Smart Greenhouse System

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1 Introduction

Automatic irrigation systems are commonly used in the agricultural industry as a means to efficiently water crops without needing direct human supervision and intervention. These smart systems use sensors to monitor the environment and adjust the irrigation accordingly. However, without careful planning, their activity could result in over or under watering, leading to wasted resources and potential crop damage.

In this project, a smart greenhouse system is presented to irrigate plants efficiently and effectively and to mantain the optimal temperature for their growth.

2 Setting

2.1 Field

An hypothetical greenhouse is considered as setting for this project. Its walls and ceiling are completely made of glass for sun to shine through. It has a square base, whose area is completely covered with soil. Its dimensions are presented in table 2.

2.2 Physical components

The following hardware is included in the system:

– a single central sprinkler, which is able to irrigate in a uniform fashion using a series of underground pipes; it provides an adjustable water flux in the range $[0, 10]$ L/s;

– an air-conditioning system, whose job is to regulate the internal temperature of the greenhouse by transmitting and absorbing heat at need and to dehumidify the greenhouse; it works in the range $[0, 250]$ W for both the cooling and the heating components.

2.3 Actuators

The system includes the following set of actuators:

- `SprinklerController`: P controller that manages the valve of the sprinkler;
- `AirConditioningController`: PI controller that manages the intensity of the heating/cooling system.

2.4 Sensors

Time is assumed to be discrete, measured by an internal clock, and the timestep t is assumed to be $t = 1\,\mathrm{s}$. The system includes the following set of sensors:

- 1 soil moisture sensor: it measures the volumetric water content θ in the field, which is defined as follows [1]:

$$\theta = \frac{V}{V_T}\,, \tag{1}$$

  where V is the volume of water present at any moment in the field, while $V_T = V + V_s$ is the total volume of the field, including both water and soil;
- 3 environmental thermometers, which measure temperature in K; one is placed inside to measure the internal temperature T, one outside for the temperature T_e and one in the water tank for the temperature T_w.

3 Equations

The equations that governs the volume of water in the field and the temperature are the following:

$$\frac{dV}{dt} = F - \epsilon(T) \tag{2}$$

$$\frac{dT}{dt} = \frac{1}{V_r \rho_a C_{p,a}} \left[\frac{1}{d} \lambda_g a_g (T_e - T) + \sigma\epsilon(T_e^4 - T^4) + C_{p,w} V \rho_w (T_w - T) + P \right]; \tag{3}$$

symbols are presented in table 2. $\epsilon(t)$ is the evapotranspiration rate: it is a phenomenon that encompasses both evaporation caused by the sun's heat, as well as transpiration, which is the transportation of water from the soil to the atmosphere through plants [2]. Its relation with temperature can be approximated using the following function:

$$\epsilon(T) = \alpha_1 + \alpha_2 T\,. \tag{4}$$

The heat absorbed by the system depends on the conduction with the external environment and with the volume of water, by the radiation transfer and by the power of the air-conditioning system P. Positive values of P refer to the power used by the heating module, while negative ones refer to the cooling one.

4 Requirements

In order to function properly, the smart greenhouse system must respect the following conditions (a time window of 2 hours is considered):

- within the first hour of the simulation, the oscillations $o_T(t) = |T(t) - T(t-1)|$ of the temperature should settle under $o_{T,threshold,1}$, from one point on:
$$\phi_1 = \mathbf{FG}_{[0,1]}\left(o_T(t) < o_{T,threshold,1}\right); \quad (5)$$
- during the second hour of the simulation, the oscillations o_T should stay under $o_{T,threshold,2} = o_{T,threshold,1}/2$:
$$\phi_2 = \mathbf{G}_{[1,2]}\left(o_T(t) < o_{T,threshold,2}\right); \quad (6)$$
- during the entire simulation, the oscillations o_M should stay under $o_{\theta,threshold}$:
$$\phi_3 = \mathbf{G}_{[0,2]}\left(o_\theta(t) < o_{\theta,threshold}\right); \quad (7)$$
- in the second half of the simulation, the steady state error $s_T(t) = |T(t) - T_{target}|$ of the moisture should not exceed a fixed threshold:
$$\phi_4 = \mathbf{G}_{[1,2]}\left(s_T(t) < s_{T,threshold}\right); \quad (8)$$
- in the second half of the simulation, the steady state error $s_\theta(t)$ of the moisture should not exceed a fixed threshold:
$$\phi_5 = \mathbf{G}_{[1,2]}\left(s_\theta(t) < s_{\theta,threshold}\right); \quad (9)$$

