Environmental Control of a Greenhouse System Using NI Embedded Systems Technology

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Abstract—**This paper presents the application of an automated environmental control system for a prototype greenhouse system using commercial embedded systems technology. The prototype greenhouse system was developed and instrumented with appropriate sensors to measure various environmental variables like the temperature, the light intensity, the soil moisture, the air humidity and CO_2 concentration. These measurements are provided to the control algorithm which is implemented on a commercial embedded system and manipulates various actuators like, a heating and cooling actuator, fans, lights, irrigation system, and louvers in order to achieve the desired set-points, as specified by the user through a Human-Machine Interface implemented in LabView software. Certain aspects of the greenhouse dynamics have been modeled in Matlab/Simulink using nonlinear differential equations and the simulation model has been validated against experimental data, showing good agreement between the simulation and the experimental data. The purpose of this work is to enhance research related to the accurate environmental control of greenhouse systems in order to minimize energy and water consumption and to develop a robust educational platform for teaching control system design, analysis, instrumentation and embedded systems development at the Engineering School of Bahrain Polytechnic.**

Index Terms—**environmental control, automated greenhouse system, embedded system, temperature regulation**

I. INTRODUCTION

A. Environmental Control of Greenhouse Systems

The environmental control of a greenhouse implies the regulation of day and night air temperatures, the relative humidity and the carbon dioxide levels to ensure optimal plant growth. Heat, water vapor and carbon dioxide are transferred in and out of the greenhouse space in order to maintain the required set-points of temperature, relative humidity and carbon dioxide concentration. Heat is transferred by conduction, convection and radiation and various mass transfer processes are also occurring utilizing fans and louvers resulting in complex flows that involve both heat and mass transfer. A good introductory reference detailing the basic functions of a greenhouse system is found in [1]. A more detailed account of the functionality of an automated greenhouse system is presented in [2]. The authors discuss the various functionalities of a greenhouse such as light intensity control, heating control, cooling control, air circulation control and humidity control. Various active and passive actuation devices are presented in order to achieve the desired regulation effect. A brief discussion on closed-loop (feedback) control is given, detailing some requirements on sensing environmental variables and on control algorithm implementation. Interestingly, the authors present their analysis based on the application of a greenhouse automated system for the extreme Alaskan weather. They quote: ``By optimizing light, temperature and humidity, in conjunction with the proper fertilization, watering and selection of adapted varieties, an endless array of growing opportunities awaits the Alaska greenhouse gardener and commercial producer''. Moving towards the more moderate Mediterranean climate, the authors in [3] present an analysis of the most important functionalities of an automated greenhouse system, namely the temperature and relative humidity control. The authors provide indicative set-point values for these variables that favor plant growth and based on the climograph information for a given location, they determine the levels of cooling or heating required to maintain these set-point values. The climograph contains information regarding the mean solar radiation and mean air temperature for a given location all around the year. It constitutes the starting point in identifying the actuation requirements for an automated greenhouse system. Special attention is given to energy efficiency and sustainability. The authors focus on providing favorable conditions for plant growth during the hot periods of the Mediterranean climate while using energy efficient processes like ventilation, shading, evaporative cooling and effective insulation. Similar design requirements are addressed in [4], where the authors present the application of an automated greenhouse system for the production of tomatoes.

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B. Modelling of Greenhouse Systems

The automation of a greenhouse implies the implementation of a closed-loop (feedback) control algorithm, from the simplest on/off strategies employing thermostats to the most advanced PID and gain-scheduled controllers requiring accurate sensor measurements and algorithm development on embedded systems. The advantage of the implementation of a more advanced control algorithm is the ability to account for optimal design and operation requirements, like minimum energy control and accurate regulation in the presence of external weather disturbances and uncertainty in modeling accurately the biological processes characterizing the growth of plants. The design of an advanced control algorithm requires a good knowledge of the open-loop system dynamics, in our case, the greenhouse system. The process of acquiring knowledge and representing the open-loop dynamics of a system is called physical and mathematical modeling. The objective is to obtain a set of mathematical equations relating the inputs to the outputs of the greenhouse system. The outputs are chosen to be the environmental variables that we wish to regulate, like the temperature of the air, the relative humidity, the soil moisture, the light intensity and any other environmental state that we can measure with an appropriate sensing device. The inputs of the system can be the power of the heating or cooling actuators, the power of the fans, the opening of the ventilation ducts, the coverage of the shading system, etc. These mathematical equations that describe the system dynamics are usually very complicated and nonlinear for a given physical system like the greenhouse system. For this reason, it is more convenient to represent these equations in the format of a simulation model in appropriate simulation software. This implies that the nonlinear, continuous time equations are discretized and solved numerically using a computer. The available computing power these days provides for very accurate solutions for the majority of physical systems, and most definitely for greenhouse systems, whose dynamics evolve over relatively slow times due to their large thermal inertia. The formulation of the mathematical equations themselves is quite challenging due to the distributed nature of the thermal system of a greenhouse. This means that environmental variables like temperature and relative humidity vary not only temporally (over time) but also spatially (over distance). On top of that, the governing physical processes are quire complex, involving highly nonlinear processes like heat transfer through convection and radiation, forced fan flows, ventilation flows, transpiration of plants, photosynthesis, condensation, chemical reactions and external disturbances due to external weather changes. The task of modeling the greenhouse dynamics remains challenging depending on the level of model complexity required.

