Volume 56 • Issue 1 • 2023 ISSN 2405-8963

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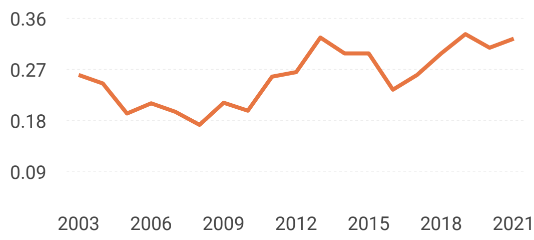

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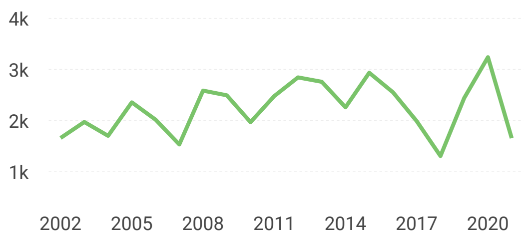

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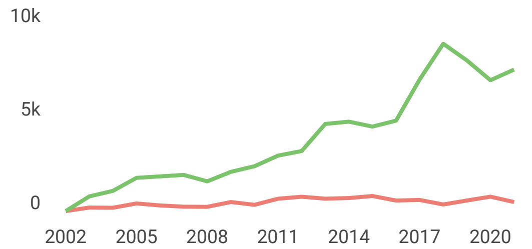

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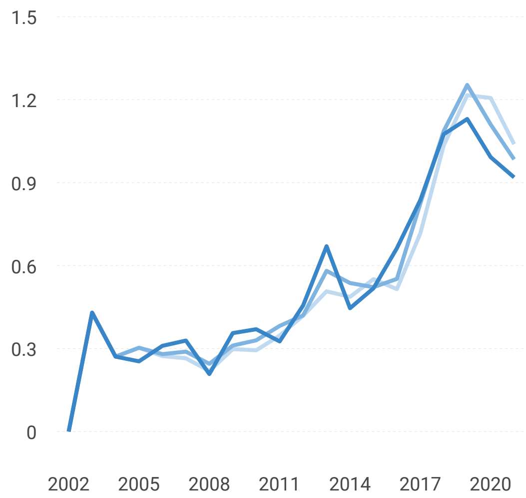

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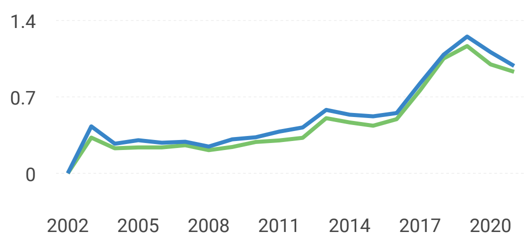

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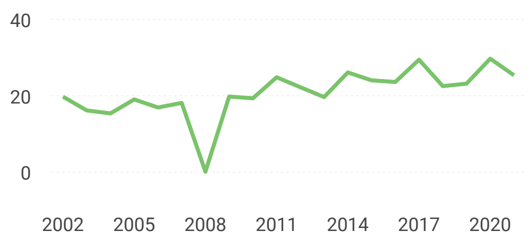

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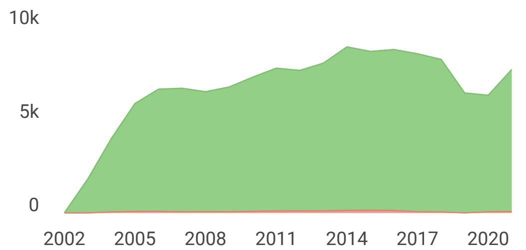

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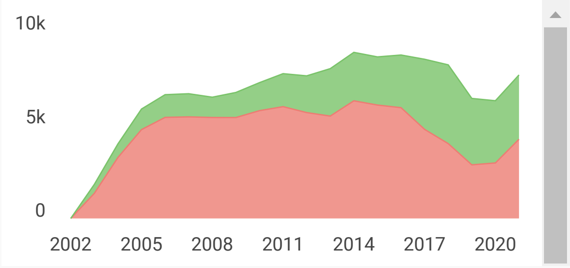

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ISSN: 2405-8963

Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 54-20 (2021) 735–740

An Energy Balance Model Parameter Estimation with an Extended Kalman Filter

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Abstract: This paper presents modeling and parameter estimation of a thermal system, which is often nonlinear, with nonlinearities found in its parameters. As a result, it requires an additional online parameter estimation. In this paper, we implement an Extended Kalman Filter for modeling and parameter identification of such a device. The thermal device that we use is an educational device developed in-house. First, we derive the device's mathematical model using a zero-order energy balance model as the template model. Next, we find the model's best parameters by performing an optimization process. Finally, we implement an Extended Kalman Filter technique to accommodate the possibility that those parameters may change over time. Our experiments show that when we have reliable measurements and a reliable system model, the Kalman filtering technique can perform well as an online parameter estimator and act as a basis to build an adaptive model.

