1}{V} u_2(t) \tag{3.3b}$$

$$\begin{cases} \underbrace{\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix}}_{} = \begin{bmatrix} \frac{-U_A}{\rho C_p V} & 0 \\ 0 & -\frac{\beta_T}{V} \end{bmatrix} \cdot \underbrace{\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}}_{x} + \begin{bmatrix} \frac{1}{\rho C_p V} & \frac{U_A}{\rho C_p V} & 0 \\ \frac{a}{\lambda V} & 0 & 0 \end{bmatrix} \cdot \underbrace{\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}}_{v} \\ \quad + \begin{bmatrix} \frac{1}{V}[v_2 - x_1] & -\frac{\lambda}{\rho C_p V} \\ \frac{1}{V}[v_3 - x_2] & \frac{1}{V} \end{bmatrix} \cdot \underbrace{\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}}_{u} \\ \underbrace{\begin{bmatrix} y_1 \\ y_2 \end{bmatrix}}_{y} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \end{cases} \tag{3.3c}$$

Note that: i) the system (3.3) is characterized by a high nonlinearity and coupling, ii) the input variable u_1 takes only positive values ($u_1 > 0$), and iii) the state variables $x_1 = T_{in}$, and $x_2 = w_{in}$, are considered also as output variables. Because the matrix:

$$\begin{bmatrix} -\left(\frac{UA}{\rho C_p V} + \frac{u_1}{V}\right) & 0 \\ 0 & -\left(\frac{\beta_T}{V} + \frac{u_1}{V}\right) \end{bmatrix}$$

is negative definite, the MIMO system (3.3) is stable, hence for constant inputs *u* and *v,* a steady state regime is achieved.

3.2. Decoupling Strategy

Since (3.3) is stable, the control structure and design method proposed in [ALB'01] and [PAS'03], based on a well-known feedback-feedforward linearization and decoupling technique [SLO'91], [ISI'95] for plants with measurable external disturbances, will be further considered. In this case, the system (3.3), representing the plant, can be brought to the form:

$$\dot{y} = F(y,v) + G(y,v) \cdot u \tag{3.4}$$

where:

$$F(y,v) = \begin{bmatrix} f_1(y,v) \\ f_2(y,v) \end{bmatrix} = \begin{bmatrix} \frac{-U_A}{\rho C_p V} y_1 + \frac{1}{\rho C_p V} v_1 + \frac{U_A}{\rho C_p V} v_2 \\ -\frac{\beta_T}{V} y_2 + \frac{\alpha}{\lambda V} v_1 \end{bmatrix},$$

$$G(y,v) = \frac{1}{V} \cdot \begin{bmatrix} v_2 - y_1 & -\frac{\lambda}{\rho C_p} \\ v_3 - y_2 & 1 \end{bmatrix}.$$

Assuming that $G(y,v)$ is nonsingular, also:

$$\Delta(t) = \rho C_p[v_2(t) - y_1(t)] + \lambda[v_3(t) - y_2(t)] \neq 0 \qquad (3.5)$$

a nonlinear control function of the form (3.6) is considered:

$$u = G^{-1}(y,v) \cdot [-F(y,v) + \hat{u}]. \qquad (3.6)$$

Where $\hat{u} = \begin{bmatrix} \hat{u}_1 & \hat{u}_2 \end{bmatrix}^T$ is the new control input vector.
By substituting u from (3.6) in (3.4) we get:

$$\dot{y} = \hat{u} \qquad (3.7)$$

This result illustrates a linear decoupled final interaction along the channels $\hat{u}_1 \to \dot{y}_1 \to y_1$ and $\hat{u}_2 \to \dot{y}_2 \to y_2$. A simple look inside the problem brings to the surface the significance of the new control variables: $\hat{u}_1$ is the rate of change for y_1 (i.e. the temperature), and $\hat{u}_2$ the rate of change for y_2 (i.e. the humidity).
Consequently, the nonlinear decoupling low (3.6) that assures the behavior (3.7) should be:

$$u_1 = [U_A y_1 + \lambda\beta_T y_2 - (1+\alpha)v_1 - U_A v_2 + \rho C_p V\hat{u}_1 + \lambda V\hat{u}_2] / \Delta \qquad (3.8a)$$

$$u_2 = (y_2 - v_3)(U_A y_1 - v_1 - U_A v_2 + \rho C_p V\hat{u}_1) / \Delta + \rho C_p(-y_1 + v_2)(\beta_T x_2 - \frac{\alpha}{\lambda} v_1 + V\hat{u}_2) / \Delta \qquad (3.8b)$$

The whole decoupling strategy is illustrated in Fig. 3.2.

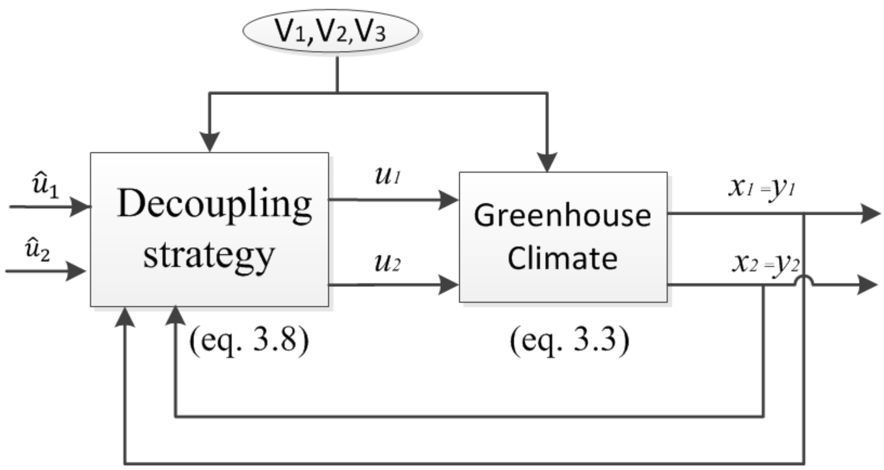


Fig. 3.2. Decoupling structure (ideal version) of greenhouse climate process

The inside greenhouse variables, i.e., the temperature and absolute humidity, necessary to implement the decoupling algorithm, are measured with sensors, typically located at a certain distance from the moisturizing devices like wet-pads and foggers, and also from fans and window openers. The measurement and propagation processes are associated with time delays. Hence, two dead times d_1 and d_2, one for each system output y_1 and y_2 should be considered. Consequently, based on the assumption that the disturbance variable v is measurable and the input variable u is available from control, the decoupling low (3.8) becomes:

$$u_1(t) = [U_A y_1(t-d_1) + \lambda\beta_T y_2(t-d_2) - (1+\alpha)v_1(t) - U_A v_2(t) + \rho C_p V\hat{u}_1(t) + \lambda V\hat{u}_2(t)] \,/\, \Delta(t,d_1,d_2) \quad (3.9a)$$

$$u_2(t) = [(y_2(t-d_2) - v_3(t))\cdot(U_A y_1(t-d_1) - v_1(t) - U_A v_2(t) + \rho CpV\hat{u}_1(t) + \rho Cp(-y_1(t-d_1) + v_2(t))(\beta_T y_2(t-d_2) - \frac{\alpha}{\lambda}v_1(t) + V\hat{u}_2(t)] \,/\, \Delta(t,d_1,d_2) \quad (3.9b)$$

with:

$$\Delta(t) = \rho C_p(v_2(t) - y_1(t-d_1)) + \lambda(v_3(t) - y_2(t-d_2)) \quad (3.9c)$$

Instead to obtain (3.7), rewritten here as $\dot{y}(t) = \hat{u}(t)$, the real input-output relationship is:

$$\dot{y}(t) = F(y(t),v(t)) + G(y(t),v(t))\cdot G^{-1}(y(t,d_1,d_2),v(t)) \cdot[-F(y,d_1,d_2),v(t) + \hat{u}(t)] \quad (3.10)$$

Indubitable, the real decoupling strategy shown in Fig. 3.3, is no more effectively when compared with the ideal decoupling from Fig. 3.2.

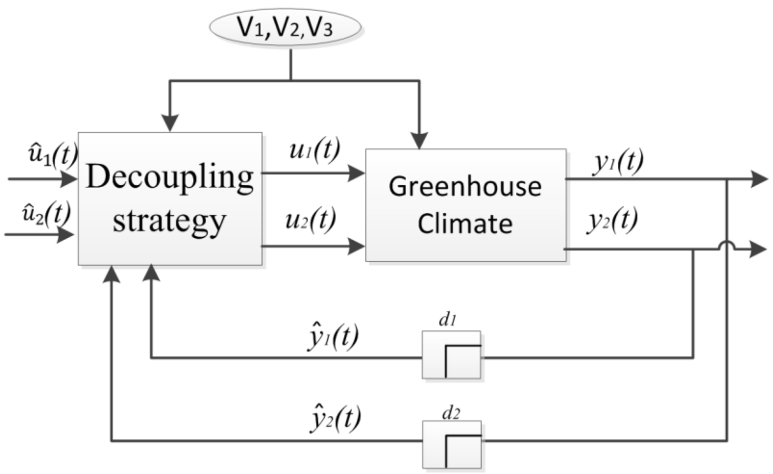


Fig. 3.3. Decoupling structure (real version) with time delay of greenhouse climate process

A rigorous analysis of this structure is difficult to follow and therefore a qualitative inspection may be helpful. Fig. 3.4 illustrates the comparative behavior of the ideal and real decoupling structures for a greenhouse with parameters listed in Table 3.2.

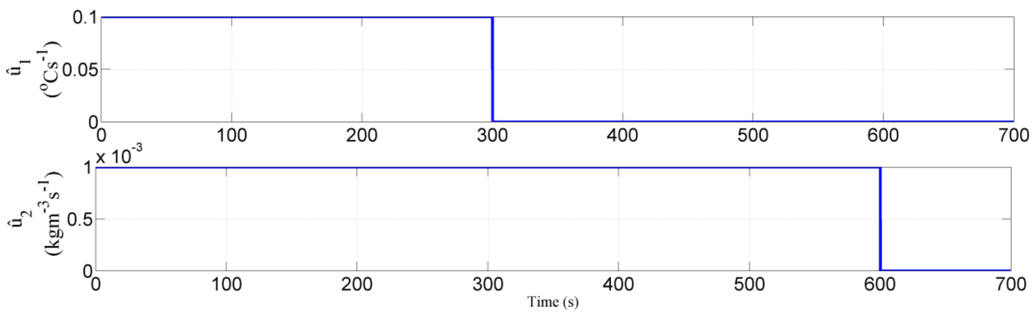
Table 3.2. Simulation condition for greenhouse climate decoupling structure validation

$\hat{u}_1$	Step change, 0,1 to 0 at t=300 s
$\hat{u}_2$	Step change, 0,001 to 0 at t=600 s
x_1,init. cond.	25 °C
x_2,init. cond.	0.018 kg/m^3
S_i, v_1	300 W/m^2
T_{out}, v_2	22 °C
w_{out}, v_3	0.004 kg/m^3
α	0.1249
λ	2257 J/g
V	2800 m^3
d_1, d_2	30 s

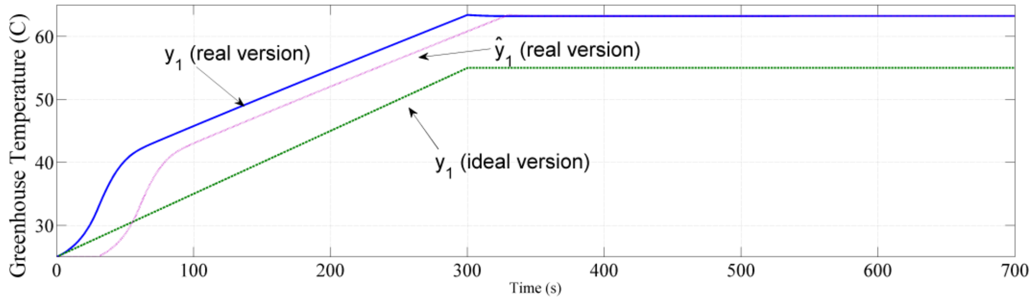
Two experiments are summarized in Fig. 3.4, taking in consideration the ideal and real decoupling structure, employing a stepwise increase for the greenhouse air temperature and humidity rate of the change (Fig. 3.4a and eq. 3.11 with $\sigma(t)$ unit step signal):

$$\hat{u}_1(t) = 0.1 \cdot [\sigma(t) - \sigma(t - d_1)]$$
$$\hat{u}_2(t) = 0.001 \cdot [\sigma(t) - \sigma(t - d_2)] \quad (3.11)$$

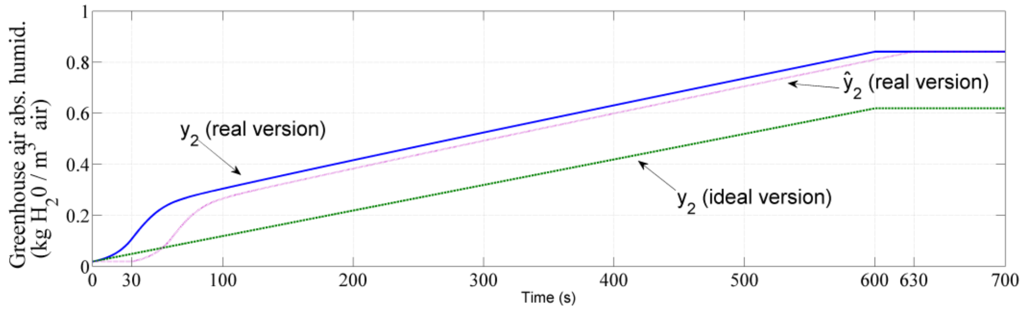
The time variations of y_1 and y_2 appear in Fig. 3.4b and Fig. 3.4c, while the corresponding control signals in Fig. 3.4d and 3.4e.



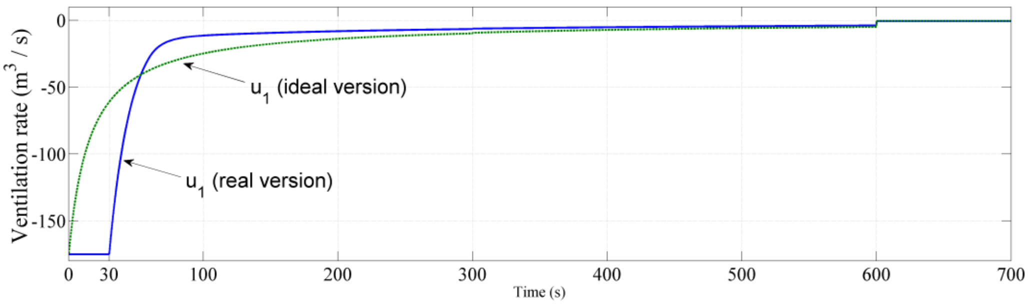
-a-


Greenhouse Temperature (C)
Time (s)
y_1 (real version)
$\hat{y}_1$ (real version)
y_1 (ideal version)

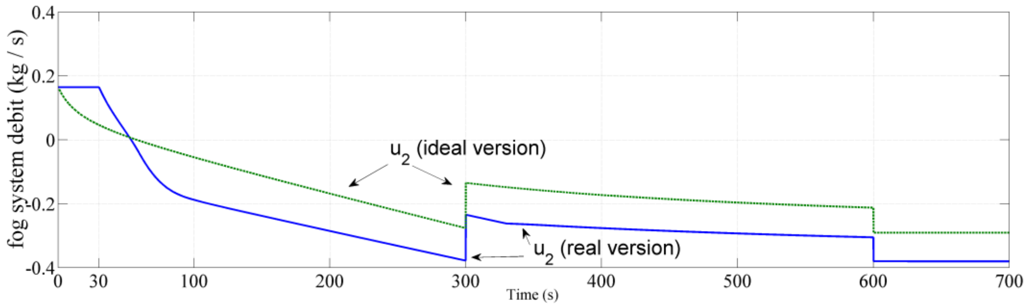
-b-


Greenhouse air abs. humid. (kg $H_2$0 / m^3 air)
Time (s)
y_2 (real version)
$\hat{y}_2$ (real version)
y_2 (ideal version)

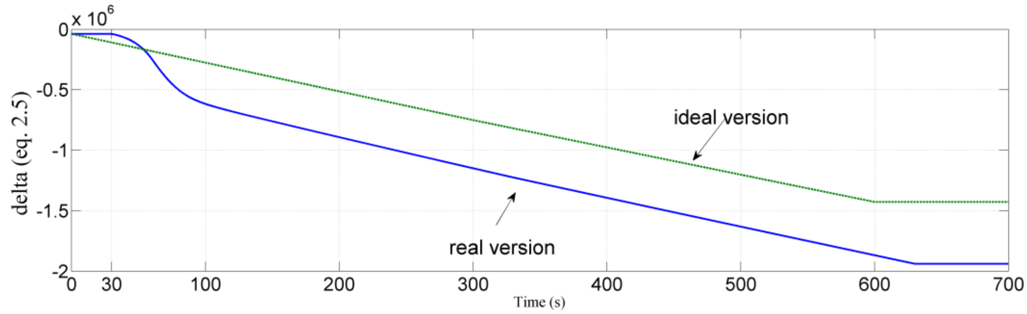
-c-


Ventilation rate (m^3 / s)
Time (s)
u_1 (ideal version)
u_1 (real version)

-d-


fog system debit (kg / s)
Time (s)
u_2 (ideal version)
u_2 (real version)

-e-



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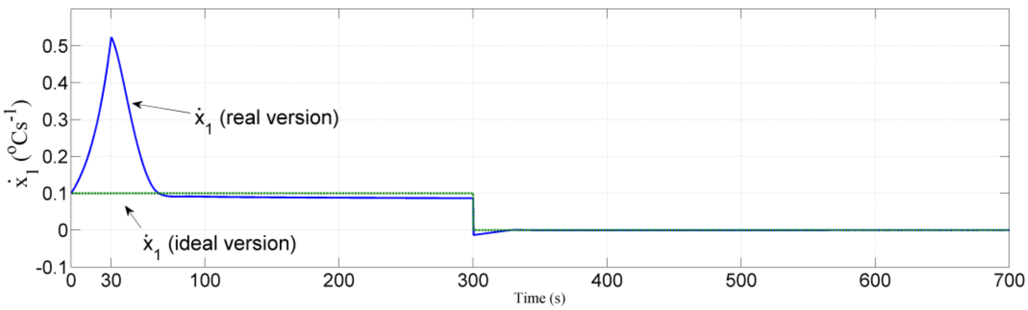

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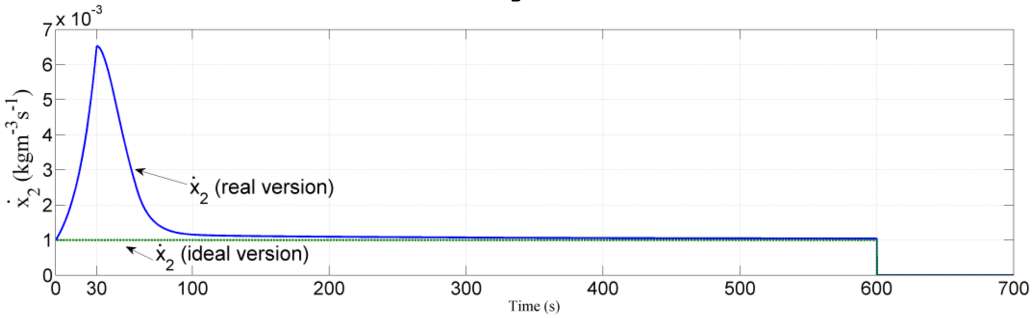


-h-

Fig. 3.4. Comparative behavior of ideal (Fig. 3.2) vs. real decoupling structure (Fig. 3.3) – simulation results

It is clear that the delayed feedback signals $\hat{y}_1(t) = y_1(t - d_1)$ and $\hat{y}_2(t) = y_2(t - d_2)$ induce a different behavior of the real structure, but equally important is the maintaining of the decoupled behavior at the level of output variables even if there is a high cross interactions in the driving signals $u_1(t)$ and $u_2(t)$. The fact that the steady state regime differ does not allow us to use the real version from Fig. 3.3.

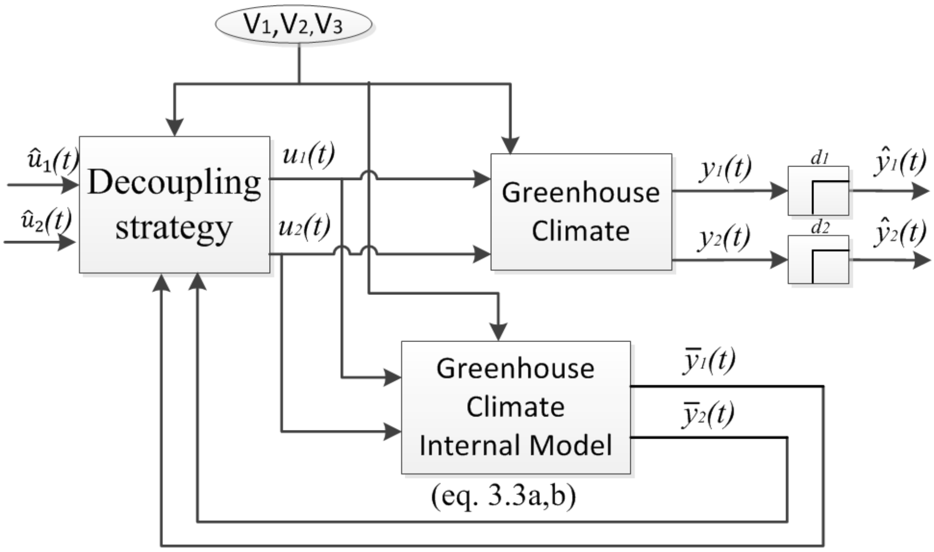
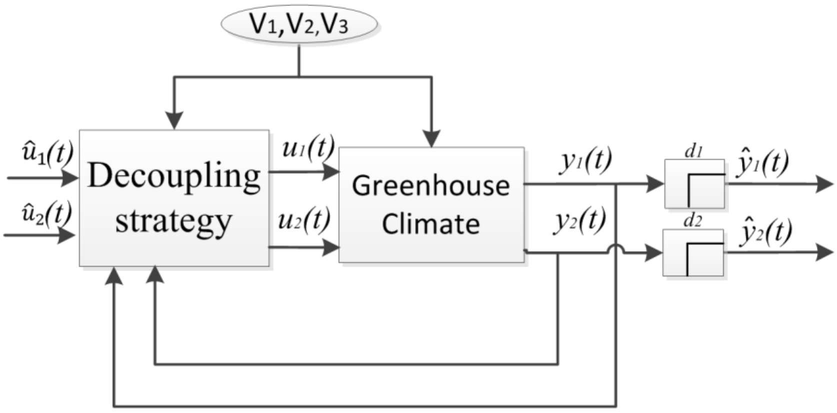


Fig. 3.5. Linearization and decoupling using the greenhouse climate internal model

The outgoing from this situation is to use for carrying out the decoupling reaction, an internal model of the process (Fig. 3.5). The output variables of the internal model, used to feedback were marked with $\bar{y}_1$ and $\bar{y}_2$.

In practical terms this means that the control can be further developed by using the quasi-equivalent structure in Fig. 3.6a. Finally, by taking into account eq. (3.7), the decoupled structure is clarified in Fig. 3.6b.



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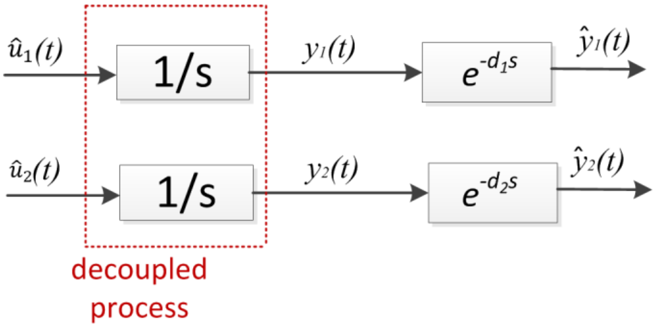


-b-

Fig. 3.6. Decoupled process with time delay used in controller designs: a) quasi-equivalent structure, b) equivalent IPDT model

3.3. State Observer

As was presented in the previous subchapter for computing the command variables u_1 and u_2 responsible for linearization and decoupling we need the undelayed output variables values y_1 and y_2. The only available output signals are delayed $\hat{y}_1(t) = y_1(t-d_1)$ and $\hat{y}_2(t) = y_2(t-d_2)$ thus in steady state regime the two control loops are decoupled, but for the dynamic regime a different behavior is imposed.

One method for obtaining the state variables without delay by using the internal model was proposed.

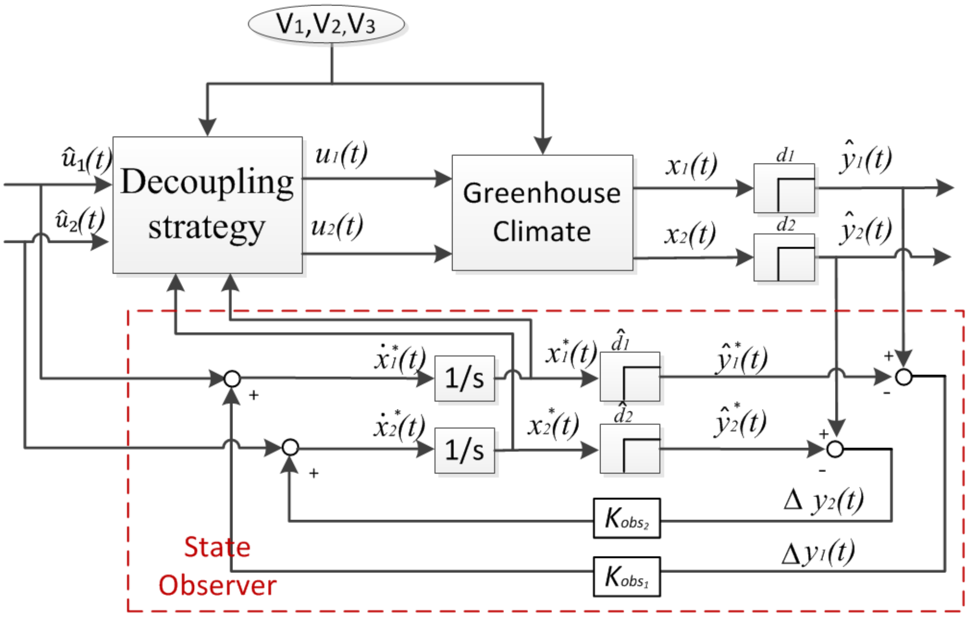


Fig. 3.7. Linearization and decoupling using state observer

In this subchapter another solution is presented, it was implemented by using a state observer that was developed taking in consideration the IPDT behavior for the two decoupled, temperature and humidity, channels.

The greenhouse climate model and the linearization and decoupling procedure imposes an integrator behavior for the temperature and humidity channels where $\hat{u}_1$ is the temperature rate of change and $\hat{u}_2$ is the humidity rate of change. The state observer (Fig. 3.7) exploits this behavior and also adjust the state variables by using the difference between the measured outputs of the system $\hat{y}_1(t)$ (greenhouse air temperature), $\hat{y}_2(t)$ (greenhouse air absolute humidity) and the estimated delayed outputs $\hat{y}_1^*(t)$ and $\hat{y}_2^*(t)$. The expressions for the estimated state variables are:

$$\dot{x}_i^*(t) = k_{obs_i}[\hat{y}_i(t) - \hat{y}_i^*(t)] + \hat{u}_i(t)\ , \quad i = 1 \text{ or } 2 \tag{3.12}$$

$$\dot{x}_i^*(t) = k_{obs_i}[x_i(t-d_i) - \hat{x}_i^*(t-d_i)] + \hat{u}_i(t)\ , \quad i = 1 \text{ or } 2\ . \tag{3.13}$$

This corresponds to the system in Fig. 3.8.

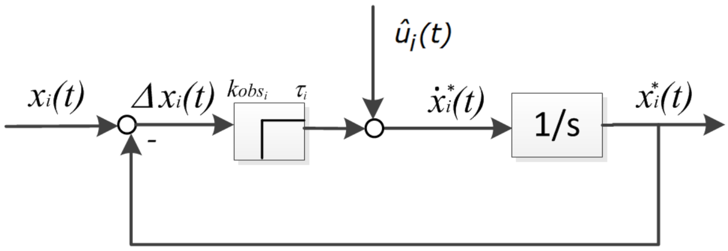


Fig. 3.8. Equivalent state observer structure to estimate the state variable without delay $\dot{x}_i^*$

State observer compensator (k_{obs}) design

The open loop transfer function is:

$$\tilde{H}_i(s) = \frac{x^*{}_i(s)}{\Delta x_i(s)} = \frac{k_{obs}}{s} \cdot e^{-d_i \cdot s}\ , \quad i = 1 \text{ or } 2$$

In our case, the dead times for temperature and humidity are equal, $d_1 = d_2$, and thus the open loop transfer functions can be expressed in frequency domain as:

$$\tilde{H}(j\omega) = \frac{k_{obs}}{\omega} \cdot e^{-j(\frac{\pi}{2} + \omega d)} \tag{3.14}$$

The phase margin stability criterion states that the closed-loop system is stable if the phase margin $\varphi_M = \pi + \arg \tilde{H}_i(j\omega_c)$ is greater than 0($\varphi_M > 0$), where ω_c is the gain crossover frequency.

The gain crossover frequency ω_c is obtained from $\left|\tilde{H}\right|_{dB} = 20\,lg\left|H(j\,\omega)\right| = 0$ this means $\left|H(j\,\omega)\right| = 1 \Rightarrow \frac{k_{obs}}{\omega} = 1$, in this case $\omega_c = k_{obs}$.

The phase crossover frequency ω_π is obtained from $arg\,H(j\,\omega) = -\frac{\pi}{2} - \omega d = -\pi$ in this case $\omega_\pi = \frac{\pi}{2d}$.

Hence, considering the Bode plots (Fig. 3.9) of the open-loop system $\left|\tilde{H}\right|_{dB} = 20\,lg\left|\tilde{H}(j\omega)\right|$ and $\varphi_{\tilde{H}} = arg\,\tilde{H}(j\omega)$, the system is stable when $\omega_c < \omega_\pi$ therefore :

$$k_{obs} < \frac{\pi}{2d}. \tag{3.15}$$

For the considered case study this translate to: $k_{obs} < 0.0524$.

A gain k_{obs}=0.04 has been chosen, which corresponds to the phase margin of $\varphi_M = 22^\circ$.

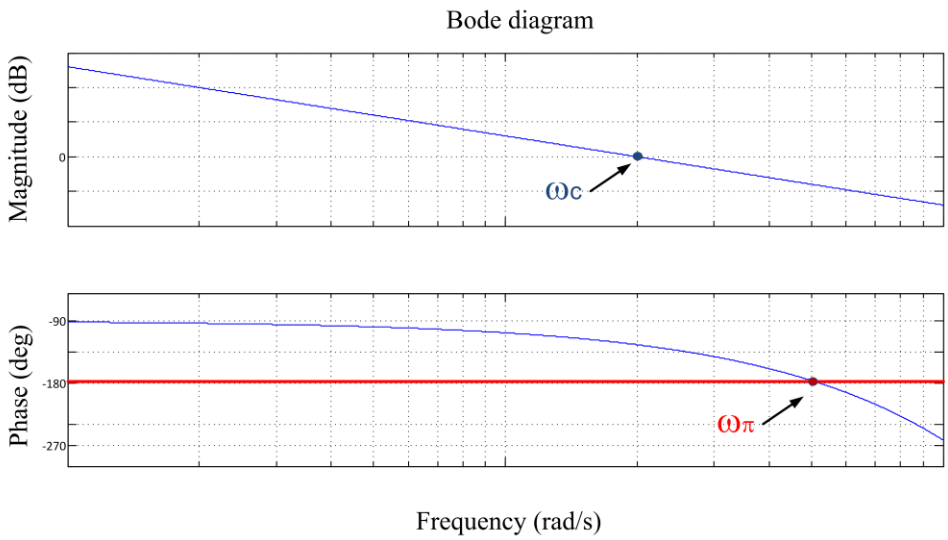


Fig. 3.9. Bode plots for $\tilde{H}(j\omega)$

If we compare the system outputs considering the two structures used for obtaining the undelayed system outputs: internal model (Fig. 3.5) and the state observer (Fig. 3.7), it can be seen in Fig. 3.10 that the system outputs are identical.

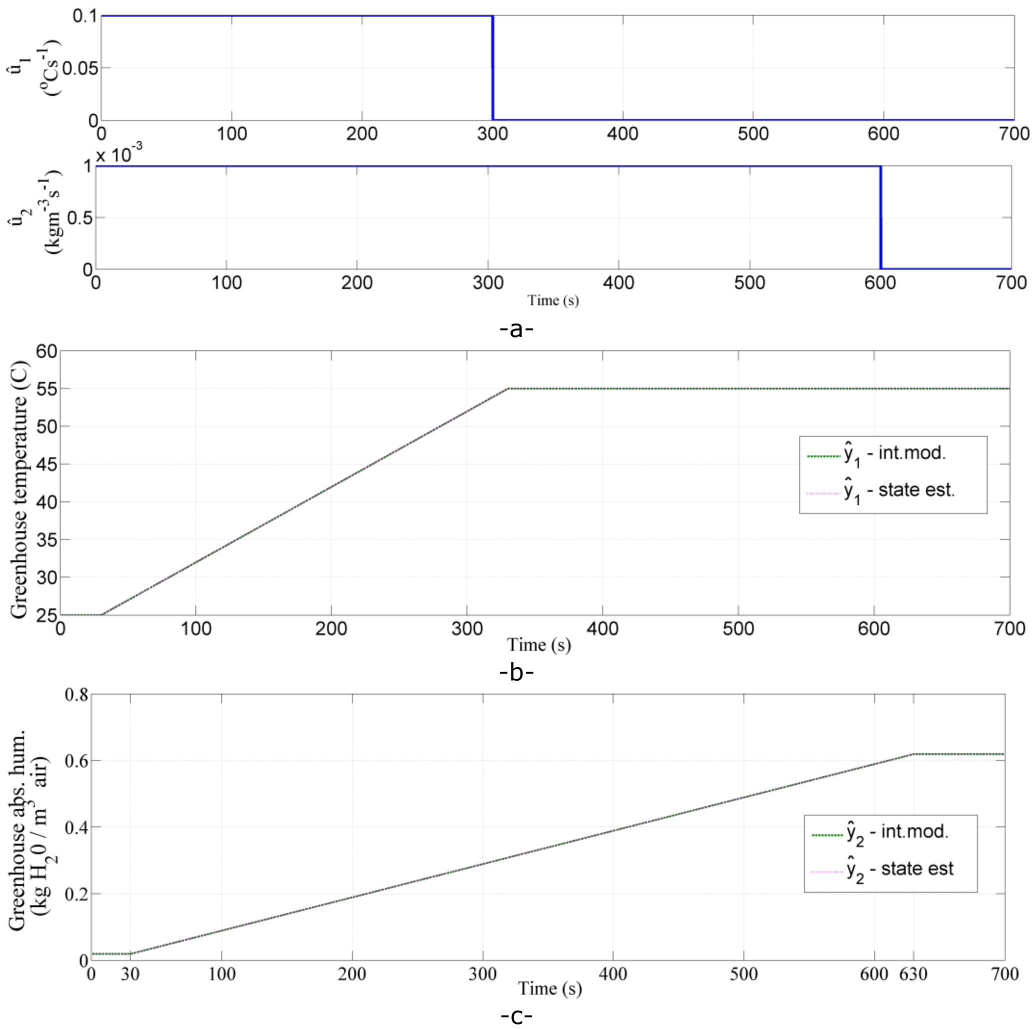


Fig. 3.10. Comparative behavior of the decoupled system considering the two structures used for obtaining the undelayed system outputs: internal model of the process and the state observer.

To compare the system outputs (Fig. 3.10.), a step change is used for the two control variables $\hat{u}_1$ (temperature rate of change) $\hat{u}_2$ (humidity rate of change) the initial condition and the parameters values used for this simulation are listed in Table 3.2. (pg. 42) The usage of the proposed state estimator provides very good estimation of state variables without delay.

System robustness considering the internal model and the state observer

Considering the nonlinear strongly coupled model of the greenhouse climate system, the parameters which are considered susceptible to modeling uncertainty/ time variation where identified. The problem has a high importance because the process is nonlinear and coupled, and after the linearization and decoupling procedure, the command variables u_1 and u_2 are influenced by wrong parameter estimation that affects the ideal decoupling.

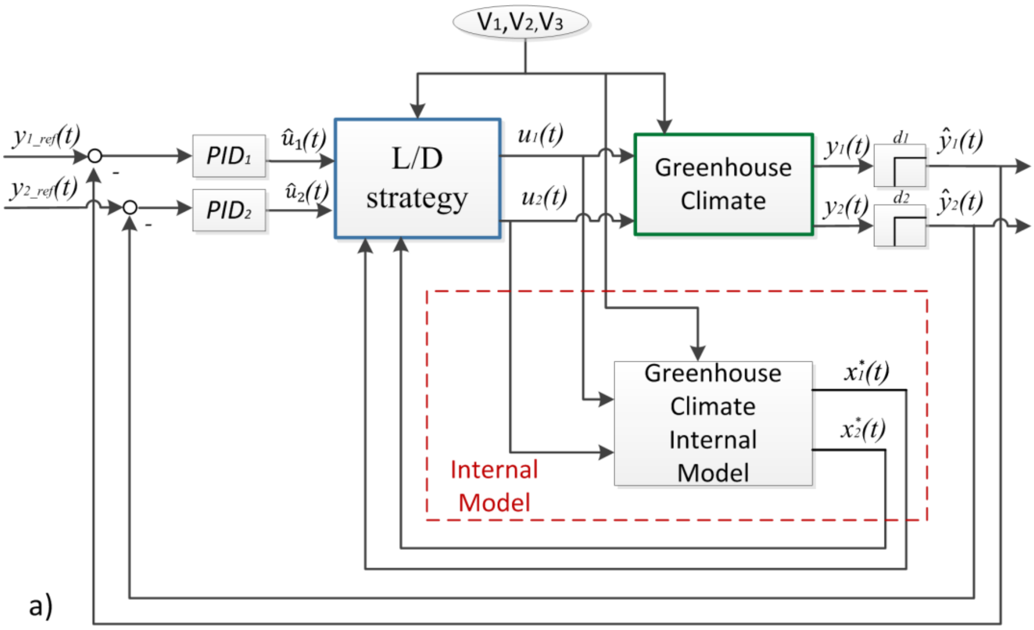
Wrong estimation of the heat transfer coefficient (U_A), the shading and leaf area index coefficient (α), coefficient to accounting for thermodynamic constants and other factors affecting evapotranspiration (β_T) are taken into consideration in the study of system responses.

The simulation scenario consists of constant setpoints for temperature and humidity and a 6 minutes ramp set-point decrease for both greenhouse temperature (with $\Delta y_1 = \Delta\theta = 5°C$) and absolute humidity (with $\Delta y_2 = \Delta h = 0.006$ kg H_2O/m^3). This scenario corresponds to diurnal to nocturnal transient regime.

