OPTIMAL CONTROL FOR CONTROLLINGTHE TEMPERATURE INTOMATO GREENHOUSE BASED ON ADYNAMIC SYSTEM

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Abstract - An optimal control to regulate the temperature inside of a greenhouse can be obtained from a mathematical model, where such mathematical model integrates the dynamic model of the crop (tomato crop) and the greenhouse. This paper considers the dynamic model exclusive from northern mountain range of Puebla, Mexico. This means that all parameters were determined from a harvest throughout a period of 80 days in the winter season. The dynamic model considered 5 state variables, three of them are relative from the crop, they are the number of nodes (plant development), the biomass dry canopy, and the biomass dry root. The last 2 variables state are linked to the greenhouse, these are the temperature inside of the greenhouse and the relative humidity. Applying the optimal control theory with a proposal criterion of optimization, admissible trajectories for the variables state were obtained; such trajectories maximize the benefit of the crop, thereby the farmers and harvest improves (benefit) the crop production, and reduce the energy consumption. An algorithm was built, which gives a solution for the optimal control and simulates a harvest throughout a period of 80 days .As well as perform several physical tests, with which it is intended to reach the desired temperature inside the greenhouse and perform the physical implementation.

Index Terms - Optimal control, dynamic model, microclimate, performance index.

I. INTRODUCTION

A growing crop can be considered as a dynamic model, this dynamic model add the environment, which describe the temperature and the relative humidity, those equations create a suitable environment where the crops can grow with good results. This means it is a complex system, which gives accurate information throughout the development. The information is enough for certain application. The environmental control is the principal point for a great growing crop. However, a simple control is not enough due to the over energy expenditure. The optimal control has the solution, but the problem is adjust the variables that needed to maximize and what to minimize. There are different jobs in which different methods are applied to optimize resources, which are mainly focused on minimizingthe energy expenditure to increase or decrease the temperature inside of the greenhouse, mainly consist of considering the equations describing the greenhouse-microclimate [5] and [6], where the first considers only two equations that describe the temperature and the carbon dioxide inside the greenhouse, and solve the optimal problem of optimal control through a MATLAB extension called PROPT, which is a platform of control and estimation of parameters. While in[6] consider the weather forecast to operate the greenhouses and thus reduce the energy cost.

II. GENERAL FORMULATION OF THE OPTIMAL CONTROL PROBLEM

Consider the state equations who describe the controllable process:

$$\dot{x} = f(x(t), u(t), t) \qquad (1)$$

Where $x(t)$ is the states vector, $u(t)$ is the control signal and t is the time. A criterion is required to evaluate the performance of the system, normally, the functional is defined by:

$$J = \phi(x(t_f), t_f) + \int_{t_o}^{t_f} L(x(t), u(t), t)dt \qquad (2)$$

The fundamental problem of optimal control is determinate an admissible control which makes that equation (1) follows one admissible trajectory x^* that minimize the performance measure showed in the equation (2). Then u^* is called optimal control and x^* is an optimal trajectory.

Necessary conditions for a solution.

The restrictions (1) are added to the functional (2) with a

Lagrange multipliers vector $\Psi(t)$, the functional is rewritten as follow:

$$J = \phi(x(t_f)) + \int_{t_o}^{t_f} [L(x(t), u(t), t) - \\ -\Psi^T f(x(t), u(t), t) - \dot{x}]dt \qquad (3)$$

Then, we define the Hamiltonian scalar function:

$$H(x(t), u(t), \Psi(t), t) = \\ = L(x(t), u(t), t) + \Psi(t)f(x(t), u(t), t) \qquad (4)$$

An infinitesimal variation in $u(t)$ is considerate and itis denominated like $\delta u(t)$, this variation produces a changein the functional. If $x(t_0)$ is specified then $\delta x(t_0)$also isspecified.This variation can be calculated as follow:

$$\delta J = \Psi^T(t_o)\delta x(t_o) + \int_{t_o}^{t_f} \left[\frac{\partial H}{\partial u}\delta u\right] dt \qquad (5)$$