Keywords: Recursive identification, process modeling and identification, embedded computer control systems and applications.

1. INTRODUCTION

Heat transfer modeling on thermal systems is a essential since it provides engineers better insights into the system processes and allows sophisticated control implementations. However, this modeling task can be challenging since a thermal system's nonlinear behaviors are commonly found in the model parameters. In contrast, the used model itself is linear (see Jonsson and Palsson (1994)). As a result, the model performance may deteriorate if the parameters are assumed to be constant at all times.

In a situation where the nonlinear behaviors are found in the system's parameters or where the parameters are actually changing as functions of time, online parameter estimation can be used as one of the solutions. For this purpose, a Kalman filtering technique can be used, such as found in the works by Song et al. (2017), Kim et al. (2016), Jonsson and Palsson (1994), Mutambara and Al-Haik (1999) and Yanou et al. (2016). In general, a Kalman filtering technique is used for state estimation. However, it can also be used to perform parameter estimation by extending the system's state model with the model parameters that we want to estimate (see Blanchard et al. (2007) and Walker (2006)). As the result, the Kalman filter will estimate both the state variables and the added model parameters.

To model a thermal system, an energy balance model can be used as a template model. An energy balance model is most common in environmental science where it is used to model the climate systems (see Roques et al. (2014)). In this paper, we use a zero-dimensional energy balance model. The term zero-order is used to describe that there is no spatial variable in the model. Such model is the simplest form of an energy balance model. Park et al. (2020) also use a zero-order energy balance model in their work, although they do not include time delay in their energy balance equations. As for the model parameters, we use an optimization process to find their best values.

In order to test the proposed concept, we have developed a thermal device that is originally developed for teaching purpose (see Section II). Recently, educational thermal devices have become more widely used in several engineering courses, such as in Park et al. (2020), Tran et al. (2019), and Barbosa (2020). Besides teaching, the same devices can also be used for research, such as as test devices for control system developments (see Cui et al. (2020)). These educational devices are typically compact in size, low-cost, and easy to build. Since the thermal process is generally slow, it does not require a high-performance control computer and data acquisition system.

This paper takes the references above and investigates the use of a Kalman filtering technique to enhance a thermal system modeled by using an energy balance model with delayed input and an already optimized set of parameters. Our contribution will be the overall investigation process that we introduce in this paper. Here we demonstrate that if noises do not significantly contaminate the state variables, a Kalman filtering technique should perform very satisfactorily as an online parameter estimator. Additionally, we also contribute to the application of a Kalman

10.1016/j.ifacol.2021.11.259

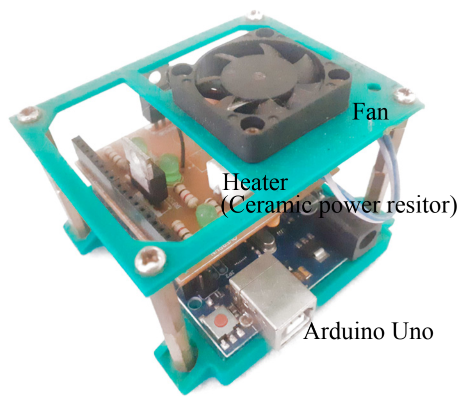

Fig. 1. The developed temperature control device.

filtering technique in heat transfer science. To the best of the authors' knowledge, a Kalman filtering technique is not very common in heat transfer science. Moreover, using a Kalman filtering technique for parameter estimation is not as common as using it for state estimation.

This paper organizes as follows. In Section 2, we describe the hardware design of the thermal test device. In Section 3, we perform system modeling. In Section 4, we implement and test the online parameter estimation procedures. In Section 5, we evaluate the estimation results. Finally, we present our conclusion in Section 6.

2. HARDWARE DESCRIPTION

The thermal device that we use for testing purpose in this paper is shown in Fig. 1. The device is compact in size and stacked on top of an Arduino Uno (Arduino AG, Italy) board. To program the Arduino, we use MATLAB Simulink (MathWorks Inc., USA) software in the control computer. The Arduino Uno acts only as an input-output server. The main control program, written with Simulink, runs in the control computer with a sampling frequency of 10 Hz.

The developed device is equipped with one heater (a 27 Ω/5 W ceramic power resistor) and one small fan. Both the heater's temperature and the fan's speed can be controlled by sending Pulse-Width-Modulation (PWM) signals. An external 12 V / 2 A power supply powers both the heater and the fan. To measure the temperature of the heater, an analog temperature sensor is attached to the heater (LM35).