Whether the distributed system modeling approach or the lumped capacitance modeling approach is used, the underlying physical laws of conservation of energy and conservation of mass are the starting point of the modeling process. The authors in [5] have used the lumped capacitance modeling approach to derive differential equations in state-space form by applying the principle of conservation of energy governing the heat transfer processes occurring in a typical greenhouse system. The authors in [6] have used the thermal network approach to model the dynamics of a solarium/greenhouse system. The thermal network approach has strong links to the electrical network approach, where various nodes are chosen characterized by their respective temperatures. Subsequently, the law of conservation of energy is applied at each node to determine the balance between the internal energy at the node and the energies transferred in and out of the node. Similar to the electrical network approach, the stored internal energy of the node is influenced by the thermal capacitance of the node and the amount of energy transferred in and out of the node is influenced by the thermal conductance of the paths between adjacent nodes. The authors in [7] have utilized a dedicated software modeling package (TRNSYS) to derive a thermal model for an experimental greenhouse in Nepal. A very informative account of the modeling process adopted for the characterization of greenhouse dynamics can be found in [8]. The authors present a detailed analysis of the various physical processes affecting the greenhouse dynamics, like the external solar radiation, the heat transfer processes due to convection and conduction, the air flows due to leakages and natural ventilation, the water vapor fluxes and the canopy transpiration. The modeling process follows the lumped capacitance modeling approach where the greenhouse system is separated into a finite number of subsystems each characterized by its temperature. One of the key assumptions is that all subsystems are considered homogeneous, which implies that they have a uniform temperature and an average thermal capacity can be used for each subsystem.

C. Project Objectives

The objectives of the Greenhouse Project are:

- to develop a prototype greenhouse system that is equipped with appropriate instrumentation in terms of sensors, actuators and control hardware/software,
- to design control algorithms to regulate the environmental variables within the greenhouse system,
- to implement the control algorithms on a robust embedded platform and to construct a Human-Machine Interface between the operator and the greenhouse system,
- to apply physical and mathematical modeling techniques for the construction of a high-fidelity simulation model for the greenhouse system,
- to investigate the design of advanced control algorithms for minimum energy consumption,
- to investigate the design of more efficient passive and active actuators for cooling and heating,
- to utilize the greenhouse system as an educational platform for the design and implementation of control algorithms.

Objective 1 has been achieved with the construction of the prototype greenhouse system, fully instrumented with environmental sensors, actuators and control hardware. Objective 2 has been partially achieved with the design of a control system for the regulation of the greenhouse air temperature. Further work is required to design control systems for the regulation of other environmental variables like the relative humidity, the light intensity, the soil moisture and the carbon dioxide concentration. Objective 3 has been fully achieved with the design and implementation of the control algorithms on the robust embedded platform NI Compact RIO (http://www.ni.com/compactrio/) and the design of a Human-Machine Interface using the LabView software (http://www.ni.com/labview/). Objective 4 has been partially achieved with the partial modeling and validation of the heating actuator of the greenhouse system. A simulation model of the heating actuator subsystem has been constructed using the Simulink/Matlab software. Further work is required to model and validate the complete greenhouse system dynamics. Objectives 5, 6 and 7 have not been addressed at this stage and will be considered in future research and development work.

D. *Layout of the Paper*

The remainder of the paper will consist of two main sections, the Prototype Greenhouse System section and the Experimental Results section.

The first section will address the hardware and software development for the system in more detail. A subsection will be devoted to the description of the functionality of the system, a subsection will be devoted to the presentation of the hardware and software components and a third subsection will focus on the presentation of the modeling work related to the heating actuator subsystem.