Chose the multiplier $\Psi(t)$, from this, the auxiliary system equations are formed:

$$\dot{\Psi}^T = -\frac{\partial H}{\partial x} = -\frac{\partial L}{\partial x} - \Psi^T \frac{\partial f}{\partial x} \quad (6)$$

And the final conditions can be obtained as follow:

$$\Psi^T(t_f) = \frac{\partial \phi}{\partial x}(t_f) \quad (7)$$

For a stationary solution, it is required that the functional with an arbitrary variation must be equal to zero, $\delta J(t) = 0$. This is true when:

$$\frac{\partial H}{\partial u} = \frac{\partial L}{\partial u} + \Psi^T \frac{\partial f}{\partial u} = 0 \quad (8)$$

Note that from (7) it is possible get the control form from the Hamiltonian function. The control form depends on the variable $\Psi(t)$ in each instant time. Then to find the vector function of control u(t) that produce a stationary value of functional, then must solve the following differential equation system:

$$\begin{cases} \dot{x}(t) = f(x(t), u(t), t) \\ \dot{\Psi}(t) = -\frac{\partial H^T}{\partial x} \end{cases} \quad (9)$$

The boundary conditions for the differential equations are separated, it means, some of them are defined in $t = t_0$ and the others in $t = t_f$. This is a problem with boundary values of two points.

III. DYNAMIC MODELS OF THE CROP AND OF THE GREENHOUSE

The development environment and the crop are strictly connected, it is necessary for a good description and development selection. The next equations described the main states:

Dynamic Model of the Microclimate- cultivation System

The dynamic model of the microclimate in a greenhouse covers many aspects. Those aspects describe the phonological development and increase in dry weight of vegetative body plant [2]. For that reason, the principal variables state from the reduced model [1] are chosen as follow:

Number of Nodes:

This state represent the rate of plant development, this variable state was modeled as the growth speed per day:

$$\frac{d}{dt}N = N_m f_n(T_g) \quad (10)$$

Where N_m is the development speed from the plant, $f_n(T_g)$ is the function to modify node development rate, who depend of the temperature, and this temperature is assumed to depend on time, t, with an hourly basis. That function f_n was calculate exclusive from northern mountain range of Puebla.

Biomass Dry Canopy Growth

Development biomass its calculate by photosynthesis:

$$\frac{d}{dt}W_c = E\left(P_g - R_m(W_r + W_c)\right)f_c \quad (11)$$

That variable state describes the speed fruit growth, with growth efficiency, ratio of biomass to photosynthate available for growth E, gross photosynthesis P_g, daily maintenance respiration R_m, biomass dry root W_r, biomass dry canopy W_c, function partitioning of biomass to roots as a function of development f_c.

Biomass dry root growth

But the biomass dry canopy is not enough, the growing mass need the state variable root, because is a complement for the describe development biomass accumulation.

$$\frac{d}{dt}W_c = E(P_g - R_m(W_r + W_c))(1 - f_c) \quad (12)$$

The biomass accumulation is the result of the many variables, where the principal variable is the photosynthesis.

And the parameters are:

$$P_g = D\frac{\tau C p(T_g)}{K} \times \times \ln\left[\frac{\alpha K I_o + (1-m)\tau C}{\alpha K I_o e^{-KLAI} + (1-m)\tau C}\right]; \quad (13)$$

$$p(T_g) = \left[1 - \left(\frac{\Phi_h - T_g}{\Phi_h - \Phi_1}\right)^2\right]; \quad (14)$$

$$LAI = \frac{\rho\delta}{\beta}\ln(1 + e^{\beta(T_g - n_b)}); \quad (15)$$

All parameters were determinate from the area of the northern mountain range of Puebla.