3. PHYSICAL MODELING AND PARAMETER OPTIMIZATION

To model the temperature test-bench, we deployed an energy balance model with a time delay in its input. In an energy balance model, the amount of heat received by a system equals the amount of heat dissipated by that system added with the amount of heat stored in that system. The dissipated heat occurs through both convective and radiative heat losses.

Taking into account the heat loss due to the running fan, we introduce to the model two convective losses: the normal convective loss and the forced convective loss. As a result, the governing dynamic equation of the proposed thermal test device can be expressed as follows:

Table 1. Parameter constraints and the optimized parameters.

	Constraints		Optimized
	Upper	Lower	Values
h_1	100	10	41.563
h_2	200	10	99.955
ε	1	0.9	0.950
c_r	2000	1	1599.672
θ	15	5	10.002

$$\begin{aligned}\underbrace{\alpha(t-\theta)P_{\max}}_{\text{Generated heat}} = \underbrace{mc_r\frac{dT_r(t)}{dt}}_{\text{Stored heat}} + \underbrace{h_1\left(T_r(t)-T_\infty\right)}_{\text{Normal convective loss}} + \\ \underbrace{\varepsilon\sigma A\left(T_r(t)^4-T_\infty^4\right)}_{\text{Radiative loss}} + \underbrace{\gamma(t)h_2\left(T_r(t)-T_\infty\right)}_{\text{Forced convective loss}}\end{aligned} \tag{1}$$

The nomenclature for Equation 1 is as follows:

- c_r is the heat capacity of the power resistor (in J/(kg K)).
- h_1 and h_2 are the normal and forced convective heat transfer coefficients, respectively (in W/(m^{2}K)).
- T_r and T_∞ are the power resistor's temperature and the ambient temperature, respectively (in Kelvin).
- ε is the emissivity (unitless).
- σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/(m^{2}K^4)).
- γ is the applied PWM input to the fan (from 0 to 1, unit-less).
- α is the PWM input applied to the heater (from 0 to 1, unit-less).
- θ is the input time delay (in seconds).
- $P_{\max}$ is the maximum power that can be delivered to the power resistor ($P_{\max} = 5.3$ W).

Additionally, there are several parameters whose values are approximated from measurements by using a ruler and a weight scale. They are the mass ($m = 0.005$ kg) and the surface area ($A = 0.0008\text{m}^2$) of the ceramic power resistor.

Once we have established the template model, the next step is to find the unknown parameters' values, which are h_1, h_2, ε, c_r, and θ, using an optimization technique. To do this, we stimulated the test device with arbitrary PWM signals for both inputs while at the same time we recorded the resulting temperature (the top plot in Figure 2). After that, we then performed an optimization process to find the optimal values of the parameters mentioned above using the collected data (the center plot in Figure 2). Here, we use a MATLAB built-in `fmincon` command, a nonlinear optimization technique with predefined parameter constraints. Details on this topic can be found in Kristiana and Manurung (2021).

The predefined constraints and the resulting optimized parameters are shown in Table 1. In Figure 2, we compare the output from the optimized model with the actual measurements. The optimized energy balance model fits the actual measurements nicely with a maximum absolute error of 5 degrees centigrade.

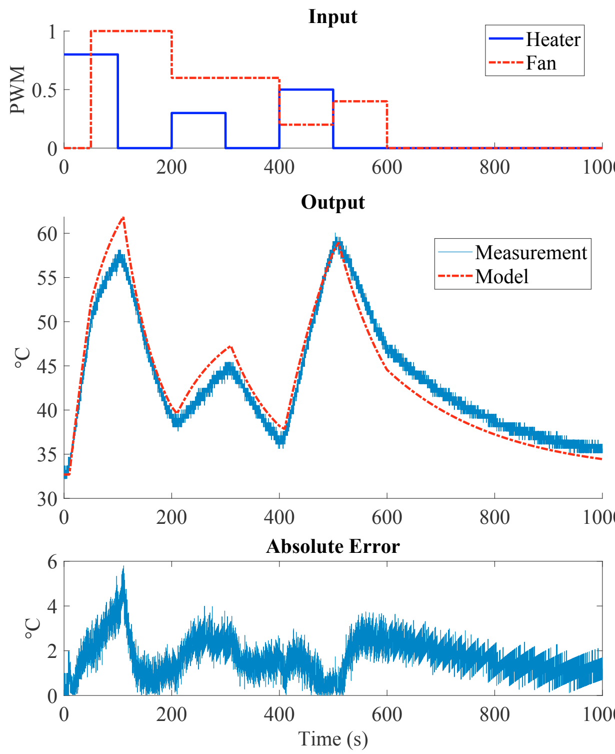

Fig. 2. Comparison between the actual temperature and the temperature calculated by the optimized model.