The second section will focus on the presentation of the experimental results from the testing of the heating actuator subsystem in order to validate the simulation model. Also, a subsection is devoted to the presentation and analysis of the closed-loop experimental results from the operation of the greenhouse system.

Finally, the conclusions will be presented along with directions for future research and development work.

II. THE PROTOTYPE GREENHOUSE SYSTEM

A. *System Functionality*

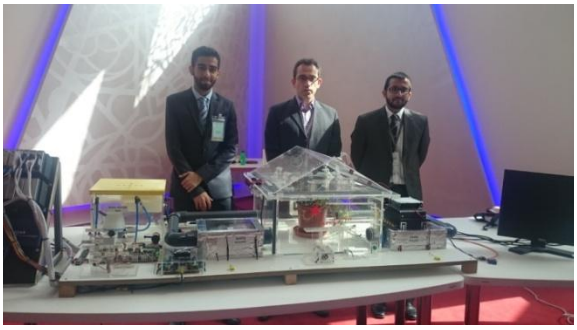


Figure 1. The prototype greenhouse system

In this section, we present the hardware functionality of the prototype greenhouse system, which is described in more detail in [9]. The prototype greenhouse system is shown in Fig. 1. From the far left we can identify the embedded system NI Compact RIO, the water tank with the yellow lid, the heating actuator, the greenhouse and on the far right the cooling actuator and the HMI (host computer). The following control systems are implemented.

1) *Greenhouse temperature regulation*

The greenhouse air temperature is regulated by a cascaded PID controller architecture. There exist two inner PID controllers manipulating the PWM signals to the heating elements and the cooling Peltiers respectively in order to maintain the desired air temperatures within the heating and cooling actuators.

There also exist two outer PID controllers that manipulate the PWM signals of the fans for the heating and cooling actuators respectively. The outer PID controllers react to the error signal between the desired and actual greenhouse temperature in order to induce the flow of the right proportion of hot and cold air into the greenhouse.

2) *Regulation of light intensity*

There exists capacity for a control system to regulate the light intensity in the greenhouse. The control system receives an input from the light sensor and manipulates the actuator (Halogen Lights) in order to achieve the desired set-point of light intensity. This system can also operate on Manual Mode, with the user varying directly the intensity of the halogen lights.

3) *Regulation of Soil Moisture*

There exists capacity for a control system to regulate soil moisture content. The measurement is provided by an electrical conductivity sensor that relates the conductivity of the soil to the soil moisture. On Automatic Mode the controller controls the Actuator (Water Pump) but on Manual Mode the user will be able control the actuator directly and supply the desired amount of water to the plants.

4) *Monitoring of other environmental conditions*

Besides the regulation of the greenhouse air temperature, light intensity and soil moisture, the system monitors and displays the following environmental conditions:

- Relative Humidity inside the Greenhouse.
- Relative Humidity of the Environment.
- CO_2 concentration inside the Greenhouse.

Each environmental condition is displayed in the form of a real-time graph using the LabView front panel application.

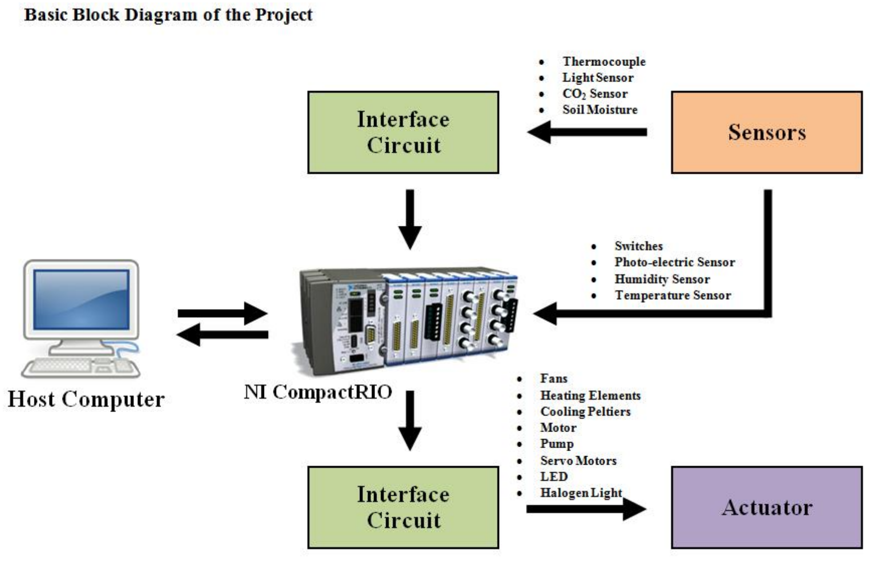
5) *Automated doors*

The greenhouse has an automated door which opens when a person comes close to the proximity sensor and closes when the person has completely entered the greenhouse. The reason for an automated door is to ensure the door remains closed so that heat losses are minimized and the temperature control system has smaller external disturbances to cope with.