Dynamic Model of Greenhouse

Temperature inside of greenhouse

The model describes the energy balance, those are determinate by energy fluxes as incoming sun radiation, heat losses through the wall, ceiling and the floor [3], the model describes the most important variable state for development growth crop tomato:

$$C_g\frac{d}{dt}T_g = k_v(T_o - T_g) + Q_{calef} + I_o + + k_r(T_o - T_g) + k_s(T_s - T_g) \quad (16)$$

Where T_g the greenhouse air temperature, G the incoming short-wave radiation, C_g the greenhouse heat capacity, k_v the ventilation heat transfer coefficient, k_r the celling heat transfer coefficient, k_s the floor heat transfer coefficient, I_o the radiation conversion factor, T_o the outside air temperature, T_s the greenhouse floor temperature.

Humidity Mass Balance

The equation air vapor describes the condensation and transpiration, this variable state is often a variable to control for pest and diseases. It air assumed that the all greenhouse is covered with plastic, then the only source of vapor is the crop transpiration, with a variable control:

$$\frac{d}{dt}V_i = \frac{A_g}{v_g}(E_t - G_v(V_i - V_o)) \quad (17)$$

Where V_i is the inside absolute humidity concentration, V_o is the outside absolute humidity

concentration, G_v is the ventilation flux through the windows, A_g/v_g is equal to the average greenhouse height. E_t is the transpiration, who was develop by [4], who describes the most water up take by plant is used for transpiration.

$$E_t = \frac{2LAI}{(1+\epsilon)r_b + r_s}\left[VCD + \frac{\epsilon r_b}{2LAI}\frac{R_n}{\lambda}\right] \quad (18)$$

Where ϵ is the radio of the latent to sensible heat content of saturated air for a change of 1°C in temperature, VCD is the vapor concentration deficit of air, λ is the latent heat of vaporization of water, r_b is the resistance to heat transfer of the leaf boundary layer, r_s is the stomatal resistance, R_n is the net radiation of the crop.

The Complete Dynamic Model

All equations described were chosen based on several high-order mechanistic models, those equations or variables state describes the main behaviors observed in tomato crop growth in greenhouse, then:

$$\dot{N} = N_m f_n(T_g); \quad (19)$$

$$\dot{W}_c = E\left(P_g - R_m(W_r + W_c)\right) f_c; \quad (20)$$

$$\dot{W}_r = E\left(P_g - R_m(W_r + W_c)\right)(1 - f_c); \quad (21)$$

$$\dot{T}_g = \frac{1}{C_g}\left(k_v(T_o - T_g) + Q_{calef} + I_o + k_r(T_o - T_g) + k_s(T_s - T_g)\right); \quad (22)$$

$$\dot{V}_i = \frac{A_g}{v_g}(E_t - G_v(V_i - V_o)); \quad (23)$$

All variables states are linked to the temperature inside of the greenhouse, that reason that variable state is the most important of them. The temperature inside of the greenhouse T_g describes the development of all variables states from the dynamic model, in this case Q_{calef} is the control variable,which is intendedthe all system will have a good development and increase growth of the crop, thereby choose a good behavior for Q_{calef} reduce the energy used for the nodes, biomass dry canopy and biomass dry root.

IV. DESIGN AND SIMULATION OF THE CONTROL LAW

Chosen J,the system:

$$J = \frac{1}{2}\left(N^2(t_f) + W_r^2(t_f) + W_c^2(t_f)\right) + \frac{1}{2}\int_{t_o}^{t_f}(-N^2(t) - W_r^2(t) - W_c^2(t) + Q_{calef}^2(t)) \quad (19)$$

J minimizes the energy with the variable Q_{calef} and maximizes as possible the number of nodes (N) and the total biomass (W_c and W_r), the rest of variable as Humidity do not have any change in the system.