For $t \in [0, 2000]$, the system is considered to be in steady state regime defined by: $y_1(0) = 25$ °C (greenhouse air temperature), $y_2(0) = 0.019$ kg H_2O/m^3 (greenhouse air absolute humidity), $v_1 = 300 W/m^2$ (intercepted solar radiant energy), $v_2 = 20$ °C (outside greenhouse temperature), and $v_3 = 0.004$ kg H_2O/m^3 (outside greenhouse absolute humidity).

There where compared the system responses in the nominal cases and the cases when we consider a 20% variation for each parameter: U_A, α, β_T.

Both methods proposed for obtaining the two state variables x_1, x_2 where tested considering parameter variation. In each control loop it has been used a PID controller using the Ziegler–Nichols tuning methods for IPDT processes presented in chapter 4.



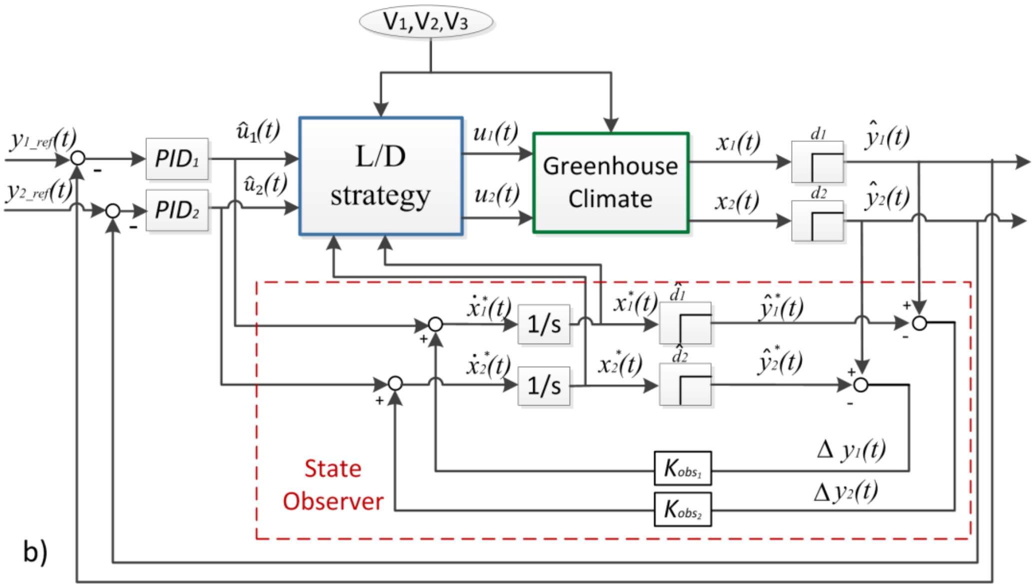


Fig. 3.11. Greenhouse climate system with decoupling for temperature and humidity control using: a) Internal model b) State observer

To analyze the parameter variation impact, the maximum difference between the system outputs in nominal case ($\hat{y}_{i\ nom}$) and the system outputs considering a 20% variation ($\hat{y}_{i\ ParV}$) for each of the 3 parameters was calculated (Table 3.3). The usage of both structures, internal model and state observer, has been taken into consideration (Fig. 3.11).

Also it has been compared the state variable estimation for both structures when the system is in steady state by calculating the difference between the process system states and the estimated system states, $x_i - x^*_i$.

When considering wrong estimation of the U_A, α, β_T parameters, by employing the state observer it has been obtained a very good estimation of the two system states variables. For obtaining an exact approximation, the initial state observer structure (Obs_K) was modified by replacing K_{obs} with a PI controller (Obs_PI). The controller was tuned using the Zieger-Nichols PI tuning technique for IPDT processes (detailed in chapter 4).

Table 3.3. System response considering nominal case and a 20% parameter variation using Internal Model and the two state observer structures for linearization and decoupling.

		$max(\hat{y}_{i\ nom} - \hat{y}_{i\ ParV})$			$x_i - x^*_i$		
Param.		Internal Model	Obs_K	Obs_PI	Internal Model	Obs_K	Obs_PI
U_A	Temp.	-0.06	-0.038	-0.038	0.25	0.05	0
	Humid.	$-3.3\text{-}*10^{-5}$	$-2.5*10^{-5}$	$-2.4*10^{-5}$	0	0	0
α	Temp.	$2.09*10^{-3}$	$2.1*10^{-3}$	$2.07*10^{-3}$	0	0	0
	Humid.	$4.6*10^{-5}$	$-7.5*10^{-6}$	$-8*10^{-6}$	$1.3*10^{-4}$	$1.3*10^{-5}$	0
β_T	Temp.	$-6.4*10^{-4}$	$-7*10^{-4}$	$-7*10^{-4}$	0	0	0
	Humid.	$-2.7*10^{-5}$	$2.2*10^{-6}$	$2.2*10^{-6}$	$-5.4*10^{-5}$	$-5.2*10^{-6}$	0

When comparing by simulation results, the maximum difference between the systems outputs in nominal case and when considering a 20% variation, are insignificant, thus the system is robust to the parameter variations for both solutions. The difference between process system states and the estimated system states when using the internal model and the state observer structure (Obs_K) are negligible when considering parameter variation. When employing the Obs_PI state observer the two undelayed process system states are exactly estimated thus the linearization and decoupling is no longer impacted by the wrong state estimation.

In conclusion, both solutions for estimation of vector state without delay are robust to parameter variations, therefore, for implementation is recommended as a simpler and efficient solution, i.e., the implementations with state observer (Fig. 3.11b).

3.4. Summary and Conclusions

In this chapter is developed the greenhouse climate model [ALB’01] described trough two differential equations. The first equation describes the temperature dynamics, while the second one describes the humidity dynamics under the hypothesis that the main disturbances considered are: outside temperature, outside humidity, and the solar radiation.

The greenhouse climate model is characterized by high nonlinear interaction between the biological subsystem and the physical subsystem, and also presents strong coupling of the two main controlled variables: greenhouse air temperature and humidity.

The greenhouse climate nonlinear model with dead-time and measurable disturbances is decoupled by feedback-feedforward linearization method [ISI’95], [SLO’91] resulting in two decoupled control loops with an integrator plus dead-time behavior.

The author contributions offer two solutions to estimate the state vector without time delay required by feedback-feedforward linearization method. The first solution proposes to use the internal model structure. The second solution is based on a state estimator structure, taking advantage that the equivalent process model with feedback-feedforward linearization has an integrator behavior for each channel (temperature and humidity).

Both solutions are robust to parameter variations proved by simulation results. Therefore, the solution based on state observer is recommended for implementation as a simpler and efficient solution.

The results obtained in this chapter where disseminated in [GUR'12], [GUR'13a] and [GUR'14a].

4. GREENHOUSE CLIMATE CONTROL

In this chapter are employed four control structures for greenhouse climate control: i) conventional PID control structure, ii) two degree of freedom (2DoF) control structure, iii) PID control structure tuned by employing genetic algorithms and iv) Smith predictor.

As showed in [GUR'12], the feedback linearization procedure [SLO'91]; [ISI'95], can lead to an efficient control. By employing this technique, an equivalent decoupled system is obtained with an integrator plus dead-time (IPDT) behavior, permitting the usage of PID controllers.

i) Conventional PID tuning methods, mainly synthesized by [VIS'11], can be used. By using the greenhouse climate model and the linearization and decoupling procedure presented in the previous chapter, in the current chapter is given a comparative study using different *conventional PI/PID controllers tuning techniques specialized for IPDT process*. Simulation tests with system responses to set-point step and ramp changes, and disturbance step changes, are analyzed and compared.

Another important problem, which is discussed in this chapter, is the system behavior and robustness to modeling uncertainties. The first step was to identify the parameters or disturbances that are more susceptible to wrong estimation. This problem presents a high importance because the process is coupled and nonlinear, and after the linearization and decoupling procedure, new control variables are introduced, which could be highly influenced by wrong parameter/ disturbance estimations. In this case, the decoupling could be lost. Two process parameters and an external disturbance where identified as most susceptible to wrong measurement/ estimation.

ii) The quality indicator degradations, considering the system response for setpoint step change, lead to the reconsideration of the initial control structure. That is why in this chapter is developed a *two degree of freedom (2DoF) control structure* for greenhouse climate system, where the performance of the regulatory control for disturbance rejection and the servo control for setpoint tracking are separately tuned. Simulation tests are used for comparing the system responses using the conventional and the 2DoF PID controllers.

iii) The *genetic algorithms* prove to be a useful tool for PID tuning [FLE]; [ZAL'99]. They offer so called suboptimal results. The results obtained by using genetic algorithms to determine the K_P, T_I, T_D parameters of the two PID controllers (temperature and humidity channels) are reported, by employing a proposed minimum cost function and by using in the initial population PID controllers tuned by four PID tuning methods. Comparative simulation results in real proposed scenarios show enhanced performances for PID tuning by GA in comparison with the four conventional PID tuning methods.

iv) A control structure for greenhouse climate control using the proposed state estimator (chapter 2) and a modified Smith predictor is presented. The simulation tests are presented, showing good results.

The results obtained in this chapter where disseminated by papers published in two IEEE conference proceedings [GUR'12], [GUR'13a] and an article submitted to a journal [GUR'14a].

4.1. PID Controller Tuning Methods for Integrator Plus Dead-Time (IPDT) Process

The greenhouse climate system (Fig. 4.1) contains the nonlinear coupled state-space model (3.3a, b) with added dead times, the linearization and decoupling compensator (3.8a, b), and usually employs PID controllers for temperature and humidity regulations. These controllers have the integral plus dead time (IPDT) systems as equivalent decoupled controlled processes.

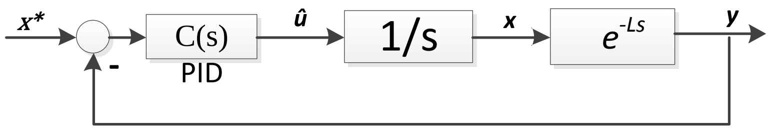


Fig. 4.1. Greenhouse control system for temperature and humidity regulations using equivalent integral plus dead time (IPDT) decoupled processes.

Several tuning methods for PID and PI controllers are considered focused on integral plus dead time processes [ZIE'42], [MOR'89], [ARB'07], [CHI'03], [SES'09], [WAN'97], [VIS'11]. The PID tuning methods taken into account include empirical formulae, analytical methods and frequency-domain methods. The standard PID transfer function *C(s),* and IPDT process transfer functions *P(s)* are:

$$C(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) / \left(T_f s + 1\right); \quad P(s) = K / s\, e^{-Ls}, \tag{4.1}$$

where K_p, T_i, T_d, T_f are the PID parameters (including filter), and K in the gain and L is the dead time of the IPDT process.

The first order Pade approximation for dead time: $e^{-Ls} = \left(1 - \frac{L}{2}s\right) / \left(1 + \frac{L}{2}s\right)$

can be used. Five PID tuning methods for IPDT process are shortly presented, pointing out the specific PID parameter design, particularized for the greenhouse climate model. In our particular case K = 1 and L = 30 s.

A comparative study of system performances using different PID tuning methods is performed with a setpoint step change for greenhouse temperature and humidity.

4.1.1. Ziegler–Nichols Rules

One of the well-known empirical PID-controller tuning methods is the Ziegler–Nichols empirical formulae [ZIE'42] for parametric model (Table 4.1). Ziegler–Nichols tuning provides good load disturbance rejection.

Table 4.1. Ziegler–Nichols PID tuning rules base on parametric model

	K_p	T_i	T_d
PI	0.9/(KL)	3L	-
PID	1.2/(KL)	2L	L/2

PID parameters: K_p=0.04, T_i= 60, T_d= 15, β=0.4; and for PI: K_p= 0.03, T_i=90. As can be seen further in this chapter, in Table 4.6, and Fig. 4.2a, 4.3a (subchapter 4.2), the step response is oscillatory with a big overshoot. By using a set-point weight β<1, the overshoot is decreased but the settling time is almost double.

4.1.2. Internal Model Control

Internal Model Control (IMC) [MOR'89] is a controller design approach that uses the process model in the controller implementation. In Table 4.2, two approaches are considered: one to minimize the integrated square error (ISE) and the other to minimize the integrated absolute error (IAE). The choosing of the tuning parameter λ is a compromise between the system robustness and speed response. There are different suggestions for λ choosing, e.g.,: $\lambda = L\sqrt{10}$ [ARB'07].

Table 4.2. IMC-based PID tuning rules

	K_p	T_i	T_d	T_f
ISE optimal	$\frac{3L+2\lambda}{2L^2+4\lambda L+\lambda^2}$	$3L+2\lambda$	$\frac{2L(L+\lambda)}{3L+2\lambda}$	$\frac{L\lambda^2}{2L^2+4\lambda L+\lambda^2}$
IAE optimal	$\frac{2}{L+\lambda}$	$2(L+\lambda)$	$\frac{L(L+2\lambda)}{2(L+\lambda)}$	

PID parameters for $\lambda=L\sqrt{10}$ are: K_p=0.012, T_i= 279, T_d= 26.8, T_f= 12.2 for ISE optimal; and K_p= 0.016, T_i=249, T_d= 26.4 for IAE optimal.

By using these two PID tuning methods, a small overshoot and a satisfactory rise time is obtained as it can be seen in Table 4.6 and in Fig. 4.2b, 4.3b (subchapter 4.2).

4.1.3. Closed-loop Transfer Function Coefficients Matching

For the systems where the set-point following performance is important, a solution for PID tuning is presented in [CHI'03]. The proposed tuning method consists in matching the coefficients of the nominator and denominator polynomial of the close-loop transfer function. Based on this method, the tuning rules for PI and PID controller are presented in Table 4.3.

Table 4.3. PID tuning rules based on coefficients matching of the closed-loop transfer function

	K_p	T_i	T_d
PI	$\frac{2\alpha}{KL(1+\alpha)}$	$0.5L\left(\frac{1+\alpha}{\alpha-1}\right)$	-
PID	$\frac{4\alpha^2}{KL(1+\alpha^2)}$	$0.5L\left(\frac{1+\alpha}{\alpha-1}\right)$	$0.25L\left(\frac{1+\alpha}{\alpha}\right)$

In [CHI'03] it is suggested to choose α =1.25.

PID parameters for α=1.25 are: K_p=0.02, T_i=135, T_d=13.5; and for PI: K_p=0.04, T_i=13. Both controllers present high oscillation and a big overshoot that leads the fan ventilation command into saturation.

4.1.4. Direct-Synthesis-Based Design

To increase the system performances described in section 4.1.3, a filtered PID controller can be used. To tune this controller (Table 4.4), the direct synthesis method [SES'09] is used based on a desired closed-loop transfer function selection.

Table 4.4. PID tuning rules based on direct-synthesis design

K_p	T_i	T_d	T_f
$\frac{2\lambda+1.5L}{K(\lambda^2+2\lambda L+0.5L^2)}$	$2\lambda+1.5L$	$\frac{L\lambda+0.5L^2}{2\lambda+1.5L}$	$\frac{0.5\lambda^2 L}{\lambda^2+2\lambda L+0.5L^2}$

It is suggested to choose $\lambda\in$ [0.8L, 3L], and to use a set-point weight $\beta\in$ [0.3, 0.4] to reduce the step response overshoot [9].

PID parameters for $\lambda=L$ are: K_p=0.03, T_i= 105, T_d= 12.8 and T_f= 4.28. The system response using this tuning method presents a high overshoot and a high settling time comparing with IMC-based tuning methods.

4.1.5. Specification of Desired Control Signal

A PID tuning method based on the specification of the desired control signal is proposed in [WAN'97] based on appropriate selection of the transfer function between the set-point variable (reference) and the control variable u. For a damping factor ξ = 0.707, the PID parameters are given in Table 4.5.

Table 4.5. PID tuning rules based on specification of desired control signal

K_p	T_i	T_d
$\frac{1}{KL}\frac{1}{0.7318\alpha+0.3904}$	$L(1.402\alpha+1.208)$	$\frac{1}{KL}\frac{1}{1.417\alpha+1.7}$

where the parameter α is chosen as a trade-off between the system speed response and the robustness. PID parameters for α=1 are: K_p=0.03, T_i=78.3, T_d= 0.01.

In conclusion, comparing the above tuning techniques it can be seen that for step change reference the smallest settling time is obtained for Ziegler-Nichols PID tuning rules, and the smallest overshot for IMC based IAE/ISE optimal tuning.

4.2. Comparison Simulation Results Using PID Tuning Methods

For the simulation tests, a greenhouse area of 1000 m^2 with 4 m height, thus V=4000 m^3 is considered. A shading screen that reduces the solar radiation in the greenhouse by 60% is used. Maximum ventilation rate is $\dot{V}_{max}$ =22.2 m^3/s, and the maximum water capacity of the fog system is Q_{fog_max}=1.233 kg H_2O/s. β_T is considered negligible, α =0.1249 and λ=2257 J/g. The dead times for both state variables are considered the same d_1=d_2=L=30s. Due to physical constraints, the command variables u_1 - ventilation rate and u_2 - water capacity of the fog system are limited to specific maximum values.

Three simulation test scenarios are considered to compare the control system performances with different PID controller tuning-methods: set-point step changes, set-point ramp changes and disturbances step changes.

4.2.1. Set-Point Step Changes

In the first simulation test (Fig. 4.2 - Fig. 4.5), a set-point step change is considered for both greenhouse inside air temperature T_{in} and absolute humidity w_{in}, successively applied. The initial output variable values are: x_1 = T_{in} = 30 ^oC, x_2 = w_{in} = 0.018 kg H_2O/m^3 and for external disturbances: v_1 = 300W/m^2 10^3 m^2 (Si), v_2 = 35 ^oC (T_{out}), v_3 = 0.004 kg H_2O/m^3 (w_{out}) Fig. 4.6.

A step set-point for humidity x_2* = w_{in}* = 0.024 kg H_2O/m^3 is applied at t =2000 s succeeded by a step set-point for inside air temperature x_1* = T_{in}* = 35 ^oC at t = 4000 s. For this setup, a comparison analysis of system performances employing nine PID/PI controller tuning methods is given in Table 4.6.

Note that in Fig. 4.4-4.5, the command u_1 and u_2 are saturated, thus the temperature and humidity decoupling control can no longer be achieved through the intermediary commands $\hat{u}_1$ and $\hat{u}_2$. As a result, in Fig. 4.3 the temperature T_{in} oscillates at t = 2000 s when the humidity set-point is changed, and in Fig. 4.2 the humidity w_{in} oscillates at t = 4000 s when the temperature set-point is changed.

Table 4.6 . Step response performance criteria for greenhouse temperature and humidity set point step changes for PID controller tuning methods: 1) Ziegler-Nichols (Z-N) PID, 2) Z-N PID with set-point weight, 3) Z-N PI, 4) IMC-IAE PID, 5) IMC-ISE PID, 6) Closed-loop transfer function coefficient matching PID, 7) Closed-loop transfer function coefficient matching PI, 8) direct synthesis based design PID, 9) desired control signal based specification PID.

	Humidity unit-step response performance			Temperature unit-step response performance		
	Max. overshoot(%)	Rise time (s)	Settling time(s)	Max. overshoot(%)	Rise time (s)	Settling time (s)
1	29.2%	94	484	10.6%	20	246
2	27.5%	113	921	12.6%	46	604
3	26.7%	77	519	17.0%	21	312
4	7.5%	106	713	3.7%	87	612
5	7.9%	106	675	4.2%	88	586
6	20.0%	106	478	6.4%	48	336
7	22.1%	86	578	17.4%	81	313
8	17.1%	112	971	9.2%	79	690
9	28.8%	75	600	19.1%	21	394

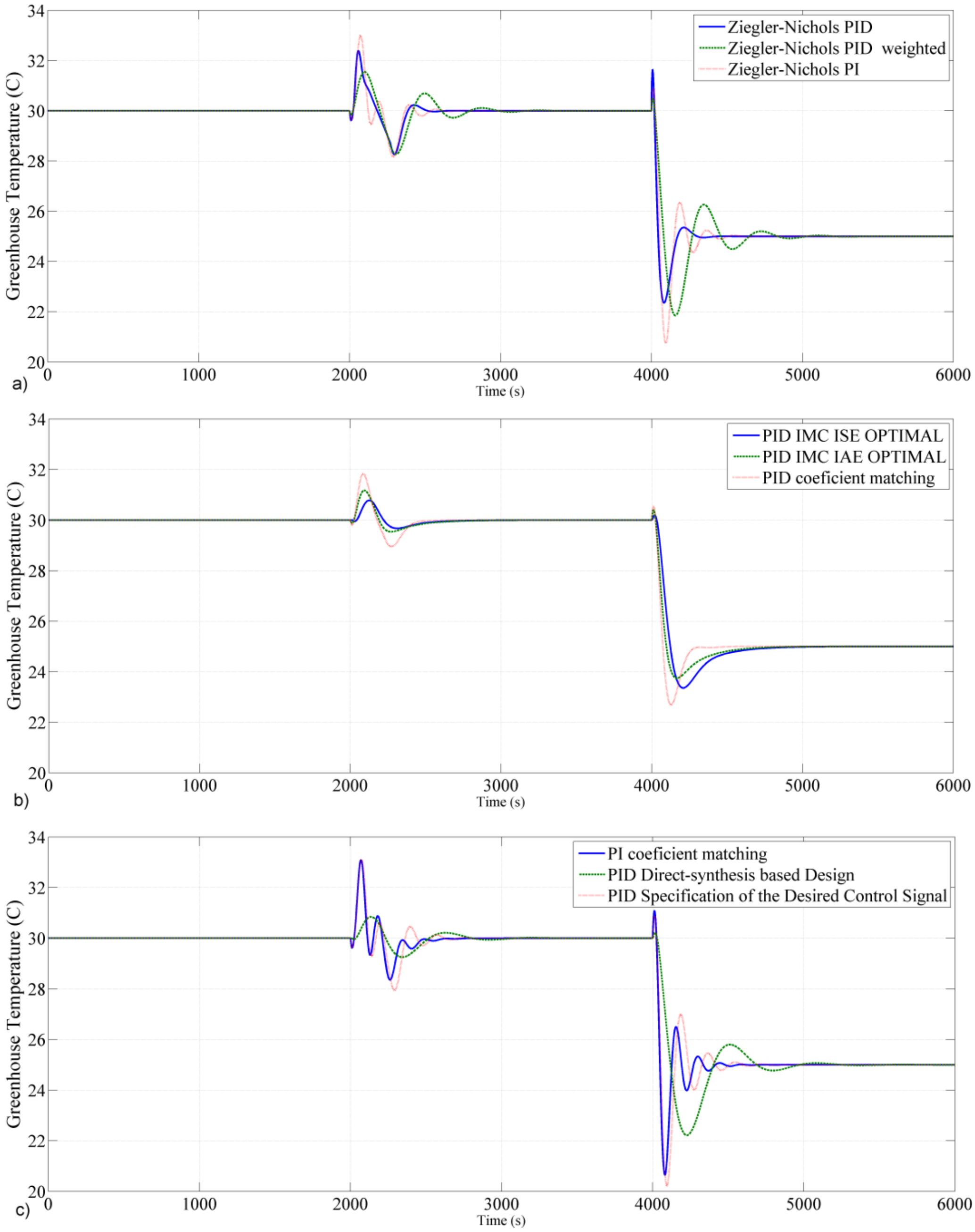


Fig. 4.2. Greenhouse temperature (T_{in}) responses for step set-point change in humidity (t=2000s) and temperature (t=4000s) using the following controller tuning methods: Ziegler-Nichols PID/PI, Ziegler-Nichols PID with sp. weight, IMC ISE/IAE optimal PID tuning, Closed-loop transfer function coefficient matching PID/PI, desired control signal based specification PID.

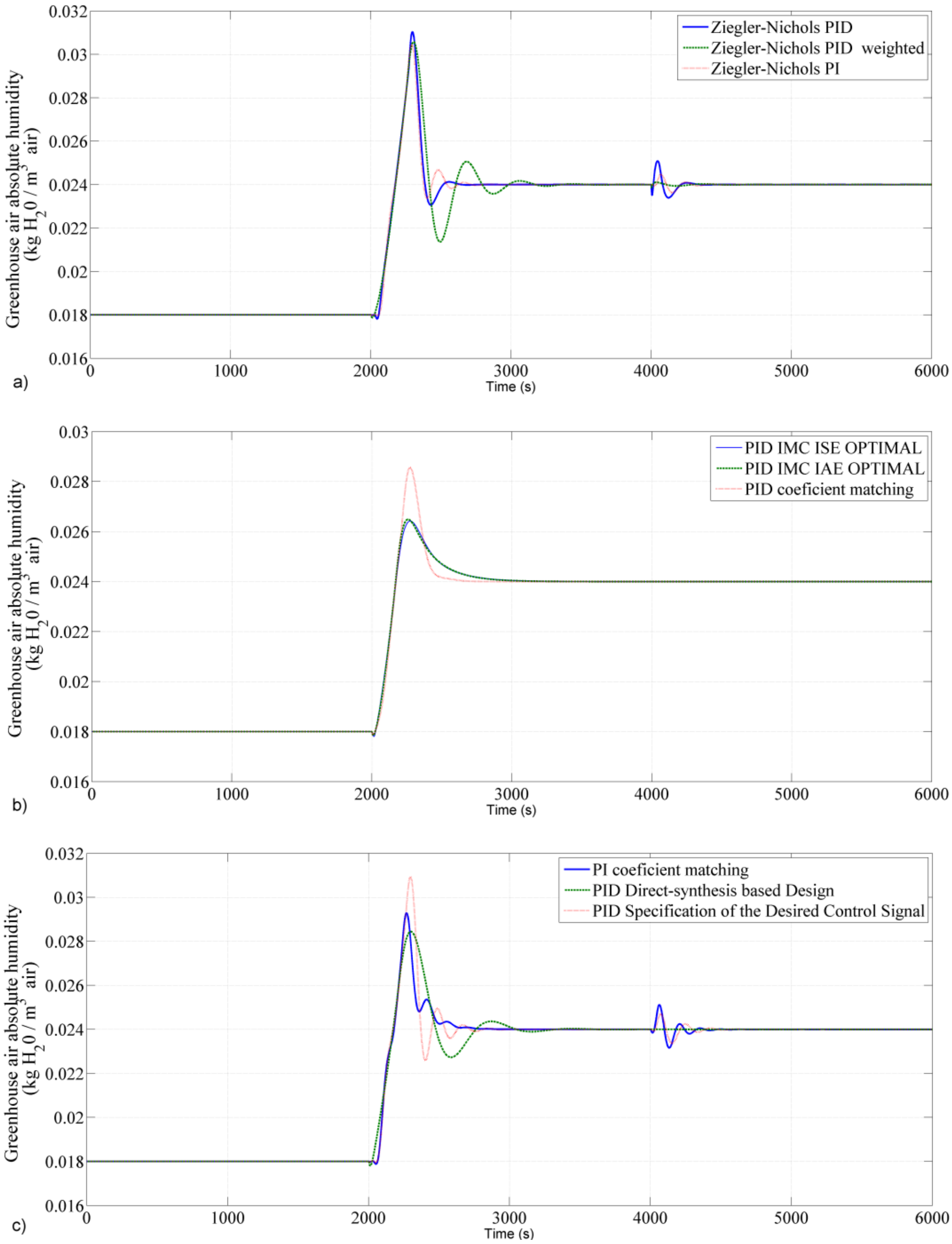


Fig. 4.3. Greenhouse humidity (w_{in}) responses for step set-point change in humidity (t=2000s) and temperature (t=4000s).

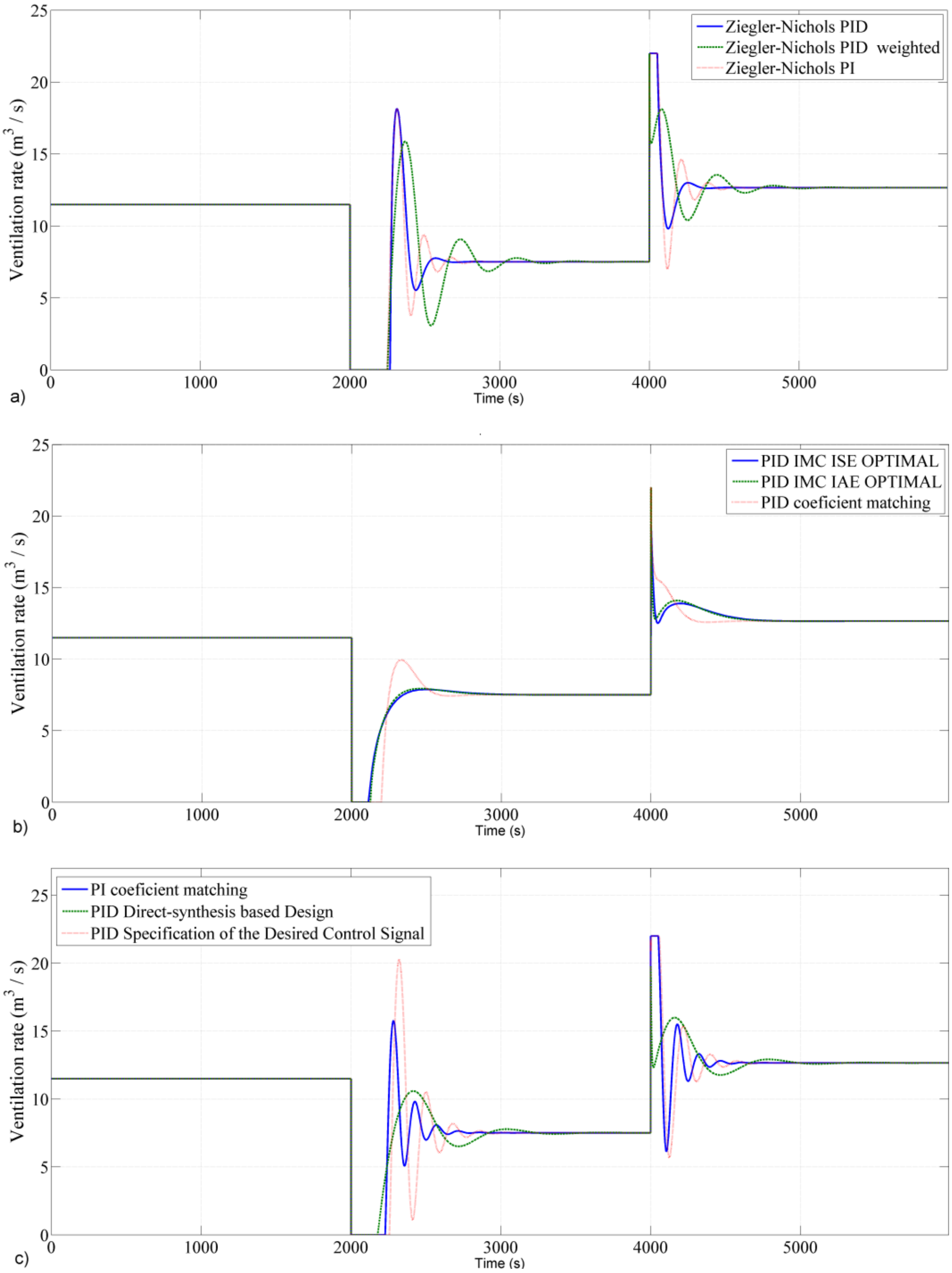


Fig. 4.4. Greenhouse ventilation rate control (u_1) responses for step set-point change in humidity (t=2000s) and temperature (t=4000s).

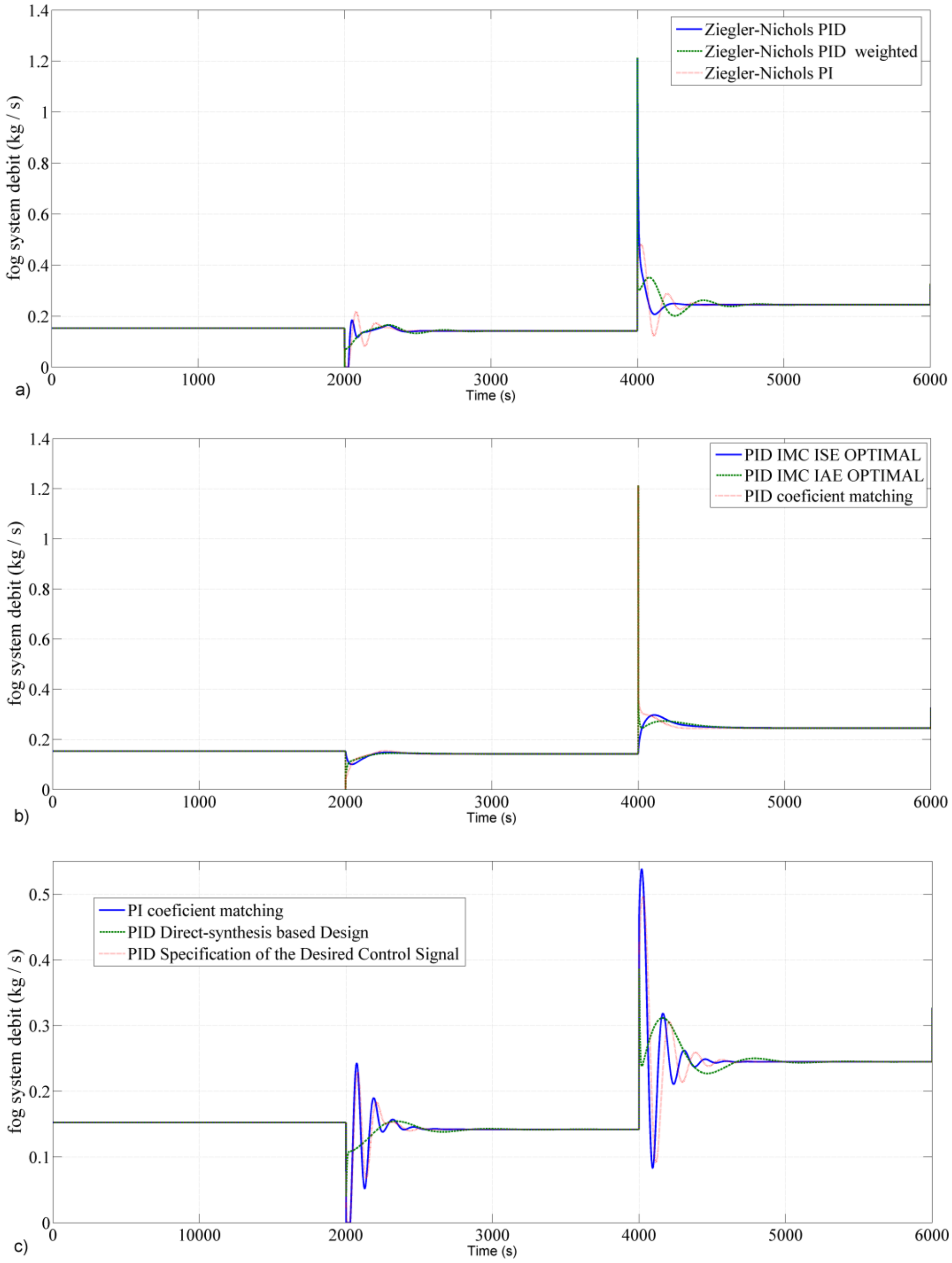


Fig. 4.5. Greenhouse fog debit control (u_2) responses for step set-point change in humidity (t=2000s) and temperature (t=4000s).

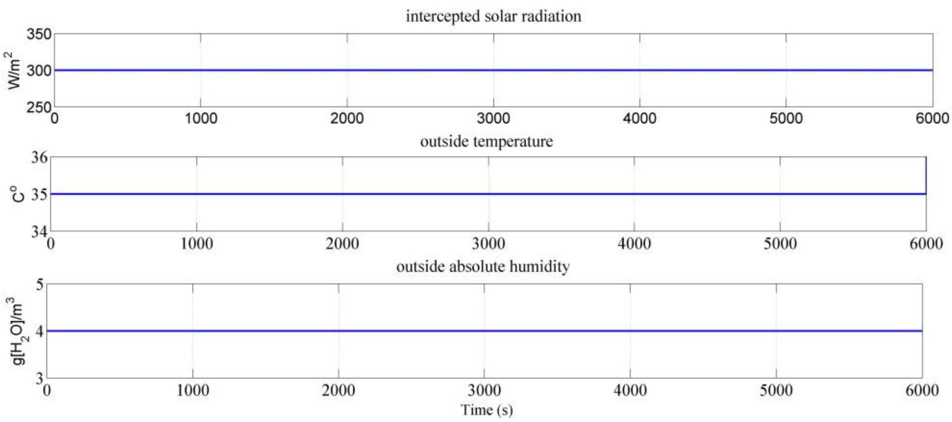
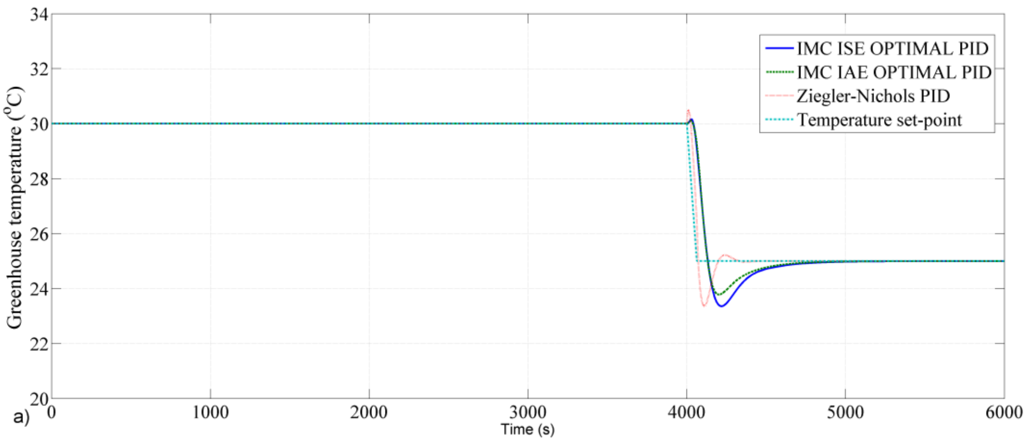


Fig. 4.6. External disturbances input set.

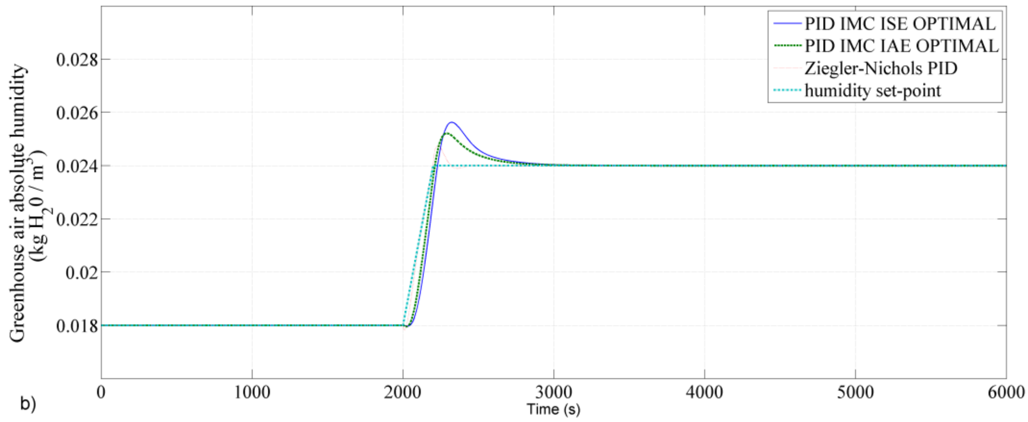
4.2.2. Set-Point Ramp Changes

In the second simulation test (Fig. 4.7), a set-point ramp changes are considered for both greenhouse inside air temperature and humidity. The initial conditions are the same as in the first case. A set-point ramp change with 150 s rise time is used for humidity set-point, and with 60 s rise time for temperature. Three PID tuning methods are considered: IMC-IAE, IMC-ISE and Ziegler-Nichols rules (Fig. 4.7) because they present the smallest overshot or settling time.