6) *Human-Machine Interface (HMI)*

There is a LabView HMI which provides both data-entering and data-receiving functionality and allows the user to communicate efficiently with the system by receiving real-time information regarding the status of the system and also to enter the set-points for the various control systems. The HMI allows both automatic control operation and manual control operation.

7) Safety features of the system



Note: - Some sensors have to go through a interface circuit rest can be connected directly to the compactRIO due to variety of modules available. For Actuators, all the output of the compactRIO goes through an interface circuit.

Figure 2. Architecture of the embedded system for the greenhouse control

The HMI interface is secure and restricts unauthorized personnel to change the settings and parameters of the system, since at every step of the program the user is asked to enter a password.

8) Other features of the system that add flexibility

- The user is able to control the angle of the vents (louvers)and the power of the ventilation fan under manual mode.
- There is a data logging function with which the user can save real-time data.

B. Hardware and Software Development

The following NI hardware and software products have been utilized for the implementation of the prototype greenhouse system.

1) Software

a) LabView FPGA Module
b) LabView Real-Time Module
c) NI-RIO Driver
d) LabView Control Design Toolkit
e) NI LabView PID and Fuzzy Logic Toolkit
f) LabView MathScript RT Module
g) LabView Control Design and Simulation Module
h) NI MAX (National instrument measurement and Automation Explorer)

2) Hardware

a) NI Compact RIO

- Controller NI cRIO-9025
- Chassis cRIO-9118
- Modules 5 x NI 9401
- Module 1 x NI 9215
    - Module 1 x NI 9203
    - Module 2 x NI 9219

b) Power supply NI PS-15

Below we present the sensor and actuator modules:

NI 9203: This is a module that receives a measured current signal in the range -20 to 20 mA. This module is used to receive the measurement of the temperature sensor and the relative humidity sensors. This module provides a 16-bit resolution.

NI 9215: This is a module that receives a measured voltage signal in the range -10 to 10 V. This module is used to receive the measurements of the light sensor, the soil moisture sensor and the capacitive humidity sensor. This module provides an adequate resolution and a high sampling rate which makes it suitable for the light intensity control system.

NI 9401: This is a digital input/output module that receives a measured digital voltage signal of 5 V. This module is used to receive the measurements from all the digital sensors which are contact switches, proximity sensors and limit switches. The importance of this module is its bi-directionality which allows it to be used both as an input and output digital signal module. It is used for producing the PWM signal for all the actuators, like the PTC (positive temperature coefficient) heaters, the cooling Peltiers, the fans and the pumps.

NI 9219: This module receives signals from the thermocouples which are placed in various parts of the system. The thermocouples are wired directly to it and it reads the voltages at a resolution of 24 bits. This module is a universal Analog input which can read various signals like voltage, current and temperature.

3) Embedded system architecture (Fig. 2)

a) Compact RIO

The Compact RIO is an embedded platform that allows the real-time implementation of algorithms. Due to the FPGA architecture, it allows parallel processing and data acquisition. Its modular architecture allows the simultaneous use of multiple input and output modules. The modules selected for our greenhouse system are compatible to a large variety of industrial sensors which makes it straightforward for data acquisition and analysis. When using the Compact RIO, it is straightforward to change modules efficiently and due to its reconfigurable FPGA and Real-Time Processor, it allows for rapid prototyping of new engineering systems. The FPGA architecture also allows for parallel processing and the real-time Processor can work in stand-alone mode without being connected to the host program.

b) Host computer with LabView

In this project a laptop with a LabView installation is used as the Host. The Host provides the environment for a LabView application to receive and send data to the Compact RIO.

c) LabView application

In this project, 3 main VIs had to be created. The first one is the Host.vi which is a LabView Program that allows the user to interact with the greenhouse system (Human Machine Interface). The second one is the Target.vi which runs on the Real-Time Processor. This application provides communication between the Host and the FPGA. The third one is the FPGA.vi which runs on the FPGA and it provides data acquisition and interfacing with the sensors and actuators. All VIs communicate with each other to achieve accurate control of the greenhouse system. The benefit of using LabView is its graphical programming capability and the transparency it provides to the software engineer. Many built-in functions of LabView were used like data logging, simulation kits and control kits in order to design the application for the greenhouse system. Since the project is focused on automation and control system design, the control system design toolkit was used extensively.

