

Bang-bang temperature controller for a custom-made SMD reflow oven

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Abstract. This paper present the preliminary results regarding the application of a simple bang-bang control strategy to a custom-made SMD reflow oven. This appliance was built by retrofitting a recycled electric oven where both measurement and actuation chains are included. It will be shown that set-point tracking cannot be attained accurately and that severe temperature oscillations are observed.

Keywords: Bang-bang controller, reflow oven, SMD soldering

1 Introduction

The use of surface-mounted devices (SMD) in printed circuit boards (PCB) is not only required for companies that target mass-production appliances. Indeed, at the present, the use of those types of electronic components must be equated even at the prototyping level. This is true since many companies are offering only integrated circuits, or electronic components in general, arranged in SMD packages. However, the soldering process of SMD components is more complex than that of common through-hole devices. This is due to the fact that a simple soldering iron is generally not suited to solder SMD. Especially if they are lead-free. For soldering SMD components, usually, a reflow oven is required. This type of equipment is usually expensive since they are not mass-production appliances. For this reason, this paper addresses the retrofitting of an off-the-shelf electric oven and repurposes it to become an SMD reflow equipment.

Due to the fact that the soldering process requires a particular temperature profile, the oven must include a controller capable of following this temperature reference signal with minimum deviation [?]. There is a myriad of possible control strategies that can be employed to carry out this task. Proportional, integral and derivative (PID) control is a very popular methodology but, in this paper, an even simpler method will be evaluated on its ability to provide good set-point tracking. In particular, this work provides experimental results regarding the use of a simple bang-bang controller.

After this introduction, Section ?? will describe the overall mechatronic setup associated with the construction of the reflow oven. Section ?? will be devoted to analysing the open-loop step response and Section ?? will present the set-point accuracy results regarding the set-point tracking ability of a bang-bang controller. In the final section, the main conclusions are highlighted followed by future work directions.

2 The mechatronic structure of the reflow oven

The temperature profile of a typical industrial reflow electric oven is divided into different types; one is composed of different phases of heating (ramp-soak-spike) and the other is a ramp from the starting temperature until the peak temperature (ramp-to-peak)[?]. In order to follow such a temperature profile, closed-loop control must be implemented. In this context, the goal of the current work is to design and implement a temperature controller able to track the required temperature for soldering SMD components into PCBs.

Usually, the reflow process of SMD components requires temperatures that can reach 250 C. Those temperatures are within the grasp of common domestic appliances and, for this reason, a common electric oven was retrofitted with suitable actuators and sensors. Figure ?? show the overall aspect of the solution under development. The left-hand side of this figure shows an additional heating element added at the top of the grill where the PCB will stand. Moreover, the same figure also shows a bracket built to hold the temperature sensor. The right-hand image illustrates both the electronic actuation and instrumentation chains.



Fig. 1. Commercial electric oven.

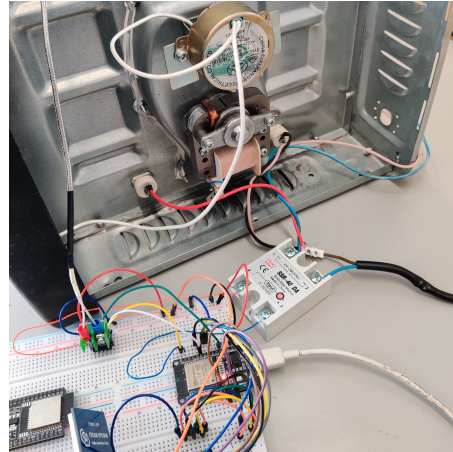


Fig. 2. Oven internal view.

The temperature inside the oven is measured via a K-type thermocouple [?] and its signal conditioning was handled by a MAX6675 integrated circuit that performs cold junction compensation and A/D conversion.

The power delivered to the heating elements is commanded by a 40A solid state relay excited by a pulse-width modulated control signal. This signal is provided by an ESP-WROOM-32 development board according to the control algorithm that runs inside.

The user can interact with the reflow oven through a graphical user interface displayed on a 1.8 inch TFT screen. The user can navigate among the provided menu by means of a rotary encoder.

3 The open-loop step response

In this section, the dynamic response of the oven to a step input signal will be evaluated. The signal was applied to the solid-state relay and the temperature delivered by the thermocouple was recorded with a sampling period of 200 ms. The obtained result is presented in Figure ??.