The Hamiltonian is constructed as follows:

$$H = \frac{1}{2}(-N^2(t) - W_r^2(t) - W_c^2(t) + Q_{calef}^2(t) - V_i^2(t) + \lambda_1(\dot{t})\dot{N}(t) + \lambda_2(t)\dot{W}_c(t) + \lambda_3(t)\dot{W}_r(t) + \lambda_4(t)\dot{T}_g(t) + \lambda_5(t)\dot{V}_i(t)) \quad (20)$$

The auxiliaries' states are describes as below:

$$\dot{\psi}_1 = N; \quad (21)$$

$$\dot{\psi}_2 = \psi_2 E R_m f_c + \psi_3 E R_m(1 - f_c) + W_c; \quad (22)$$

$$\dot{\psi}_3 = \psi_2 E R_m f_c + \psi_3 E R_m(1 - f_c) + W_r; \quad (23)$$

$$\dot{\psi}_5 = \frac{\psi_5 A_g}{v_g} G_v; \quad (24)$$

one of the auxiliary state have a special consideration, this consideration is due to the variable state involve in all dynamic model and even implicit in the controlled variable (T_g):

$$\dot{\psi}_4 = -\frac{\partial}{\partial T_g}\left[\psi_1(\dot{t})\dot{N}(t) + \psi_2(t)\dot{W}_c(t) + \psi_3(t)\dot{W}_r(t) + \psi_4(t)\dot{T}_g(t) + \psi_5(t)\dot{V}_i(t)\right] \quad (25)$$

And obtained the solution, which is describe how will be the control variable Q_{calef}

$$\frac{\partial}{\partial u}H = Q_{calef} + \psi_4 = 0 \quad (31)$$

$$Q_{calef} = -\psi_4 \quad (32)$$

On the equation (22)

$$\dot{T}_g = \frac{1}{C_g}(k_v(T_o - T_g) + \psi_4 + I_o + k_r(T_o - \quad - T_g) + k_s(T_s - T_g)) \quad (33)$$

The system describes for the variable states and auxiliary states with boundary condition is:

$$\dot{N} = N_m f_n(T_g); \quad (34)$$

$$\dot{W}_c = E\left(P_g - R_m(W_r + W_c)\right)f_c; \quad (35)$$

$$\dot{W}_r = E\left(P_g - R_m(W_r + W_c)\right)(1 - f_c); \quad (36)$$

$$\dot{T}_g = \frac{1}{C_g}(k_v(T_o - T_g) + Q_{calef} + I_o + k_r(T_o - T_g) + k_s(T_s - T_g)) \quad (37)$$

$$V_i = \frac{A_g}{v_g}(E_t - G_v(V_i - V_o)); \quad (38)$$

$$\dot{\psi}_1 = N; \quad (39)$$

$$\dot{\psi}_2 = \psi_2 E R_m f_c + \psi_3 E R_m(1 - f_c) + W_c; \quad (40)$$

$$\dot{\psi}_3 = \psi_2 E R_m f_c + \psi_3 E R_m(1 - f_c) + W_r; \quad (41)$$

$$\dot{\psi}_4 = -\frac{\partial}{\partial T_g}\left[\psi_1(\dot{t})\dot{N}(t) + \psi_2(t)\dot{W}_c(t) + +\psi_3(t)\dot{W}_r(t) + \psi_4(t)\dot{T}_g(t) + \psi_5(t)\dot{V}_i(t)\right] \quad (42)$$

$$\dot{\psi}_5 = \frac{\psi_5 A_g}{v_g} G_v; \quad (43)$$

The previous system has the thoughtfulness to reduce the energy necessary for controlled the variable Q_{calef}, for then controlled the dynamic model described in the previous section.