C. Mathematical Modelling of the Heating Actuator

This section presents the mathematical modeling of the heating actuator subsystem that is used to provide heat to the greenhouse. The method that was adopted will be briefly explained, while the key equations will be discussed. The operation of the heating actuator subsystem relies on the operation of the PTC (Positive Temperature Coefficient) heating elements that convert the electrical power into heat. This heat is stored in a heat sink and transferred by forced and natural convection to the air around and above the heat sink. The operation of the two fans transfers the hot air into the greenhouse in order to increase the greenhouse air temperature.

1) Lumped capacitance modelling methodology

Fig. 3 shows a schematic diagram of the heating actuator subsystem. The two inputs of the system are the duty cycle of the heating elements ($T\%_{\text{Heat}}$) PWM signal and the duty cycle of the fans ($T\%_{\text{Fans}}$) PWM signal. The outputs are the temperature of the sink (T_{sink}) and the temperature of air (T_{air}) within the heating actuator. The temperature of the input air (T_{in}) and the environment temperature (T_{env}) are external inputs to the system. All temperatures are in degrees Kelvin.

We use the lumped capacitance modeling methodology, described by the following equation, in order to model the heating actuator subsystem:

$$\sum(P_{in} - P_{out}) = C\frac{dT}{dt}$$

Where P_{in} is the power input in Watts, P_{out} is the power output in Watts, C is the thermal capacitance in J/K, T is the temperature in K and t is the time in seconds.

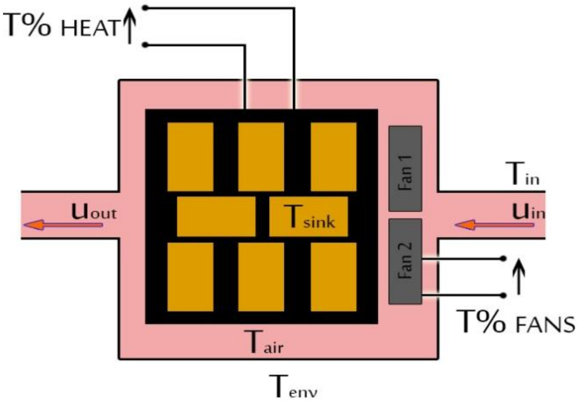


Figure 3. Schematic of the heating actuator subsystem

This equation is basically a statement of the conservation of energy, stating that the rate of increase of the internal energy of the system is equal to the total power supplied to the system minus the total power lost by the system.

The above equation is used twice, once for the heat sink and once for the air surrounding the heat sink. We assume that the temperature of the PTC heating elements is uniform and equal to the heat sink temperature and also that the air temperature is uniform throughout the enclosure of the heating actuator. Two heat transfer processes are considered to transfer heat from the heat sink to the air, namely those of convection and radiation. The air will gain heat from the heat sink due to convection and radiation, and will lose heat due to the flow of air out of the heating actuator subsystem, and also due to conduction losses through the walls of the actuator. Thus, we have the following two equations:

$$P_{electrical} - P_{convection} - P_{radiation} = C_{sink}\frac{dT_{sink}}{dt}$$

$$P_{convection} + P_{radiation} - P_{conduction} - P_{airflow} = C_{air}\frac{dT_{air}}{dt}$$

The various power components are calculated as follows. $P_{electrical}$ is the total electrical power input supplied by the PTC heating elements. It is determined by multiplying the squared peak voltage, by the duty cycle and dividing by the resistance of the heating elements,

$$P_{electrical} = \frac{V_o^2}{R(T_{sink})}T\%_{Heat}$$

The temperature of the heating elements affects their resistance. Being PTC implies that the resistance increases as the temperature of the heating element increases. The relationship between temperature and resistance was found experimentally and it is shown in Fig. 4.