5 Falsification

The temperature requirement ϕ_4 is a hard requirement, because plants' health could be put at risk if it is not respected. To verify robustness of the system with respect to this requirement, several external temperature conditions have been tested. Specificylly, the external temperature can be modeled using the following formula:

$$T_e(t) = A_T \sin\left(\frac{2\pi t}{P_T}\right) + \bar{T} + N(0, \sigma_T^2), \quad (10)$$

where A_T is the amplitude of the temperature oscillation during the day, $\bar{T}$ is the mean temperature of the day, P_T is the period, corresponding to 24 h and the last term indicates a random Gaussian noise given by the presence of occasional weather conditions, which is sampled every 10 min. A grid search on different combinations of $\bar{T}$ and A_T has been carried to search for negative robustness values. Since a random component related to weather is present in the formula, each condition has been tested multiple times. The initial time is supposed to be midnight. The results can be seen in table 1.

6 Conclusion

The proposed smart greenhouse system is able to regulate the correct moisture level of the plants by acting on the flux of water from the sprinkler. The temperature requirement ϕ_4 can be falsified if the external temperature is extremely cold (around $-15\,^{\circ}$C). The variables T and V appear in both differential equations that govern their temporal evolution, however, their coupling is weak, which permits the utilization of two independent PID controllers to manipulate them individually. The project can be found in the dedicated GitHub repository [3].

References

[1] *Handbook of Technical Irrigation Information - Hunter Industries*. 2015. URL: https://www.hunterindustries.com/sites/default/files/tech_handbook_of_technical_irrigation_information.pdf.

[2] K. Preeyaphorn. "Air Temperature and Actual Evapotranspiration Correlation Using Landsat 5 TM Satellite Imagery". In: *Nat. Sci.* (2009).

[3] *Smart Greenhouse System repository*. 2023. URL: https://github.com/gigug/smart-greenhouse-system.

Appendix

The following plots show temperature and moisture control for 2 h. The orange dotted line indicates the desired value and the red dotted lines indicate the interval delimited by the steady state error.

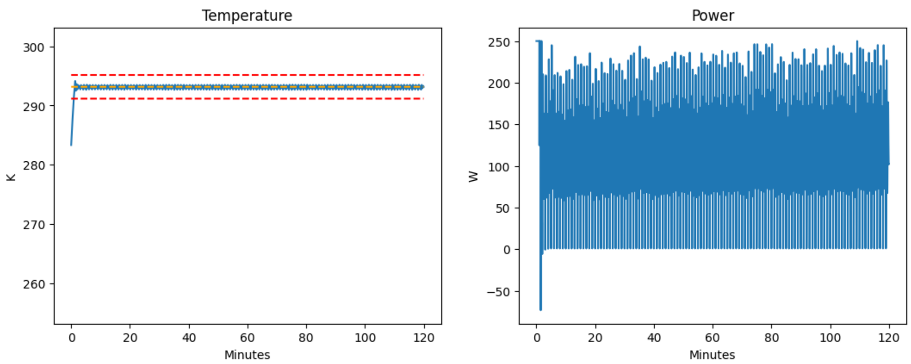

Figure 1: Temperature control with $\bar{T} = 5\,^{\circ}\mathrm{C}$.

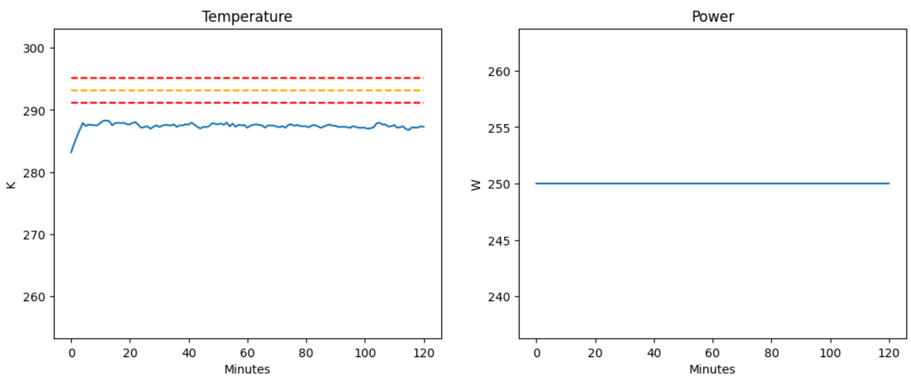

Figure 2: Temperature control with $\bar{T} = -20\,^{\circ}\mathrm{C}$.

