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Control Of An Oven With Space-Distributed Sensors

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Abstract. PID controllers are robust and easily synthesized. The are many techniques that allow its tuning with simple steps, with or without a system model. The direct synthesis method allows us to find gain expressions in terms of the model parameters, using its canonical representation. We used a thermal system, available at the Signals and Systems Laboratory of CEFET-MG's campus V, which is composed of 9 sensors placed in series along an acrylic path with forced ventilation. Three resistances and a damper act as actuators for the system, heating the air and regulating its flow. We identified 1280 first-order models for this system, using different combinations of damper opening, resistance power and selected output sensor by using the complementary output method and used a subsample of those to create controllers using direct synthesis. We use a set of equations developed by ourselves and another set found in an article. We tested them in the real system with satisfactory results.

Keywords: control theory, direct synthesis, PID

1 Introduction

Figure 1 shows an oven with acrylic walls, with three resistances (R1, R2 and R3), one damper (hidden behind the monitor), ten sensors (S1 to S10) and a cooler that forces cold air entrance. The cooler is not controllable and always operates at maximum speed. The circuitry controls the resistance on/off time, working like a PWM (pulse width modulation) with a switching frequency of 1 second. As the system's dynamic is very slow, it is not affected by this rather low frequency. The damper is an acrylic barrier attached to a servo-motor, which regulates the airflow.

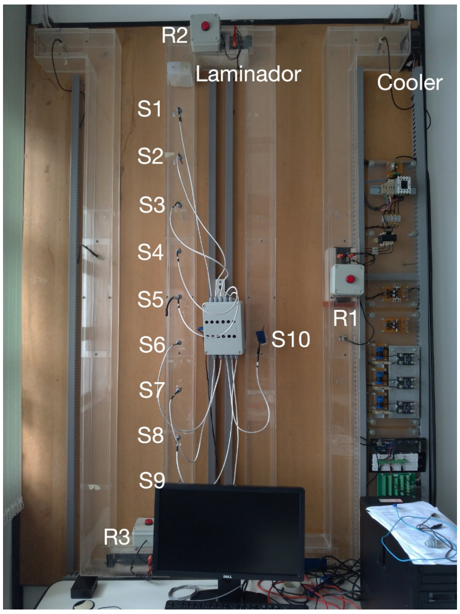

Figure 1. Oven system

Using the complementary response method [1], we fitted 1280 first-order models for the system. To do so, we fixed values for the damper opening and the resistance's power, and then created one model for each combination of opening, power and sensor. Every model is single-input-single-output, with the R1 resistance's power as input (in percentage) and the respective sensor's temperature as output (in ºC).

The direct synthesis PID tuning method [2] allows using the system's model to derive functions for the PID gains. This way, to get a controller for a given system, the designer only has to apply the model's and desired dynamic's parameters to those functions. Because the calculation is so simple, it is an excellent choice for us, as we need to derive thousands of controllers. Also, it shows the relationship between the controller and the closed-loop dynamics explicitly, making it a great didactic tool.

We chose to use the PI controller since the oven has a first-order response, making the derivative action unnecessary [3, 4]. Using the direct synthesis technique, we found explicit formulas for K_p and K_i, which we used to design controllers for various configurations and points of operation.

2 Methodology

The direct synthesis equates the desired closed-loop system with the real system in a closed-loop with the PID model. This way, one has the desired closed-loop equating the real closed-loop. Equation (1) shows the system's first-order transfer function and Equation (2) shows the controller's transfer function.

$$G(s) = \frac{K}{\tau s + 1}, \tag{1}$$

$$C(s) = K_p + \frac{K_i}{s}, \tag{2}$$

where K_p is the proportional gain, K_i is the integral gain, K is the system gain, τ is the system time constant and s is Laplace's complex frequency.

To find the explicit formulas for K_i and K_p, first, one equates Relation (3), the system's closed-loop transfer function, with (4), the transfer function with the desired dynamic characteristics.

$$\frac{\frac{K_i K}{\tau}}{s^2 + (\frac{K_p K + 1}{\tau})s + \frac{K_i K}{\tau}} \tag{3}$$

$$\frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \tag{4}$$

This equation of terms, after some algebraic manipulation, results in Equations (5) and (6), which only contains the desired terms. Choosing $\omega_n = \frac{4\sqrt{2}}{\tau_d}$ and $\zeta = \frac{\sqrt{2}}{2}$, we can isolate K_p and K_i as shown in (7) and (8).

$$2\zeta\omega_n = \frac{K_p K}{\tau} + \frac{1}{\tau} \tag{5}$$

$$\frac{K_i K}{\tau} = \omega_n^2 \tag{6}$$

$$K_p = \frac{2\zeta\omega\tau - 1}{K}, \tag{7}$$

$$K_i = \frac{\omega_n^2 \tau}{K}. \tag{8}$$

By equating a different desired closed-loop model and using different algebraic manipulations, Chen and Seborg [2] found different explicit equations for the gains. The following equations are equations 16 and 17 from that article.

$$K_p = \frac{\tau}{\tau_d K} \tag{9}$$

$$K_i = \frac{K_p}{\tau} \tag{10}$$

3 Results Analysis

The Tables 1 and 2 show the found K_p and K_i values for some configurations, using our derived equations and the ones from Chen and Seborg [2], where a is the damper opening (percent), u is the control signal (percent), K is the system DC gain, τ is the time constant and Y_0 is the equilibrium output.