By using a set-point ramp changes, the control variables u_1 and u_2 are no longer limited, so the temperature and humidity control are completely decoupled. The performance of the IMC-based tuning methods remains similarly like in the case of set-point step changes. On the other hand, the Ziegler-Nichols PID tuning has a decreased settling time, just one third of the initial settling time, and most important, the maximum is the same as in the case of the IMC tuning.



a)



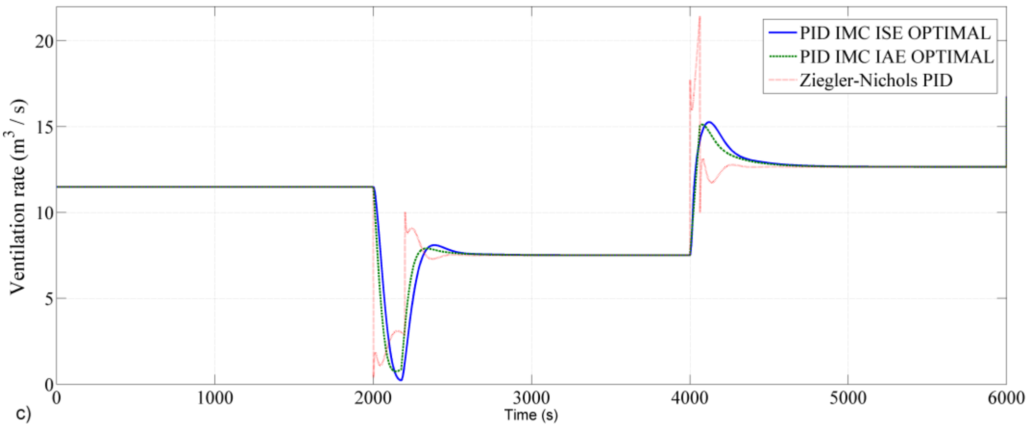


Fig. 4.7. Greenhouse temperature (T_{in}), humidity (w_{in}) and ventilation rate control (u_1) responses for ramp set-points change in humidity (t=2000s) and temperature (t=4000s) using the following controller tuning methods: Ziegler-Nichols PID, IMC ISE/IAE optimal PID tuning

4.2.3. Step Changes in Disturbances

The third simulation test (Fig. 4.8.) proves that the feedback-feedforward linearization and decoupling procedure succeeds to compensate for external disturbances. The initial conditions are the same as in the first case. The disturbance step changes are as following:

at t = 1000s v_1 changes from 300 to 150 W/m^2·10^3 m^2;
at t = 2000s v_2 changes from 35 ^{o}C to 37 ^{o}C;
at t = 3000s v_3 changes from 0.004 to 0.002 kg H_2O/m^3.

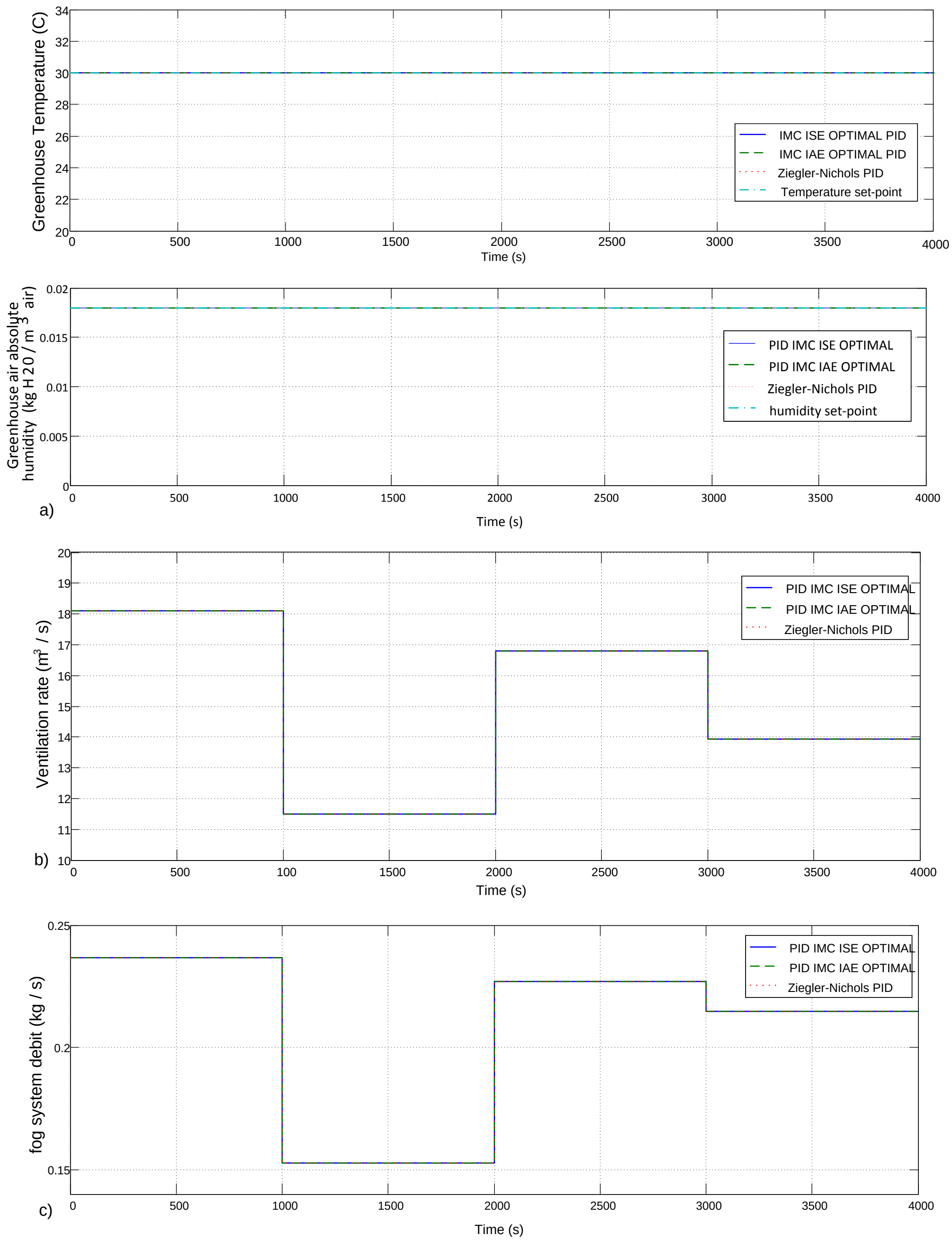


Fig. 4.8. System responses at disturbance step changes: a) Temperature and humidity output variable, b) Ventilation rate control (u_1), c) fog debit control (u_2) for step changes in external disturb.: at t = 1000s v_1=150W/m^2·10^3 m^2; t = 2000s v_2= 37 ℃; t = 3000s v_3=0.002 kg/m^3 using the following controller tuning methods: Ziegler-Nichols PID, IMC ISE/IAE optimal PID.

4.3. Greenhouse Model Parameter Variations

From the nonlinear strongly coupled model of the greenhouse climate system (3.2a,b), there are identified terms (parameters and disturbances) which are considered susceptible to modeling uncertainties. The problem has a high importance because the process is nonlinear and coupled, and after the linearization and decoupling procedure, the complex command variables u_1 and u_2 (3.8a,b) are highly influenced by wrong parameter/ disturbance estimation that affects the ideal decoupling.

Wrong estimation of the heat transfer coefficient (U_A), the shading and leaf area index coefficient (α), and the intercepted solar radiant energy (S_i) are taken into consideration in the study of system responses. A factor between 0.6 and 1.9 is considered in simulation for selected parameter variation.

The solar radiation energy (S_i) is selected because it is not obtained from sensors placed in the greenhouse proximity, but by using approximated information from near meteorological stations.

When varying the intercepted solar radiant energy (S_i) or the shading and leaf area index coefficient (α), the system response is highly influenced when a humidity set-point step change occurs. On the other hand, in the same conditions, the influence is negligible for a temperature set-point step change. Wrong estimation of the heat transfer coefficient (U_A) has a greatest impact on overall system response (maximum overshot and settling time) as can be seen in chapter 4.5. In order to obtain a robust system to parameter variations and disturbance uncertainties, the previous 1DoF controller is replaced by a 2DoF controller.

4.4. 2DoF Controller Tuning Methods for IPDT Process

In control system, the degree of freedom represents the number of closed-loop transfer functions that can be independently tuned [HOR'63]. The closed loop control system presented in fig. 4.9 can describe a 1DoF or 2DoF control system.

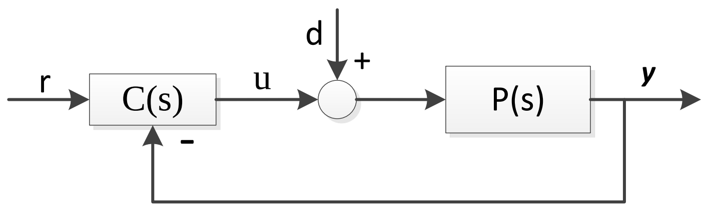


Fig. 4.9. Standard closed loop control system structure

For 1DoF controller, the control is based on the error signal. For 2DoF controller, the control is split in two components, with different weights for the proportional and derivative terms. One component is applied on the system output and the other on the reference signal. In industry, the PID controllers predominate in usage. In a survey of 11,000 controllers, over 97% were feedback PID controllers [DES'02]. The highly usage is based on the controller simple structure and its simplicity, having just three parameters that have to be tuned. For the integrating processes, the most used controller is the 1DoF feedback structure with PID controller [DWY'09]. In industry, the predominated situations employ the setpoints that remains constant, and the controller is tuned for load and disturbance rejection [SHI'02]. In this case, one problem is the setpoint following performance.

A solution that permits selecting servo control performance (system behavior referred to setpoint input) and regulatory control performance (system behavior referred to disturbance input) was proposed by Araky [ARA'03] by introducing the two-degree-of-freedom (2DoF) controller.

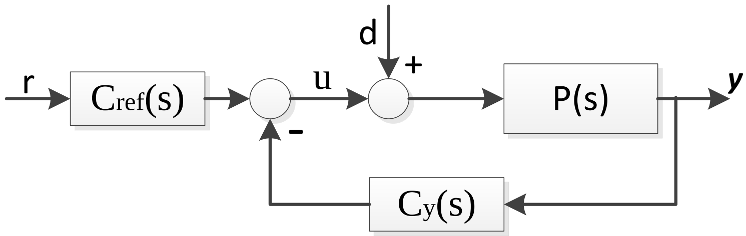


Fig. 4.10. 2DoF control system structure

For the 2DoF system from Fig. 4, the closed loop transfer functions for the servo control loop and regulatory control loop are:

$$y(s)/r(s) = \frac{C_{ref}(s)\cdot P(s)}{1+P(s)\cdot C_y(s)} \quad (4.2a)$$

$$y(s)/d(s) = \frac{P(s)}{1+P(s)\cdot C_y(s)} \quad (4.2b)$$

The command *u(t)* is composed from three components, i.e., the proportional, derivative and integral parts.

The proportional (u_p) and derivative command (u_d) terms of u command include the setpoint weights β and γ, respectively:

$$u_p = K_p\left(\beta r(t) - y(t)\right) \quad (4.3a)$$

$$u_d = K_p T_d\left(\gamma\frac{d}{dt}r(t) - \frac{d}{dt}y(t)\right) \quad (4.3b)$$

The command u(t) is summarized as:

$$u(t) = K_p\left[\beta r(t) - y(t) + 1/T_i\int_0^t e(t)dt + T_d\left(\gamma\frac{d}{dt}r(t) - \frac{d}{dt}y(t)\right)\right] \quad (4.4)$$

Where *C(t)* can be seen as composed of two controllers, $C_{ref}(t)$ and $C_y(t)$:

$$u(t) = C_{ref}(t)\cdot r(t) + C_y(t)\cdot y(t), \quad (4.5)$$

where $C_{ref}(t)$ is the set-point controller transfer function and $C_y(t)$ is the feedback controller transfer function.

Considering the two controllers, the desired performance in the case of set-point changes and load-disturbance can be addressed separately (2DoF control).

The control architecture makes possible to achieve servo control and regulatory control specification by proper tuning of the two controllers.

If β and γ are selected to be equal to 1, the two transfer functions $C_{ref}(t)$ and $C_y(t)$ are equal and one-degree-of-freedom (1DoF) controller is obtained.

For 2DoF control structure, usually the first step is to consider the regulatory control performance. After that, the servo control performance can be set by selecting β and γ. For the proportional term β, values in [0 1] interval can be considered. If a step input is applied to the set-point, it is recommended to avoid high instantaneous change due to derivative term, also known as derivative-kick. In this case $\gamma = 0$, and thus the derivative action is not applied on the error signal, but on the system output. There are also 2DoF controller tuning techniques where the set of tuning parameter are determined at once, both regulatory and servo control performance have been considered at the same time.

In [ALF'12] was proposed a PI 2DoF tuning method for IPDT processes. The proposed model reference robust tuning (MoReRT), considers a damping ratio of 0.8 for the regulatory and servo control loops and also the close loop system robustness. The 2DoF PI tuning parameters are presented in table 4.7.

A tuning technique based on the multiple dominant pole (MDP) method for IPDT was proposed in [VIT'08], [VIT'11]. This method ensures that the system response has no overshoot and no oscillation. The set of tuning parameters are presented in table 4.7, where T=0 for analog 2DoF PI controller.

Huba [HUB'11] propose a 2DoF tuning method based on performance portrait method. This tuning method imposes a transient response considering the specific deviation from ideal form at the process input and output, and also uses IAE optimization. The set of tuning parameters are presented in table 4.7.

Table 4.7. 2DOF PI parameters for IPDT process, tuned by: 1) model reference robust tuning (MoReRT); 2) multiple dominant pole (MDP); 3) performance portrait method (PPM)

	K_p	T_i	β
1	$0.599/(K\cdot L)$	$4.802\cdot L$	0.477
2	$\dfrac{0.461}{\left[K\left(L+\frac{T}{2}\right)\right]}$	$5.82(L+T/2)$	$0.293\cdot\dfrac{L}{L+\frac{T}{5}}$
3	$0.5776/(K\cdot L)$	$4.4796\cdot L$	0.3

4.5. Comparison Simulation Results Using PID 1DoF and 2DoF Tuning Methods

The greenhouse clime model has the following set of parameters used in simulation. A floor area of 500 m^2, with a gable roof structure having a covered area of 2000 m^2 and a total volume of 1500 m^3 is used. The transmittance of shading screen is of 40%. The imposed actuator limitations are: 22 m^3/s for the ventilator, and a debit of 1.2 kg H_2O/s for the fogging system. A 30 s dead time for both state/output variables are considered.

The initial values for the process disturbances are: 300 W/m^2 for intercepted solar radiant energy, 35 ^oC for outside temperature and 0.04 kg H_2O/m^3 for exterior absolute humidity. The state variable initial conditions are: inside temperature of 30 ^oC, and inside absolute humidity of 0.018 kg H_2O/m^3.

For testing the servo control performance, a setpoint step change is used for the two system references. Firstly, at 2000 s a absolute humidity step setpoint change from 0.018 kg H_2O/m^3 to 0.024 kg H_2O/m^3 is performed, followed at 4000 s by a temperature step setpoint change from 35 ^oC to 30 ^oC.

As previously presented, using this setup and without parameter variations, a comparison study of system performances employing nine PID/PI controller tuning methods was performed in [GUR'12]. The smallest settling time is obtained for Ziegler-Nichols PID tuning rules, and the smallest overshot for Internal Model Control based IAE/ISE optimal tuning (table 4.8).

4.5.1. System Response Considering System Parameters and Disturbance Estimations Uncertainties using 1DoF PID Controller

In this subchapter, the performances of three PID tuning techniques for IPDT processes are compared taking into account the parameter uncertainty (U_a, α), or wrong disturbance measurement (S_i).

The scenarios taken into account are:

a) for Ziegler-Nichols PID: 1.1) U_A = U_A_proc * 1.4, 1.2) U_A = U_A_proc * 1.9, 1.3) U_A = U_A_proc * 0.6, 1.4) α = α _process * 1.4, 1.5) α = α _process * 0.6, 1.6) S_i_process = S_i*1.5;

b) for IMC-ISE PID 2.1) U_A = U_A_proc * 1.4, 2.2) U_A = U_A_proc * 1.9, 2.3) U_A = U_A_proc * 0.6;

c) for IMC-IAE PID 3.1) U_A = U_A_proc * 1.4, 3.2) U_A = U_A_proc * 1.9, 3.3) U_A = U_A_proc * 0.6.

In this case, as can be seen in table 4.8, a decrease in performance is observed for wrong approximation of the: heat transfer coefficient (U_A), shading and leaf area index coefficient (α), and intercepted solar radiant energy (S_i).

Table 4.8. Step response performance of greenhouse climate system considering parameter variations, (U_A, α), and disturbance estimation uncertainty of intercepted solar radiant energy (S_i) for set point step changes of temp. and humid., using 3 PID controller tuning methods.

scenario	Humidity unit-step response performance			Temperature unit-step response performance		
	Max. overshoot	Rise time (s)	Settling time(s)	Max. overshoot	Rise time (s)	Settling time (s)
1.1	29.2%	94	486	12.6%	20	268
1.2	27.2%	92	486	15.7%	21	374
1.3	26.2%	94	519	8.68%	20	246
1.4	27.50%	113	921	10.6%	20	246
1.5	29.2%	94	519	10.6%	20	246
1.6	29.2%	110	410	10.6%	20	246
2.1	7.50%	108	486	8.6%	75	697
2.2	7.92%	110	720	17.9%	67	1525
2.3	7.50%	104	720	0.4%	120	180
3.1	7.92%	107	677	7.76%	79	596
3.2	7.92%	109	680	13.8%	72	978
3.3	7.92%	105	673	1.4%	105	427

The comparison evaluates the rise time, settling time and maximum overshot in the case of absolute humidity and temperature setpoint step change for different variation of the identified possible model uncertainties.

To analyze the system performance to parameter variations, the following multiplication coefficients for control system applied to nominal process values of the specific parameters are considered: 0.6, 1.4 and 1.9 for the estimated heat transfer coefficient (U_A); 0.6 and 1.4 for the shading and leaf area index estimated coefficient (α); and finally a deviation of 50% for the intercepted solar radiant energy (S_i).

When Ziegler-Nichols PID controller is used, the greatest influence in system response is observed for U_A parameter modeling error. Therefore, the IMC ISE and IAE are tested just for U_A parameter deviation.

For U_A multiplication coefficient of 1.9, the system responses at temperature step setpoint change present the following performance degradations (considering parameter uncertainty case vs. nominal case, i.e., the difference of quality indicators): i) for Ziegler-Nichols PID tuning: 5.1% for the maximum overshot and 52% for the settling time; ii) for the IMC ISE PID tuning: 14.2% for the maximum overshot and 149% for the settling time; and iii) for the IMC IAE PID tuning: 9.6% for the maximum overshot and 66% for the settling time.

In conclusion U_A is the most important parameter in robustness study because it induces the highest system performance degradation. Therefore, in the next subchapter, only U_A parameter variation will be considered.

4.5.2. System Response Considering System Parameter Uncertainty using 2DoF PID Controller

Considering identical simulation conditions, the performance of 2DoF PID controller based on Ziegler-Nichols PID tuning methods is studied, where $C_y(s)$ is tuned according to Ziegler Nichols, and $C_r(s)$ set point weights are β=0.1 and γ=1. A considerable improvement in the system response overshoot is observed in Table 4.9.

Comparing the nominal model and the uncertainty model, using 1DoF Z-N PID controller leads to the saturation of the system input variables (u_1 and u_2) (Fig. 4.11c,d. Consequently, the temperature and humidity decoupling control is no longer achieved through the intermediary commands $\hat{u}_1$ and $\hat{u}_2$. As a result, the temperature T_{in} oscillates at t = 2000 s (Fig. 4.11a) when the humidity set-point is changed, and the humidity w_{in} oscillates at t = 4000 s (Fig. 4.11b) when the temperature set-point is changed.

When using 2DoF controller, at temperature set-point change, the humidity doesn't oscillate because the actuators don't enter into saturation. By employing a 2DoF PID control structure, using the Ziegler-Nichols tuning rules for greenhouse climate control, not only improves the system response at setpoint step changes, but also in the case of wrong parameter/disturbance estimation. In the case of MoReRT 2DoF tuning technique, the system does not show any overshoot and the settling time is acceptable when the parameter uncertainty is not considered. When U_A is wrongly estimated, a small overshoot (5%) is seen at temperature set point step change.

If MDP method for IPDT [VIT'08] was considered, the system response presents good settling time, no oscillation with 0% overshoot for both system outputs. The robustness of this methods shows it's limitation when the same parameter (U_A) variation is considered as in the previous case. The overshoot is 7.2% but the settling time significant increases.

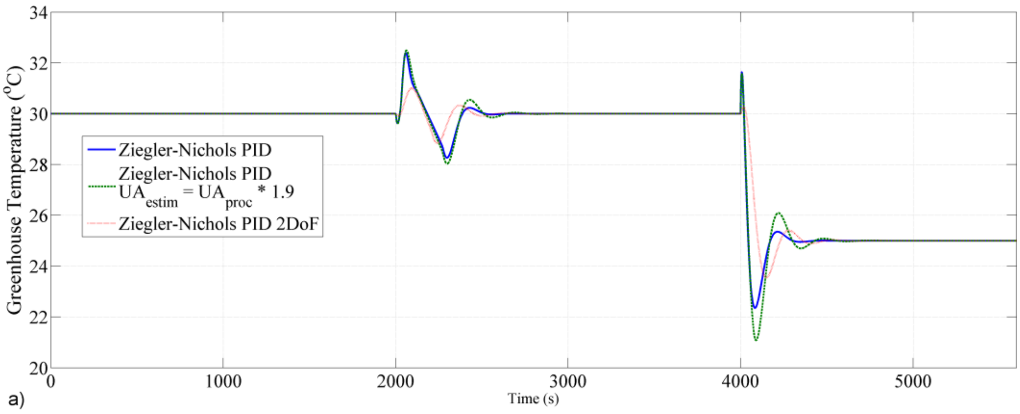
For Huba 2DoF tuning method [HUB'12], very good performance is obtained for humidity setpoint step change with and without U_A uncertainty considered. This tuning method gives the best response for nominal process. If wrong estimation of U_A is considered, better system response comparing with MDP method is obtained.

The scenarios taken into account are:

a) for Ziegler-Nichols PID: 1.1) U_A = $U_{A_}$proc, 1.2) U_A = $U_{A_}$proc * 1.9;
b) for Ziegler-Nichols 2Dof PID: 1.3) U_A = $U_{A_}$proc, 1.4) U_A = $U_{A_}$proc * 1.9;
c) for 2DoF MORERT: 2.1) U_A = $U_{A_}$proc, 2.2) U_A = $U_{A_}$proc * 1.9;
d) for 2DoF MDP: 3.1) U_A = $U_{A_}$proc, 3.2) U_A = $U_{A_}$proc * 1.9;
e) for 2DoF HUBA: 4.1) U_A = $U_{A_}$proc, 4.2) U_A = $U_{A_}$proc * 1.9.

Table 4.9. Step response performance of greenhouse climate system considering U_A parameter variation for set point step changes of temperature and humidity, using Ziegler-Nichols and 2DoF PID controller tuning methods.

scenario	Humidity unit-step response performance			Temperature unit-step response performance		
	Max. overshoot	Rise time (s)	Settling time(s)	Max. overshoot	Rise time (s)	Settling time (s)
1.1	29.2%	94	484	10.6%	20	246
1.2	27.2%	92	486	15.7%	21	374
1.3	15,8%	108	408	2%	59	200
1.4	16.6%	110	410	6%	50	313
2.1	0	115	173	0	145	301
2.2	0	116	173	5%	81	355
3.1	0	174	263	0	175	263
3.2	0	174	263	7.20%	107	700
4.1	1.25%	111	163	0%	109	171
4.2	1.25%	111	164	6.40%	81	528



a)

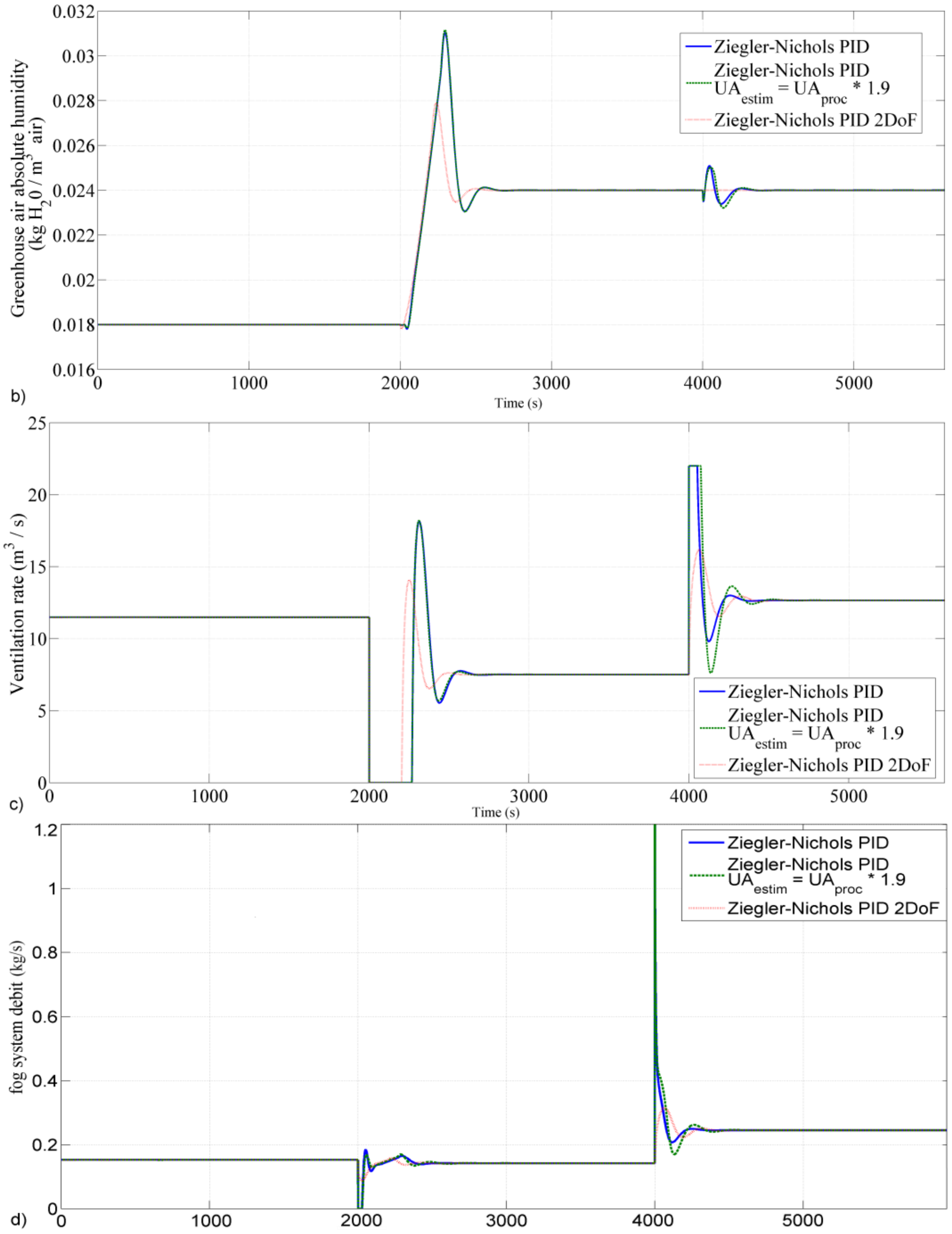


Fig. 4.11. Climate process outputs(y_1- temperature, y_2-absolute humidity), and control variable (u_1 –ventilation rate and u_2- H_2O debit) in the case of setpoint step variation using 1DoF Z-N PID controller with/without modeling uncertainty, and 2DoF Z-N PID and modeling uncertainty.

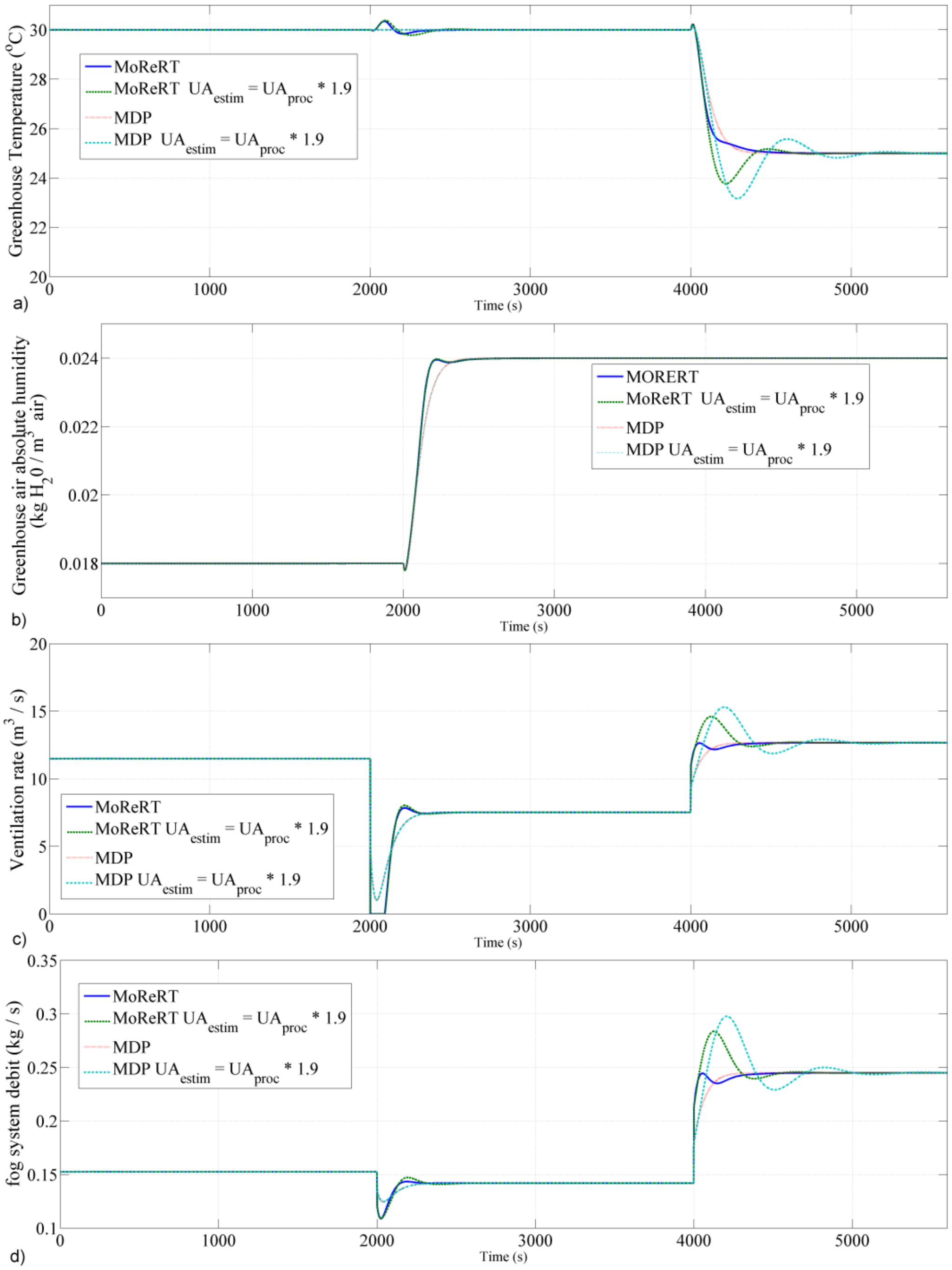


Fig. 4.12. Climate process outputs(y_1- temperature, y_2-absolute humidity), and control variable (u_1 –ventilation rate and u_2- H_2O debit) in the case of setpoint step variation using : model reference robust tuning (MoReRt), multiple dominant pole (MDP) tuning with/without U_A modeling uncertainty

4.6. Genetic Algorithms for PID Controller Tuning

4.6.1. Genetic Algorithms Methodology

The genetic algorithms (GA) are heuristic searches, inspired by the evolutionary species concept, used to determine a global suboptimal solution [FLE], [ZAL'99]. The PID parameter values from chapter 4.1 are considered as a proper basis for further investigations by using genetic algorithms to determine the parameters K_P, T_I, T_D of the PID controllers $C_1(s)$ and $C_2(s)$ according to a minimum cost function.

For the controller tunings using genetic algorithms, two milestones are necessary (m = 1, 2) with different scenarios for each stage. In the first stage $C_1(s)$ and $C_2(s)$ are considered identical, and then different in the second stage.

Every time, the tuning process by applying the GA approach follows the steps from Fig. 4.13 The explanations refer only to the first stage, in the second stage the things are similarly.

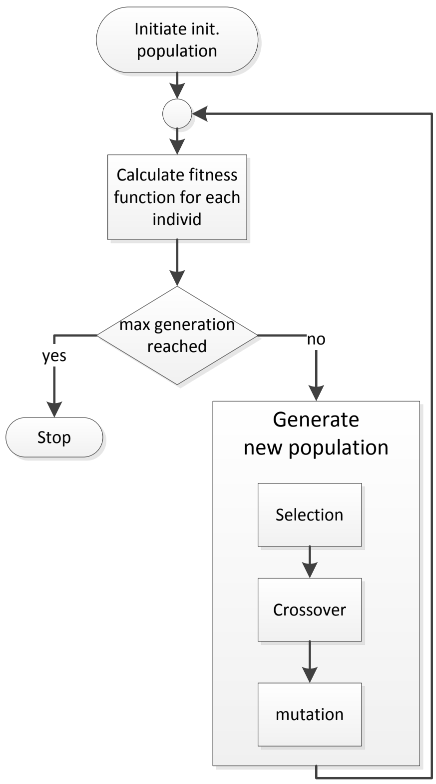


Fig. 4.13. Genetic algorithm flowchart.

- *Gathering of the initial population*

The evolutionary process starts from an initial population, i.e., generation $\ell = 0$, composed by n individuals: $\{(K_{Pij\ell}, T_{Iij,\ell}, T_{D,j,\ell})\}_{j=\overline{1,n},\ell=0}$ defined by the PID controller parameters. Each parameter plays the role of a chromosome that has three genes.

The initial population individual chromosomes can be generated automatically, can be defined by the user, or can combine the previous two situations. A set of n=10 individuals for each population are considered. Four of them are described in next subchapter 4.6.2 -Table 4.10. The rest of 6 individuals are randomly generated by the Matlab Optimization tool, where the initial interval, defined by the 4 parameter sets based on PID tuning techniques, is extended with ± 30%.

- *Evaluation of the current generation (ℓ) individuals*

Each individual from each generation, i.e., each controller, is evaluated through its effect on the corresponding control system. Due to the large manifold of possible effects in a control system, a relevant operating regime is chosen. For the evaluation of the system behavior in adopted regime, fitness functions J_m, $m=l$, are defined and a fitness value is computed for each individual. As evaluation criteria, the ascending order in respect to the computed values of J_m is considered: i.e., the individual with the lowest fitness value is viewed as the best and has the rank 1.

- *Inspection of stopping criteria*

As GA stopping criteria, the reaching of maximum number of generations is chosen. Hence, if $\ell < \ell_{max}$, where ℓ_{max} is the maximum number of generations, a new generation of n individuals is built. Otherwise, the GA is stopped.

- *Building of a new generation,* $\ell + 1$

A new generation is created using 3 basic evolution mechanisms: selection, crossover and mutation. The *selection* mechanism, based on the principle of elitism, decides to survive the best two individuals (rank 1 and rank 2) from each generation to the next generation. For obtaining the rest of 8 individuals of generation $\ell + 1$, the individuals of generation ℓ are playing the role of parents. For every new individual, a pair of parents, or only one parent is selected by roulette wheel selection method. In the first case, with a crossover fraction of 0.8, the *crossover* mechanism combines the characteristics of the selected pair of parents and generates new values for K_P, T_I and T_D. In the second case, the mutation mechanism changes randomly the value of one of the parameters T_I and T_D.
Finally, the new generation replaces the old generation of parents and the whole process restarts.

4.6.2. GA Initial Population of PID Controllers Tuned by Conventional Methods

A wide range of tuning methods for PID (and PI) controllers, based on empirical formulae, analytical methods and frequency-domain approaches, focused on integral plus dead-time processes, are available [ZIE'42]; [MOR'89]; [ARB'07]; [CHI'03]; [RAO'10]; [WAN'97]; [VIS'11]; [VIL'12].

Four of these methods, applied in [GUR'12] for a greenhouse climate system described at the top of Table 4.10, led to the results given in the same table. The control system design was done under the assumption that $C_1(s) = C_2(s)$. Where $C_1(s) = C_2(s)$ are the PID controllers transfer functions:

$$C_i(s) = K_{Pi}(1 + \frac{1}{T_{Ii}s} + T_{Di}s)\ , \quad i = 1 \text{ or } 2\ . \tag{4.6}$$

The control system structure chosen for the entire greenhouse climate system is illustrated in Fig. 4.14a, and it behaves as two decoupled conventional control loops like in Fig. 4.14b.

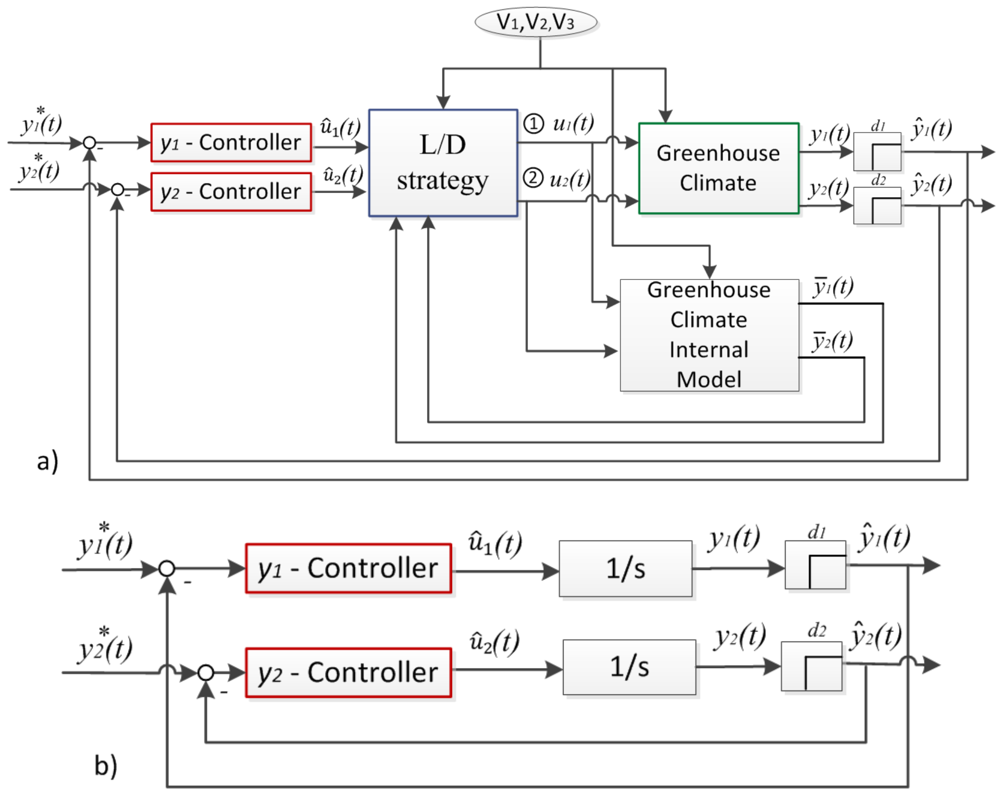


Fig. 4.14. (a) Greenhouse climate system for temperature and humidity control, and (b) equivalent decoupled control structure with time delay.