4. EXTENDED KALMAN FILTER DESIGN

An EKF is a type of Kalman filter for a nonlinear system. From Equation 1, we notice that the system's nonlinearity comes from the radiative term. However, the contribution of this radiative term is minimal when compared to the other two convective terms. Thus, the nonlinearity most certainly comes from the model's parameters, not from the model itself.

In this section, we first generate a new state-space model that includes the four parameters we want to estimate, which are T_∞, h_1, h_2 and c_r. After that, we apply the EKF procedure to estimate the values of those parameters.

4.1 The Parametrization

To implement the EKF, we must first formulate the energy balance model model in Equation 1 into its canonical state-space model. First, Equation 1 can be rewritten as follows:

$$\begin{aligned}\frac{dT_r(t)}{dt} =& \frac{1}{mc_r}\Big\{\alpha(t-\theta)P_{\max} + h_1\big(T_\infty - T_r(t)\big) + \\ & \gamma(t)h_2\big(T_\infty - T_r(t)\big) + \varepsilon\sigma A\big(T_\infty^4 - T_r(t)^4\big)\Big\}\end{aligned} \tag{2}$$

Next, by using a finite difference method, we can discretize Equation 2 as follows:

$$\begin{aligned}\frac{dT(t)}{dt} &= \frac{T_r(t+\Delta t) - T_r(t)}{\Delta t} \\ T_r(t+\Delta t) &= \frac{dT(t)}{dt}\Delta t + T_r(t)\end{aligned} \tag{3}$$

where Δt is the discretization sampling time. Substituting Equation 2 to Equation 3 will give us:

$$\begin{aligned}T_r(t+\Delta t) =& \frac{\Delta t}{mc_r}\Big\{\alpha(t-\theta)P_{\max} + \\ & h_1\big(T_\infty - T_r(t)\big) + \gamma(t)h_2\big(T_\infty - T_r(t)\big) + \\ & \varepsilon\sigma A\big(T_\infty^4 - T_r(t)^4\big)\Big\} + T_r(t)\end{aligned} \tag{4}$$

After that, we selected four model parameters that we want to estimate by using the EKF. They are the ambient temperature (T_∞), the normal convective heat transfer coefficient ($h_1(t)$), the forced convective heat transfer coefficient ($h_2(t)$) and the power resistor heat capacity ($c_r(t)$). From this point, those four parameters are now functions of time. Let us now introduce new state variables $\mathbf{z}(k)$ as follows:

$$\begin{aligned}\mathbf{z}(k) &= \left[z_1(k)\ z_2(k)\ z_3(k)\ z_4(k)\ z_5(k)\right]^{\mathrm{T}} \\ &= \left[T_r(k)\ T_\infty(k)\ h_1(k)\ h_2(k)\ c_r(k)\right]^{\mathrm{T}}\end{aligned} \tag{5}$$

where $k = 0, 1, 2, \ldots$ and $t = k\Delta t$. In total, there are five new variables: one state variable and four parameters.

Let us consider an input vector $\mathbf{u}(k) = \left[u_1(k)\ u_2(k)\right]^{\mathrm{T}} = \left[\alpha(k)\ \gamma(k)\right]^{\mathrm{T}}$. Thus, we can complete the state-space form as follows:

$$\begin{aligned}z_1(k+1) =& \frac{\Delta t}{m\ z_5(k)z_1(k)}\Big\{u_1\Big(k - \frac{\theta}{\Delta t}\Big)P_{\max} + \\ & z_3(k)\big(z_2(k) - z_1(k)\big) + \\ & u_2(k)z_4(k)\big(z_2(k) - z_1(k)(t)\big) + \\ & \varepsilon\sigma A\big(z_2(k)^4 - z_1(k)^4\big)\Big\} + \\ & z_1(k) + v_1(k) \\ z_2(k+1) =& z_2(k) + v_2(k) \\ z_3(k+1) =& z_3(k) + v_3(k) \\ z_4(k+1) =& z_4(k) + v_4(k) \\ z_5(k+1) =& z_5(k) + v_5(k)\end{aligned} \tag{6}$$

where $\mathbf{v}(k) = \left[v_1(k)\ v_2(k)\ v_3(k)\ v_4(k)\ v_5(k)\right]^{\mathrm{T}}$ is the additive process noise. Since the only measurable output is $z_1(k)$, the output becomes a scalar and its equation can be written as follows:

$$\mathbf{y}(k) = [1\ 0\ 0\ 0\ 0]\ \mathbf{z}(k) + \mathbf{w}(k) \tag{7}$$

where $\mathbf{y}(k) \in \mathbb{R}$ is the output vector and $\mathbf{w}(k) \in \mathbb{R}$ is the additive measurement noise vector. Both $\mathbf{v}(k)$ and $\mathbf{w}(k)$ are assumed to be zero-mean white Gaussian distribution.