However, for the inverse time the equations change, then the final condition are now initial condition and for then the all system have a system with initial condition and the ode45 from MATLAB can resolve.

$$\tau = t_f - t \quad (44)$$

And the system changes as:

$$\dot{N} = N_m f_n(T_g); \quad (45)$$

$$\dot{W}_c = E\left(P_g - R_m(W_r + W_c)\right) f_c; \quad (46)$$

$$\dot{W}_r = E\left(P_g - R_m(W_r + W_c)\right)(1 - f_c); \quad (47)$$

$$\dot{T}_g = \frac{1}{C_g}(k_v(T_o - T_g) + Q_{calef} + I_o + k_r(T_o - T_g) + k_s(T_s - T_g)) \quad (48)$$

$$V_i \quad (49)$$

$$= \frac{A_g}{v_g}(E_t - G_v(V_i - V_o));$$

$$\dot{\psi}_1 = -N; \quad (50)$$

$$\dot{\psi}_2 = -(\psi_2 E R_m f_c + \psi_3 E R_m(1 - f_c) + W_c); \quad (51)$$

$$\dot{\psi}_3 = -(\psi_2 E R_m f_c + \psi_3 E R_m(1 - f_c) + W_r); \quad (52)$$

$$\dot{\psi}_4 = \frac{\partial}{\partial T_g}\left[\psi_1(\dot{t})\dot{N}(t) + \psi_2(t)\dot{W}_c(t) + +\psi_3(t)\dot{W}_r(t) + \psi_4(t)\dot{T}_g(t) + \psi_5(t)\dot{V}_i(t)\right] \quad (53)$$

$$\dot{\psi}_5 = -\frac{\psi_5 A_g}{v_g} G_v; \quad (54)$$

V. SIMULATION AND RESULTS

To make the synthesis of control, the parameters that complement the dynamic model were measured during a harvest period by theCOLEGIO DE POSGRADUADOS, and they are exclusive exclusive from northern mountain range of Puebla.

Parameters	Definition	Units	Estimated
D	Coefficient converter photosynthesis	unitless	0.108
τ	LAI Conductance	$\frac{\mu molCO_2}{m^2 s}$	0.0664
C	Concentration of CO2 in the air	$\frac{\mu molCO_2}{air\ mol}$	350
K	Coefficient of extinction of light in the canopy	Unitless	0.58
α	Efficiency of the use of light in the leaf	$\frac{\mu molCO_2}{\mu mol\ fotones}$	0.056
I_m	Maximum density of Luxury day	$\frac{\mu molfotones}{m^2 s}$	400
m			.1
ϕ_h	The temperature at which the photosynthesis of the leaf is maximum	°C	30
ϕ_1	The temperature below where the photosynthesis on the leaf is zero	°C	5
ρ	Plant density	Unitless	4
δ	Maximum leaf area expansion per node	Unitless	0.074
β	Coefficient partitioning of new growth to fruit	Unitless	.38
n_b	Coefficient in expolinear equation	Unitless	13.3

Table 1 shows the parameters used to perform the simulations presented in this article obtained by the COLEGIO DE POSTGRADUADOS.

The dynamic model was simulating a long 80 days, and the parameter are on the table 1, and where has the next considerations:

For the simulate is important consider the solar radiation, shown as below:

$$I_o \begin{cases} I_m \sin(2\pi(t_d - 6)) & I_o > 0 \\ 0 & I_o \leq 0 \end{cases} \quad (55)$$

that function pretends to give a description the solar radiation throughout the day.

For other considerations have some variables as constants, like the outside air temperature, and the floor temperature, even windows are constants, then the air flux through the windows is constant.

Two simulations are carried out, where the system with the optimal control developed, and one without it, both have the same parameters for the northern region of Puebla, this in order to compare the data of the developed control and the system without any type of external manipulation.

To solve both systems we used ode45 from MATLAB, with the inverse time, the system becomes a system of differential equations with initial conditions, even for the system of auxiliary states.

The simulation dynamic model without control show a function as sinusoidal (top right fig 1), then the growth (nodes, biomass dry canopy, biomass dry root) have a constant development (fig 1), and the relative humidity is a sinusoidal between 80% and 85%, but the model with the optimize control have a significant improve, this improves show 10% more nodes per square meter, 25% more biomass dry canopy and 15% more biomass dry root.