The following aspects were taken into account:

- The empirical tuning rules of Ziegler-Nichols are providing good load disturbance rejection performances, but not very good set-point following performance, and therefore, the obtained results should be considered as a starting point for further improvements.
- The analytical methods as Internal Model Control and Closed-loop Transfer Function Coefficients Matching, based on exploiting of the closed-loop system transfer function, are control design approaches characterized by an acceptable trade-off between nominal performance and robustness. But, this is done with the price of using Padé approximants for the exponential e^{-ds}, and thus, by transforming of an infinite dimensional system into a finite dimensional one of second order.
- The approach based on the specification of the desired control signal, that is a technique consisting in the selecting the transfer function between the set-point and the control variable in a given canonical form, has the disadvantage of using just a canonical form that is not physically realizable (a proper transfer function and not a strictly proper one).

Table 4.10. PID parameter values and simulation conditions

Greenhouse climate system description: · Floor area: 500 m^2; · Height: 4 m; · Volume: 2800 m^3; ·Solar radiation reduced inside the greenhouse by 50% (with a shading screen); · Control constraints: upper and lower bounds for the ventilation rate: u_{1max} = 22.2 m^3/s and 0 m^3/s, and for the fog system: u_{2max} = 1.2 kg H_2O/s and 0 kg H_2O/s; · α = 0.1249; and λ = 2257 J/g.

No.	PID tuning method	K_P	T_I [s]	T_D [s]	Design parameter
1	Ziegler-Nichols (M_1)	0.04	60	15	-
2	Specification of desired control signal (M_2)	0.03	78.3	0.01	$\xi = 0.707$ $\alpha = 1$
3	Closed-loop transfer function coefficients matching (M_3)	0.02	135	13.5	$\alpha = 1.25$
4	Internal model control (M_4)	0.016	249	26.4	IAE, $\lambda = d_i \sqrt{10}$

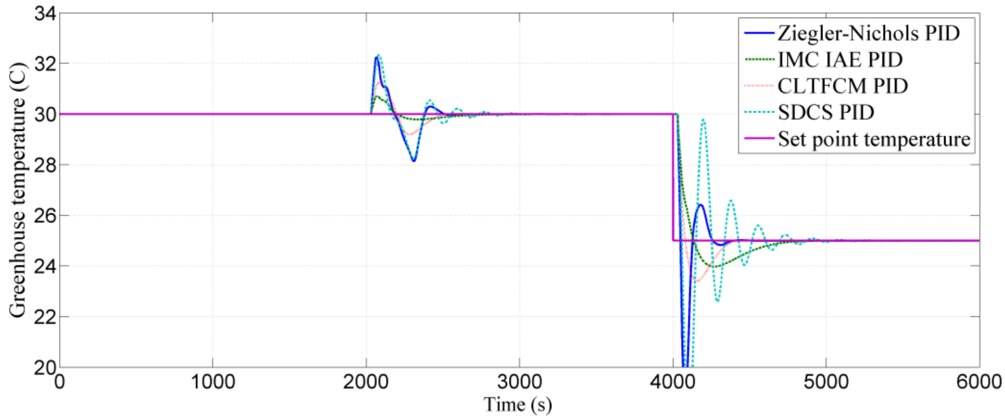
Where λ, α and ξ are specific design parameters [VIS'11].

An overview on the control system performances obtained using these controllers can be seen in Fig. 4.15 where a setpoint step change was used for greenhouse air temperature and humidity. First, y^*_2 is increased at t = 2000 s (Fig. 4.15b), than y^*_1 is decreased at t = 4000 s (Fig. 4.15a).

Some relevant aspects should be notice: i) Due to the limitations of u_1 (Fig. 4.15c) the decoupling is lost several times, so that both control loops react after every step (Figs. 4.15a, b). ii) The limitations of u_2 act in the same manner, but for a shorter time interval (Fig. 4.15d). iii) The most "nervous" system, but also the system with the shortest transient regime, is the control system tuned according to Ziegler-Nichols method (M1).

From Table 4.10, it is also obvious the scattering of controller parameter values. The explanation must be sought in relation with the realistic design assumptions and methodological peculiarities.

Except the requirement for stability, the design assumptions of the PID tuning methods M1,..., M4 are different. Therefore, it is useful to evaluate the behaviors of the four solutions by the same criteria, and to try to improve the solution by using genetic algorithms.



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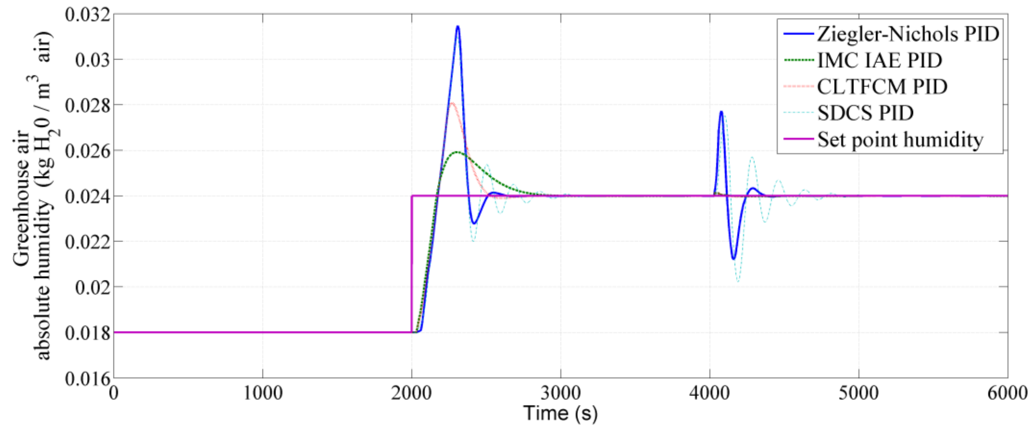

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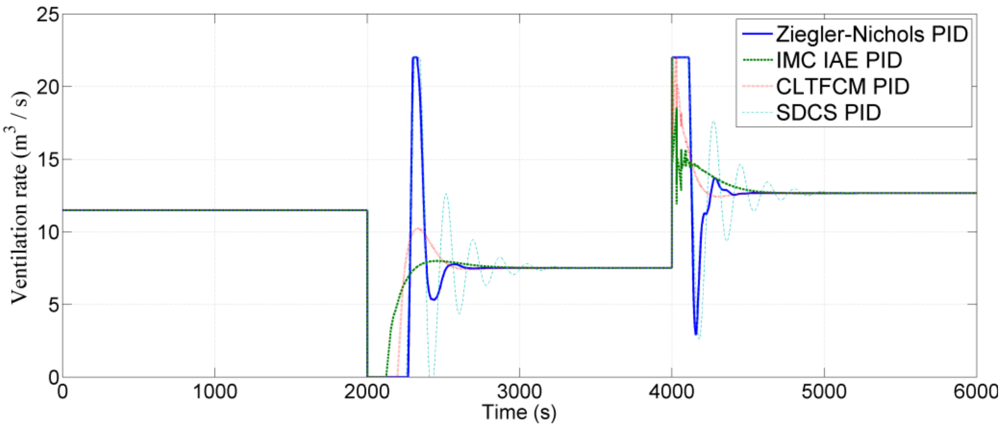

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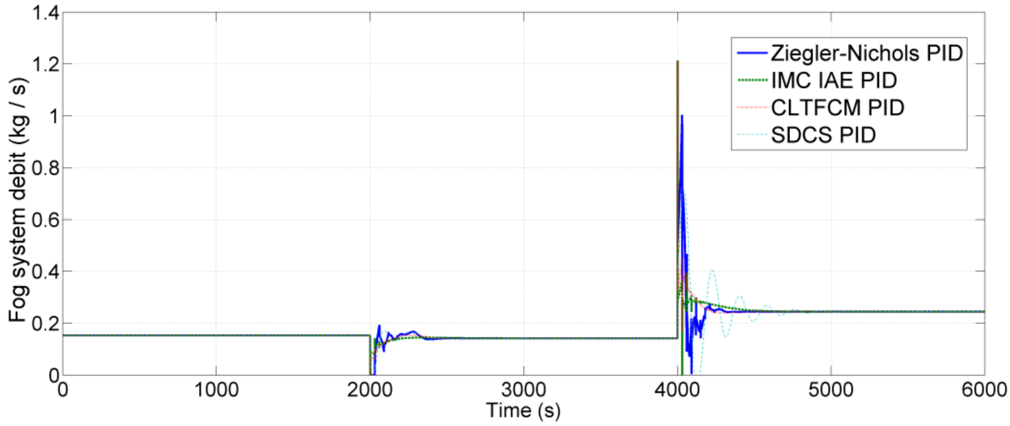


-d-

Fig. 4.15. Step responses of the control system from Fig. 4.14 with PID controllers tuned according to Table 4.10.

4.6.3. PID Controller Tuning by GA for Dusk Regime (Diurnal to Nocturnal Transient Regime) – A Case Study

The 1st relevant operating regime for the control system from Fig. 4.14 consists on a 6 minutes ramp set-point decrease for both greenhouse temperature (with $\Delta y_1 = \Delta\theta = 5^oC$) and absolute humidity (with $\Delta y_2 = \Delta h = 0.006$ kg H_2O/m^3). This scenario corresponds to *diurnal to nocturnal transient regime*.

$$y_1^*(t) = 25 - \frac{1}{72}\cdot\left[r(t-2000) - r(t-2360)\right]$$
$$y_2^*(t) = 0.019 - \frac{0.001}{60}\cdot\left[r(t-2000) - r(t-2360)\right] \quad (4.7)$$
with
$$r(t) = t\cdot\sigma(t) = \begin{cases} 0, & t < 0 \\ t, & t \geq 0 \end{cases}$$

In (4.7) the temperature reference signal unit is 1^oC ($y_1^*(t)$) and the humidity reference signal unit is 1 kg H_2O/m^3 ($y_1^*(t)$). Its final value of 0.013 kg H_2O/m^3 corresponds to a 74% relative humidity level.

For $t \in [0, 2000]$, the system is considered to be in steady state regime defined by: $y_1(0) = 25^oC$ (greenhouse air temperature), $y_2(0) = 0.019$ kg H_2O/m^3 (greenhouse air absolute humidity), $v_1 = 300W/m^2$ (intercepted solar radiant energy), $v_2 = 20^oC$ (outside greenhouse temperature), and $v_3 = 0.004$ kg H_2O/m^3 (outside greenhouse absolute humidity).

The objective cost functions associated as fitness function for above scenario are:

$$J_1 = f_\theta(\tau) + \alpha\cdot g_\theta(\tau) + p_\theta(2000,\tau) \quad (4.8)$$

where:

$$f_\theta(\tau) = \int_{2000}^{\tau} \left| \frac{y_1^*(t) - \theta(t)}{\Delta\theta} \right| dt \tag{4.9}$$

is the penalty component for temperature, on the time horizon [2000, τ], with τ = 2650 s;

$$g_\theta(\tau) = \frac{1}{\tau - 2000} \int_{2000}^{\tau} (u_1(t))^2 \, dt \quad , \alpha = 0.1 \tag{4.10}$$

give the penalty component for command variable;

$$p_\theta(2000,\tau) = \begin{cases} 0, & \text{if no saturation occurs} \\ & \text{during the time interval } [2000,\tau] \\ 15, & \text{if saturation occurs} \\ & \text{during the time interval } [2000,\tau] \end{cases} \tag{4.11}$$

is the penalty component for saturation of actuator output (the saturations act in the points ① and ② from Fig. 4.14a).

Table 4.11 reveals the results obtained after a number of $\ell_{max} = 20$ generations. The notation M_5 is introduced for genetic algorithm method, σ_{max} for the maximum overshoot and t_s for the settling time.

Fig. 4.16 provides a narrow view on the behavior of genetic algorithms approach. The final solution is reached in practice since the 11th generation. In the abscissa is given ℓ, the rank of the generation, and in ordinate - the best individual in the corresponding generation.

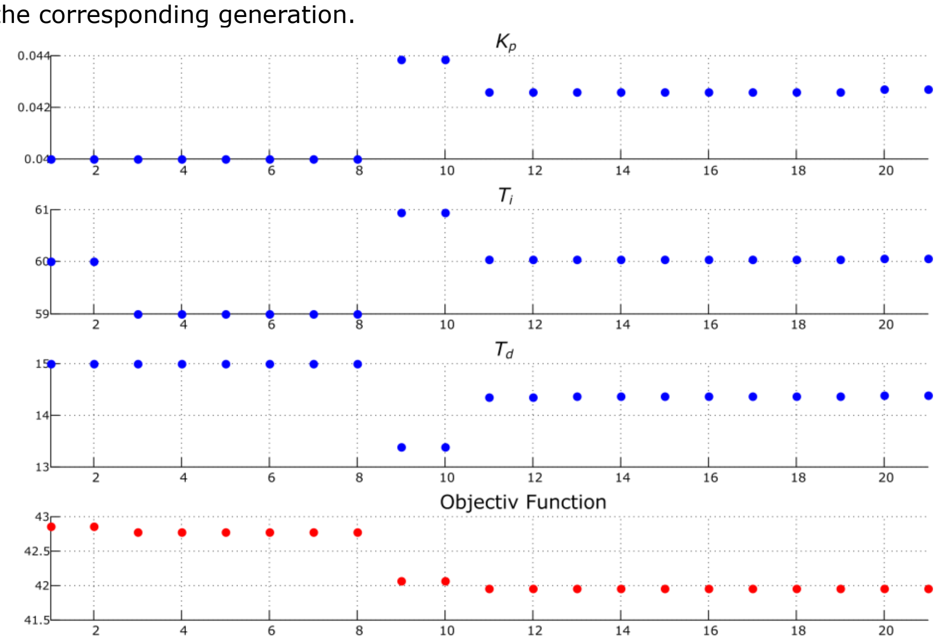


Fig. 4.16. Relating to the tuning process by GA in dusk regime (GA_1 case).

Table 4.11. Cost functions values (J_1), PID parameters and performance indicators(σ_{max}, t_s) in Dusk Regime

No	Tuning method	J_1; (f_θ, g_θ)	K_P T_I [s] T_D [s]	σ_{max} [%]	t_s [s]
1	M_1 –ZIEGLER NICHOLS	42.84; (10.7, 171.5)	0.04 60 15	2.27	411
2	M_2	47.83; (29.78, 180.5)	0.0302 78.29 0.0107	2.80	444
3	M_3	72.47 (39, 184.7)	0.0203 135 13.5	3.05	509
4	M_4	108; (73.7, 193)	0.016 249.7 26.40	2.83	642
5	M_5	41.94; (9.77, 171.8)	0.0427 60.05 14.37	2.25	410

Table 4.11 shows that the best solution for the initial PID controllers is obtained by the Ziegler-Nichols tuning method (J_1 = 42.84) with the parameters from Table 4.10. The solution determined by genetic algorithms seems to be better because in this case the obtained values of objective function (J_1 = 41.94), overshoot (2.25 %) and settling time (410s) have the lowest values. The worst behavior appears for methods M_3 (Closed-loop transfer function coefficients matching) and M_4 (Internal model control - IAE optimal). Fig. 4.17 reveals comparatively the behavior in the cases M_4 and M_5.

In the cases M_1, M_2 and M_5 the solutions are very close. For the evaluation of differences, the Cartesian distance of relative values is used:

$$D_\zeta = \sqrt{\left(1 - \frac{K_{P,M_\zeta}}{K_{P,M_5}}\right)^2 + \left(1 - \frac{T_{D,M_\zeta}}{T_{D,M_5}}\right)^2 + \left(1 - \frac{T_{I,M_\zeta}}{T_{D,M_5}}\right)^2}\ ,\ \zeta = \overline{1,4} \quad (4.12)$$

The results are given in the Table 4.12 in the column GA_1.

Because D_1 = 0.076, the idea to use the M_1 controller in the initial population having a role of attractor is plausible. Therefore, a 2*nd attempt* is made with an initial population that doesn't include Ziegler-Nichols controller.

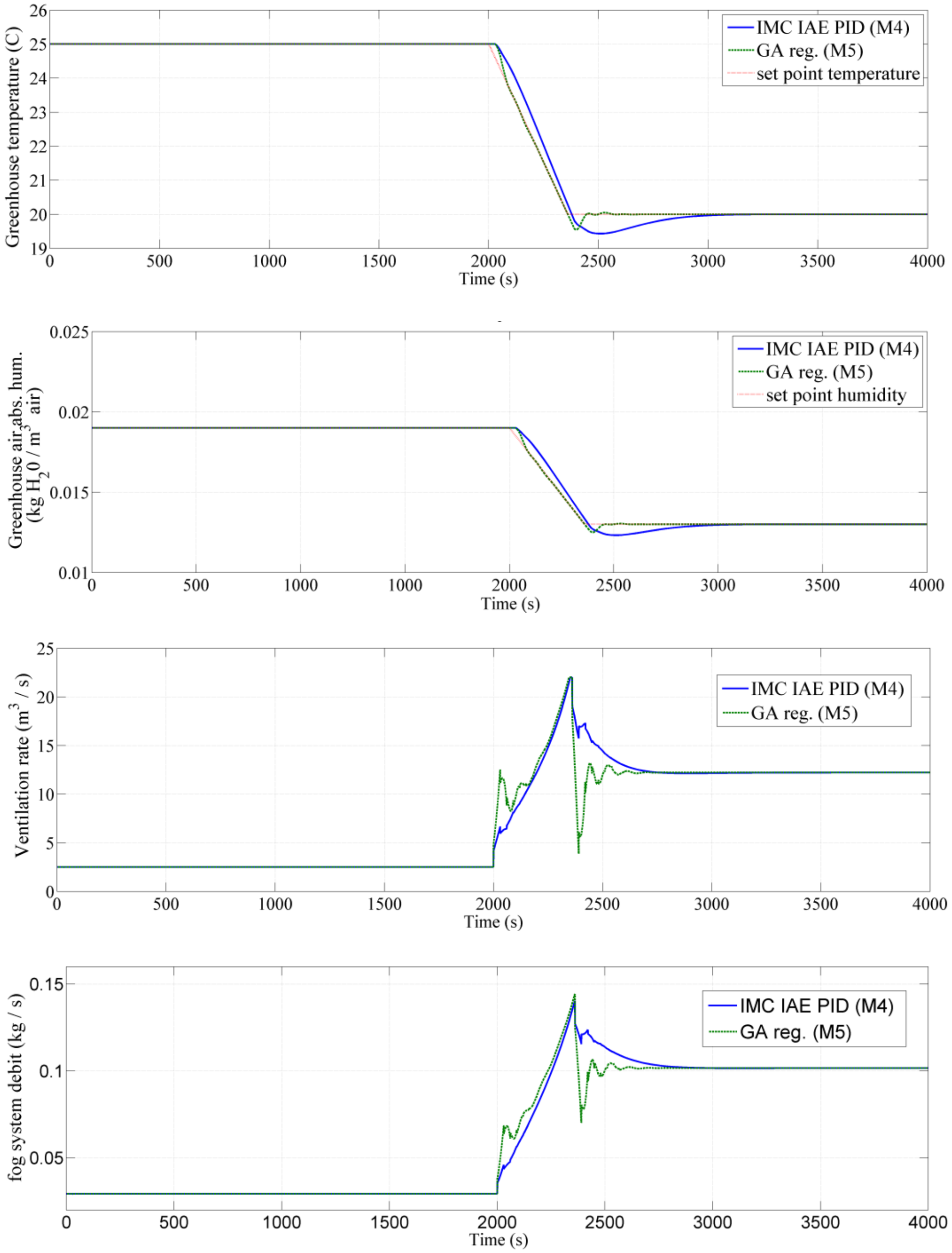


Fig. 4.17. System responses for diurnal to nocturnal transient (dusk regime) using M4(IMC - IAE) and M5(GA1) PID tuning methods.

The new results are given in the Table 4.12 in the column GA_2. For each generation a population of 10 individuals is set, and maximum number of generations is 20. By using genetic algorithms, the minimum cost function is J_1 = 43.48 and the PID parameters are: K_P =0.038, T_I = 47.5s, T_D =17.9s.

Table 4.12 shows that the new obtained PID parameters by genetic algorithm is closer to the Ziegler-Nichols PID, even if it was not included in the initial population.

Table 4.12. Distances D_1-D_4 from the PID parameter set in M_1-M_4 cases relative to the set M_5 set given by GA in two cases: GA_1 –initial population includes Zigler-Nichols, GA_2–initial population without Zigler-Nichols.

No.	Cartesian distance	GA_1	GA_2
1	D_1	0.076	0.31
2	D_2	1.084	1.212
3	D_3	1.355	1.919
4	D_4	3.327	4.325

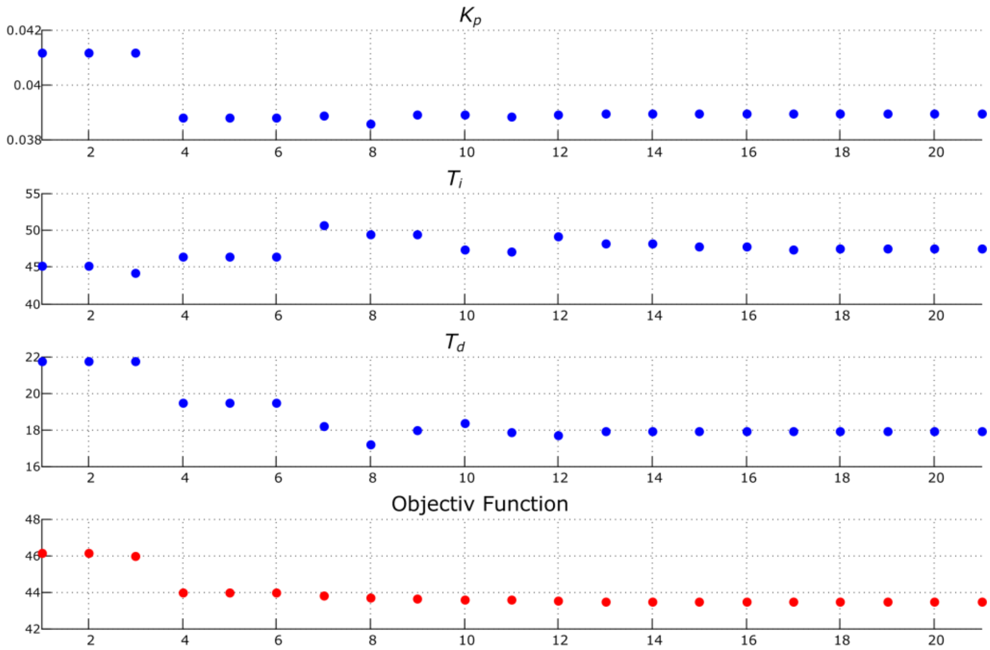


Fig. 4.18. Relating to the tuning process by GA in dusk regime, without Ziegler-Nichols controller in initial population (GA_2 case).

A narrow view on the behavior of genetic algorithm approach for this second tuning case is provided in Fig. 4.18. Also in this case, the final solution is reached in the 11th generation.

Study of control systems behavior considering uncertainties of solar radiant energy estimation

To strengthen the conclusion that de GA PID tuning is better, a validation scenario of the first stage is considered, namely: the study of control systems behavior for diurnal normal regime by taking into account the *uncertainties of solar radiant energy estimation*.

The decoupling strategy adopted in chapter 3 is based on the assumption that the disturbances v_1, v_2 and v_3 are measurable. Particularly, the intercepted solar radiant energy v_1 is obtained every 10 minutes (600 seconds) and used like staircase function (see Fig. 4.19) from the nearest meteorological station, and not from sensors placed in the greenhouse close vicinity. If the real value of the solar radiant energy in greenhouse is v_{1r}, by considering a multiplicative modeling manner, the value used in the decoupling strategy is $v_{1r} = \rho v_1$. For example, supposing that the estimation error does not exceed $\pm$ 30 %, if v_1 takes the string of values:

$v_1 \in \{300, 290, 240, 220, 350, 240, 340, 500, 700, 300, 710\}$

and for ρ the corresponding string of values is:

$\rho \in \{1, 1.1717, 0.9684, 0.8732, 1.2179, 1.0937, 0.8708, 1.0867, 0.8581, 0.8049, 0.9212\}$,

then the time variations of v_{1r} and v_1 is like in Fig. 4.19. The deviation vector has been generated using the Matlab random number generator. The first element of the deviation vector takes the value of 1 as initial condition, i.e., the same solar radiation at the greenhouse location and at the meteorological station.

In these circumstances, the *2nd relevant operating regime* of the control system for <u>*diurnal normal regime*</u> is defined as:

- $y_1^*(t) = 30\ (^oC),\ \ y_2^*(t) = 0.018\ (\ kg\ H_2O\ /\ m^3\ )$
- v_1(t) has the shape shown in Fig. 4.19, v_2 = 35 °C, v_3 = 0.004 kg H_2O/m^3,
- The initial state/output variable values are: x_1 = 30 °C, x_2 = 0.018 kg H_2O/m^3, representing a 59% relative humidity.
- The PID regulators have the parameters from Table 4.10.

The scenario validation did not lead to significant differences from previous results (see Table 4.13), i.e., the control system is robust to uncertainties in disturbance measurements.

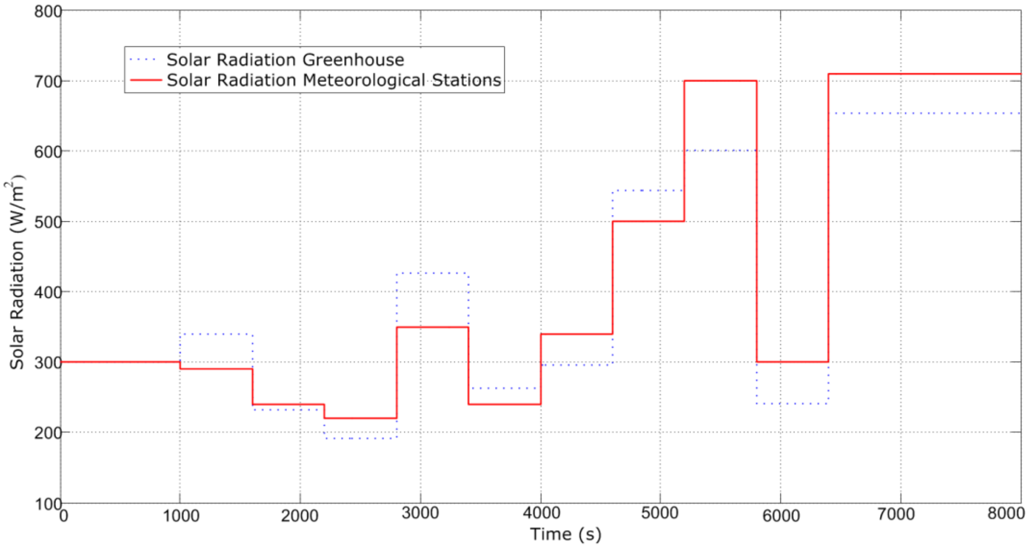


Fig. 4.19. Solar radiation energy (estimated, real - dot line) trend in diurnal regime.

Table 4.13. Control performances for solar radiation uncertainties

No.	Tuning method	Maximum overshoot (%)	Settling time (s)
1	M_1	2.267%; (19.5466)	411
2	M_2	2.8%; (19.44)	444
3	M_3	3.05% (19.39)	509
4	M_4	2.83%; (19.43)	642
5	M_5	2.246% (19.5508)	410

4.6.4. PID Controller Tuning for Morning Transient Regime

The 3rd relevant operating regime for the control system consists on a 7 minutes ramp set-point increase for both greenhouse temperature (with $\Delta y1 = \Delta\theta = 6\ ^0C$) and absolute humidity (with $\Delta y_2 = \Delta h = 0.006$ kg H_2O/m^3). This scenario corresponds to the <u>*morning transient regime*</u>.

$$y_1^*(t) = 15 + \frac{1}{70}\cdot\left[r(t-2000) - r(t-2420)\right]$$
$$y_2^*(t) = 0.013 + \frac{0.001}{70}\cdot\left[r(t-2000) - r(t-2420)\right] \quad (4.13)$$

For $t \in [0, 2000]$, the system is considered to be in steady state regime defined by: $y_1(0) = 15$ °C, $y_2(0) = 0.013$ kg H_2O/m^3, and on whole time interval holds: $v_1 = 300$ W/m^2 (intercepted solar radiant energy), $v_2 = 20$ °C, and $v_3 = 0.004$ kg H_2O/m^3.

In this case, the parameters of the temperature and humidity controllers are considered as independent variables, in contrast to the previous scenarios. Now, every parameter plays the role of a chromosome that has six genes. The objective function, associated as fitness function, contents a distinguish component for each control loop:

$$J_2 = J_\theta + J_H \ ,$$
$$J_\theta = f_\theta(\tau) + 10 \cdot g_\theta(\tau) + 3 \cdot p_\theta(2000, \tau) \ , \qquad (4.14)$$
$$J_H = f_H(\tau) + 10 \cdot g_H(\tau) + 3 \cdot p_H(2000, \tau)$$

where:

$$f_\theta(\tau) = \int_{2000}^{\tau} \left| \frac{y_1^*(t) - \theta(t)}{\Delta\theta} \right| dt \ , \qquad (4.15a)$$

$$f_H(\tau) = \int_{2000}^{\tau} \left| \frac{y_2^*(t) - h(t)}{\Delta h} \right| dt \qquad (4.15b)$$

are the penalty components for the temperature and humidity outputs, on the time horizon [2000, τ] with τ = 2650 s;

$$g_\theta(\tau) = \frac{1}{T - 2000} \int_{2000}^{T} \left(\frac{u_1(t)}{u_{1\_final}} \right)^2 dt \ , \ u_{1\_final} = 4.1 \ , \qquad (4.16a)$$

$$g_H(\tau) = \frac{1}{T - 2000} \int_{2000}^{T} \left(\frac{u_2(t)}{u_{2\_final}} \right)^2 dt \ , \ u_{2\_final} = 0.0532 \ , \qquad (4.16b)$$

are the penalty components of the command variables and

$$p_\theta(t) = \int_{2000}^{\tau} s_\theta(t)\, dt \ , \qquad (4.17a)$$

$$p_H(t) = \int_{2000}^{\tau} s_H(t)\, dt \ , \qquad (4.17b)$$

$$s_\theta(t), s_H(t) = \begin{cases} 0, \text{ if no saturation occurs} \\ 1, \text{ if saturation occurs} \end{cases} \qquad (4.18)$$

are the cost function penalty components for the saturation of actuator outputs (the saturations act in the points ① and ② from Fig. 4.10a).
After an evolutionary tuning process stabilized during 20 generations, the components of the fitness function achieve the values given by the last row from

Table 4.14 (case M_6). In the same table are given also the values of the components for the previous five cases already discussed (M_1, …, M_5).

Table 4.14. Cost functions(J_{θ}, J_H) including penalty component values(p_{θ} p_H)in morning transient regime for: conventional M1-M4 PID tuning methods, GA tuning method M5 using J_1 cost function, and GA tuning method M6 using enhanced J_2 cost function

Tuning method	J_{θ}; (f_{θ}, g_{θ}, p_{θ})	J_H; (f_H, g_{θ}, p_h)	J_2
M_1	34.10; (8.88, 1.0121, 15.09)	23.72 (8.85; 1.488, 0)	57.83
M_2	227.1895 (25.021; 1.526; 186.9)	39.32 (23.21; 1.611, 0)	266.5
M_3	56.64; (31.91; 1.423; 10.5)	48.39 (31.78; 1.661,0)	105
M_4	150.5 (54.86; 1.575; 79.8)	72.33 (54.54; 1.779,0)	222.85
M_5	37.7 (8.063; 1.023; 19.41)	22.89 (8.037; 1.486,0)	60.59
M_6	19.88 (9.52; 1.035; 0)	27.58 (12.61; 1.49; 0)	47.46

The parameters obtained for the temperature PID controller ($M_{6\ temp}$) are: $K_{P\theta}$ = 0.0385, $T_{I\theta}$ = 63.14 s, $T_{D\theta}$ = 13.03 s, and for the humidity PID controller ($M_{6\ hum}$) are: K_{PH} = 0.0407, T_{IH} = 105 s, T_{DH} = 18.44 s.

The new parameter values for the temperature PID controller are not significantly different from those in cases M_5 and M_1, but for the humidity PID controller the difference is obvious.

4.6.5. System Stability Analysis

The transfer function of each loop from Fig. 4.10 (b) is

$$\tilde{H}_i(s) = K_{Pi}(1 + \frac{1}{T_{Ii}s} + T_{Di}s) \cdot \frac{1}{s} \cdot e^{-d_i \cdot s}\ , \quad i = 1 \text{ or } 2 \qquad (4.19)$$

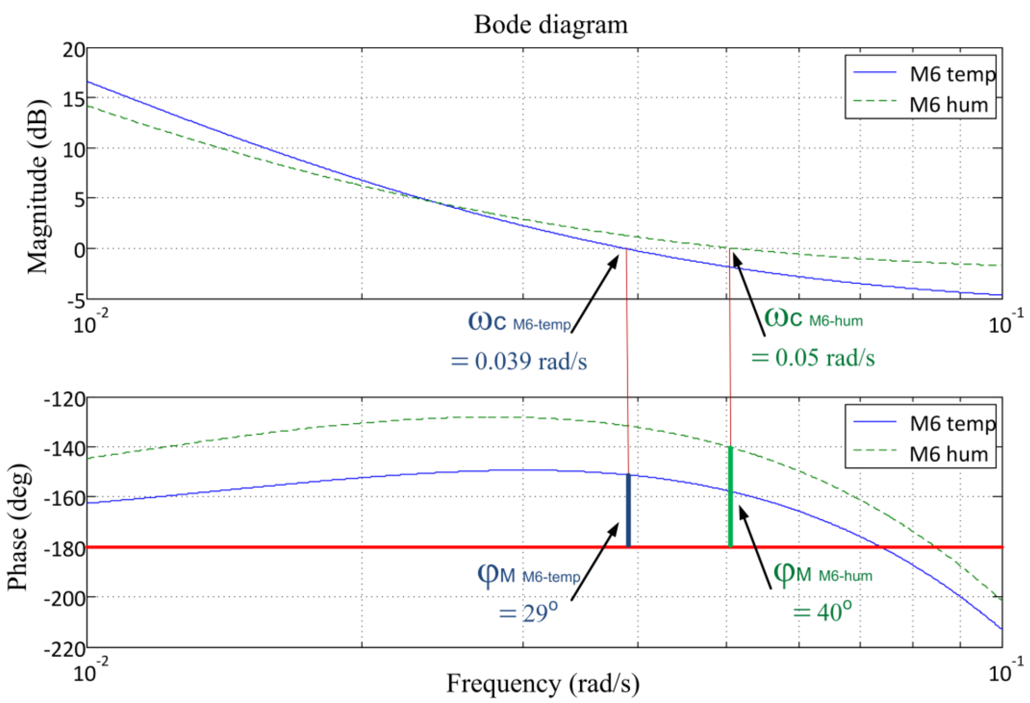
Due to the presence of dead time, the phase margin stability criterion is applied [FÖL'13]. Hence, considering the Bode plots of the open-loop system $\left|\tilde{H}_i\right|_{dB} = 20\,lg\left|\tilde{H}_i(j\omega)\right|$ and $\phi_{\tilde{H}_i} = arg\,\tilde{H}_i(j\omega)$, the crossover frequency $\omega_C = max\{\,\omega \in R_+ \big|\, \left|\tilde{H}_i\right|_{dB} = 0\}$ and the phase margin $\phi_M = \pi + arg\,\tilde{H}_i(j\omega_C)$, the phase margin stability criterion shows that the closed-loop system is (theoretically) stable if $\phi_M > 0$ (practically if $\phi_M > \frac{\pi}{9}$).

Table 4.15 presents the results for phase margin and crossover frequency obtained with the controllers considered in this paper. The Bode plots, the crossover frequencies and phase margins for two of the studied cases are illustrated in Fig. 4.20.