$P_{convection}$ is assumed to be due to natural convection when the fans are turned off, and due to forced convection when the fans are turned on. The equations for calculating the heat transfer due to both forced and natural convection were taken from [10], and are of the form:

$$P_{convection} = hA(T_{sink} - T_{air})$$

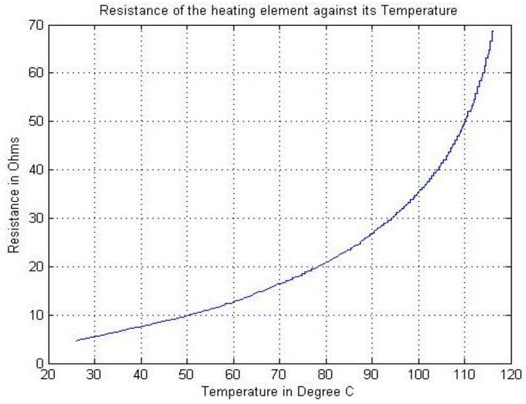


Figure 4. Nonlinear relationship between the temperature of the PTC heating element and its resistance

The convection coefficient h and the convection area A change accordingly to the forced or natural convection situations. It is important to note here that the convection coefficient h is a highly nonlinear function of the flow characteristics and the geometry characteristics of the heat sink fins, [11].

$P_{radiation}$ is obtained by the analytical equation below:

$$P_{radiation} = \varepsilon A\sigma({T_{sink}}^4 - {T_{air}}^4)$$

where ε is the emissivity of the body, A is the surface area that radiates heat, and σ is the Stefan-Boltzmann constant, [12].

$P_{conduction}$ is obtained from the following equation:

$$P_{conduction} = kA\frac{(T_{air} - T_{env})}{d}$$

where k is the thermal conductivity coefficient of the acrylic material that is insulating the heating actuator space, A is the surface area of that material and d is the thickness of that material, [12].

$P_{airflow}$ is the rate at which heat is transferred out of the actuator space due to the fan-induced air flow from the inlet to the outlet of the heating actuator subsystem. It is represented by the following equation:

$$P_{airflow} = u_{out}\rho_{air}c_{p_{air}}(T_{air} - T_{in})$$

where ρ_{air} is the density of air, $c_{p_{air}}$ is the specific heat capacity of air, and u_{out} is the volumetric flow rate of air. The model accounts for the variation of the properties of air as a function of the air temperature using appropriate look-up tables. The volumetric flow rate is also a nonlinear function of the duty cycle of the PWM signal that drives the fans. Fig. 5 presents this nonlinear relationship that was obtained experimentally. It was noted that due to static friction effects, the fans only start rotating after the duty cycle of the PWM signal exceeds 20%. The sink thermal capacitance, C_{sink}, is obtained by multiplying the mass of the heat sink with the specific heat capacity of the sink's material. An adjustment of C_{sink} will be required during the validation phase since the heat sink is designed to act as a heat conductor and not as a heat storage device.

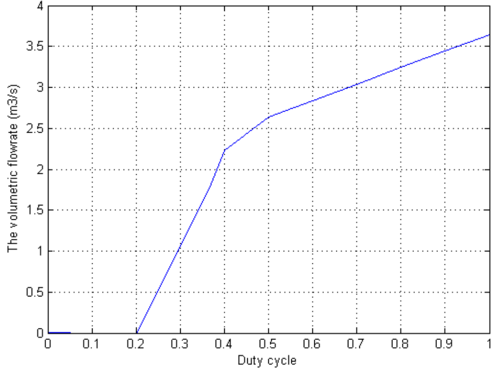


Figure 5. The variation of the volumetric flow rate of the fans as a function of the duty cycle of the PWM input signal

Therefore, the actual heat sink thermal capacitance maybe less than the theoretical value calculated above. C_{air} is obtained by multiplying the specific heat capacity of air by its mass. The mass of air is found by multiplying its density by the approximate volume of the air in the heating actuator subsystem. Once all the equations were formulated, the simulation model was constructed in Simulink (http://www.mathworks.com/products/simulink/) and all the equations were implemented. The simulation model will be validated against experimental data below.

III. EXPERIMENTAL RESULTS

A. Validation of the Simulation Model

The simulation model of the heating actuator was validated against experimental data obtained from numerous experiments under different testing conditions. Initial results were very promising but further modeling work is required in order to enhance the fidelity of the simulation model. The work related to the modeling of the heating actuator subsystem is presented in [13].

The experimental testing for the heating actuator focused mainly on the variation of the PWM signal to the heating elements and the measurement of the resulting temperatures of the heat sink and the surrounding air as a function of time. The fans were left switched off. This methodology aimed to test independently and sequentially the effects of the two inputs and provide appropriate experimental data in order to make rational adjustments to the simulation model. The objective in making adjustments to the simulation model is to minimize the error in the temperature responses between the simulated and the experimental data.