The temperature inside of the green house is greater in the model with optimize control than the one without optimize control (top fig 2), but only along the day and not for the night, where the temperature is the same during that period, this development due to mainly the nature of nodes equation, which are needed to maximize development growth.

The bottom part of figure 2 shows the behavior of the energy to be supplied on the Q_{calef} control variable, represented in Watts per square meter. Said control variable is vital for the purpose of a physical supplementation of the optimal control system, it gives the pattern to a heat transfer design, in this case with a system that supplies less than 1500 Wm^2 could guarantee a harvest optimize and reduce energy consumption.

The control variable has the particularity increased during the simulation time, that means is no necessary to waste the same energy during the crops development. For then to save energy or sinews and optimize the harvest, instead a typical control, which the energy expenditure is not the aim, and less to minimize.

The main difference in this work is that it did not need a special tool or unique program to solve the differential equations system, it is worth noting that the system integrates the key equation to maximize the harvest.

VI. CONTROL

For the development of physical tests, a closed control loop is used, which consists of an input to a control system that regulates the desired temperature (IN) with the temperature inside the greenhouse, a precision temperature sensor is used (Lm35, fig 4 Top) with a range of -5°C a 45 °C. This configuration also includes a coupling stage consisting of a first-order low pass active filter, with a cut-off frequency of 5Hz, and to achieve a maximum voltage of 3.3V to the analog input of the control system.

The control system has a memory and a real time clock to update the desired temperature inside the greenhouse and thus follow the internal temperature obtained by the simulation performed previously.