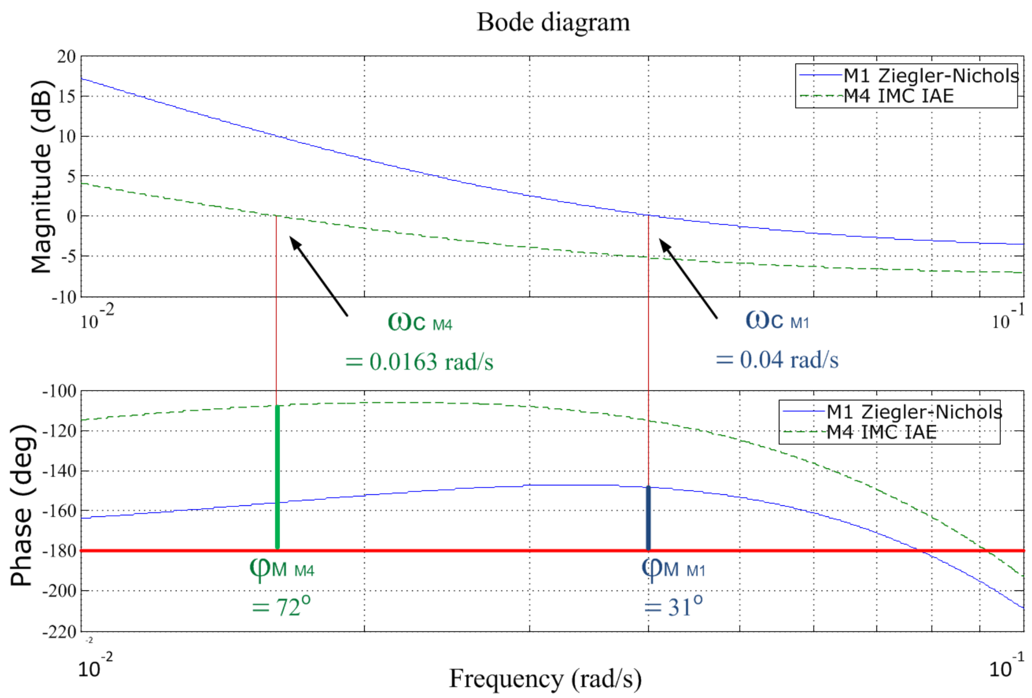
Table 4.15. Phase margin and crossover frequency of the system employing PID controllers tuned by M1-M6 methods

Tuning method	Phase margin φ_{res} (^{0})	Crossover freq. ω_c (rad/s)
M_1	31	$4.07 *10^{-2}$
M_2	13	$3.24*10^{-2}$
M_3	50	$2.03*10^{-2}$
M_4	72	$1.63*10^{-2}$
M_5	29	$4.41*10^{-2}$
$M_{6\ temp}$	29	$3.9*10^{-2}$
$M_{6\ hum}$	40	$5.09*10^{-2}$

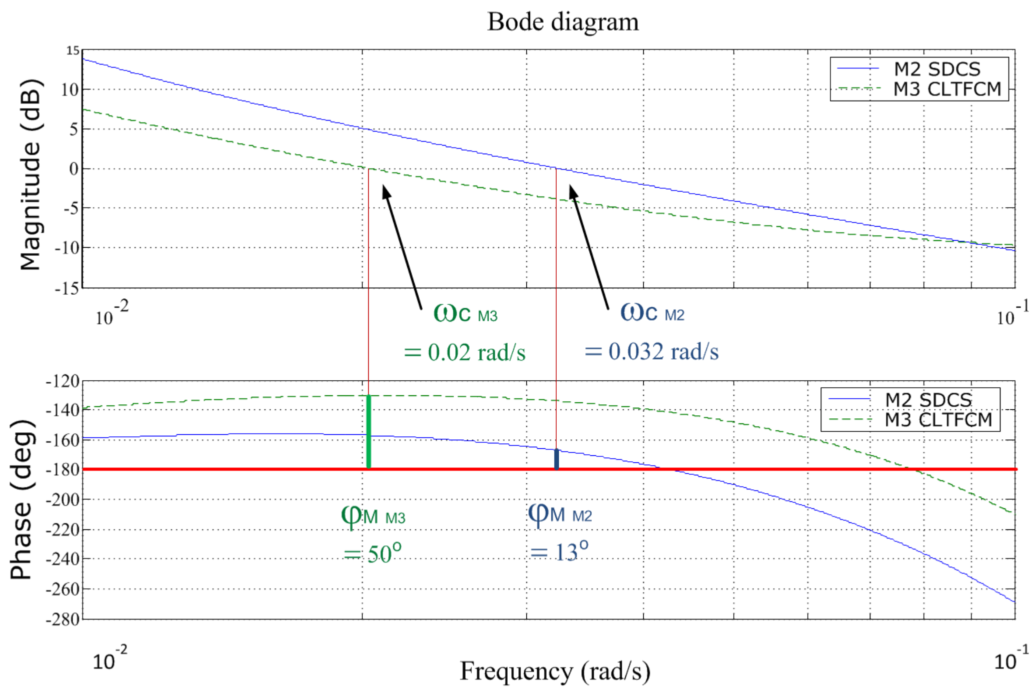
Note that every time $\omega_c \in (0.01,\ 0.1)\ s^{-1}$.



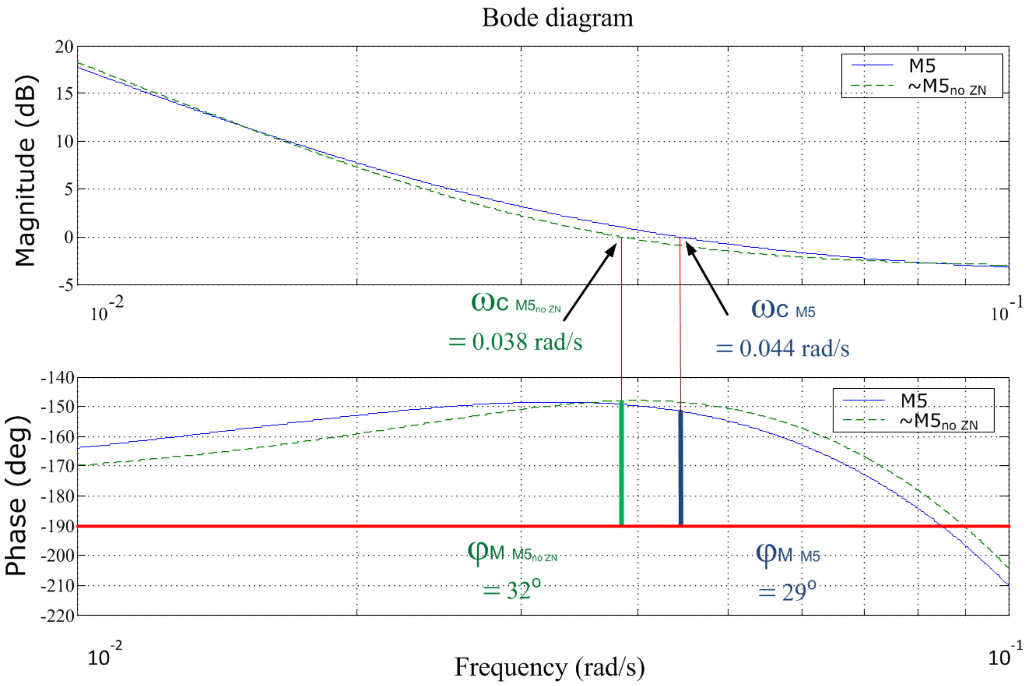
-a-


Bode diagram
Magnitude (dB)
M1 Ziegler-Nichols
M4 IMC IAE
ωc M4
= 0.0163 rad/s
ωc M1
= 0.04 rad/s
Phase (deg)
φM M4
= 72°
φM M1
= 31°
Frequency (rad/s)

-b-


Bode diagram
Magnitude (dB)
M2 SDCS
M3 CLTFCM
ωc M3
= 0.02 rad/s
ωc M2
= 0.032 rad/s
Phase (deg)
φM M3
= 50°
φM M2
= 13°
Frequency (rad/s)

-c-



-d-

Fig. 4.20. Bode plots for the system with the PID controllers (M1-M6) presented in subchapter 4.6

4.7. Greenhouse Climate Control Employing Modified Smith Predictor with State Observer

In this subchapter, a control structure for greenhouse climate control is proposed by using the improved system structure with linearization and decoupling using state observer (chapter 3 - Fig. 3.7) and a modified Smith predictor.

For processes with dead time the command variable modification effect can be observed in the system output just after a time delay defined as the system dead time. When the process is characterized by a significant dead time this prevents the achievement of a high performance control system: fast transient response (high value for gain crossover frequency) and small overshoot (satisfactory phase margin) [VIS'11]. For compensating the process dead time a well-known dead time compensator can be used, i.e., the Smith predictor [SMI'58]. The Smith predictor control structure is presented in Fig. 4.21. Where $P(s)e^{-Ls}$ is the real process and $\hat{P}(s)e^{-\hat{L}s}$ is the modeled process.

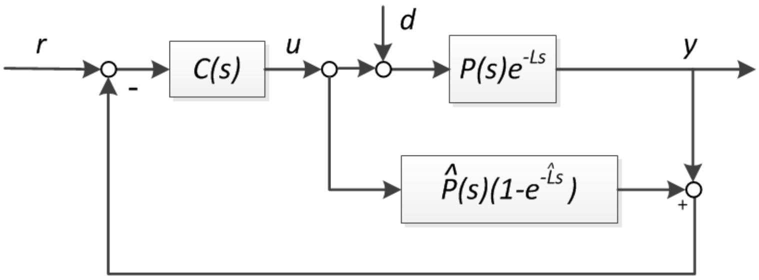


Fig. 4.21. Smith predictor structure

In the case when the delay free part of the real process and the delay free part of the modeled process are equal ($P(s) = \hat{P}(s)$), and the real process dead time and the modeled process dead time are equal ($L = \hat{L}$), the Smith predictor control structure allows controlling the process without the dead time because the dead time is outside the control loop (Fig. 4.22).

For the considered case, the decoupled and linearized greenhouse climate nonlinear model an integrator plus dead-time (IPDT) behavior has been obtained. The transfer function of the temperature and humidity channel having the form :

$K / s\, e^{-Ls}$, with K=1, L=30s.

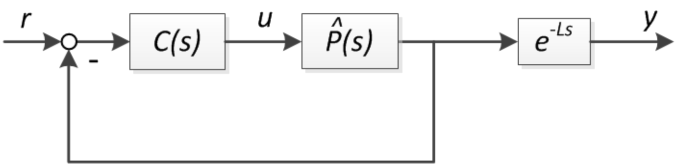


Fig. 4.22. Smith predictor equivalent structure

For IPDT processes, the classical Smith predictor structure is unable to provide a null steady state error when considering a constant load disturbance [CHI'02], [VIS'11]. For IPDT process several modified Smith structures where proposed [WAT'96], [AST'94], [GUA'07], [ZHA'96].

A modified Smith predictor that adds an additional feedback loop for compensating the effect of load disturbances was presented by Matausek et al. [MAT'99]. The modified Smith predictor control structure is presented in Fig. 4.23 where C(s) is a proportional controller (K_r) and M(s) a filtered PD structure,

$$M(s) = \frac{K_0(T_d\, s + 1)}{T_f\, s + 1} \text{ with } T_f = \frac{T_d}{10}. \quad (4.20)$$

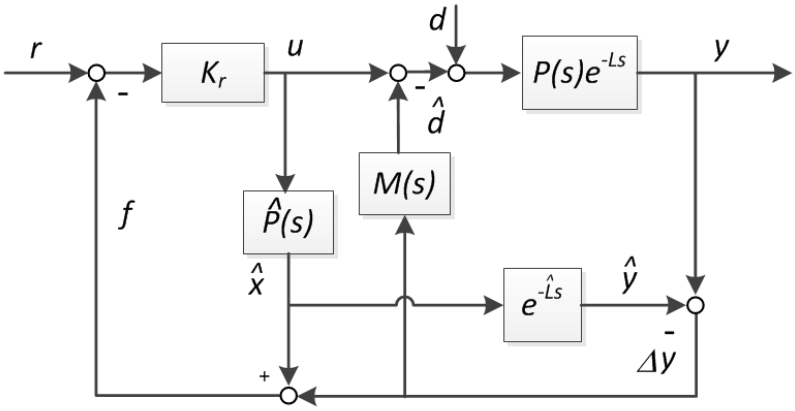


Fig. 4.23. Matausek modified Smith predictor structure

The output of the $\hat{P}(s)$ block, $\hat{x}$, estimates the undelayed state variable.

The output error $\Delta y = y - \hat{y}$ has a delayed action. In steady state Δy contains information on disturbances d and thus this disturbance is compensated by a feed-forward loop using M(s) block that delivers the disturbance estimation ($\hat{d}$).

The feedback variable f for the controller K_r contains two signals: i) state estimation $\hat{X}$ with quick action in transient regime and ii) a delayed output error Δy that is an added compensation in steady state.

The state observer proposed in section 3.3 delivers the undeleyed estimation of output signals that are used for linearization and decoupling but also for the modified Smith predictor by using the equivalent decoupled, linearized process model, i.e., integrator type.

When considering process parameter variation the state observer estimates with small errors the undelayed system outputs thus compensating the effect of parameter uncertainty or wrong disturbance estimation.

For computing the values of K_r and K_0 the following expressions are used [MAT'99]:

$$K_0 = \frac{\frac{\pi}{2} - \phi_m}{KL\sqrt{(1-\alpha)^2 + (\frac{\pi}{2} - \phi_m)^2 \alpha^2}}, \quad (4.21)$$

$$K_r = \frac{1}{KT_r} . \quad (4.22)$$

Where Tr is the time constant of the systems closed loop transfer function.

The derivative time constant, $T_{d,}$ is chosen to be proportional to the dead time coefficient L [VIS'11]: $T_d = \alpha L, \quad 0 \le \alpha \le 1.$

With suggested parameters [MAT'99] $\alpha = 0.4$ and $\phi_m = 64^\circ$ (phase margin).

Taking in consideration the IPDT behavior for the two decoupled, temperature and humidity channels, the following values where obtained: Tr =0.4, K_0 = 0.024, T_d=12, T_f=1.2, $M(s) = \dfrac{0.024(12s+1)}{1.2s+1}$.

The proposed modified Smith predictor (Matausek) control structure for greenhouse climate control with decoupling using undelay outputs variable estimated by a state observer is presented in Fig. 4.24.

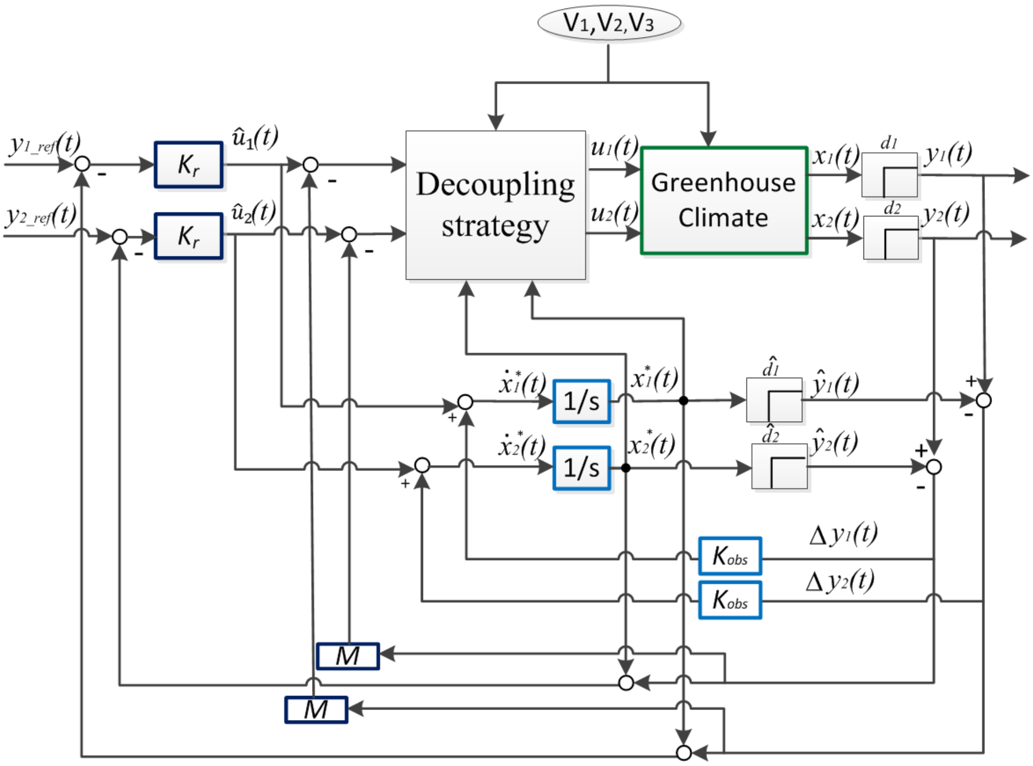


Fig. 4.24. Matausek modified Smith predictor with proposed state observer for greenhouse climate control

For testing the Smith predictor control structure with state observer a 6 minutes ramp set-point decrease for both greenhouse temperature and absolute humidity. This scenario corresponds to diurnal to nocturnal transient regime and the simulation conditions are presented in subchapter 4.6.3. The system response considering the PID controller obtained using GA (controller-M_5) and considering the modified Smith predictor is presented in Fig. 4.25.

As expected when using the Smith predictor the state variable follows the setpoint but the two system outputs(temperature and humidity) have a 30 sec lag time. For the Smith predictor structure the systems outputs don't present any overshoot and the two commands, u_1 and u_2, don't show any shock/sudden changes this translates in an improved actuator lifetime.

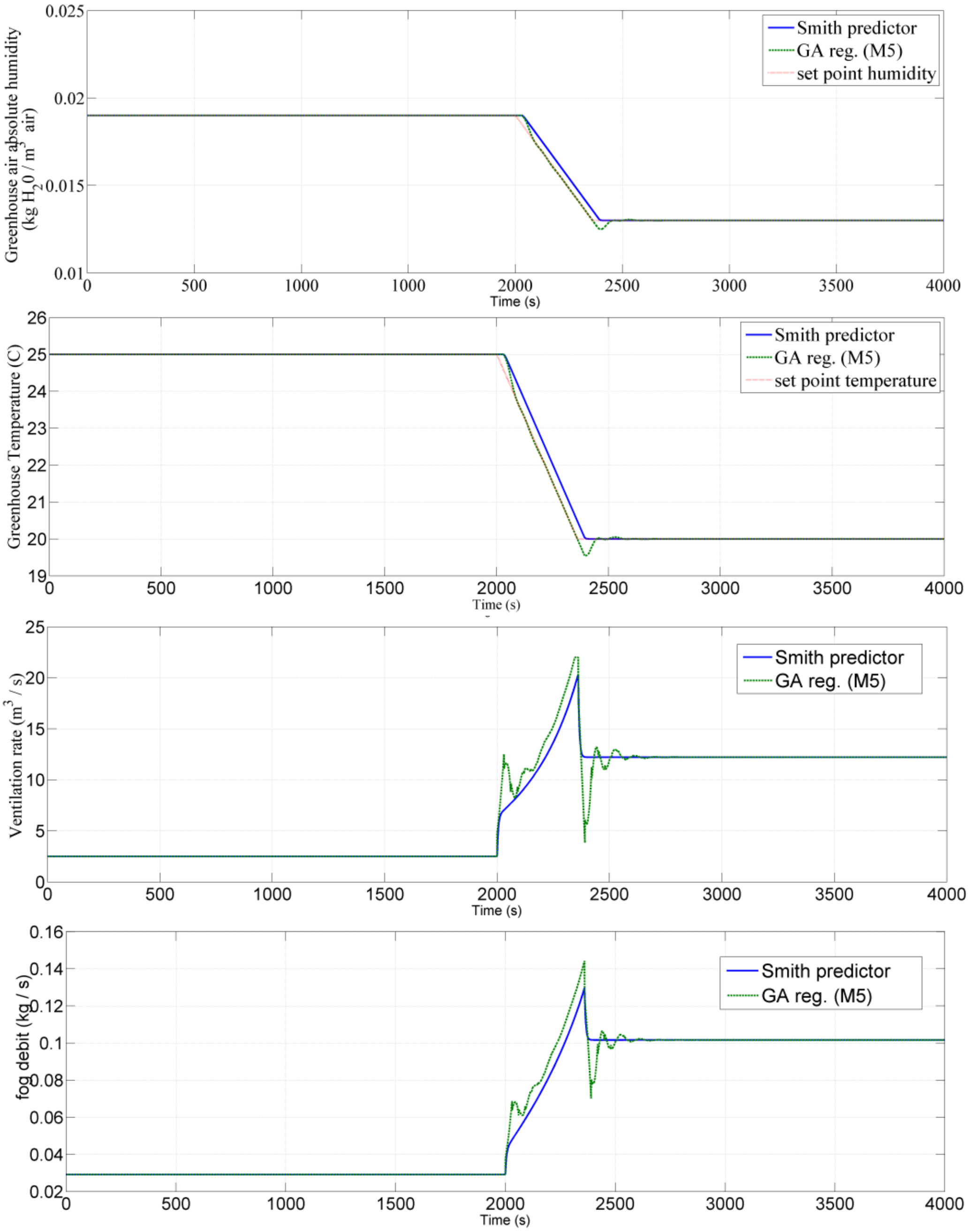


Fig. 4.25. System responses for diurnal to nocturnal transient (dusk regime) using M5 PID tuning method and the modified Smith predictor.

4.8. Summary and Conclusions

The main contributions in this large chapter are as following:

i) By using the greenhouse climate equivalent model, reduced to integral plus dead time (IPDT) decoupled processes (presented in Chapter 3), a comparison study of associated PI/PID controllers employing five different tuning techniques is performed by simulation. Simulation tests with system responses to set-point step and ramp changes, and disturbance step changes, are analyzed and compared. The smallest settling time is obtained for Ziegler-Nichols PID tuning rules, and the smallest overshot for Internal Model Control based IAE/ISE optimal tuning

ii) Greenhouse climate model parameters/disturbances, which are susceptible to wrong estimation, are identified, i.e., heat transfer coefficient (U_A), shading and leaf area index coefficient (α), and intercepted solar radiant energy (S_i). The system response, in the case of nominal model and considering different levels of model uncertainty, are compared. Significant quality indicator degradations for setpoint step responses leads to reconsider the control structure using two degree of freedom (2DoF) PID controllers. Three 2DoF PI/PID tuning technique are compared at nominal condition and under parameter variations showing good performance. The considered 2DoF solutions for IPDT process: model reference robust tuning and multiple dominant poles, show substantial improvement comparing with 1DoF controller regarding robustness to parameter variations and wrong disturbance measurements.

iii) The greenhouses are processes that, due to the lack of standards, allow the usage of more tuning methods for PID controllers. The solutions obtained by conventional methods can be improved by using genetic algorithms (GA). Objective cost functions are developed for the evaluation process. The developed objective cost functions are composed of 3 integral normalized penalty terms: penalty term for the control error, penalty term for command variable and penalty term for the actuator saturation duration. The GA starts from a population that includes 4 individuals that corresponds to four conventional PID tuning methods. Simulation results in real scenarios show improved performances for PID tuning by GA in comparison with conventional methods.

iv) A solution based on a modified Smith predictor for greenhouse temperature and humidity control is developed. The solution uses the Matausek modified Smith predictor. The state variables without time delay required by the Smith predictor structure and by the feedback-feedforward linearization method are obtained using a proposed state observer structure. By using this control structure the systems outputs does not present any overshoot and the both control commands present a smooth profile.

The results obtained in this chapter where disseminated by papers published in two IEEE conference proceedings [GUR'12], [GUR'13a] and an article submitted to a journal [GUR'14a].

5. SCADA SYSTEM AND HARDWARE-IN-THE-LOOP IMPLEMENTATION FOR GREENHOUSE CLIMATE CONTROL

Hardware-in-the-Loop (HIL) is a technique employed for rapid software implementation, verification and validation for complex embedded systems. The usage of HIL technology started in the aerospace and defense industry in early '50s [NAB'04], being adopted in automotive industry in the early '90s as a response to the increased complexity of the system design. In turn, it leads to a tight development and verification schedule and, with the ever increasing complexity of the embedded systems and a continually decreasing time-to-market, the HIL testing became a popular solution [SCH'06].

A Hardware-in-the-Loop simulator has two components, the system under test-SUT (in our case the greenhouse climate control implemented on real-time target) and the simulated test environment (greenhouse climate model on PC). By using HIL simulator, the SUT can be easily developed and validated without interacting with the real process because the virtual environment can be simulated under different test conditions using complex scenarios.

HIL simulator usage allows starting the development stage without deploying the SUT in the real environment. It also eliminates the high risk of damaging the actuators in the early development stages. HIL tests provide a cost/time-efficient way of validating the software. It also permits accelerating the testing phase by using multiple HIL testing platforms in parallel. The test conditions are repeatable, providing an efficient way for testing the developed software.

For rigorously testing of the control strategy, the simulated environment has to meet real-time (RT) constraints. Thus, not only the simulated environment response correctness is mandatory, but also the response time is important. In this case, the soft real-time constraints, in the context of the simulated environment where time constraints are not critical, are considered.

Supervisory Control and Data Acquisition (SCADA) systems have been present in the industry for more than 30 years [BOY'09]. SCADA systems can be described as the encapsulation of following actions in a unified system: distributed process data acquisition, data transmission to a central point, data processing, control actions, data storing and reporting [BAI'03]. SCADA interfaces the human operator through a human machine interface (HMI) which enables process monitoring and control [ROE'11].

This chapter presents a *SCADA system implementation* for greenhouse climate control using Hardware-in-the-Loop (HIL) and real-time (RT) concepts with experimental test results. The greenhouse climate model is implemented using National Instruments LabVIEW on PC, and the control algorithms and the decoupling and linearization module are implemented using a Siemens PLC (section 5.1). There are developed *two solutions for remote monitoring and command human machine interface (HMI).* The first solution is developed using LabVIEW (section 5.2) and LabVIEW Web UI Builder (section 5.3) providing the operator a web based solution for monitoring and command. The second one is a part of SCADA system implementation that uses GPRS data transmission (section 5.5). This provides a suitable solution for greenhouse distributed on a large area where other types of data transmission are not available.

A *generic telematics system:* GSM/Ethernet Telematics System (GE-TS) is developed and implemented in section 5.7 as a SCADA element solution using Ethernet and mobile phone networks for remote terminal unit. The main goal pursued when developing the proposed GE-TS was to create a highly configurable and upgradeable SCADA telematics system based on the GSM and Ethernet network. The remote commands and monitoring are accomplished by using two solutions: 1) GSM/3G Short Message Service (SMS) / phone calling or by 2) using the web page hosted by the PIC microcontroller. By using a hybrid communication media (GSM/3G and Ethernet network) the system provides high coverage, reliability and low cost of ownership.

The results obtained in this chapter where disseminated in two papers published in IEEE conference proceedings [GUR'11],[GUR'13b].

5.1. Hardware-in-the-Loop Implementation

This chapter describes the hardware-in-the-loop (HIL) implementation for greenhouse climate control (Fig. 5.1).

All the steps are detailed below as following: i) the process implementation in LabVIEW, ii) development of linearization and decoupling module, PI controller implemented on Siemens PLC, and finally iii) the OPC server configuration.

The first phase is the implementation in NI LabVIEW of the entire control structure: greenhouse climate model, PI/PID controls, linearization and decoupling compensator, with the front panel presented in Fig. 5.2.

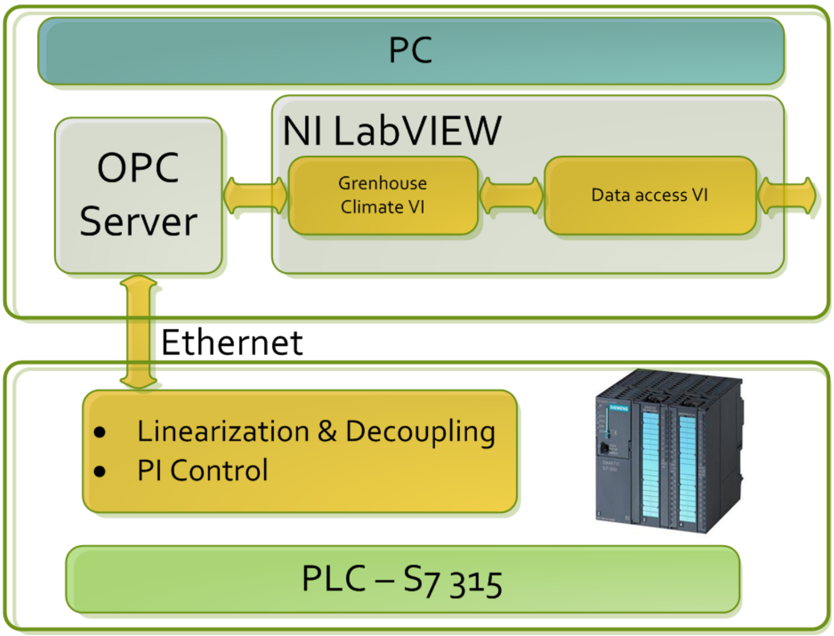


Fig. 5.1. General schematic HIL – SCADA with LabVIEW

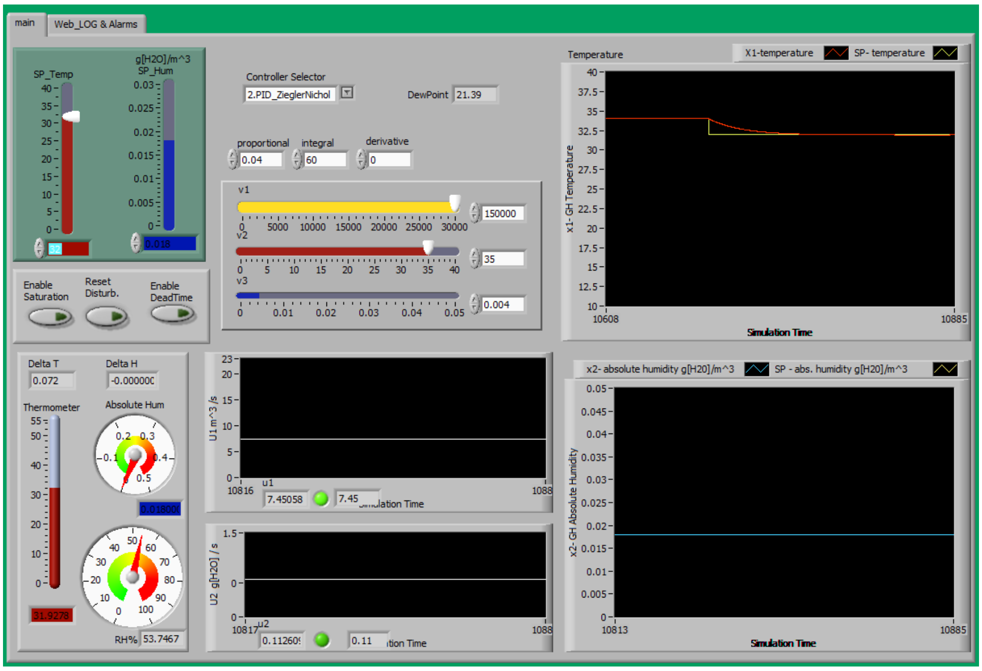


Fig. 5.2. LabVIEW greenhouse climate control system front panel

The NI Control Design and Simulation Module[NAT'09a], [NAT'12] and PID and Fuzzy Logic Toolkit 2011 [NAT'09b] is used. The simulation uses the Runge-Kutta 4 ODE solver with the time-step of 100 ms.

From the application front panel it is possible to select a desired PID controller tuning technique (IMC ISE Optimal PID or Ziegler Nichols PI/PID), or to set the PID tuning parameters manually.

After verifying the process behavior, i.e., the process subVI, linearization and decoupling subVI and the PI/PID controller subVI, the second phase is to implement the last two modules on the real-time target controller (Siemens PLC) presented below.

5.1.1. PLC Control

The PLC used is a Siemens 315F-2 PN/DP [SIE'11]. This PLC has an Ethernet interface used to program the device, debug the software, and also to connect to an OPC server.

All the PLC code was implemented by using SCL (Structured Control Language) [SIE'05]. For developing the PLC software it has been used the Siemens TIA(Totally Integrated Automation) V11 (Fig. 5.3). The software is written in a modular approach by using Function Blocks (FB). Function Blocks are routines with associated internal memory called Data Blocks (DB). There have been defined two main FBs: FB03 for linearization and decoupling (Fig. 5.4), FB04 for implementing the PI controllers.

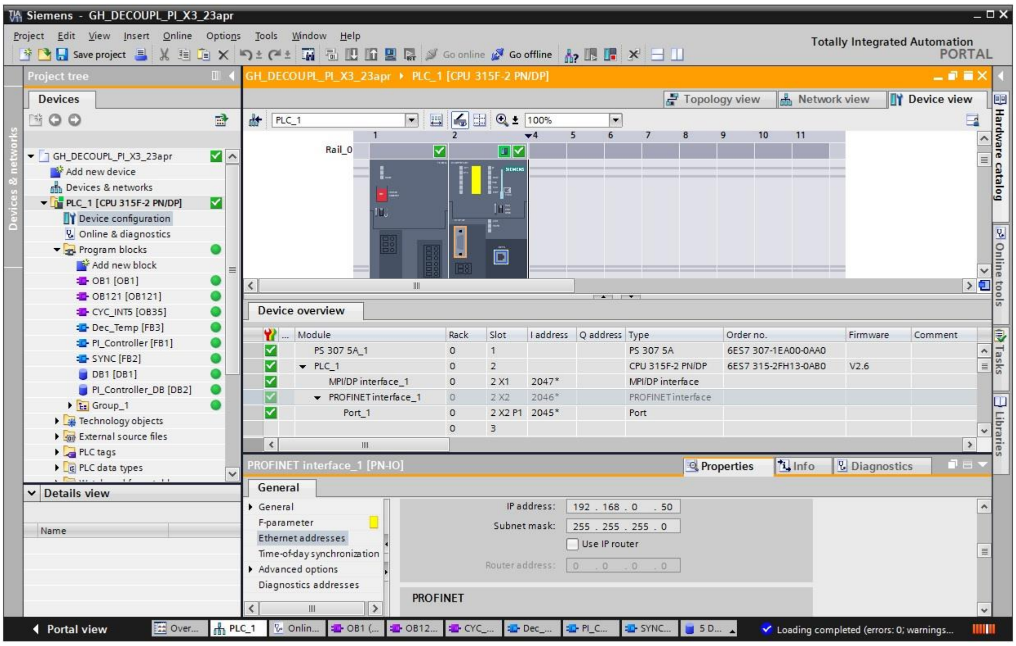


Fig. 5.3. TIA device configuration for S7-315F PLC

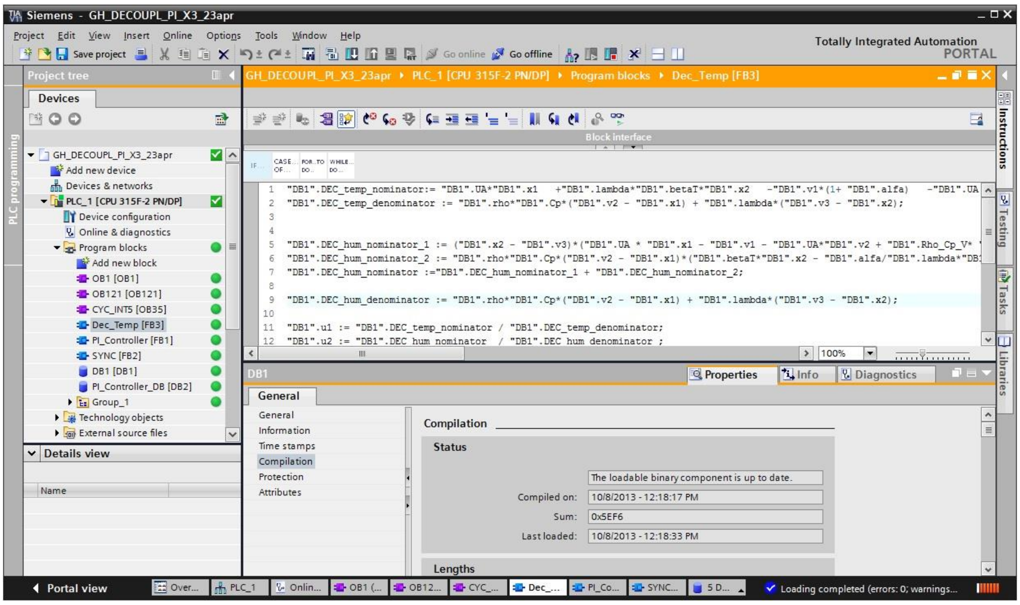


Fig. 5.4. Linearization and decoupling function block implemented in SCL (Structured Control Language)

The function blocks are periodically called by using a 100 ms cyclic interrupt in order to achieve synchronization with the OPC Server. To trigger the 100ms interrupt the OB35 has been used, where OB35 is one of the 9 cyclic interrupt that can be used (OB30 to OB38). As default the OB35 is triggered at 100ms but it can also be configured by the user.

The PLC implemented discrete PI controller (for temperature and humidity regulation) has the form (5.1), where $\hat{u}$ is the PI controller output, e is the input error, $\hat{u}_I$ is the integral component output, h is the sampling period, K_p and T_i are the PI parameters. The trapezoidal integration rule has been used.

$$\begin{aligned} \hat{u}_I[k] &= \hat{u}_I[k-1] + \frac{h}{2}(e[k] + e[k-1]) \\ \hat{u}[k] &= K_p e + \frac{K_p}{T_i}\hat{u}_I[k] \end{aligned} \qquad (5.1)$$

5.1.2. OPC Server

The OPC acronym stands for „OLE for process control", where OLE, „Object Linking and Embedding" uses the Microsoft's OLE/COM technologies, allowing programs developed for Windows OS to communicate with industrial control hardware [SIN'09]. Before the introduction of the OLE for Process Control (OPC) for interfacing the control systems with the PCs it have been used serial communication (MODBUS RS 485) which had very strong draw-backs like: very low speed transfer rate and short cable length [GHO'02]. OPC [OPC] is an open standard that uses a client – server model. The three main sets of functionalities provided by the OPC server are: data access, alarm and events and historical data access. The communication between the PLC's, HMI stations, RTUs (remote terminal units) and PC software application can be achieved even if the hardware and software components are provided by different vendors.

The PLC I/Os and memory are accessed by using an OPC server [IWA'10]. The OPC client generates read/write requests to the OPC server, which communicates to PLC by using specific device protocols.

On the OPC server side (Fig. 5.5), the following steps are taken into consideration: create a new channel (select the device driver and network adapter), add a new device (select the device model, enter the device ID, configure the timing parameters), and finally add the desired tags. For each tag, besides selecting a name and defining the resource address (memory or I/O address), the data type, client access mode and scan rate are configured. In LabVIEW project an OPC client is added. LabVIEW accesses the PLC data by using shared variable that are bounded to the tags added in the OPC server. For testing purpose, to validate the proper assignment of the variables and also the communication between LabVIEW and the PLC an OPC Client is used(Fig. 5.6).