4.2 The Extended Kalman Filter Procedure

First, let us reformulate Equation 6 and Equation 7 into their formal short forms.

$$\begin{aligned}\mathbf{z}(k) &= f\big(\mathbf{z}(k-1), \mathbf{u}(k-1)\big) + \mathbf{v}(k-1) \\ \mathbf{y}(k) &= h\big(\mathbf{z}(k)\big) + \mathbf{w}(k)\end{aligned} \tag{8}$$

Next, we will implement the EKF procedure for the two equations above, which consists of two repetitive procedures (see Chui and Chen (2017)): time update and measurement update.

Time Update Let us introduce $\hat{\mathbf{z}}_p(k)$ and $\hat{\mathbf{z}}(k)$ as the prior and posterior estimate of $\mathbf{z}(k)$, respectively. Hence, the time update procedure of the EKF can then be written as follows:

$$\begin{aligned}\hat{\mathbf{z}}_p(k) &= f\big(\hat{\mathbf{z}}(k-1), \mathbf{u}(k-1)\big) + \mathbf{v}(k-1)\\ \mathbf{P}_p(k) &= \mathbf{F}(k)\mathbf{P}(k-1)\mathbf{F}^{\mathrm{T}}(k) + \mathbf{Q}\end{aligned} \quad (9)$$

where $\mathbf{P}_p(k) \in \mathbb{R}^{5\times5}$ and $\mathbf{P}(k) \in \mathbb{R}^{5\times5}$ are the prior and posterior error covariance matrix, respectively; and $\mathbf{Q} \in \mathbb{R}^{5\times5}$ is the covariance matrix of $\mathbf{v}(k)$. $\mathbf{F}(k) \in \mathbb{R}^{5\times5}$ is the Jacobian of $f(\hat{\mathbf{z}}(k))$ and can be calculated as follows:

$$\mathbf{F}(k) = \frac{\partial f\big(\hat{\mathbf{z}}(k-1), \mathbf{u}(k-1)\big)}{\partial \hat{\mathbf{z}}(k-1)} \quad (10)$$

Equation 10 is solved numerically by using a finite difference method.

Before the first iteration, we initialize $\hat{\mathbf{z}}(0)$ and $\mathbf{P}(0)$ as follows:

$$\begin{aligned}\hat{\mathbf{z}}(0) &= \begin{bmatrix} 32.7 \; 32.7 \; 41.563 \; 99.955 \; 1599.672 \end{bmatrix}^{\mathrm{T}}\\ \mathbf{P}(0) &= \mathbf{I} \in \mathbb{R}^{5\times5}\end{aligned} \quad (11)$$

where $\mathbf{I}$ is an identity matrix. The initial value for $\hat{z}_1(0)$ and $\hat{z}_2(0)$ are set to be close to the current room temperature. While for the remaining, their initial values are the optimal values that we have already found in the previous section (see Table 1).

Measurement Update Let us introduce $\mathbf{K}(k) \in \mathbb{R}$ as the Kalman gain, $\mathbf{R} \in \mathbb{R}$ as the covariance matrix of $\mathbf{w}$, and $\mathbf{I} \in \mathbb{R}^{5\times5}$ as an identity matrix. The measurement update is implemented as follows:

$$\begin{aligned}\mathbf{K}(k) &= \mathbf{P}_p(k)\mathbf{H}^T(k)\Big(\mathbf{H}(k)\mathbf{P}_p(k)\mathbf{H}^{\mathrm{T}}(k) + \mathbf{R}\Big)^{-1}\\ \hat{\mathbf{z}}(k) &= \hat{\mathbf{z}}_p(k) + \mathbf{K}(k)\Big(\mathbf{z}(k) - \mathbf{H}(k)\hat{\mathbf{z}}_p(k)\Big)\\ \mathbf{P}(k) &= \Big(\mathbf{I} - \mathbf{K}(k)\mathbf{H}(k)\Big)\mathbf{P}_p(k)\end{aligned} \quad (12)$$

where $\mathbf{H} \in \mathbb{R}^{1\times5}$ is the Jacobian of $h(\hat{\mathbf{z}}(k))$ and can be calculated as follows:

$$\mathbf{H}(k) = \frac{\partial h(\hat{\mathbf{z}}_p(k))}{\partial \hat{\mathbf{z}}_p(k)} \quad (13)$$

Similar to Equation 10, we also solve Equation 13 numerically by using a finite difference method.