An example of the validation exercise is shown in Fig. 6. The top subplot represents the PWM signal for the fans, which is zero therefore the fans are left switched–off. The second subplot represents the PWM signal for the heating elements and this is chosen as a square pulse signal of varied amplitude in order to investigate both the heating and natural cooling response of the system. The experiment lasts for 30 minutes and during this time the temperatures of the heat sink and the surrounding air are measured and recorded. These are presented in the 3rd and 4th subplots respectively. From an initial look the results look satisfactory and the same trends are observed both in the simulated and the experimental data. The differences in the simulated and experimental temperatures are of the order of 10% for the heat sink temperature and of the order of 12% for the air temperature.

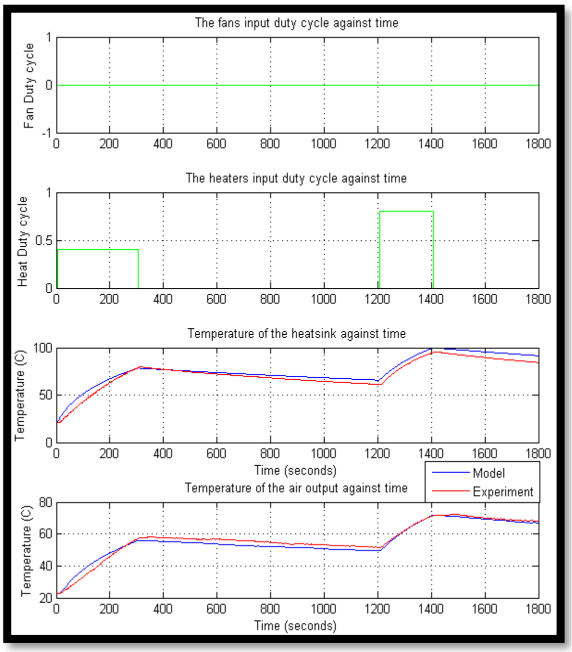


Figure 6. Comparison of simulated and experimental data from the testing of the heating actuator subsystem

From a control designer's point of view, the agreement between the model and the real system shown in Fig. 6 is more than satisfactory for the design of a good feedback control system. Steady-state errors can be accommodated using integral action in the controller.

Further experimental testing is required with the inclusion of the fans input. This will be conducted at a future stage and future modifications in the model are likely to occur in order to capture the real dynamics occurring with the variation of both the inputs of the system.

B. *Closed-loop Experimental Testing*

In this section we will present the results from the closed-loop experimental testing of the greenhouse air temperature control system. The air temperature within the greenhouse is considered as the highest priority environmental condition that needs to be regulated accurately. The control system block diagram is shown in Fig. 7. The functionality of the closed-loop system is that of cascaded PID control systems. The objective is to regulate the greenhouse temperature by blowing the correct proportion of hot and cool air in the greenhouse. The hot and cool air is generated independently in the respective heating and cooling actuators. Therefore, the inner PID controllers, one for the heating actuator and one for the cooling actuator are responsible for maintaining the desired air temperature within the actuator subsystems. These inner PID controllers manipulate directly the PWM signals to the PTC heating elements and the cooling Peltiers respectively. It is evident from the block diagram that the reference temperature for the heating actuator air is 50 degrees Celsius and the reference temperature for the cooling actuator air is 18 degrees Celsius.

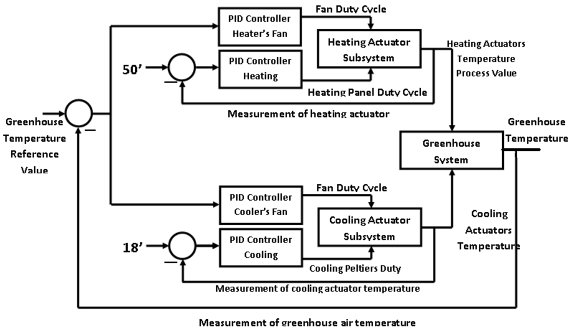


Figure 7. Block diagram of the closed-loop system for the regulation of the greenhouse temperature

The outer loop PID controllers manipulate the fans within the heating and cooling actuators respectively based on the error signal between the reference greenhouse air temperature and the measured greenhouse temperature. In this way the correct proportion of hot and cold air is sent into the greenhouse in order to maintain the air temperature at its desired set-point.