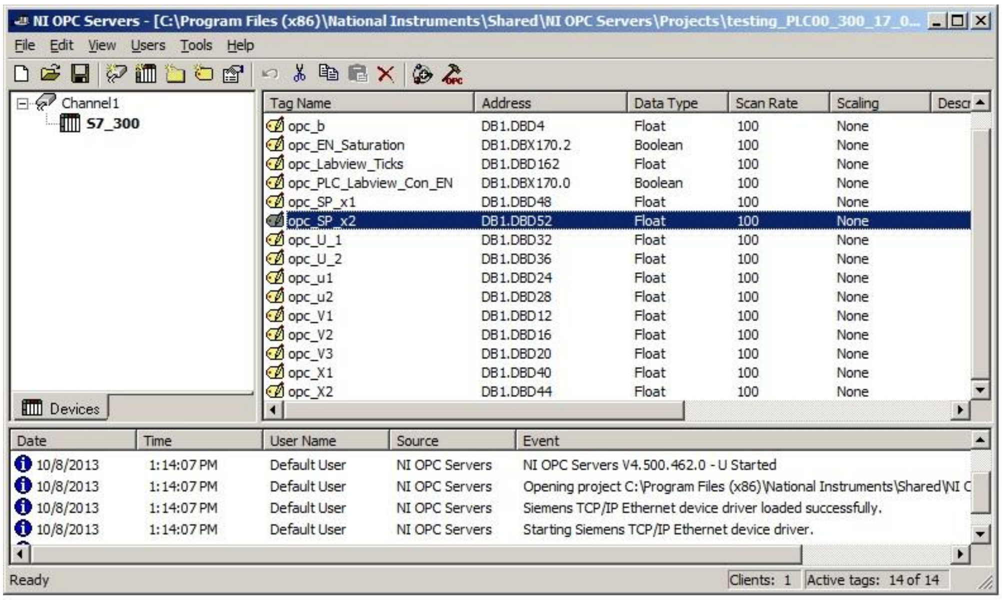


Fig. 5.5. NI OPC server

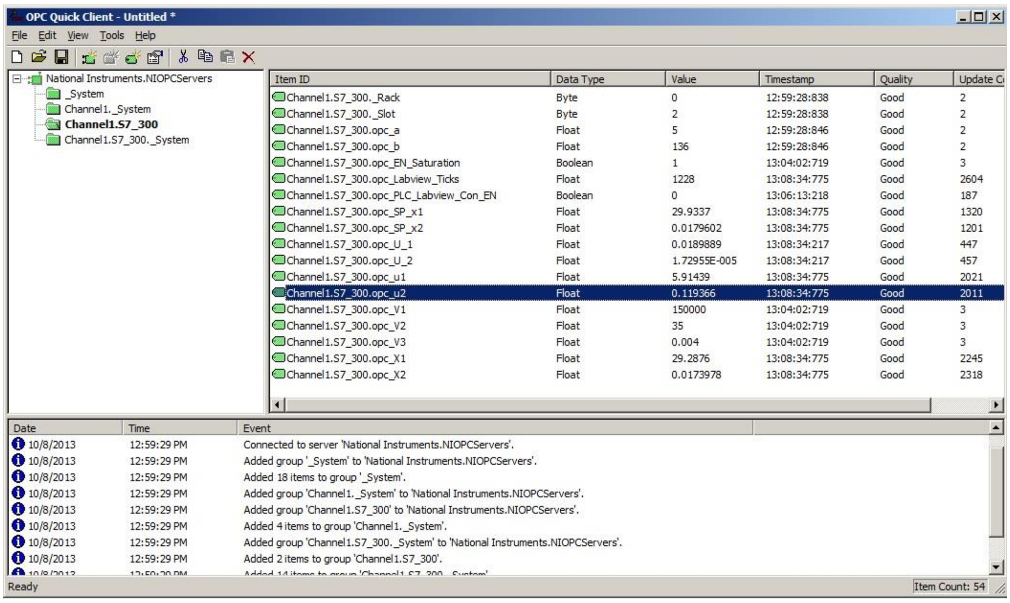


Fig. 5.6. NI OPC client

5.2. HMI Implementation Using LabVIEW WEB UI Builder

NI offers, trough LabVIEW Web UI Builder, the option to create HMI web based remote monitoring and command interface. This allows running the web interface on different OS and browsers, with the availability of Microsoft Silverlight plugin for the desired browser as only constraint. The thin client, i.e., the Web based interface, performs the following actions: connects to LabVIEW web services, processes the information and displays it as plain text or in HMI manner. The web application runs inside the browser; this way the thin client interacts with outside world only through the web interface (access to the client machine hardware is not possible, the application runs in the browser "sandbox").

The HMI was developed for providing remote monitoring and command functionality to the hardware-in-the-loop (HIL) implementation for greenhouse climate control (Fig. 5.7).

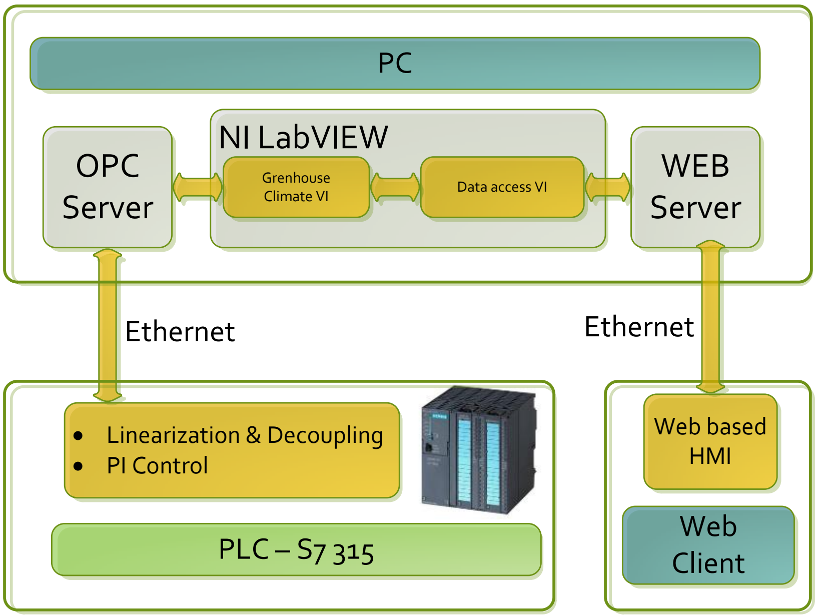


Fig. 5.7. General schematic HIL – SCADA with HMI by LabVIEW WEB UI Builder

NI offers the option of running the NI web-server on Windows hosted PC's and also on LabVIEW Real-time devices. The users create web services in LabVIEW and deploy to the web server. When providing remote monitor and control, two parts are involved: the thin client on one side, and the LabVIEW application providing associated web services on the other side.

The three main steps for creating a thin client LabVIEW Web UI are briefly presented below. The first step is the creation of a VI, where the front panel is in fact the web interface. The second step is to add a web service reference (server IP address and the web service provided by the web server), where the web services function is imported as a subVI in the main VI. The final step is to generate and deploy the thin client application.

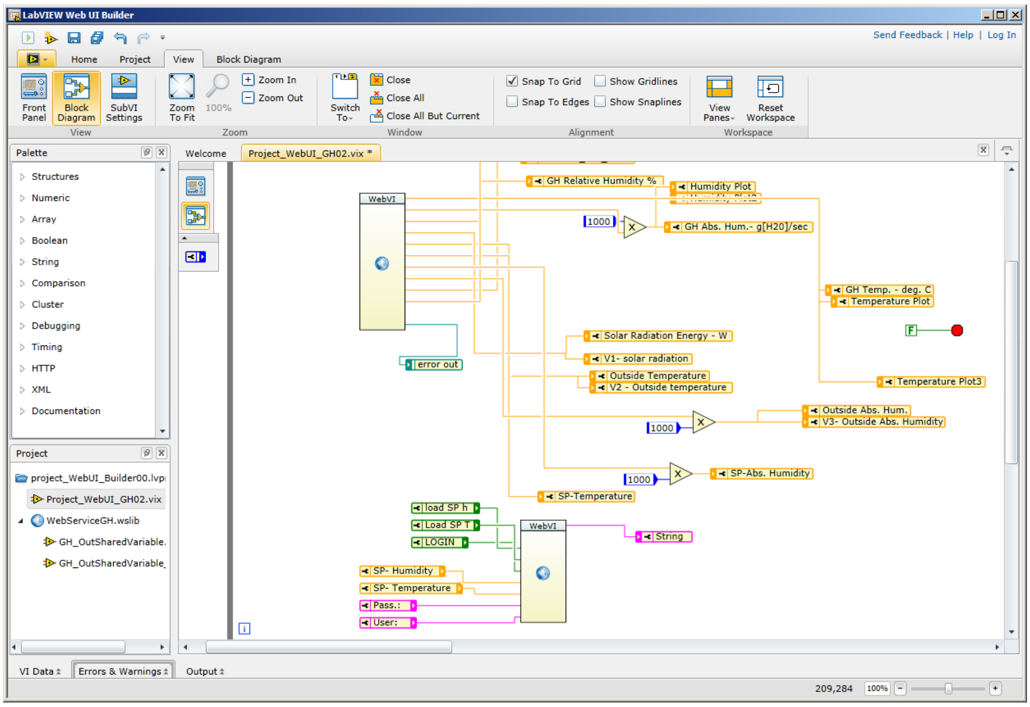


Fig. 5.8. LabVIEW Web UI Builder interface

On the other side, LabVIEW is configured to provide web services to the web client. To achieve this fact, the user operates to: create the sub VI's that will be accessible to the clients through the webserver as web methods, enable the webserver, create a web service adding the previously created VI, build the web service and finally deploy the web service to the web server.

Considering that LabVIEW web service and LabVIEW are different instances, they do not share the same memory space. In this case, network published shared variable are used to transmit information between web services and LabVIEW.

The developed web-based UI (Fig. 5.9-5.12) offers the possibility to remotely monitor all the significant data from the process. In our case, there are the greenhouse air temperature, absolute humidity and relative humidity, the disturbances (outside air temperature, absolute humidity and solar radiation energy) and the actuators command (the fan ventilation rate and the fogger flow rate). There are also three window tabs containing graphs for: disturbances (Fig. 5.11), temperature and humidity (Fig. 5.9), and the actuators commands (Fig. 5.10). The web-based UI also contains a window tab for authenticating the users, a log action window and an interface for setting and loading the temperature and humidity setpoint values. The user cannot modify the temperature and humidity setpoints until it is logged in. The login required information is the username and the password. This information is filled up by the user and sent by the Web-based UI to the LabVIEW main application. If the username and password are authenticated by the LabVIEW application the logged user has the right to set new setpoints for humidity and temperature. All the user action (login request, authentication response, setpoint change) are recorded and displayed in the web UI and also on the LabVIEW main application.

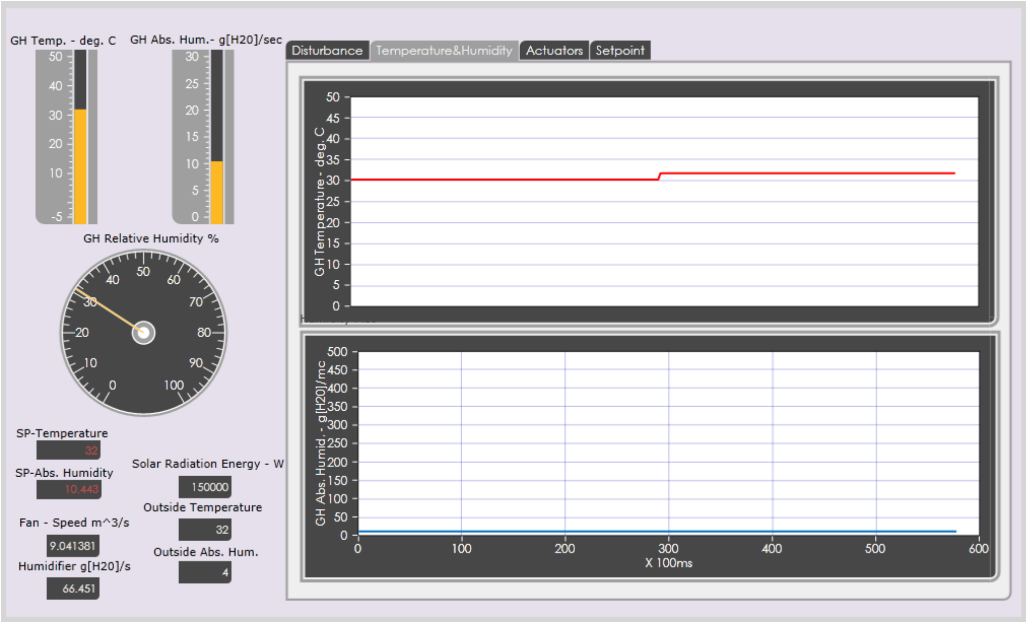


Fig. 5.9. Greenhouse climate control web based HMI – Temp. & Humid. tab

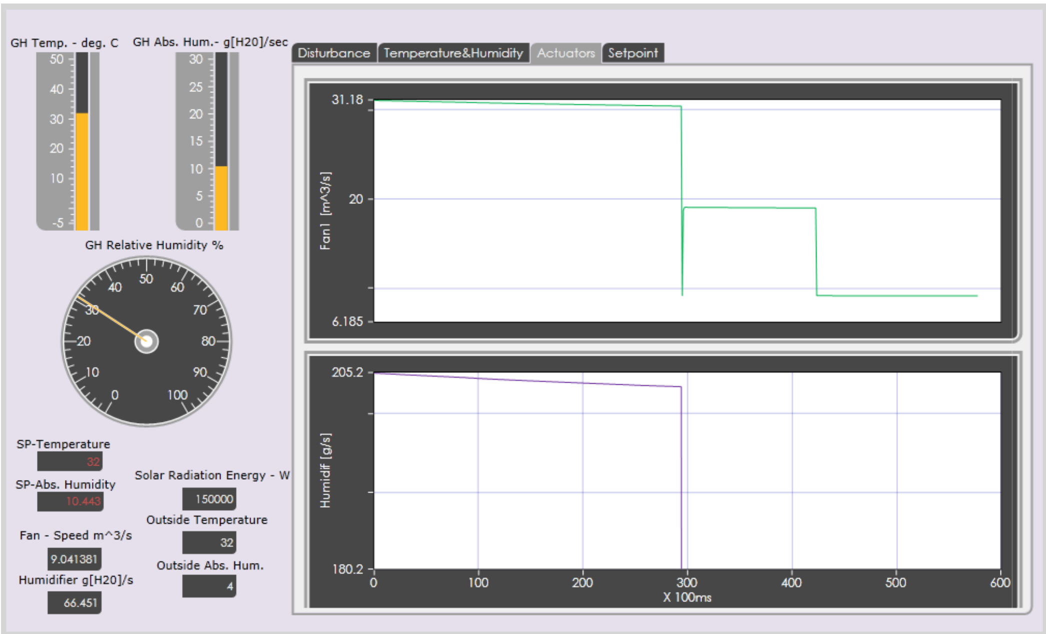


Fig. 5.10. Greenhouse climate control web based HMI –Actuators tab

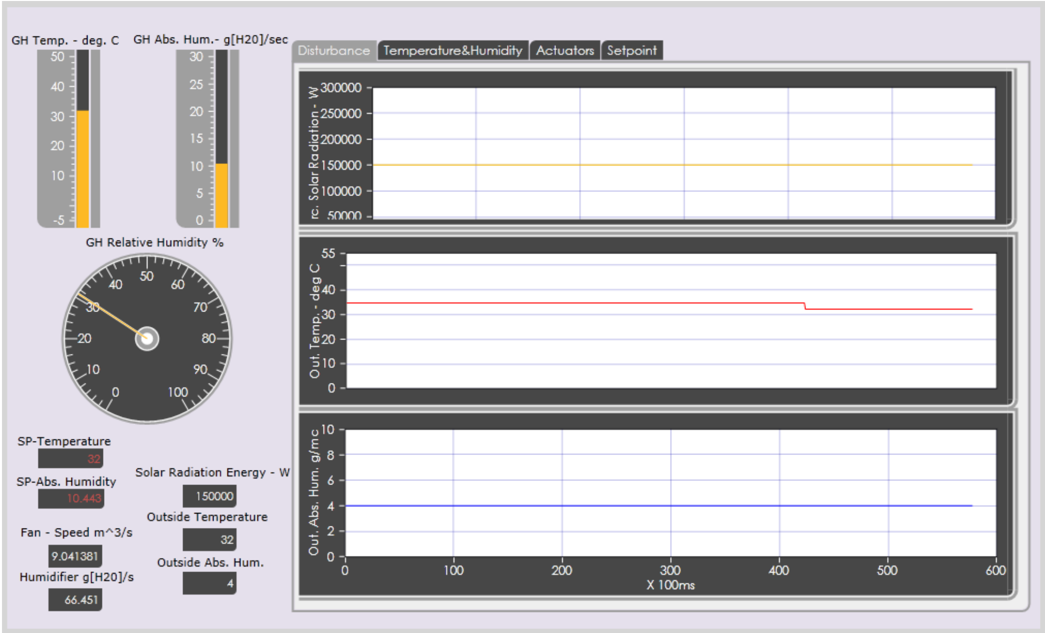


Fig. 5.11. Greenhouse climate control web based HMI – Disturbance tab

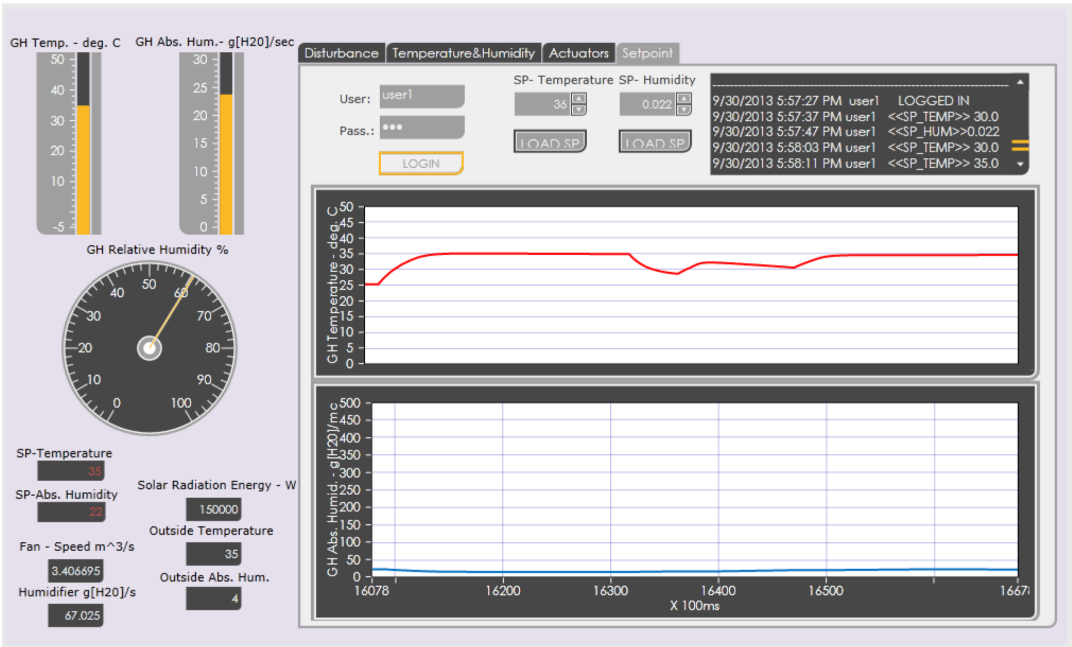


Fig. 5.12. Greenhouse climate control web based HMI – Setpoint tab

5.3. HMI Implementation Using LabVIEW Remote Front Panels

Another solution was added for Web based HMI that employs the LabVIEW Remote Front Panels functionality to remotely monitor the process and to modify the setpoints. The system block diagram is presented in Fig. 5.13.

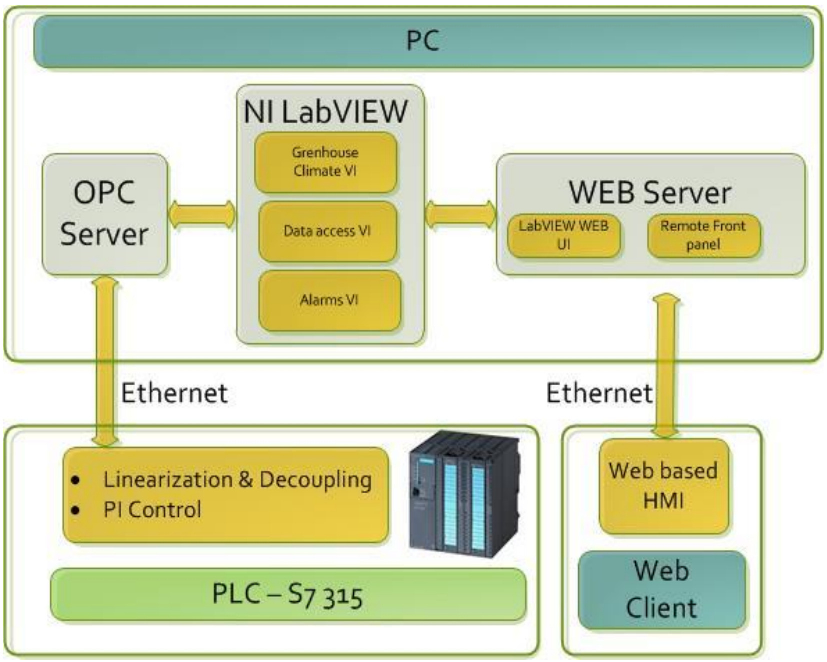


Fig. 5.13. General schematic HIL – SCADA with HMI by LabVIEW Remote Front Panels

LabVIEW offers the possibility to visualize and control the VI front panel remotely by using a web browser, where the web based interface is in fact the main VI front panel. Multiple users can simultaneous visualize remotely the VI but just one user can control the considered VI.

Configuring LabVIEW VI to be accessed remotely is a very simple and straight forward procedure. On the host side the following steps are required: enable the LabVIEW web server, generate the web page using the LabVIEW web publishing tool. On the client side the only requirement before accessing the LabVIEW VI with the web browser is the availability of LabVIEW Run-Time Engine. LabVIEW Remote Front Panel can be access in the browser by specifying the server IP address and the page name (Fig. 5.14).

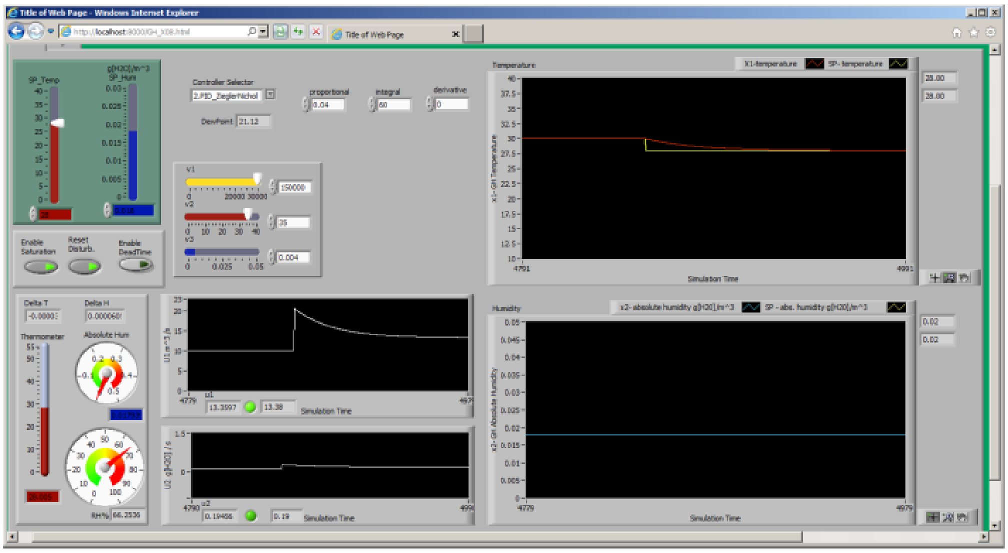


Fig. 5.14. LabVIEW front panel VI web based remote access

5.4. Alarms

Alarms have been implemented using the LabVIEW Datalogging and Supervisory Control (DSC) Module [NAT'12b], [NAT'12c]. The DSC module monitors the shared variable values and triggers an alarm when some specific conditions are met.

The alarm functionality implementation is based on DSC module. LabVIEW can access the PLC data by using shared variable that are bounded to the tags added to the OPC server. The same type of variables, network published shared variables, are used to transmit information between web services and LabVIEW. An alarm can be trigger when the monitored shared variable values is above, below a predefine value or within a predefine range of values.

One important aspect for alarm handling is the acknowledge implementation. An acknowledging procedure for each alarm has to be defined. DSC module proposes two implementations: the automatic and the manual acknowledgement. In the case of automatic acknowledgement if the condition that triggered the alarm are no longer present, then the DSC module automatically acknowledges the alarm. In the case of manual acknowledgement the alarm will persist until the user will acknowledge the alarm. An alarm is still reported in LabVIEW until is cleared by the DSC Module. For clearing an alarm the following condition have to be meet: the alarm is not active and the alarm have been acknowledged.

Just one alarm instance associated to a network-published shared variable can be active at a time.

One important aspect that has to be mentioned is that in the case of manual alarm acknowledgement if we have an alarm instance that becomes active, inactive and active the DSC modules will not generate an alarm after the first activation if the alarm is not acknowledged.

The enabling and configuring the alarms functionality associated to a shared variable can be done through the alarming tab from the Shared variable proprieties window (Fig. 5.15).

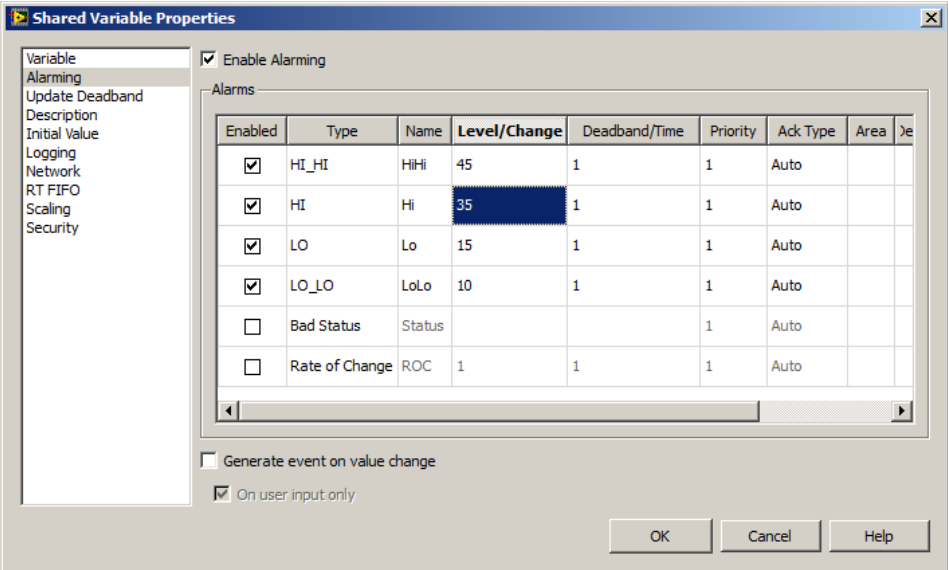


Fig. 5.15. LabVIEW shared variable properties - Alarms configuration

DSC Module implements six alarm types for the numeric data types: „HI_HI”, „HI”, „LO”, „LO_LO”, „Bad Status” and „Rate of Change”. The thresholds that have been implemented for the greenhouse climate control are presented in table 5.1.

Table 5.1 Alarms thresholds

	LO_LO	LO	HI	HI_HI
Interior Temperature	10	15	35	45
Interior Abs. Humidity	0.002	0.006	0.05	0.1
Actuator 1, vent. rate	-	-	22	25
Actuator 2, fog debit	-	-	1.2	1.4

Another method for informing the grower when monitored variable values are above/below predefine thresholds was implemented using e-mail notification (Fig. 5.16, 5.17).

Upper and lower thresholds have been defined for greenhouse temperature and humidity. In the case the threshold exceeds these values an email is sent. For this the user has to configure the sender's email address, sender's name, recipient's email address, recipient's Name, CC Recipient, the subject and can chose what information will be transmitted in the e-mail (Fig. 5.17).

The outgoing mail server (SMTP), the account user ID and password was configured when the email VI was developed and cannot be modified at the user level.

The email subVI, that is responsible for sending the alarm notification email, is called using the LabVIEW asynchronously calling functionality.

In LabVIEW when a target VI or subVI is called, the data flow is stopped until the target VI or subVI processes the information and returns the result at the output terminal of the node. By using the asynchronously calling the main VI that calls the subVI continues the execution in parallel with the execution of the subVI. A drastically improvement of the main VI execution time can be achieved but most important in our case is that the main VI execution is not blocked until the mail subVI processes the data, sends the data to the mail serve and receives confirmation from the server.

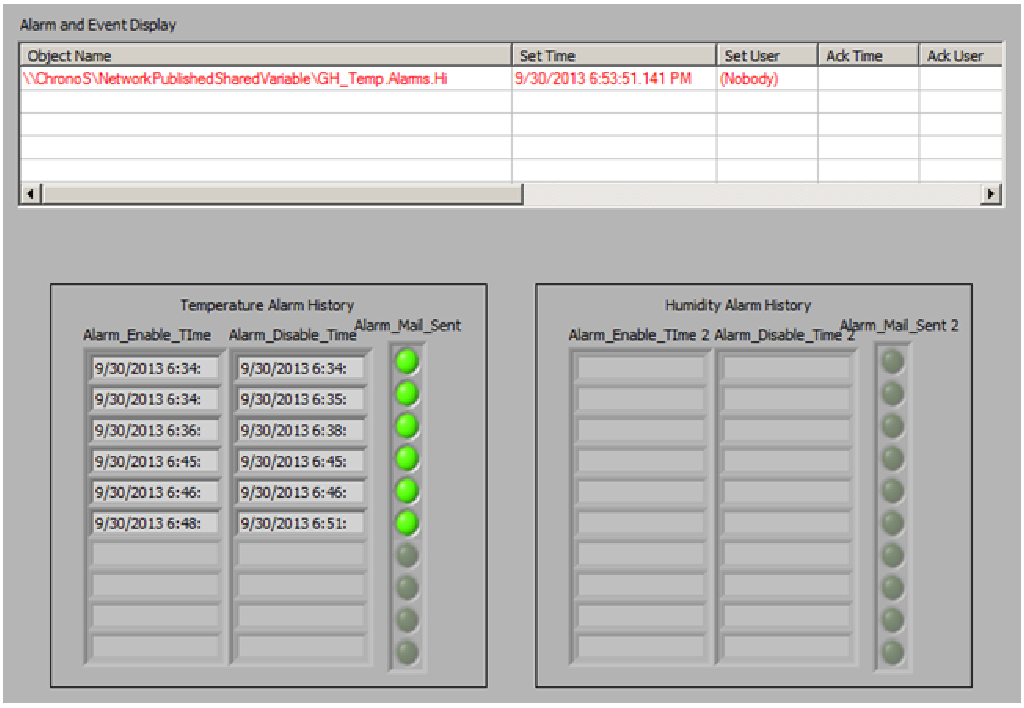


Fig. 5.16. Alarms notification HMI

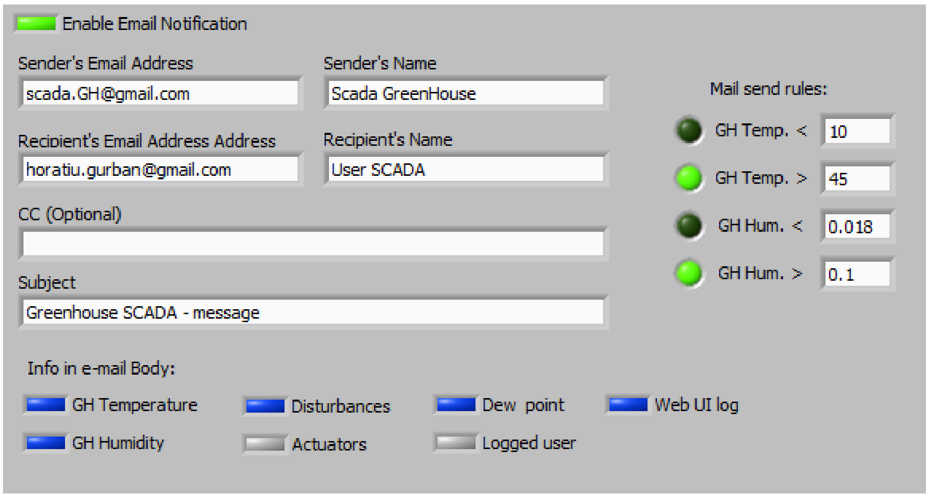


Fig. 5.17. Email notification configuration window

5.5. SCADA Implementation Using GPRS Data Transmission

In this chapter, the greenhouse control system is extended with a GPRS transmission with data buffering for long range monitoring and control purpose, the system architecture based on SCADA is presented in Fig. 5.18.

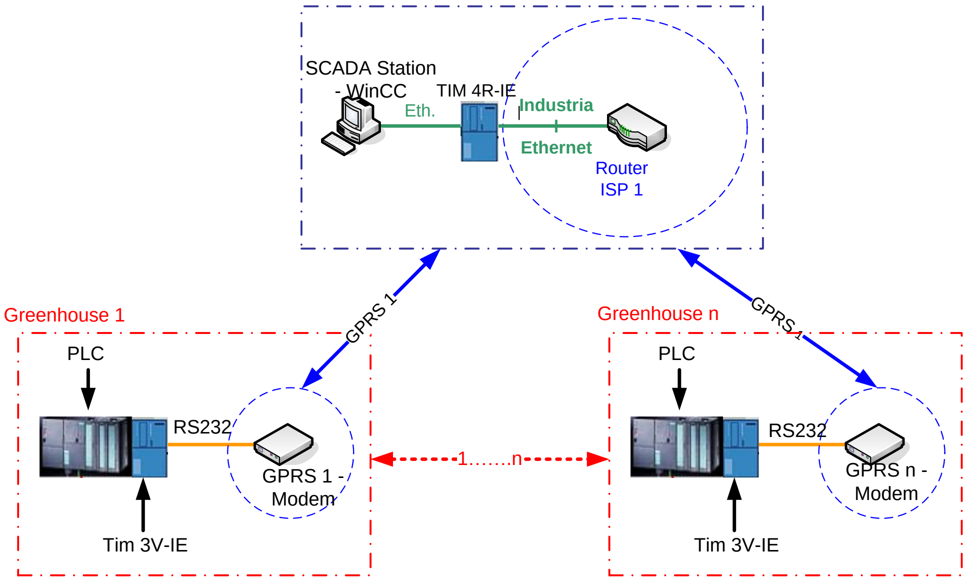


Fig. 5.18. General SCADA system architecture with GPRS

This is a good solution for the high number of cases when the greenhouses are remotely distributed on a large area where physical connections are not possible or feasible. The present GPRS system makes use of Siemens technology, hardware and software in order to remotely monitor and control one or more greenhouses. The technology used is SINAUT and Industrial Automation.

One of the main advantages of using Siemens remote terminal units - RTUs is that the modules managing the GPRS transmission are equipped with a configurable buffering memory. In case of communication failure, it stores data up to several days (depending on the acquisition cycle) and then, when the line is reestablished, they forward the data to the SCADA PC, which repopulates the missing data from the database, thus assuring data integrity.

For the greenhouse application, the RTU is connected to an OPC server, which has as main purpose to link the Siemens PLC (where the control algorithms run) to the PC with LabVIEW (where the greenhouse model runs). This is in essence a hardware-in-the-loop system, where the system under test (SUT) is the PLC with the control code. The SUT is extended with the GPRS transmission to a SCADA system.

How It's Made

The RTU contains the following modules: Siemens PLC, teleinterface module (TIM) and GPRS modem with a SIM-card with internet traffic.

The upper level SCADA system can be placed anywhere, and its architecture consists of a TIM module and a PC. The connection is always initiated by the TIM module at the RTU level due to the fixed IP address at the SCADA level.

From the software point of view, at the SCADA level runs WinCC SCADA and the SINAUT ST7cc – control center software. ST7cc server software acts as an intermediary between the RTU and WinCC, dealing with data decoding and data buffering (in case of WinCC failure). Additional software is present at the SCADA PC for developing the code for the PLC - Step7 and for configuring the GPRS connections and providing GPRS libraries at the PLC level - SINAUT ST7 Engineering. An important advantage is that the operator or engineer does not need to go on site, for each greenhouse in order to observe the RTU state or to make a software update. This is done remotely, the response of the system being observed directly on the SCADA system by means of a maintenance screen, as shown in Fig. 5.20a. Diagnosis can be executed on each RTU as well as on the ST7cc server, employing system state, error LEDs, data buffer fill-up and so on.

Several other screens are developed in order to assure a proper interaction between operators and processes as presented in Fig. 5.20, 5.21. The main screen of the SCADA system is presented Fig. 5.20b. The trends are stored in the database for one year and are presented on a time range of 20 minutes. On the right side there are the main greenhouse parameters and setpoints, e.g., temperature and humidity. Notice that there are two types of setpoints: i) by SCADA – this is the case when the system is up and running and is controlled by operators; ii) by LabVIEW – these are the setpoints introduced in LabVIEW in the PC which runs the greenhouse simulation code; this is the case for maintenance and engineering of the simulator graphical code.

Fig. 5.19. Experimental setup – main parts (in order from left to right): antenna, teleinterface module, GPRS modem, power supply, PLC with teleinterface module

The experimental setup is presented in Fig. 5.19.

The front panel of the main LabVIEW VI has a master control knob for switching the two control methods.

The alarms (Fig. 5.21a) are implemented by using the WinCC alarm management system. In this case, an alarm message is triggered when key parameters exceed a value imposed by the operator. Fig. 5.21b shows simulated disturbances generated by the LabVIEW greenhouse simulation.

The overall system concept targets to bring process simulation as close as possible to a real-life scenario, with industrial automation hardware and software, in order to get a glimpse at greenhouse process behavior and provide a real-time simulator for operator training. Furthermore, the system concept can easily be applied to real greenhouse farms having as main advantage the remote monitoring and control, through GPRS, SCADA system.