4.3 Estimation Results

For a preliminary test, we ran the EKF procedure offline for 1000 seconds, with a sampling time of 0.1 seconds, using the same dataset as in Figure 2. Matrices $\mathbf{Q}$ and $\mathbf{R}$ are heuristically set to be as follows:

$$\begin{aligned}\mathbf{Q} &= 0.4 \times \mathbf{I} \in \mathbb{R}^{5\times5}\\ \mathbf{R} &= 10\end{aligned} \quad (14)$$

where $\mathbf{I}$ is an identity matrix.

The power resistor's estimated temperature is presented in Figure 3, along with the measured temperature. Estimated model parameters: T_∞, h_1, h_2, and c_r are presented in Figure 4, Figure 5, Figure 6, and Figure 7, respectively. All of these figures show the evolution of the model parameters as functions of time although the changes are relatively very small. The largest changes that can be seen from the figures above is in the ambient temperature.

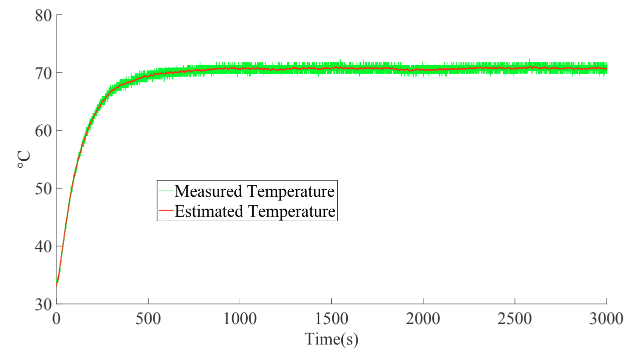

Fig. 3. Measured temperature ($y(k)$) compared to the estimated temperature ($\hat{z}_1(k)$).

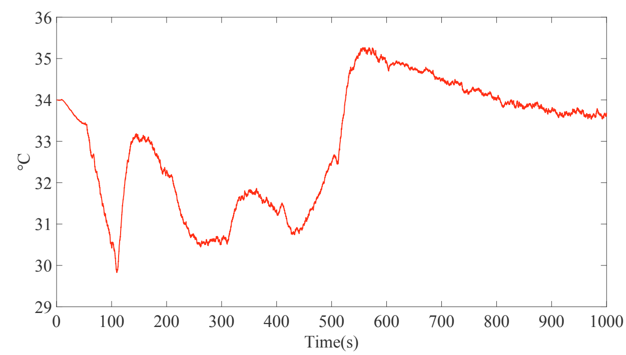

Fig. 4. Estimated ambient temperature ($z_2(k)$ or $T_\infty(k)$).

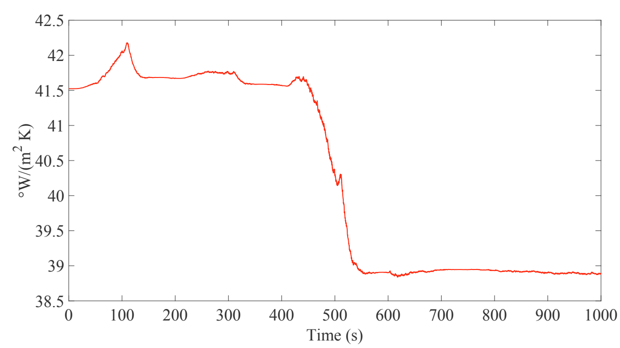

Fig. 5. Estimated normal convective heat transfer coefficient ($z_3(k)$ or $h_1(k)$).

However, there is no guarantee that we can ignore such slight variations in the model parameters. We will investigate this issue in the next section. Moreover, due to the nature of the deployed model, we must be aware that the selected initial values may significantly affect the parameter estimation results, although the state estimation may not be affected. Therefore, the preliminary optimization procedure is a crucial part of this EKF procedure.

5. EVALUATION WITH A CONSTANT INPUT EXPERIMENT

In Section 3, the data-set used for the optimization procedure was collected from the device transient phase only. On the contrary, we evaluated the developed model by using a different data-set collected during the device steady-state phase to create a more significant discrepancy between the model and the experiment. Therefore, we collected the data by applying 50% of PWM input to the heater and the

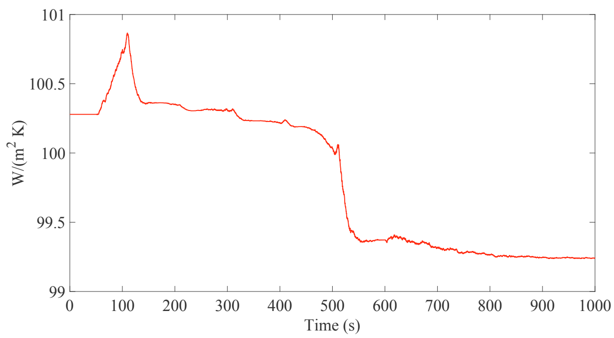

Fig. 6. Estimated forced convective heat transfer coefficient ($z_4(k)$ or $h_2(k)$).