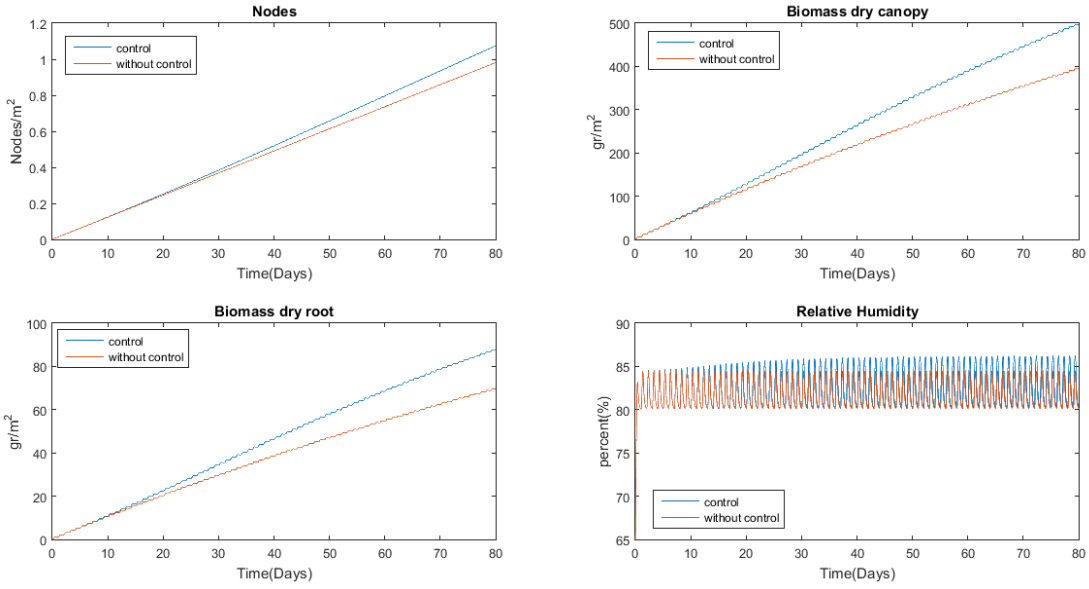


Fig 1 Nodes, Biomass canopy, Biomass root and RH

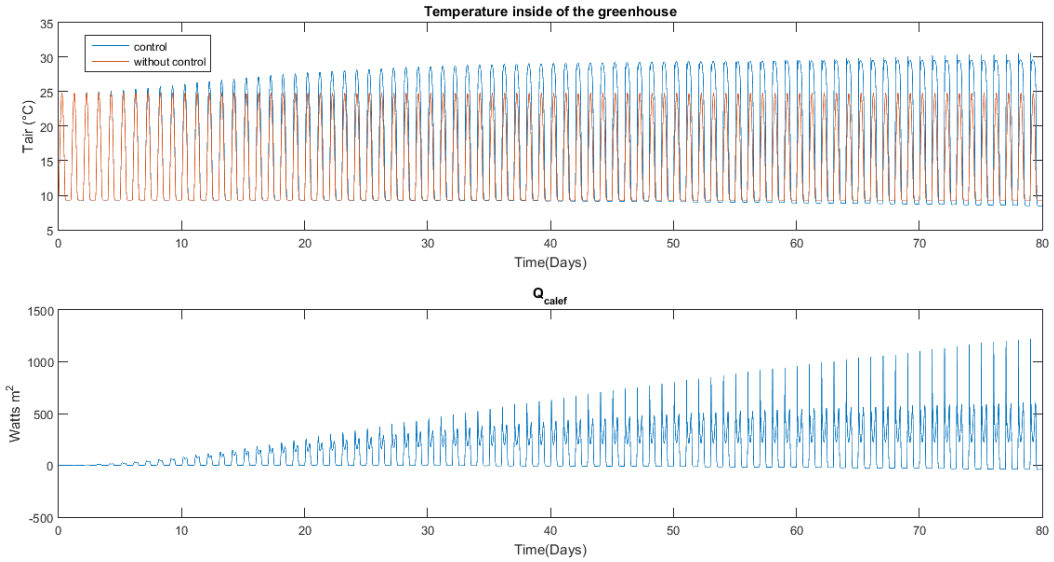


Fig 2Temperature inside of greenhouse and the variable control

To perform the control algorithm a proportional control is proposed, due to the fact that the temperature is a slow system in which a proportional-derivative control would make the same temperature change during the same time, this control goes directly to the heating system interior ofthe greenhouse.

However, the greenhouse is not an adiabatic system exempt from external disturbances, for this reason external perturbations are considered and, in this way, obtain the desired temperature at the end of the algorithm.

To control the temperature inside the greenhouse, a water heating system is used to fix the pipes. To control the hot water, the ASCO(figure 4 Bottom), proportional electronic system is used, which is a solenoid that regulates the gas pressure inside the water heater, in this way regulate the amount of heat spent in watts inside the water heater.

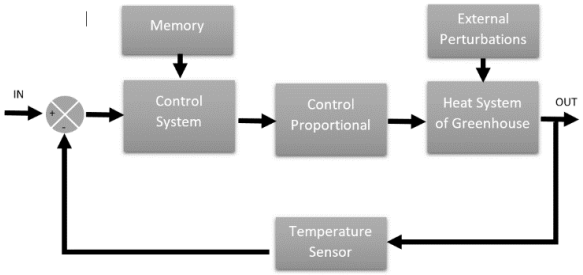


Fig3 Control Algorithm

The control system is mainly managed by a 32-bit microcontroller (fig 3 middle) that has a TFT display to visualize different parameters to be controlled during the execution of the proposed control algorithm.

This control is carried out through the pulse width modulation (PWM) carried out by the control system, which consists of regulating the pulse width modulation as a positive integer, with a working frequency of 300Hz or 700Hz [7], which is the ideal working frequency for the control of air and LP gas, respectively.