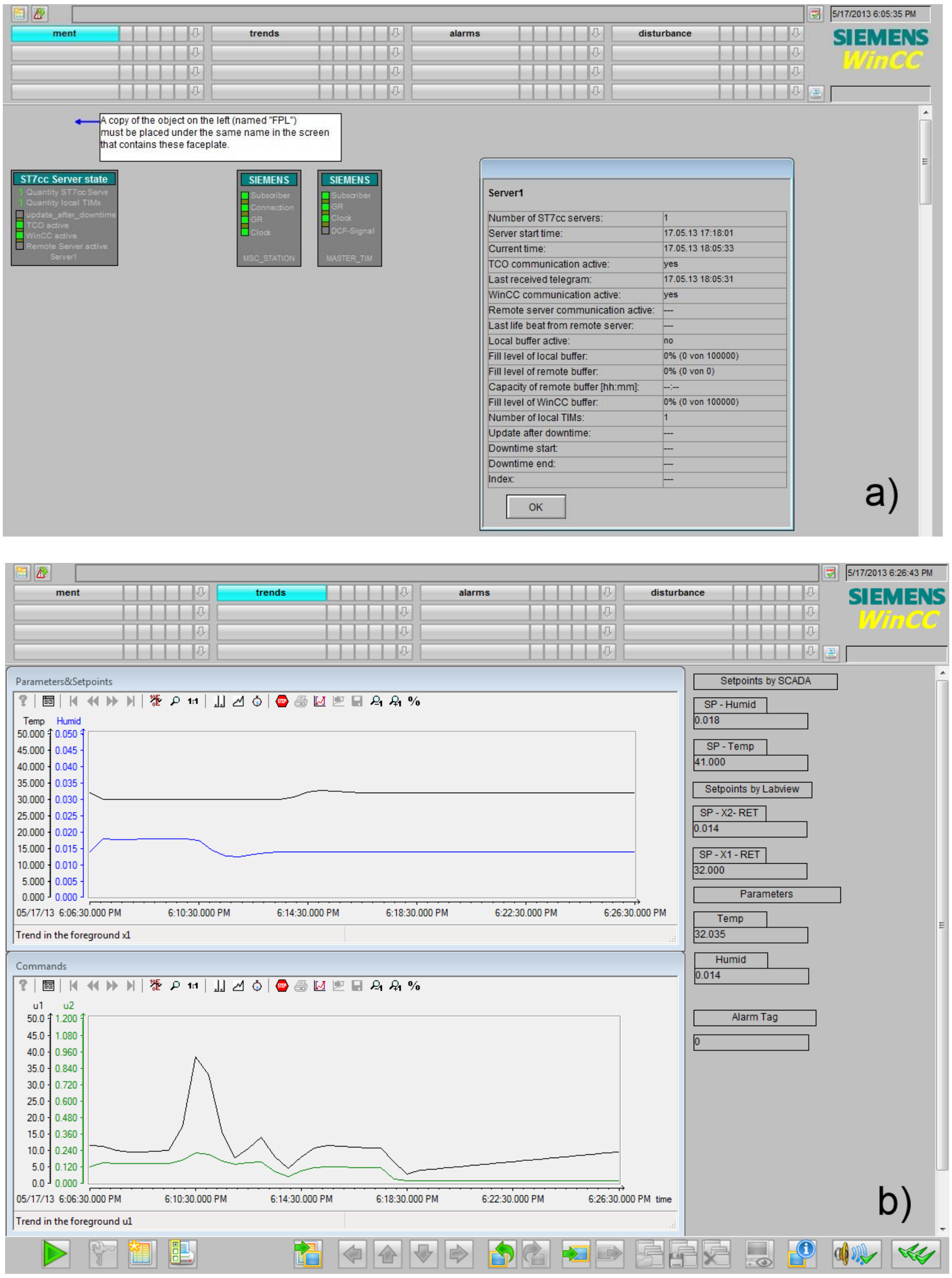


Fig. 5.20. SCADA HMI a) maintenance screen, b) controller commands and system response screen

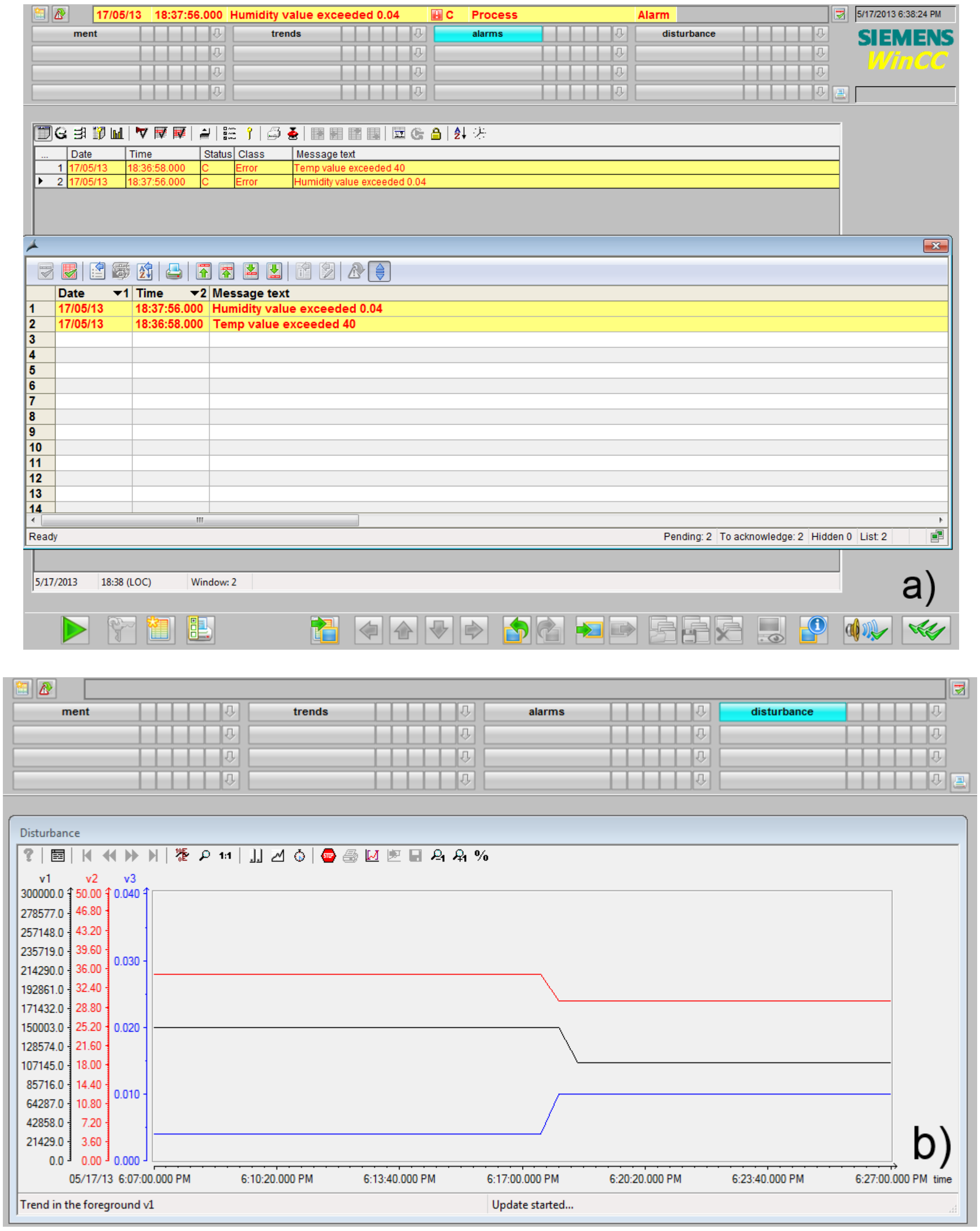


Fig. 5.21. SCADA HMI a) alarms screen, b) disturbance screen

5.6. Test Results

5.6.1. Temperature and Humidity Setpoint Filtered Step Changes

The greenhouse climate model parameters set used in the simulation are detailed below. The greenhouse structure has a floor area of 500 m^2 and a volume of 2800 m^3. A transmittance coefficient for the shading screen is also considered, having the value 0.4. The following actuator limitations are imposed: 40 m^3/s for the ventilator, and 1.2 kg H_2O/s for the fogging flow rate.

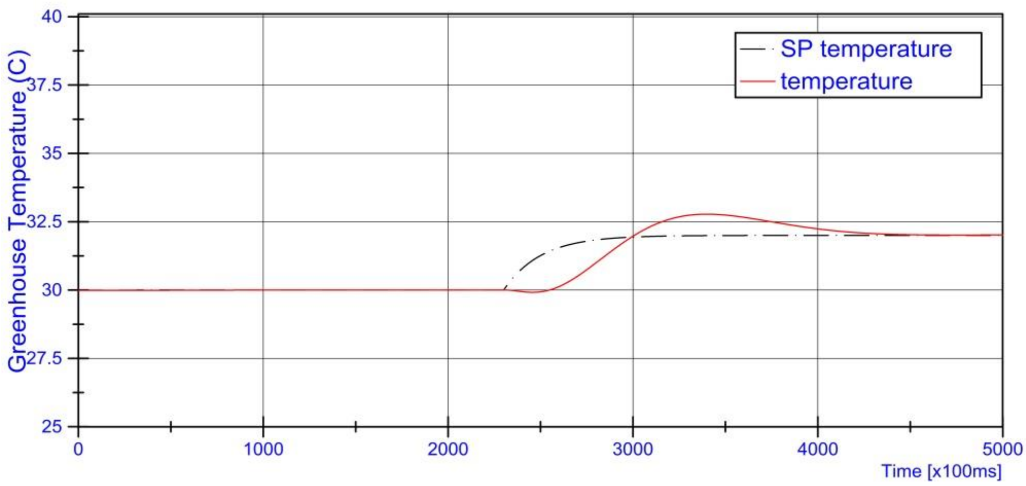
For greenhouse temperature and absolute humidity a 30 s dead time is imposed. During the simulation, constant values for the external disturbances are chosen: 300 W/m2 for intercepted solar radiant energy, 35 ^oC for outside temperature and 0.04 kg H_2O/m^3 for exterior absolute humidity. The initial condition for the greenhouse temperature and absolute humidity are 30 ^oC and 0.018 kg H_2O/m^3.

For testing the linearization and decoupling procedure and PID controller, components implemented on PLC (Fig. 5.1), a setpoint step change is used for greenhouse temperature and humidity. At 30 s, the absolute humidity setpoint is reduced from 0.018 kg H_2O/m^3 to 0.014 kg H_2O/m^3 and at 230s, the temperature setpoint is raised from 30 ^oC to 32 ^oC, as can be seen in Fig. 5.22.

A set point filter was used to reduce the overshoot. For this fact, a first order low-pass filter with a time constant of 20s is used.

The PI controllers are tuned by using Ziegler-Nichols tuning method, the obtained parameters are: K_p= 0.03 and T_i=90 [VIS'11].

The experiments presented in Fig. 5.22 prove that the linearization and decoupling procedure, implemented on PLC, properly works. In the case of temperature setpoint change, the greenhouse interior temperature rises (following the setpoint change) due to the actions of both actuators, but the greenhouse absolute humidity is kept constant. The same behavior is seen in the case of absolute humidity setpoint change. Also by employing the setpoint filtering, the actuator commands do not reach the saturation thresholds in the considered testing scenario.



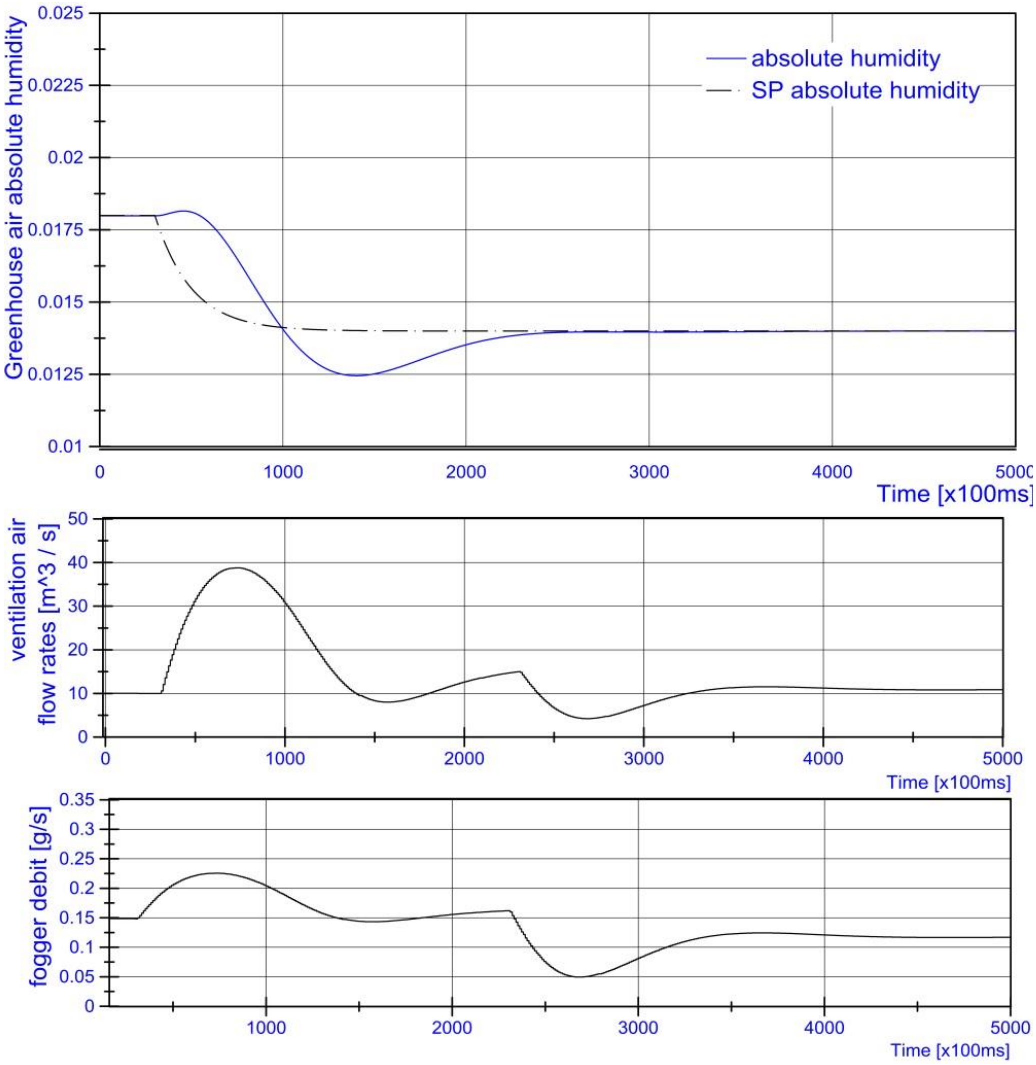


Fig. 5.22. System response (climate model output variable –temperature/absolute humidity and climate model input control variable -fan ventilation rate /fogger flow rate) in case of temperature and humidity setpoint step changes.

5.6.2. Disturbances Ramp Changes

The second simulation test (Fig. 5.23-5.25) proves that the feedback-feedforward linearization and decoupling procedure succeeds to compensate in the case of external disturbances variation. In each of the following simulation experiments the greenhouse air temperature and humidity remain constant when disturbance ramp changes are considered. The initial conditions are the same as in the previous case. The disturbance ramp changes are as following:

- Fig. 5.23 - v_1 ramp change from 300 to 150 W/ $m^2 \cdot 10^3 m^2$;
- Fig. 5.24 - v_2 ramp change from 35 ^oC to 29 ^oC;
- Fig. 5.25 - v_3 ramp change from 0.04 to 0.1 kg H_2O/m^3 .

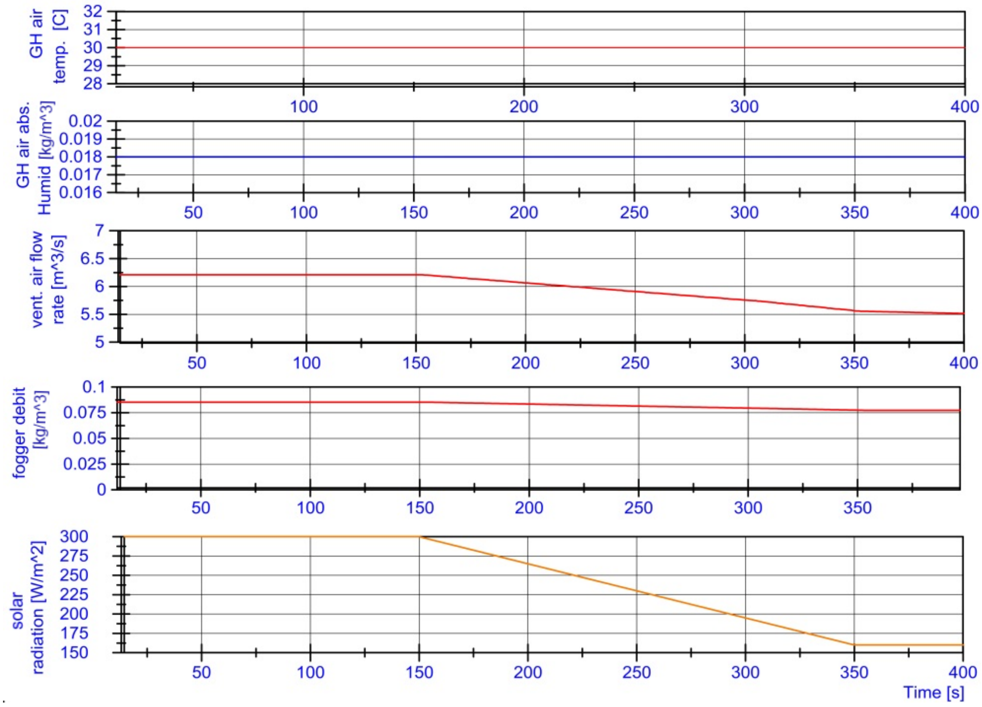


Fig. 5.23. System responses considering outside solar radiation disturbance ramp change

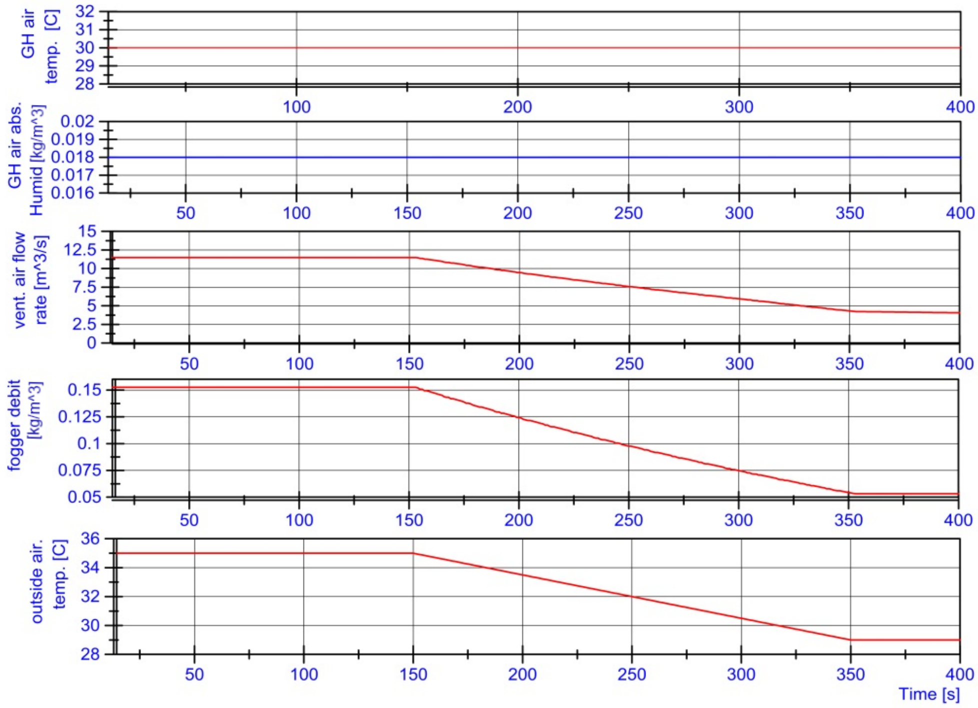


Fig. 5.24. System responses considering outside temperature disturbance ramp change

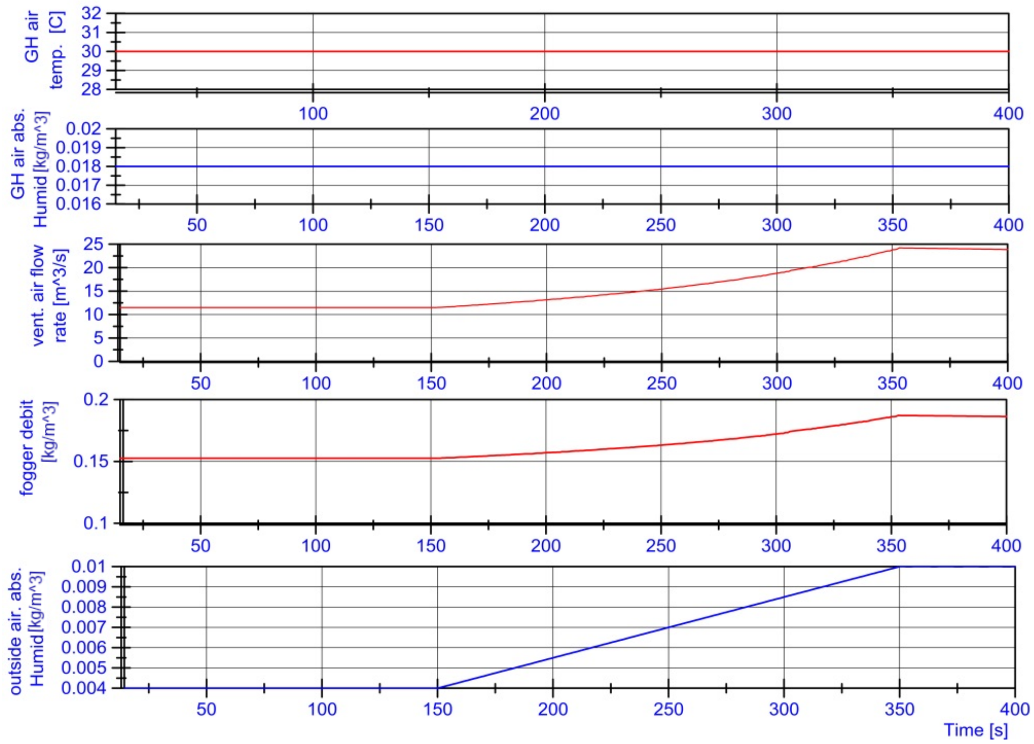


Fig. 5.25. System responses considering outside absolute humidity disturbance ramp change

5.7. Telematics Solution using Ethernet and Mobile Phone Network

The subchapter proposes, for the initial project stage, a viable solution for SCADA telematics system for distributed applications, including greenhouse environment control. The key point for this project is to develop a generic telematics system for SCADA remote terminal unit using Ethernet and mobile phone networks, which could be integrated in greenhouse SCADA applications.

This system contains the following elements: PIC18F4620 microcontroller, GSM modem, Ethernet controller, RTC board, digital thermometer and a LCD. The main I/O features are: remote command for 5 digital output lines, remote monitoring for 4 input lines and a remote monitoring for a digital thermometer.

The current trend in SCADA for remote monitoring and command is to use the wireless infrastructure resulting in a decreased interest to the traditional wired systems [IRW'06]. Feasibility studies for the GSM infrastructure using SMS where done, showing that this communication type is suitable for implementing distributed control systems data monitoring and acquisition [TSE'06].

This system has the specific hardware resources to monitor and control a greenhouse station for a SCADA complex greenhouse assemble (Fig. 5.18) and employs GSM and Ethernet communication.

Modern wireless communication technologies can be applied in distributed control system, e.g., in greenhouse automation or general agriculture automation due to their high flexibility, low cost, and high coverage area.

GSM/3G network is a wireless technology for data transmission, being present for a long time on the market, that offers a lot of features and a high percentage of users. GSM/3G networks are offering a very good coverage area worldwide at low costs of ownership, mainly because GSM technology is present on the market for over 20 years, reaching the past decade a high maturity level and gaining a lot of users. Because of the widely coverage, the GSM/3G networks can be used for implementation of telematics applications including automotive, home automation and also E-Agriculture domains.

The GSM/3G networks can use the voice capabilities but also the data transfer feature for telematics system usage. Studies regarding the usage of SMS for agriculture specific parameters remote monitoring indicated that the remote system shows good performance and reliability [AZI'09]. Telematics systems based on GSM networks can be used in critical safety systems, GPS positioning systems or in traffic reporting or diagnosis.

Home automation, building automation, greenhouse automation, E-agriculture have a common background. This includes light and climate control (ventilation, air conditioning, humidity, temperature), control of doors and window shutters, security and surveillance systems. The automated control involved in these types of systems reached a high level of maturity. One problem still remaining is the remote control, distant monitoring and distant diagnosis for those types of systems.

Even if there is a lot of distant monitoring and control technologies developed for greenhouse automation the main problem are the reliability and the coverage provided by this system. On one side, the SMS based on GPRS or GSM can meet the communication requirements if we take into account the distance and the coverage, but fail to do so after we consider the costs, possible delays in transmission and small data frames transmitted just 140bytes / SMS.

Another possibility is to use GPRS for data transmission [LI'06], but this system requires beside a microcontroller with GPRS module, a remote server that can host a web server. The architecture for creating a remote monitor and command was developed keeping in mind that the SCADA system needs technologies that provide high coverage area, redundancy in case that one communication media fails and also a low cost of ownership. First step was to choose a technology on which will be based the telematics system, thus the Ethernet and GSM/3G network where chosen.

Because the telematics is starting to be used more and more in all the automation domains, this project tries to create a generic SCADA telematics platform that can be successfully used in SCADA systems for distributed control environment. The starting point was the need for a telematics system to be integrated in a greenhouse SCADA system. The main problem was that the SCADA system should not restrain its usage due to the close location for all the distributed part of the SCADA system. In conclusion, a generic type of communication with a very good coverage had to be found. Web based distant monitoring and command solution where presented in the last period introducing a alternative way for handling the monitoring or command part for greenhouse automation [LI'06], [JAN'09], [SHI'11]. There are different web based architectures, some web servers are hosted on the microcontroller [JAN'09] others on PCs [SHI'11].

In this subchapter, one key concept is the development of an interface with the GSM/3G network that was accomplished by using a cell phone equipped with integrated GSM hardware modem that has AT commands capabilities. This particular approach was taken mainly due to the large number of GSM/3G terminals and modems on the market, the low cost and performance corroborated also with the user high level of acceptance for this common devices.

Another key concept is the usage of an Ethernet module that provides the microcontroller the possibility to host a web server, providing the user a web based interface, easy to use with worldwide coverage.

In the proposed solution the GSM/3G and Ethernet module where integrated in a single microcontroller based module providing a compact, robust solution for SCADA supervisory and alarm layer. Using a hybrid communication media, GSM and Ethernet, the telematics system gains the flexibility of web access and the high coverage of GSM networks in a fault-tolerance system.

5.7.1. Application Architecture

The basic concept was to create a telematics system for SCADA remote monitoring and commands functions. This system implements two ways for SCADA remote monitoring and command, one is based on SMS/call functionalities provided by GSM/3G network and the second one is accomplished by using a web page interface provided by a web server.

The interface with the GSM network was implemented using a cell phone equipped with integrated GSM hardware modem that has AT commands capabilities. It was particularly used this approach, because of the large number of GSM terminals on the market at prices very low in comparison with dedicated GSM modules.

The web server was implemented on the PIC microcontroller by interfacing to the Ethernet network through a SPI Ethernet controller: Microchip ENC28J60. The heart of the system is an EasyPIC5 development board with a PIC18F4620 microcontroller. This is an 8bit microcontroller that has enough hardware resources to sustain different system demands. When the microcontroller was chosen, it was taken into consideration the hardware demands for the development of a generic platform, but also the further development needs after the current described phase is accomplished. The proposed system can be remotely accessed, the user has the possibility to command 5 digital outputs, to monitor 4 digital input lines and one digital thermometer. The remote access of the 5 output lines can be done by sending SMS, by making phone calls or by using the web based interface. The status of the input lines / digital thermometer is periodically monitored and their status can be sent by SMS or seen on the web page hosted by the PIC microcontroller. The GSM-Ethernet based Telematics System project developed a reliable multi-purpose SCADA telematics system that can be personalized to meet different system demands.

5.7.2. Telematics System Hardware

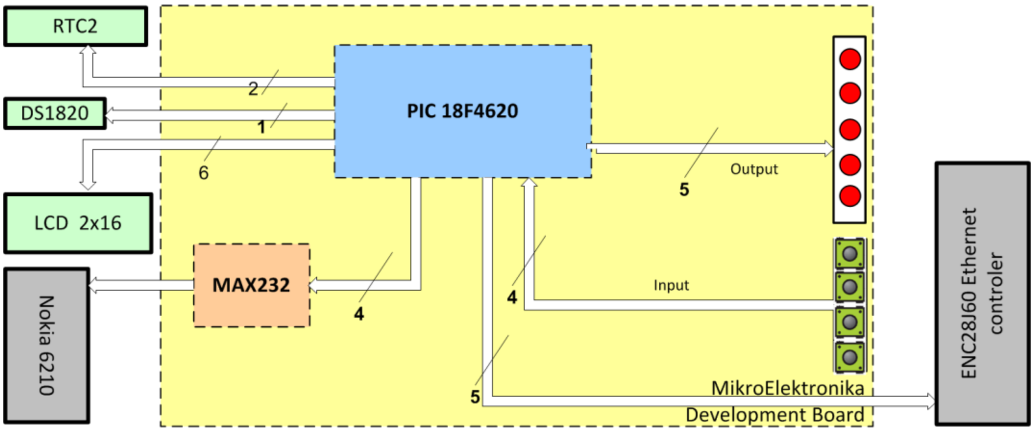


Fig. 5.26. GE-TS schematic

As it is showed in Fig. 5.26, the heart of the GSM/Ethernet Telematics System (GE-TS) is a PIC18F microcontroller. This is a 8 bit microcontroller from the PIC 18F family controller with 64KBytes of FLASH and 3968 Bytes of RAM, Master Synchronous Serial Port (MSSP) module Supporting 3-Wire SPI (all 4 modes) and I^2C Master and Slave modes and an Enhanced Addressable USART module. The development board, Fig. 5.27 presents the EasyPIC5 development board provided by MikroElektronika [MIK]. The MikroElektronika development system is composed of: development board, programming IDE and additional boards. The development board used is an Easy PIC, this board being compatible with a high range of Microchip PIC microcontrollers. The development board allows PIC microcontrollers to be easily connected to external circuits and a high range of peripheral devices.

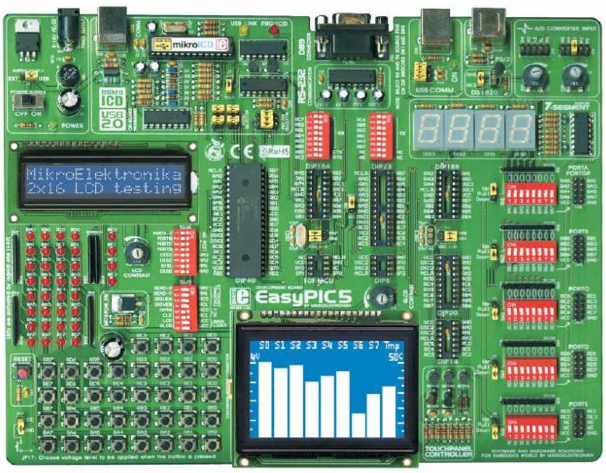


Fig. 5.27. MikroElektronika Development Board

The main features of Easy PIC 5 are: USB 2.0 on-board programmer supports 8 - 40 pin PIC microcontrollers, ICD debugger, supports additional boards provided by MikroElektronika.

Connection with the cellphone

The MAX232 is used to convert the TTL voltage levels to the EIA/TIA 574 voltage levels. This solution was preferred as the purpose was to gain interoperability with other communication equipment Fig. 5.28.

Any cell phone that has a data cable compatibility with EIA/TIA 574 standard can be used, from the hardware point of view. MikroElektronika development board has a MAX232 converter and uses for connection with other equipment a female DB9 connector. The RX and TX connectors are inverted. The compatibility between DLR-3P and the development board DB9 connector is assured by using an adaptor.

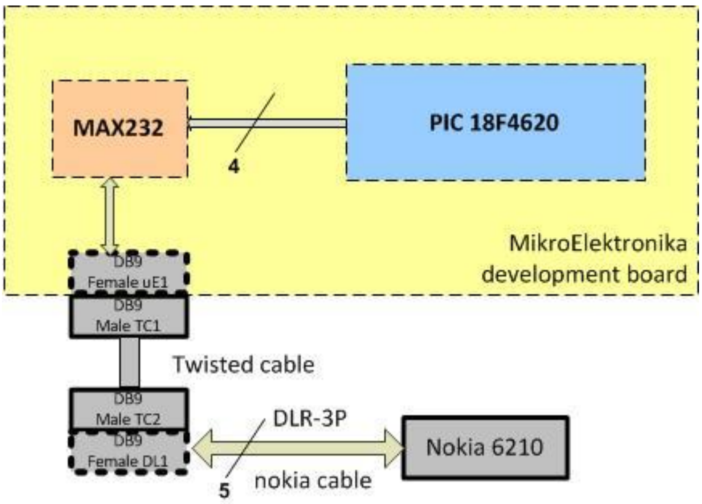


Fig. 5.28. Cell phone connection with development board

5.7.3. Telematics System Software

Software Flowchart

The GSM/Ethernet Telematics System (GE-TS), software can be divided in two main parts (Fig. 5.29): the first consists of initialization and configuration, and a second part of monitoring, processing and command. The configuration part runs once, at the startup and the monitoring, processing and command runs periodically.

First step is to configure the resources that are needed, here are configured the microcontroller hardware resources, the I/O ports, the timers, the USART module, initialization for the LCD and for the SPI Ethernet controller. To synchronize the data transmission between the GSM and the development board, the USART module is configured for different data transfer speed rates. After each initialization it is verified if the cell phone is sending back an acknowledge. If the acknowledge is indeed sent, the USART initialization state is kept, otherwise another initialization command is run. The next step is to find the phone numbers that are validated for usage by GE-TS. In this first step the ENC28J60 Ethernet controller is also initialized, configuring transmission parameters the MAC, subnet mask, IP for

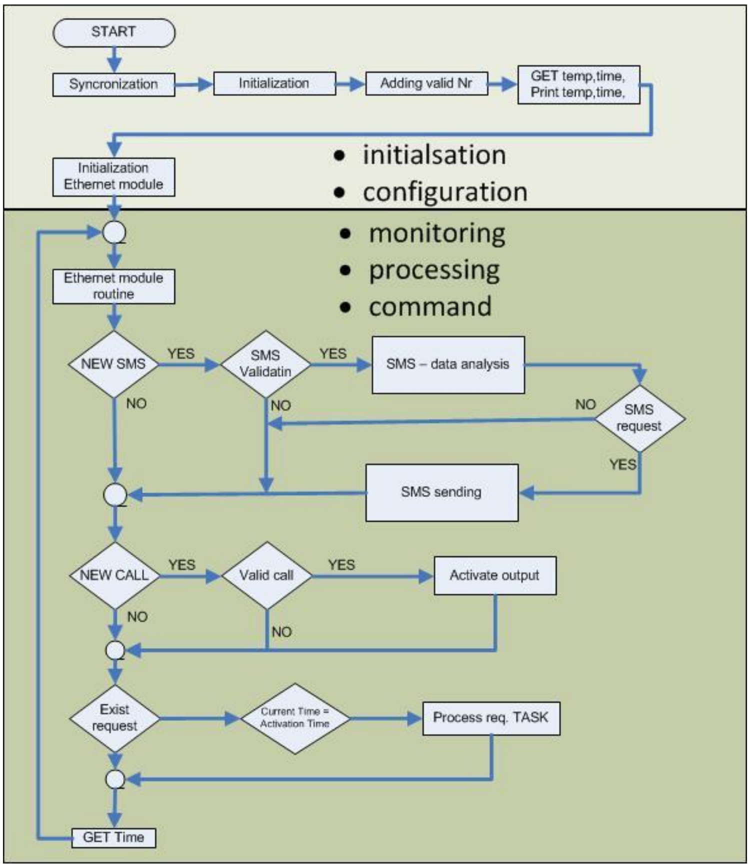


Fig. 5.29. Telematics system software flowchart

gateway, DNS and the address for the embedded device. For controlling the ENC28J60 Ethernet controller the SPI Ethernet Library provided by mikroC [MIK'09] was used.

Once the first part (initialization and configuration) is run, the software execution is continued with the second part which is processed periodically. Second part consists mainly of routine implementation for monitoring, processing and command. Temperature, four digital inputs, real time clock, occurrence of calls, messages received, occurrence of a scheduled task and the TCP/HTTP requests are monitored.

The clients can connect to the web server, hosted by the Pic microcontroller. If the user wants to modify the state of a digital output, a request will be sent to the server which will process the incoming TCP/HTTP request and take appropriate actions. If the users just want to observe the state of the system the web page is refreshed each cycle by the PIC microcontroller.

To obtain the temperature, DALLAS DS1820 1-Wire digital thermometer is interrogated periodically. The temperature is obtained at each running cycle. At each loop the microcontroller is interrogating the Nokia cell phone for new SMS receive. When a new SMS is received, it will be validated by the microcontroller, if the sender phone number is one of the 10 valid ones recorded in the cell phone agenda. In the next step it will start to process the message. If the call number is not valid an error message will be displayed on the LCD and the SMS will not be processed, so only the valid phone numbers commands are processed by GE-TS.

SMS can contain two types of commands, commands that need to be interpreted and processed immediately after reception or commands that will schedule tasks to be executed at a given time – stated in the task request SMS. The microcontroller supports a maximum of 5 tasks that can be recorded and activated at a defined moment of time. Those tasks can be performed daily or just once after the reception. If the task is configured to be run only once it will be deleted from the task queue after the processing.

If the SMS consist of an instant activation request, it will be processed immediately. In case the sender command contains a confirmation request, this can be done by calling or sending an SMS depending on type of confirmation requested. The SMS can contain one or more commands. There are 5 types of commands:

- digital output lines command
- status request
- call request
- task insertion
- task delete commands

If the task list is full, and the sender is requesting to insert another task in the list, the microcontroller will send a SMS warning message specifying how to delete the current tasks from the queue.

Next step is the detection of calls received by the cell phone. The calls are validated if the caller ID is preset in the cell phone agenda. If that happens, it will activate an output of the microcontroller. As a confirmation, the microcontroller will hang up the call.

The microcontroller is also processing of the tasks recorded in the task queue. If such tasks exist, the ECU will determine if the current time is the same as the activation request time of the tasks. If they are equal, the task is processed. If the task is not recurrent it will be deleted from the queue, after being processed.

AT Commands

AT commands are a standardized command set used to control a modem. The usage of AT commands offers the possibility to get information regarding the phone, the modem or the subscriber, establish a voice or data connection to the modem, send/receive a fax, send/read/write SMS, read/write/search phone book entries. GSM-TS is based on a GSM terminal provided by the terminal manufacturer NOKIA which can be controlled trough AT commands. A Nokia 6210 cellphone has been used. It belongs to the category of mobile phones with integrated hardware modem and has enough commands provided by the ETS 300 916/ETS 300 585 standard to support GSM-TS full application functionality. From the multitude of standards issued by ETSI [ETS’97], [ETS’99], allowing flexibility and inter compatibilities in communication networks, eloquent for GSM-TS are the followings:

- ETS 300 916 (GSM 07.07 version 5.9.1) – AT commands for voice, conference, access to SIM resources, address book, video memory or keys

- ETS 300 585 (GSM 07.05 version 4.8.1) - AT commands for the SMS (Short Message Service)

5.7.4. Telematics System Functions

The main functionalities of the GSM/Ethernet Telematics System, GE-TS, are: 1) Interfacing with the GSM/3G, Ethernet network; 2) Monitoring digital inputs, temperature, GSM terminal, Ethernet module TCP/HTTP requests; 3) Command; 4) User interface on the system LCD and WEB based interface provided by using the Ethernet module

Interfacing with the GSM Network

The interface with GSM network is provided by phone's capability to use AT commands, thus GE-TS is able to perform the following actions: receiving phone calls, making phone calls, receiving messages, sending messages, GSM additional functions like: hold, reject calls, interrogate the phone agenda, and modifying phone settings.

Based on AT commands this application is capable of making phone calls, receiving messages and of composing and transmitting messages.

Monitoring

The monitoring functions of the system can be categorized into: function for determining the current status, function of temperature monitoring, task queue monitoring based on RTC.

The information regarding the inputs/outputs of the system is published on the microcontroller hosted web page. Another way for accessing this data is by using the SMS capabilities of the GE-TS module.

The system can send a status SMS that contains the status of the digital I/O lines used by the system, the temperature, the current time and the task queue information. The system status can be requested by a SMS that has in its structure "req.sms" sequence. The status SMS is sent by the system when a SMS request is acknowledged or when a status message is imposed by task activation.

Status SMS is composed of: input lines monitored by the system, SMS controlled output, call controlled output, temperature information, SMS timestamp , the number of current tasks and the task list.

Status SMS example: "Sat 02.03.11 16:05 <temp 26><IN1 ON><IN2 OFF><IN3 OFF><IN4 ON><Toggle OFF><OUT1 ON><OUT2 ON><OUT3 OFF><OUT4 OFF>#No record#"

If there are tasks in the queue, the SMS response will not include the date, time and temperature because the full status cannot fit in a single SMS. This is the format of the SMS: "<I1-0 I2-1 I3-0 I4-1><Tg-0 L1-1 L2-0 L3-1 L4-0>#Nr req=3<req1 16:19 L1-1 L2=0 C><req2 18:09 L1-1 L2=0 S><req3 16:19 L1-1 L2=0 R>".

Command

The activation command for the 5 digital output lines can be given by: SMS, call, task scheduler and web interface.

Besides using the web interface for controlling the output state for the 5 digital lines, the GE-TS offers the possibility to use GSM module for SMS or phone calls based remote command. If the phone number of the caller is considered valid by GE-TS, the system will process the incoming call. After a caller number is validated, the microcontroller will toggle the value of an output line, or set the output for the microcontroller digital output lines.