Table 1. Direct synthesis and system parameters

Sensor	K_p	K_i	a	u	K	τ	Y_0
$S2$	10.115	$1.224 * 10^{-2}$	20	95	0.692	945	93
$S3$	10.169	$1.598 * 10^{-2}$	30	90	0.659	761	85
$S4$	10.969	$2.158 * 10^{-2}$	40	85	0.638	581	79
$S5$	11.459	$1.754 * 10^{-2}$	55	75	0.611	750	69
$S6$	11.963	$4.644 * 10^{-2}$	65	70	0.585	1178	63
$S7$	12.152	$6.39 * 10^{-2}$	80	65	0.576	856	53
$S8$	12.411	$2.06 * 10^{-1}$	90	60	0.564	275	55
$S9$	12.726	$1.8 * 10^{-1}$	100	55	0.550	324	51

Table 2. Direct synthesis and system parameters (Chen and Seborg [2])

Sensor	K_p	K_i	a	u	K	τ	Y_0
$S2$	11.38	$1.204 * 10^{-2}$	20	95	0.692	945	93
$S3$	9.623	$1.265 * 10^{-2}$	30	90	0.659	761	85
$S4$	7.589	$1.306 * 10^{-2}$	40	85	0.638	581	79
$S5$	10.229	$1.364 * 10^{-2}$	55	75	0.611	750	69
$S6$	16.781	$1.425 * 10^{-2}$	65	70	0.585	1178	63
$S7$	12.384	$1.447 * 10^{-2}$	80	65	0.576	856	53
$S8$	4.063	$1.477 * 10^{-2}$	90	60	0.564	275	55
$S9$	4.909	$1.515 * 10^{-2}$	100	55	0.550	324	51

With those values, we could apply the control rule in the real system and analyze if the response of the closed-loop system matched the desired dynamic. Figures 2 and 3 shows both methods on sensor 4 and Figures 4 and 5 shows them on sensor 7. Since there are many possible combinations, we chose those sensor for being at about one-fourth and three-fourths of the length, thus not at extremes nor in the middle. The operation points were chosen arbitrarely. Both choices aim at selecting a presentable subsample, since there are over a thousand choices.