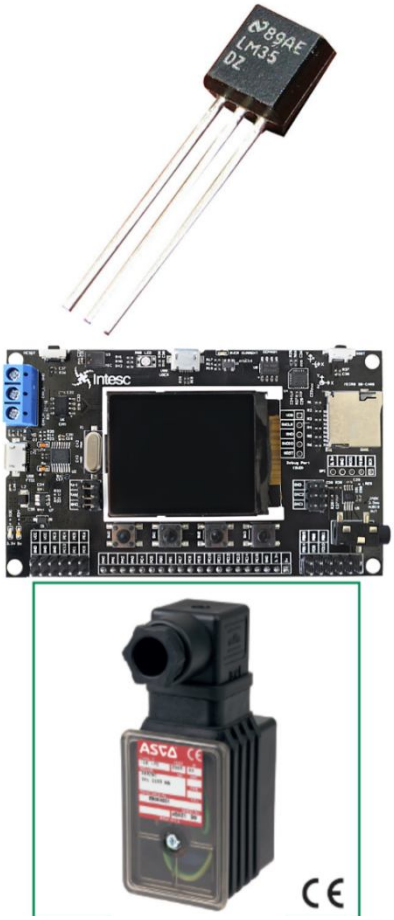


Fig 4Lm35 (Top), Microcontroller(middle), Electronic Proportional Control Unit ASCO (Bottom)

To perform the pulse width modulation control, an instrumentation stage was carried out, which consists

of raising the output voltage of the TTL control system from 3.3V to 10V, necessary to perform the proportional operation of the solenoid valve of the ASCO actuator. To do this, a comparison stage is used and the high and low logic states are defined by a reference voltage, where any voltage lower than the reference voltage is considered a logical 0, and a value greater than the reference voltage is a logical 1. The minimum consumption of the ASCO actuator is also considered and a buffer with zero calibration auto is implemented, this to avoid a cumulative error that could affect the ASCO actuator.

Figure 4 shows the PWM output of the controller in TTL level (3.3 V) in yellow and the output required for the controller in blue (10 V). A proportional control algorithm managed by the control system was developed as follows:

$$f_g = k_p \tilde{T}_g \qquad (56)$$

where f_g is a positive integer, which regulates the pulse width delivered to the ASCO solenoid, k_p the proportional gain constant, $\tilde{T}_g$ is the error inside the greenhouse between the desired temperature and the temperature measured by the temperature sensor (LM35).

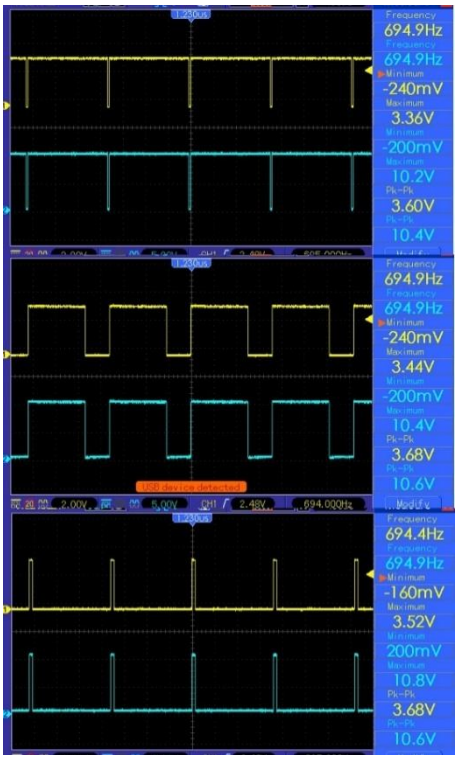


Fig 5. 95% PWM (Top), 60% PWM (middle), 5% PWM (Bottom)

Within the control algorithm, the minimum pressure required by the water heating system is taken into account, just as the electronic device can be adjusted for a minimum and maximum pressure.

CONCLUSION

The theory of optimal control was applied to a model whose parameters are exclusive to the northern region of the state of Puebla, however, the methodology presented in this article can be adequately generalized.

The optimal control law for the heating system (translated in Watts) was obtained for a harvest period of 80 days and its application increases the production of the crop according to the simulation carried out. In addition to that the relative humidity presents a quite acceptable range.

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