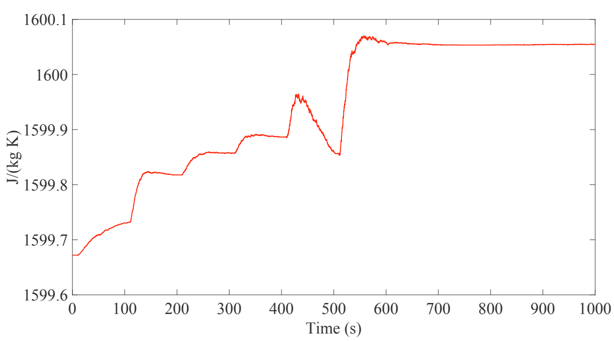

Fig. 7. Estimated power resistor's heat capacity ($z_5(k)$ or $c_r(k)$).

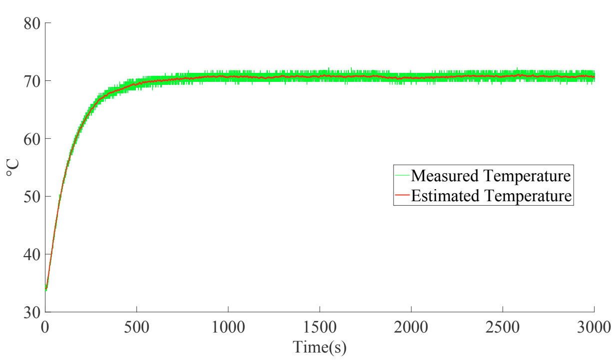

Fig. 8. Measured temperature ($y(k)$) compared to the estimated temperature ($\hat{z}_1(k)$) for constant inputs.

fan for a more extended period, which was 3000 seconds. As a result, the power resistor's temperature rose to about 70 degrees of centigrade (see Figure 8), and mostly, it was seated in its steady-state condition. At the same time, the EKF procedure was running, performing estimations to the state and the model parameters.

The EKF was initialized with the optimal parameter values as in Table 1. The estimated state, in this case, the power resistor's temperature, is also shown in Figure 8. While for the estimated model parameters, they are shown in Figure 9, Figure 10, 11, and Figure 12. Similar to the earlier experiments, changes in those model parameters are also relatively very small.

Nonetheless, those small changes may still contribute to performance differences. To test this idea, we implemented a test scenario with two models. One model receives parameter updates from the EKF, while another model

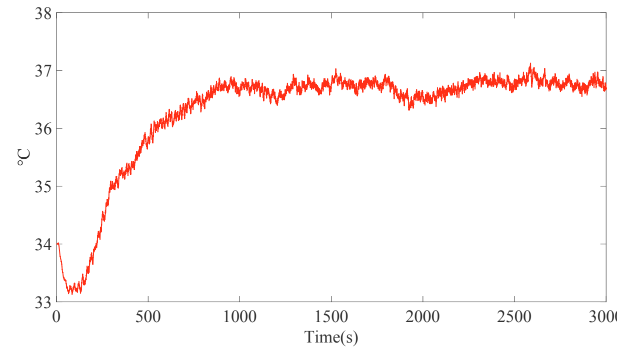

Fig. 9. Estimated ambient temperature ($z_2(k)$ or $T_\infty(k)$) for constant inputs.

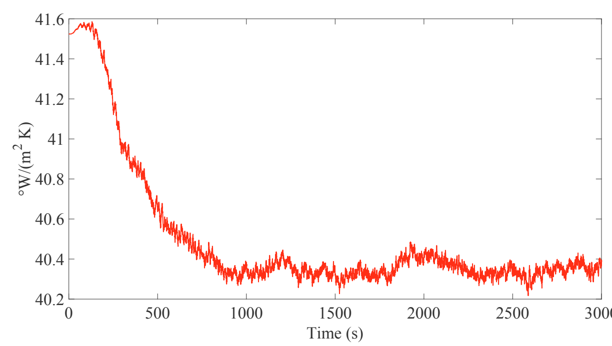

Fig. 10. Estimated normal convective heat transfer coefficient ($z_3(k)$ or h_1k) for constant inputs.