The call is hang up as a result of confirming the received request. Also, the GE-TS can command the output lines when receiving a SMS request.

The syntax of a SMS command is: [Identifier]. [Action]. The identifier can take the following values: "DOUT1", "DOUT2", "DOUT3", and "DOUT4".The action can be "ON" or "OFF".

LCD User Interface / Web Based Interface

The user is informed about the action that is currently performed or future ones, using a LCD. The LCD is set to display different types of information: receiving an SMS/CALL, sending an SMS, validating procedure status - succeed/failed, error message and task queue information. As seen in Fig. 5.30, using the web based interface it's possible to see the current state of the I/O and the temperature provided by the DS1820 digital thermometer. The web interface offers the possibility to set desired output for the 5 digital output lines. On the PIC microcontroller hosted page are also enumerate the valid phone numbers that can be used to access the GE-TS features.

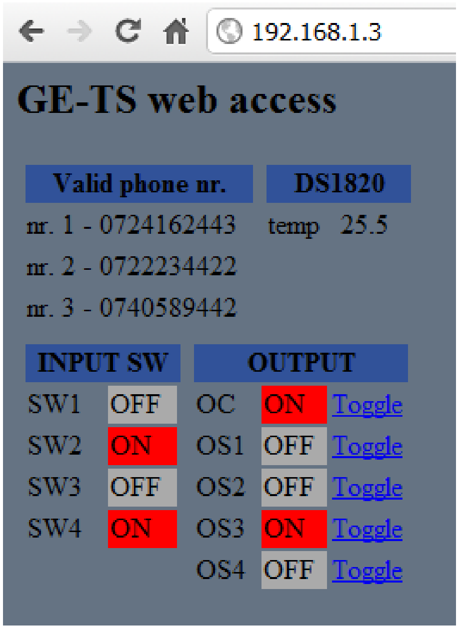


Fig. 5.30. Telematics system web interface

5.7.5. Further Development and Final Remarks GE-TS

There had been two development stages for GSM/Ethernet Telematics System, GE-TS. First stage consisted in the implementation of the remote command/monitoring by using the SMS/CALL features on a pic 16F876A. In the second development stage a new, more powerful microcontroller was used, so adding new functionalities was possible.

The next step is to test the GE-TS in a greenhouse and to configure/add new functionalities based on the grower requirements. Due to the integration of telematics module in a SCADA system for greenhouses, more functionality could be added. One important feature is to add an alarm handling module to inform the user through SMS, phone call or mail.

The main goal pursued when developing the proposed GSM/Ethernet Telematics System (GE-TS) was to create a highly configurable and upgradeable SCADA telematics system based on the GSM and Ethernet network. In the current stage, the project is fully functional, the main objective being to demonstrate the possibilities of monitoring and command through a "low cost" telematics solution based on GSM/Ethernet network. The main I/O features are: remote command for 5 digital output lines, remote monitoring for 4 input lines and a remote monitoring for a digital thermometer.

The current system implementation can easy be updated to monitor and control a wide range of sensors and common devices used in different areas. This project offers a low-cost generic SCADA solution to be used in for remote monitoring and command of greenhouse climate control systems but also for various automation domains like home/building automation, E-Agriculture and s.o.

5.8. Summary and Conclusions

A SCADA system using Hardware-in-the-Loop (HIL) for greenhouse climate control is developed and implemented by using the following main modules.

i) The greenhouse climate model is implemented on PC using National Instruments LabVIEW.

ii) The control algorithms, i.e., the PI controllers and the decoupling and linearization module are implemented using a Siemens PLC.

iii) The remote monitoring and command human machine interface (HMI) are implemented with two solutions. The first solution is a web based HMI developed using LabVIEW Web UI Builder. The second solution takes advantages of the NI LabVIEW Remote Front Panels which allows the user to access remotely the VI's front panel within a Web browser.

iv) The alarm monitoring is implemented, so the user can visualize the alarms using the HMI and it also can be informed by receiving e-mail notifications.

v) A SCADA solution using GPRS data communication is also developed.

All the system component modules and also the whole system behavior are tested with good results.

A GSM Ethernet Telematics System for remote terminal units is also develop and implemented. This is an embedded, generic telematics system that allows remote monitoring and command using: 1) GSM/3G Short Message Service (SMS) / phone calling, or by 2) using the web page hosted by the PIC microcontroller.

By using the Hardware-in-the-Loop concept, the greenhouse climate control solution and HMI implementation have been validated. The overall system concept has been implemented using industrial automation hardware and software, bringing the process simulation as close as possible to a real-life scenario.

The main contributions of this chapter are the following:

❖ Development and implementation of a hardware-in-the-loop (HIL) platform for greenhouse climate control: temperature and humidity control algorithms, linearization and decoupling algorithm - implemented on Siemens S7-300 PLC; greenhouse climate model - implemented on PC by using LabVIEW. The obtained test results prove the SCADA functionality for greenhouse climate control.

- Development and implementation of two types of HMI SCADA solutions for greenhouse climate remote monitoring and command: a) solution using the web interface developed using NI LabVIEW Web UI Builder and the NI LabVIEW Remote Front Panels and b) solution part of a SCADA which uses GPRS data transmission developed using SIEMENS WinCC SCADA and SINAUT ST7.
- Development and implementation of generic GSM Ethernet Telematics System, intended for remote sensor monitoring and actuator command, using for communication: 1) GSM/3G Short Message Service (SMS) / phone calling or by 2) using the web page hosted by the microcontroller system.

The results obtained in this chapter where disseminated in two papers published in IEEE conference proceedings [GUR’11], [GUR’13b].

6. CONCLUSIONS AND CONTRIBUTIONS

The PhD thesis develops solutions for greenhouse climate control systems (temperature and humidity control). This is an actual subject included in the more larger domain of *application of control system in agriculture*. The climate control system using a nonlinear-coupled model, with important influence of external disturbances, is implemented employing linearization and decoupling module and mainly PID controllers tuned by different methods. The comparative results and finally implemented SCADA system using Hardware in a loop is realized.

The subject of the PhD thesis fits into *control system engineering* domain, has a complex and multidisciplinary character including the following main elements of research: greenhouse climate mathematical models, nonlinear and coupled system with dead time, linearization and decoupling, state observer, specific controller, genetic algorithms, real time implementations, Hardware-in-the-loop, SCADA.

The thesis is structured in 6 chapters, summarized shortly as follows:

The first chapter presents the objective of the thesis, the structure of the thesis and a short description of the chapters.

Chapter 2 presents a state of the art for the greenhouse automation systems. The analysis and classification of their characteristics and contributions in suitable categories offers ideas for new applications and relevant research opportunities, including for the present PhD thesis.

Chapter 3 presents the nonlinear and coupled greenhouse climate model, analyses and improves the linearization and decoupling algorithm by employing state observers for estimating the state variables without time delay. The equivalent system contains two decoupled channels for temperature and humidity with an integrator plus dead time (IPDT) behavior.

Chapter 4 develops greenhouse climate control solutions for the equivalent IPDT decoupled, linearized model by employing PID controllers tuned by: conventional methods, 2DoF tuning methods, genetic algorithm. The control system performances employing the previously mentioned controllers are analyzed and compared using the simulation results. A modified Smith predictor using a proposed state observer is also developed and tested by simulation.

Chapter 5 illustrates the development and implementation of a hardware-in-the-loop (HIL) platform for greenhouse climate control using NI LabVIEW and Siemens industrial automation software package and Siemens hardware technology. This chapter details the implementation of SCADA specific modules: two Human Machine Interfaces (HMI) and a generic GSM Ethernet Telematics System.

The results of the doctoral research including theoretical aspects, comparative simulation results and practical implementation have been disseminated in seven scientific papers: four papers published in proceedings of international conferences (indexed- IEEE Xplore, Scopus, INSPEC), one scientific papers sent to an international conference and two articles sent to ISI journals still being in reviewing process. (see the list of author's papers related to the PhD thesis, pg. 132)

The main contributions of the thesis are the following:

1) Synthesis of greenhouse automation *state of the art*, reviewing the recent developments and implementations for greenhouses facilities, focusing on recent progress regarding greenhouse environment monitoring and control, with many available systems application examples.

2) Optimization of linearization and decoupling structure for greenhouse climate control (temperature and humidity), using the feedback-feedforward linearization and decoupling method trough two proposed *robust methods for estimating the state variables without time delay* (validated by comparative simulation results):
   - The first solution uses the complex *internal model* of the greenhouse climate process without decoupling module;
   - The second solution uses a Luenberger *state observer* structure, that employs a simple equivalent structure of the greenhouse climate process with decoupling module having an integrator plus dead time (IPDT) behavior, using a P or PI compensator, with the advantage of low computation effort and accurate estimation.

3) *Comparative study* by simulation results of greenhouse climate control system with decoupling employing *PI/PID controllers tuned by five conventional tuning techniques* for equivalent IPDT process, by taking into account the effect of actuator saturations. The considered conventional tuning methods are: Ziegler–Nichols, Internal Model Control IAE/ISE minimization, Closed-loop Transfer Function Coefficients Matching, Direct-Synthesis-Based Design, Specification of Desired Control Signal.

4) *Comparative robustness study* by simulation results of greenhouse climate control system with decoupling (IPDT process) employing PID controllers tuned by 3 conventional methods and *3 PI-2DoF tuning methods*, taking into account parameter variations and wrong disturbance measurements, concluding that the 2DoF PI controllers are more robust. The considered PI 2DoF tuning methods are: model reference robust tuning (MoReRT), multiple dominant pole (MDP) and performance portrait method (PPM).

5) *Procedure for optimizing* the greenhouse climate control system with decoupling using *genetic algorithms (GA) for PID controllers tuning by:*

- proposed *objective cost functions* that contains integral penalty terms for: absolute value of normalized input error, square of normalized output variable and actuator saturation duration;
- inclusion in *GA initial population* of 4 PID controller parameter set tuned by conventional tuning techniques, with the advantage of fast convergence algorithm.

6) Optimization of greenhouse climate control system with decoupling using PID tuning by *genetic algorithms (GA)* in *two proposed real scenarios* of greenhouse climate transitions: nocturnal-diurnal, diurnal-nocturnal. The obtained PID parameters could be used for *adaptive tuning* for these specific cases.

7) *Structure of a modified Smith predictor* for greenhouse climate control with decoupling by proposing a *state observer structure* based on the simplified equivalent model *to estimate the state variables without time delay*, with the advantage presented in the 2nd contribution where this observer is used also in the linearization and decoupling module.

8) *Development and implementation of a hardware-in-the-loop (HIL) platform* for greenhouse climate control: temperature and humidity control algorithms, linearization and decoupling algorithm - implemented on Siemens S7-300 PLC; greenhouse climate model - implemented on PC by using LabVIEW and an OPC Server for communication. The test results prove good performances for implemented greenhouse climate control system.

9) *Development and implementation of two Human Machine Interfaces (HMI) SCADA solutions* for greenhouse climate remote monitoring and command: a) two solutions using the web interface developed using NI LabVIEW Web UI Builder, and the NI LabVIEW Remote Front Panels and b) solution part of a SCADA which uses GPRS data transmission developed using SIEMENS WinCC SCADA and SINAUT ST7.

10) *Development and implementation of a generic GSM Ethernet Telematics System*, used as a remote terminal unit (RTU) in SCADA system for sensor monitoring and actuator command, based on microcontroller system and using for communication: 1) GSM/3G Short Message Service (SMS) / phone calling, or by 2) web page hosted by the microcontroller.

Author's Papers Related to the PhD Thesis

[1] Gurban E. H., Dragomir T.-L., Andreescu G. -D., Greenhouse Climate Control Enhancement by Using Genetic Algorithms, *Journal of Control Engineering and Applied Informatics*, (ISI journal, IF=0.228), in review.

[2] Gurban E. H., Andreescu G.-D., Pelan O., Greenhouse Environment Monitoring and Control: State of the Art and Current Trends, *Environmental Engineering and Management Journal*, (ISI journal, IF=1.117), in review.

[3] Gurban E. H., Iacob M., Andreescu G.-D., (2013), *SCADA system and hardware-in-the-loop for greenhouse climate control implementation*, Proc. 5th IEEE International Symposium on Logistics and Industrial Informatics (LINDI 2013), Wildau, Germany, Sept., 125-130. (IEEE Xplore, LINDI 2012 indexed ISI proc)

[4] Gurban E. H., Andreescu G.-D., (2013), *Employing 2DoF PID Controllers to Improve Greenhouse Climate System Robustness*, Proc. IEEE International Conference on System Science and Engineering (ICSSE 2013), Budapest, Hungary, July, 93-98. (IEEE Xplore, INSPEC, Scopus)

[5] Gurban E. H., Andreescu G.-D., (2012), *Comparison Study of PID Controller Tuning for Greenhouse Climate with Feedback-Feedforward Linearization and Decoupling*, Proc. 16th Int. Conf. on System Theory, Control and Computing (ICSTCC 2012), Sinaia, Romania, Oct., 1-6. (IEEE Xplore, INSPEC, Scopus)

[6] Gurban E. H., Andreescu G.-D., (2011), *SCADA Element Solutions Using Ethernet and Mobile Phone Network*, Proc. 9th Int. Symp. on Intelligent Systems and Informatics (SISY 2011), Subotica, Serbia, Sept., 303-308. (IEEE Xplore, INSPEC, Scopus)

[7] Gurban E. H., Andreescu G.-D., *Comparison of Modified Smith Predictor and PID Controller Tuned by Genetic Algorithms for Greenhouse Climate Control*, 9th IEEE International Symposium on Applied Computational Intelligence and Informatics (SACI 2014), May 2014, in review.

[8] Gurban E. H., *SCADA Element Solutions for Greenhouse Automation*, Proc. 1st Workshop "Interdisciplinaritatea şi Managementul Cercetării", Politehnica University of Timişoara, 24-25 Nov. 2011.

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[10] Gurban E. H., *Greenhouse Facilities Monitoring and Control*, Proc. 3rd Workshop "Interdisciplinaritatea şi Managementul Cercetării", University of Piteşti, 30-31 May 2013.

Appendix 1 – Greenhouse climate model and control, LabVIEW G code implementation

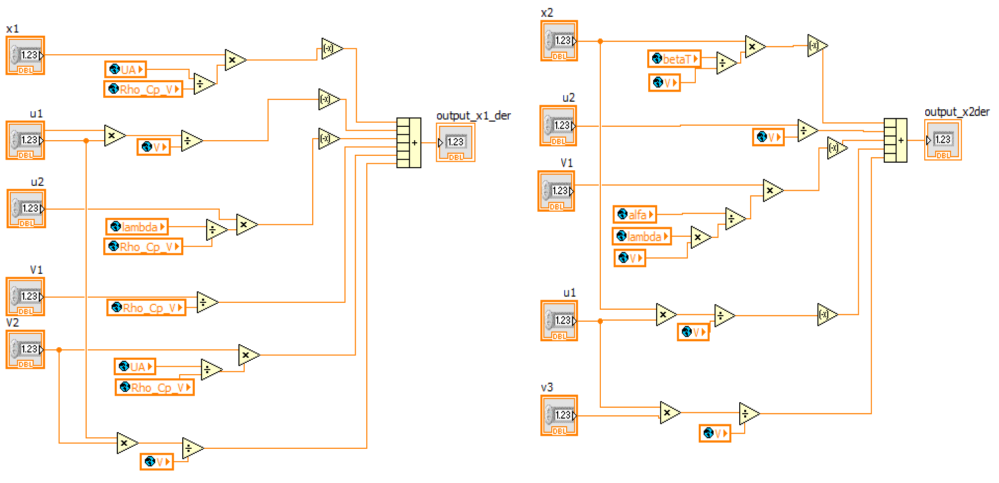

Fig. A1.1. Greenhouse climate subVI, LabVIEW G code implementation

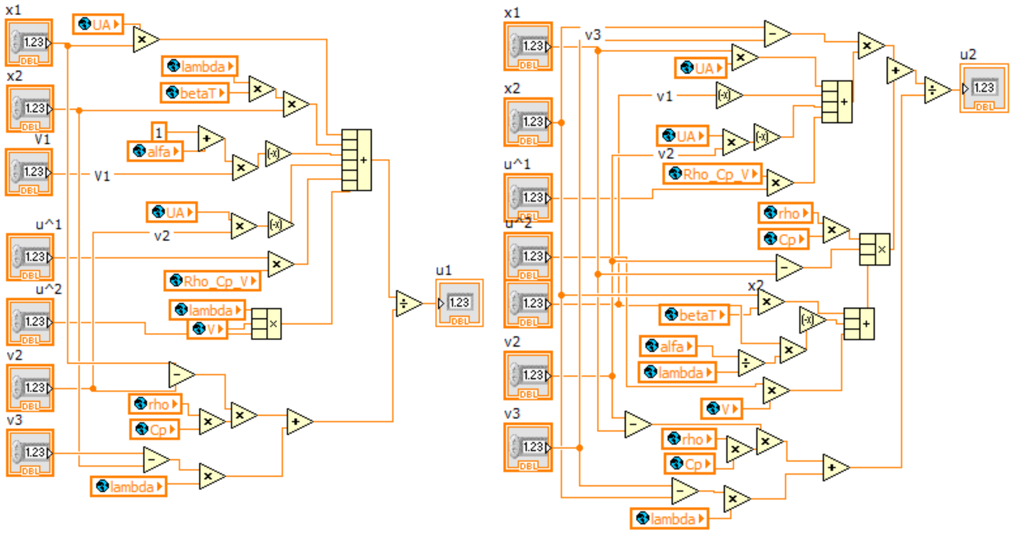

Fig. A1.2. Module for linearization and decoupling, LabVIEW G code implementation

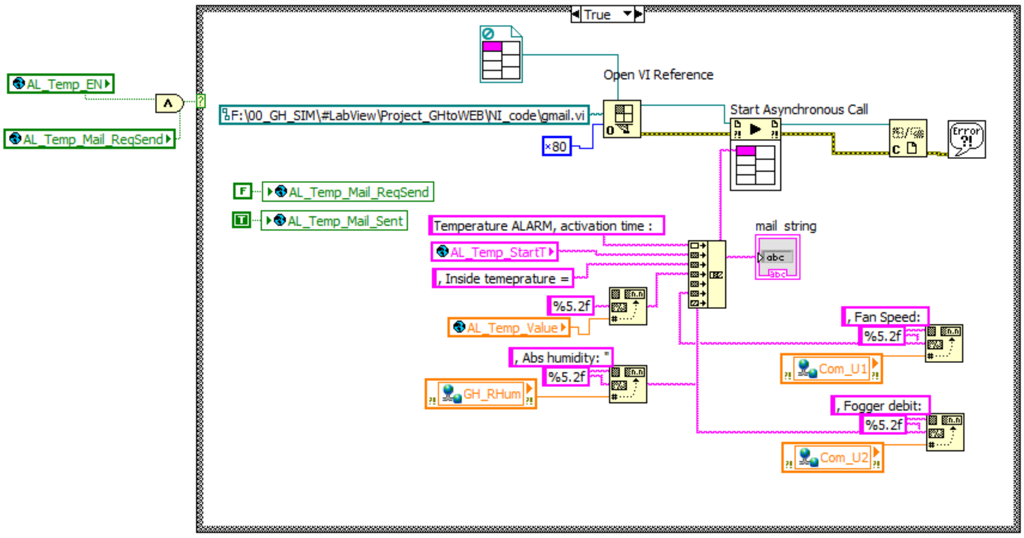

Fig. A1.3. E-mail notification LabVIEW subVI block diagram

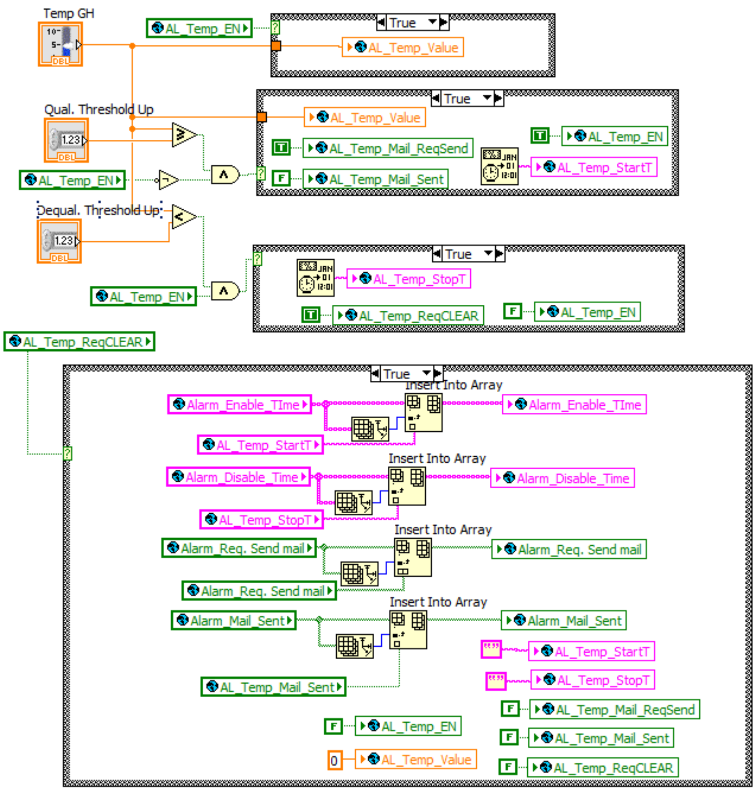

Fig. A1.4. Alarm module LabVIEW subVI block diagram

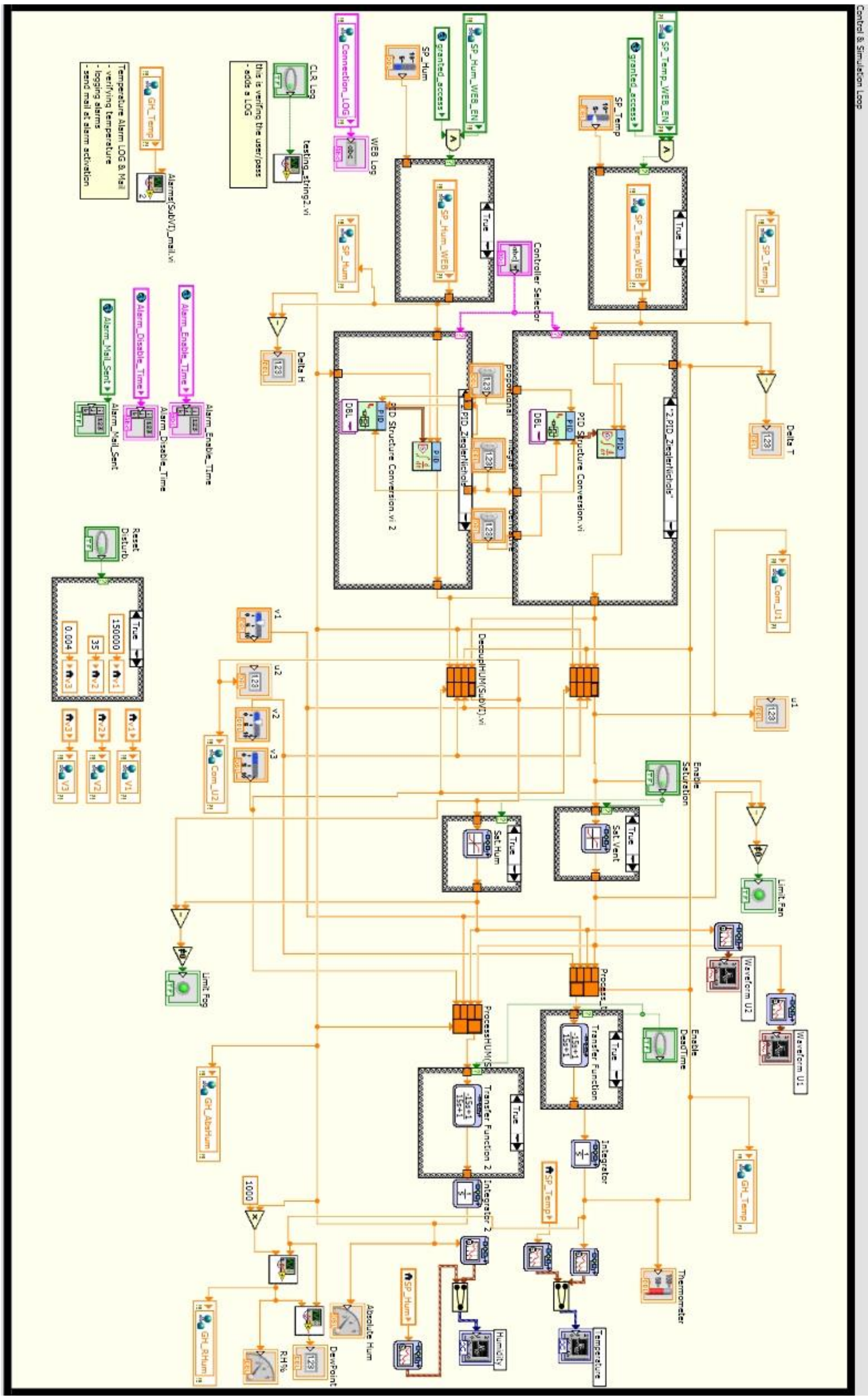

Fig. A1.5. LabVIEW Main VI block diagram developed for interfacing with LabVIEW Web UI HMI

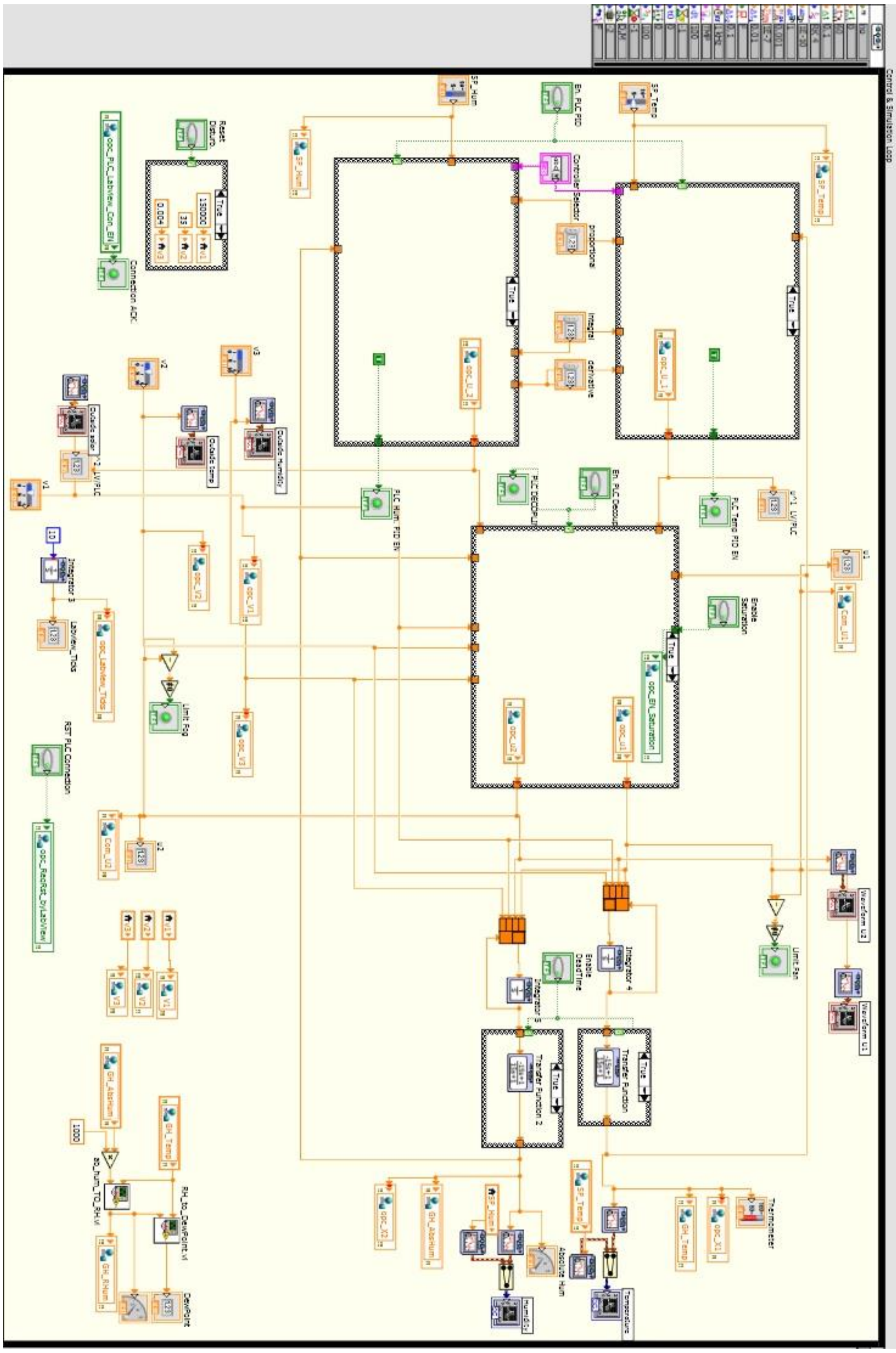

Fig. A1.6. LabVIEW Main VI block diagram

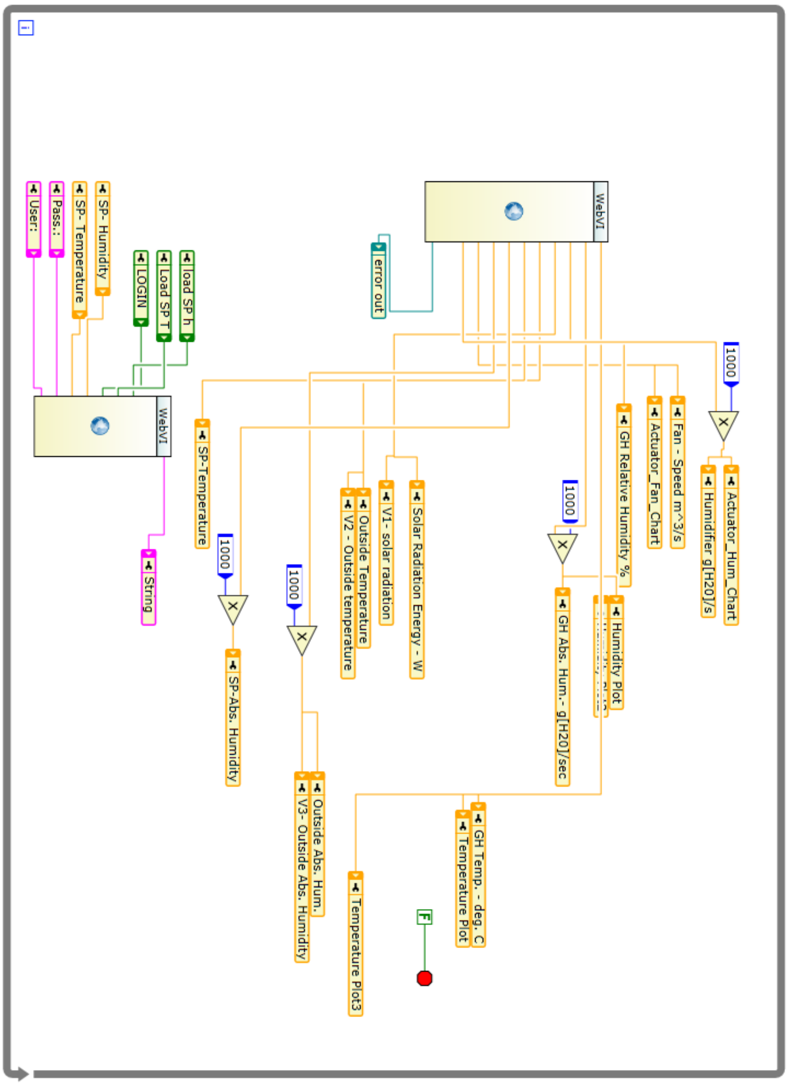

Fig. A1.7. LabVIEW WEB UI block diagram

Appendix 2 – Greenhouse climate model and control, MATLAB Symulink implementation

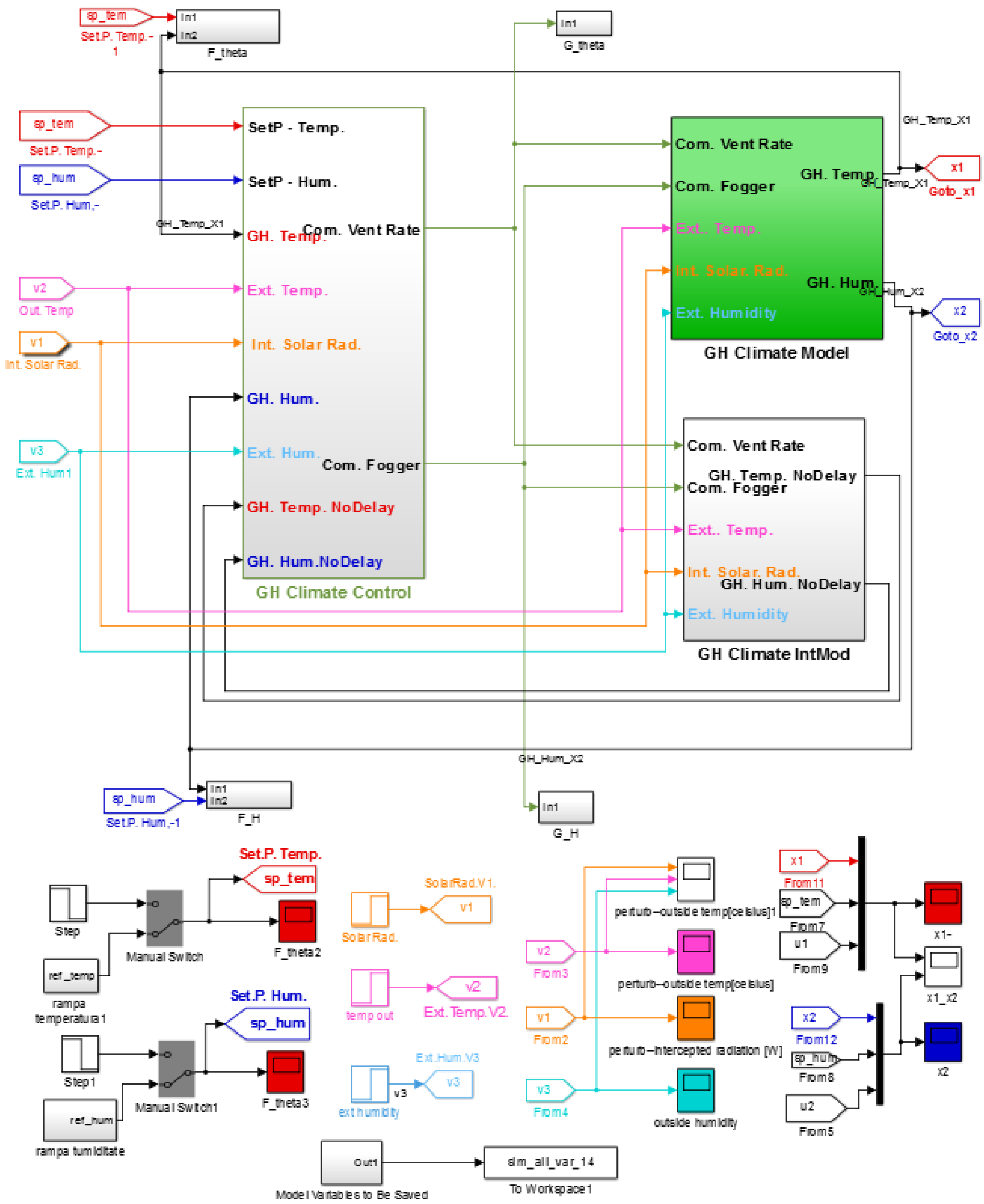

Fig. A2.1. Greenhouse climate model and control developed in Matlab-Simulink

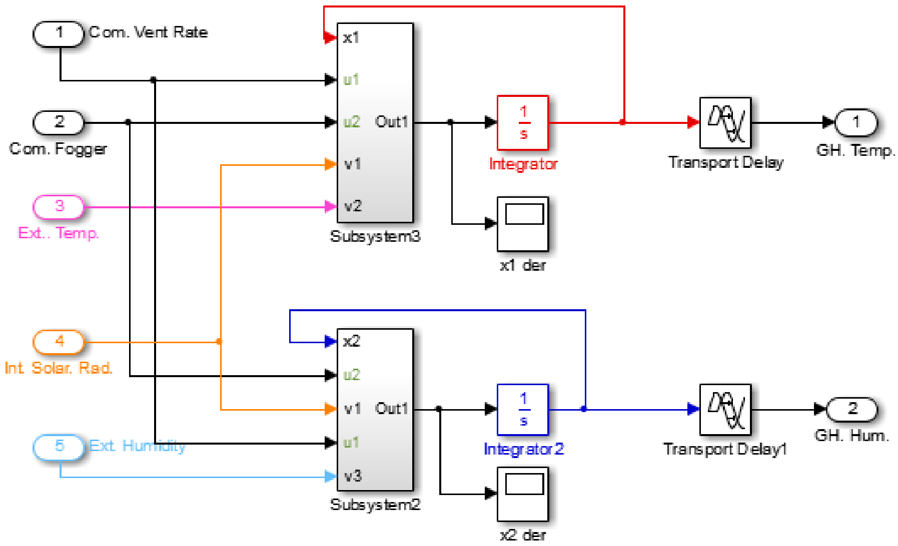

Fig. A2.2. Matlab-Simulink greenhouse climate model block

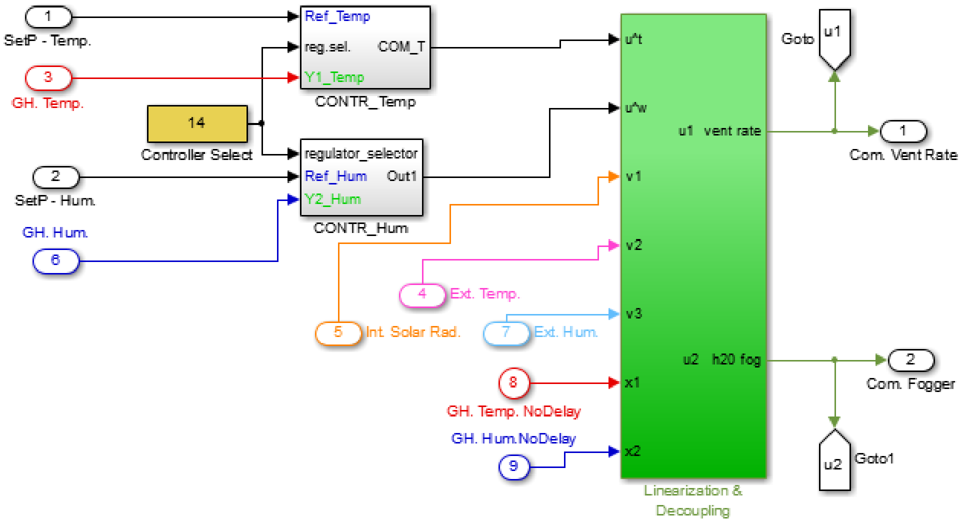

Fig. A2.3. Matlab-Simulink greenhouse climate control block

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