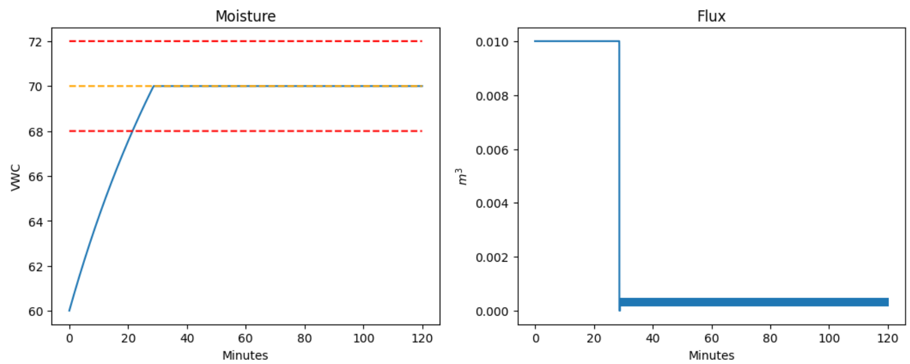

Figure 3: Moisture control.

		A_T			
		0.5	1	5	10
$\bar{T}$	255	0.16	0.38	-3.10	-7.53
	260	0.93	0.95	0.64	-2.93
	265	1.24	1.19	0.92	0.65
	270	1.38	1.35	1.24	0.93
	275	1.48	1.48	1.39	1.26
	280	1.59	1.60	1.50	1.39
	285	1.72	1.71	1.62	1.53
	290	1.83	1.81	1.74	1.62
	295	1.94	1.92	1.86	1.75
	300	1.84	1.84	1.93	1.86
	305	1.73	1.73	1.82	1.93

Table 1: Robustness results. The row values show different mean temperatures $\bar{T}$, measured in K, while the columns indicate the sinusoidal amplitude of the daily temperature A_T.

Dimension	Symbol	Value
Height	h	$3\,\mathrm{m}^2$
Area	A	$10\,\mathrm{m}^2$
Area glass	A_g	$220\,\mathrm{m}^2$
Volume room	V_r	$30\,\mathrm{m}^3$
Depth soil	d	$0.2\,\mathrm{m}$
Thickness glass	d	$0.03\,\mathrm{m}$
Density air	ρ_a	$1.204\,\mathrm{kg/m}^3$
Density water	ρ_w	$997\,\mathrm{kg/m}^3$
Specific heat air	$C_{p,a}$	$1005\,\mathrm{J/(kg/K)}$
Specific heat water	$C_{p,w}$	$4.196\,\mathrm{J/(kg/K)}$
Thermal conductivity glass	λ_g	$0.27\,\mathrm{W/(mK)}$
Stefan–Boltzmann constant	σ	$5.67 \times 10^{-8}\,\mathrm{W/(m^2K^4)}$
Emissivity glass	ϵ	0.9
Evapotranspiration coefficient 1	α_1	$2.0 \times 10^{-5}\,\mathrm{m}^3$
Evapotranspiration coefficient 2	α_2	$1.0 \times 10^{-6}\,\mathrm{m^3/K}$
Target moisture	θ_{target}	70
Target temperature	T_{target}	$293.15\,\mathrm{K}$
Steady state error moisture	s_θ	2
Steady state error temperature	s_T	$2\,\mathrm{K}$
Maximum Oscillations T	$o_{T,threshold}$	$1\,\mathrm{K}$
Maximum Oscillations θ	$o_{\theta,threshold}$	0.6
Steady state error T	$s_{T,threshold}$	$2\,\mathrm{K}$
Steady state error θ	$s_{\theta,threshold}$	2
Variance temperature	σ_T^2	$1\,\mathrm{K}$

Table 2: Symbols definitions