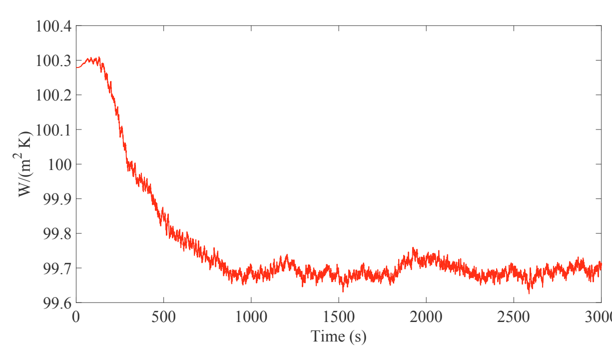

Fig. 11. Estimated forced convective heat transfer coefficient ($z_4(k)$ or $h_2(k)$) for constant inputs.

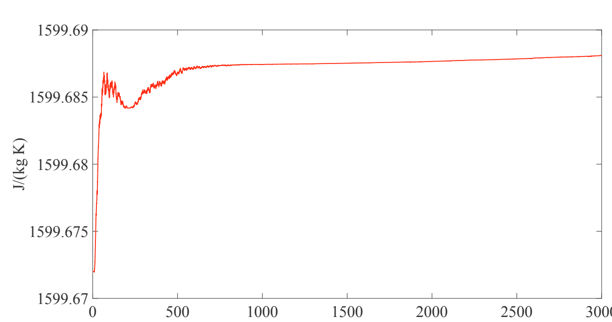

Fig. 12. Estimated power resistor's heat capacity ($z_5(k)$ or $c_r(k)$) for constant inputs.

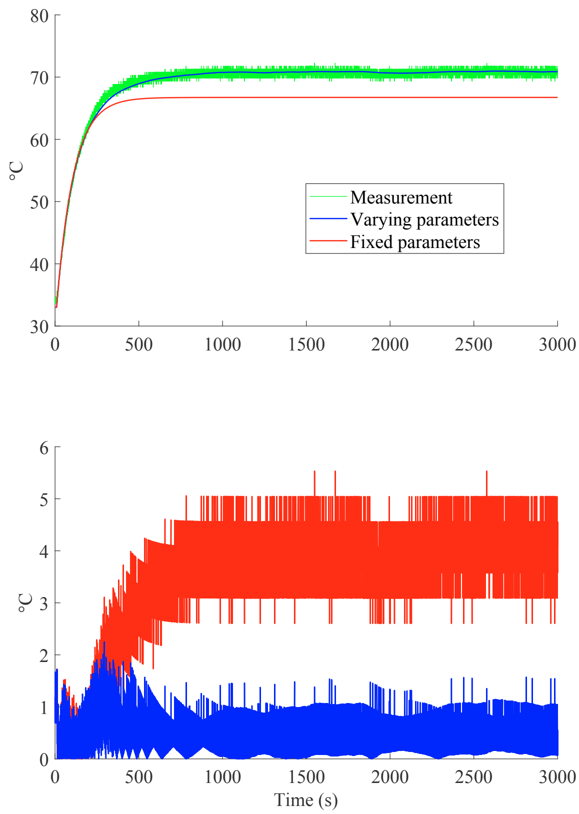

Fig. 13. The model with sn online parameter update provides better estimations.

has its parameters set to fixed optimal values from Table 1. For each model, we compare its output to the measured temperature from the actual device. As shown in Figure 13, the model that receives parameter updates from an EKF does provide better estimation to the actual power resistor's temperature (top figure). The model with fixed parameter gives a maximum estimation error of about five degrees centigrade. As for the model with adaptive parameters, the maximum estimation error is smaller, which is about two degrees centigrade (bottom figure).

6. CONCLUSION AND FUTURE WORK

This paper has performed modeling of a thermal system and implemented an EKF to estimate its state and model parameters. Using an EKF for parameter estimation allows us to improve the modeling performance. An accurate model is often necessary for control applications, especially model-based controls. However, this method might only be applicable for a process system with low noise sensor readings and a sufficiently good initial model and parameter guesses. Such limitations are caused by the nature of the model we selected, where the implemented EKF can pick many local optimal values. Finding a more robust function template becomes another topic that needs more in-depth studies.

On the other hand, the model that we deployed can be considered as simple. It is a zero-order energy balance model with two input variables, one state variable, and one output variable. However, there are five model parameters for the implemented EKF to estimate, which causes the solutions to the model parameters to become mathematically non-unique. In a more complex system, such as in a higher-order energy balance model, in which there are more state and output variables, the improvement offered by the implemented EKF to the modeling is expected to be higher since the system has fewer local optimum solutions. Thus, in the future, we plan to implement this method into a more complex system.

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