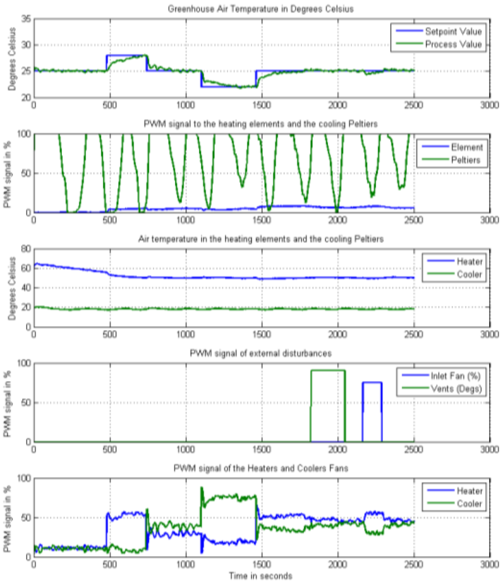


Figure 8. Regulation of the greenhouse temperature

An example of the operation of the closed-loop system is shown in Fig. 8. The desired set-point for the greenhouse temperature is started at 25 degrees, then put at 28 degrees, then put back at 25 degrees, then put at 22 degrees and finally brought back at 25 degrees. We assume that the range of temperatures between 22-28 degrees Celsius is a favorable temperature range for the growth of most plants. The 1st subplot in Fig. 8 shows the good tracking of the set-point. The 2nd subplot presents the PWM signals for the heating elements and the cooling Peltiers required to maintain the heating actuator and cooling actuator temperatures at 50 degrees and 18 degrees Celsius respectively. The temperatures of the heating and cooling actuators are presented in the 3rd subplot, where it is clearly shown that the regulation is very accurate, even in the presence of disturbances like the starting of the fans in the two actuators. The 4th subplot presents two external disturbance signals, the vents and the fan. These disturbance signals are used manually by the operator in order to demonstrate the good disturbance rejection of the control system. It is evident that the fan disturbance is more severe, but even in that case the control system manages to reject the disturbance and regulate accurately the greenhouse temperature by manipulating accordingly the fans in the heating and cooling actuators. The 5th subplot presents the PWM signals for the fans in the heating and cooling actuators. These are the control signals that are manipulated by the outer-loop PID controllers and are responsible for maintaining the desired greenhouse temperature. We can observe, for example, that around 500 seconds the set-point is put at 28 degrees, i.e. 3 degrees higher than the previous value. The control system reacts to this demand by increasing the PWM signal to the fan of the heating actuator in order to send more hot air in the greenhouse and thus increase its temperature. Similarly, around 1100 seconds, we demand a decrease in the greenhouse temperature by 3 degrees, from 25 to 22. The control system reacts to this demand by increasing the PWM signal to the fan of the cooling actuator in order to send more cold air into the greenhouse and thus reduce its temperature.

The parameters of the PID controllers, both inner and outer loop were designed after successive iterations of testing and experimentation, due to the lack of an accurate simulation model for the whole greenhouse system. In the future, we will develop further the simulation model for the greenhouse system in order to facilitate the application of more systematic control design techniques and thus reduce substantially the control development time.

IV. CONCLUSIONS

We have presented the application of an automated greenhouse system using NI Embedded Systems Technology. The system is instrumented with sensors and actuators and controlled by an embedded cascaded PID algorithm in order to provide accurate control of the air temperature within the greenhouse. A simulation model of a subsystem has also been developed and shows good agreement to the experimental results. Further modeling work is required to describe accurately the whole system's dynamics and thus design more advanced control algorithms to ensure minimum energy consumption and accurate control of the environmental conditions.

ACKNOWLEDGMENT

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Regarding Industrial Experience, he has worked as an intern in Steel United, Bahrain as Maintenance trainee and in Bahrain Polytechnic as a Technician. He is currently working in Pipeline Technologies and Services as a Supervisor of the Assembly Department.

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In February 2015, he received the duties of a PASS Leader (Peer Assisted Study Scheme) after being nominated by the Head of Engineering School, which qualified him as an academic assistant to students that require assistance and tuition in their engineering courses. In terms of his industrial experience, he completed internships at the Electricity and Water Authority (EWA) as a mechanical trainee in 2014. In 2015, Mohammed was part of the leading upstream petroleum company (Tatweer Petroleum) as a summer trainee which exposed him to an actual working environment.

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