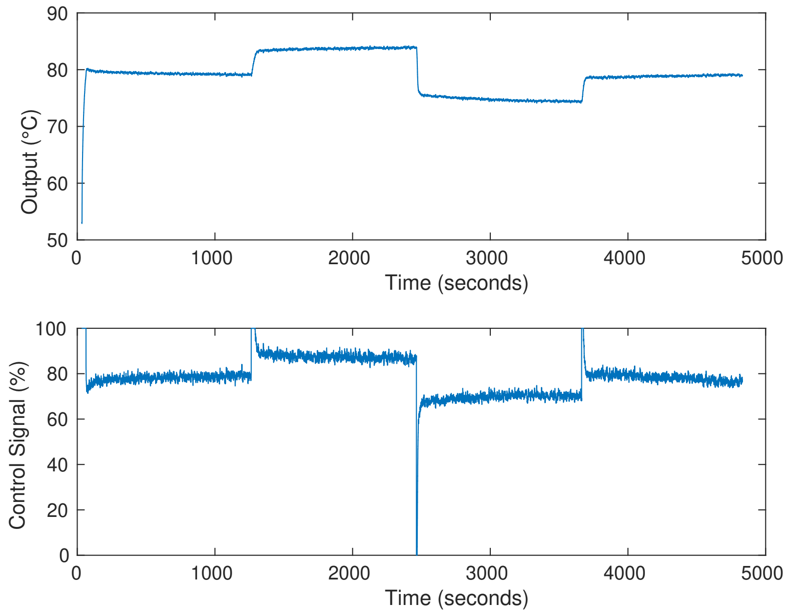

Figure 2. Our direct synthesis on sensor 4

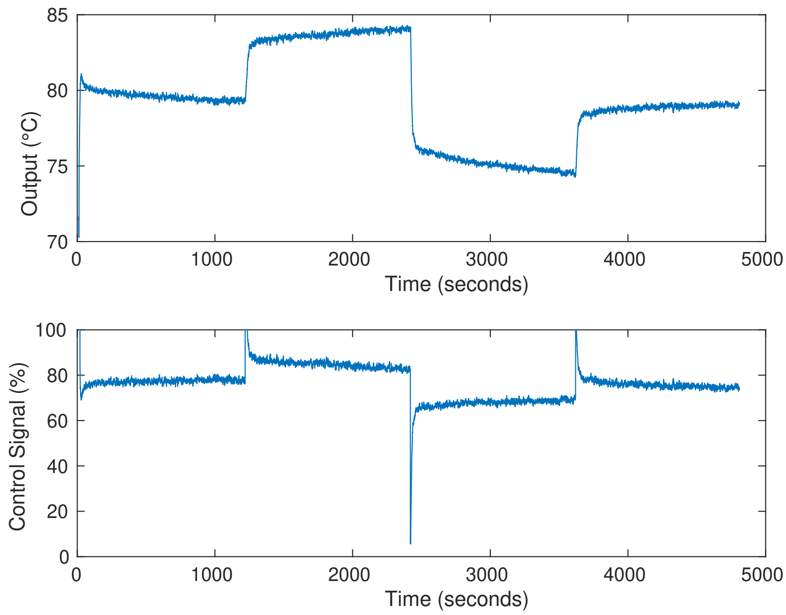

Figure 3. Chen's direct synthesis on sensor 4

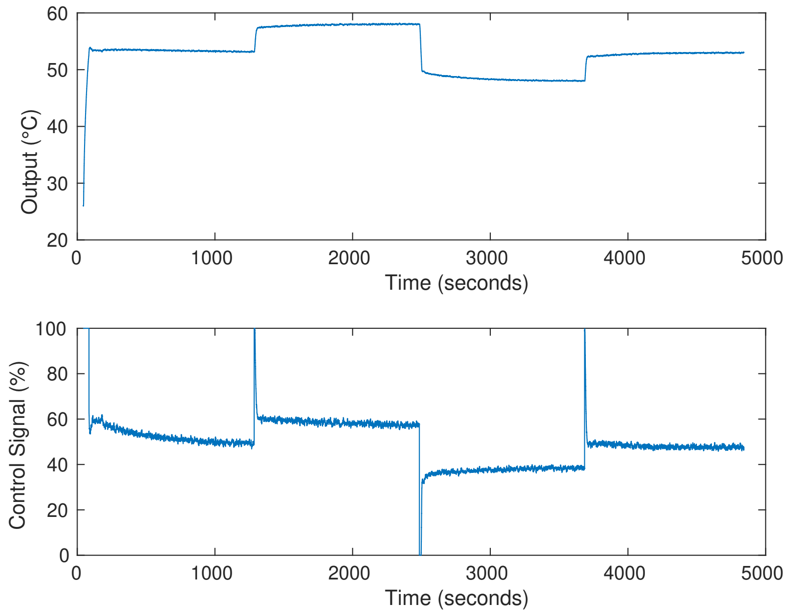

Figure 4. Our direct synthesis on sensor 7

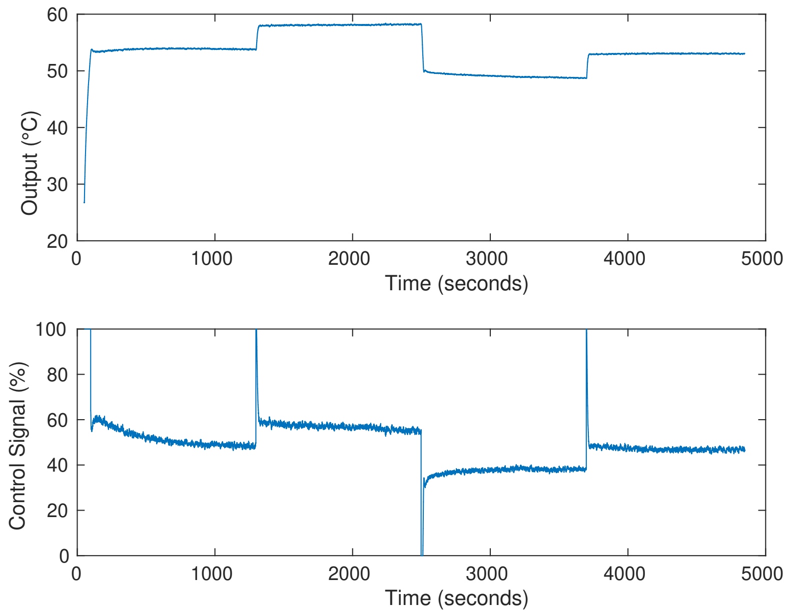

Figure 5. Chen's direct synthesis on sensor 7

Analyzing the graphs, we can see that the output followed the reference with both methods, without overshoot. Also, there is no saturation of the control signal.

4 Conclusion

The studied synthesis methods controlled the system, eliminating offset errors and decreasing the convergence time. Both methods resulted in very different equations, but the resulting controllers and their output and control signals were similar. Also, the controllers presented good disturbance rejection, as the room temperature was changing during all experiments. It is visible by the changes in control signal not accompanied by changes in output, especially at the beginning of experiments.

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