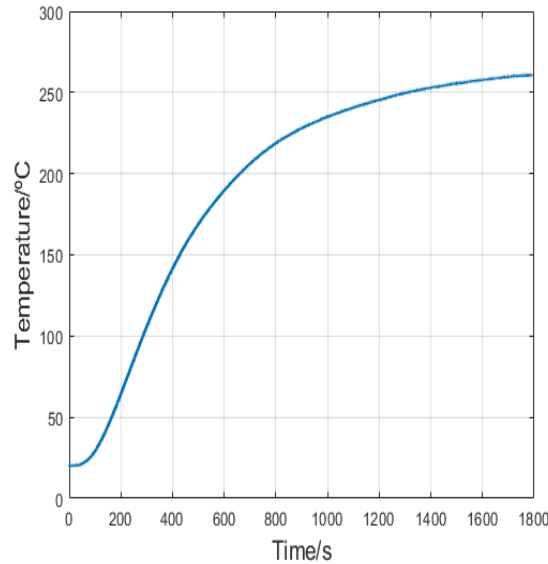


Fig. 3. Open-loop dynamic response of the reflow oven to a step input signal.

The analysis of this response suggests that the system dynamics can be approximated to a first-order transfer function with a pure time-delay with the

form [?]:

$$H(s) = K \frac{e^{(-s\tau)}}{(as + 1)} \quad (1)$$

where k denotes the system DC gain, τ the dead-time and a the time-constant.

The numeric values of each one of those three coefficients were obtained through a heuristic approach that started with a rough estimate of those variables from the step response and was empirically fine-tuned by trial and error. The obtained values that best fit the model to the measured data were found to be $K = 246$, $\tau = 108$ and $a = 433$. A comparison between the measured data and the simulated step-response using the above model is presented in Figure ??).

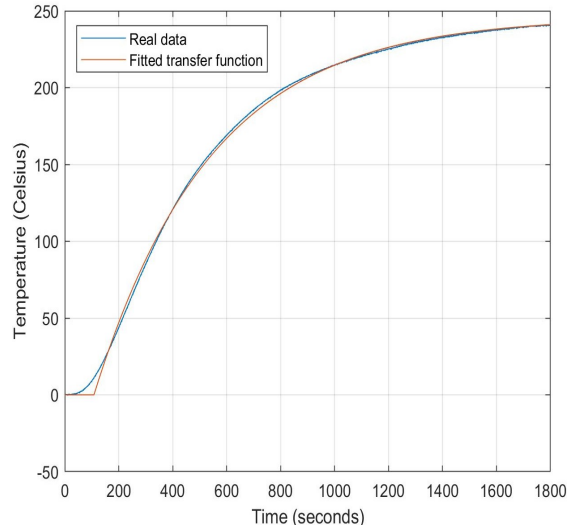


Fig. 4. Accuracy of the first-order model obtained by an iterative procedure.

As can be seen, the overall dynamics are acceptably captured by the simple first-order model. However, the initial dynamics suggest that a higher-order model could be more suitable to fully explain the system’s transient behaviour.

4 Bang-bang controller and set-point accuracy

As initially stated, the aim of this paper is to evaluate the suitability of a simple bang-bang controller to provide enough closed-loop set-point accuracy to be successfully used as the control strategy of the reflow oven.

In the control theory context, a bangbang controller describes a closed-loop feedback strategy where the control signal switches between two discrete states [?]. Usually, hysteresis is added in order to prevent stressing the actuators.

In the present context, a digital version of the bang-bang controller was implemented in the microcontroller. In short, the behaviour of this controller can be summarised as follows: if the measured temperature goes below a given region defined around the set-point, the power to the heating elements is delivered. On the other hand, if the measured temperature exceeds the upper bound of the defined region, the power is cut-off. In the current application, a ± 2.5 C hysteresis band around the set-point is considered. Moreover, three different trials, with different set-point amplitudes, have been performed: one at the low temperature of 40 C, the other at 80 C and a final trial at 180 C.

Regarding the former, Figure ?? show the closed-loop step response to a 40 C. As can be seen, the oven reaches a maximum temperature of 72 C and in the steady-state phase, the temperature fluctuates between 38 C and 63 C.

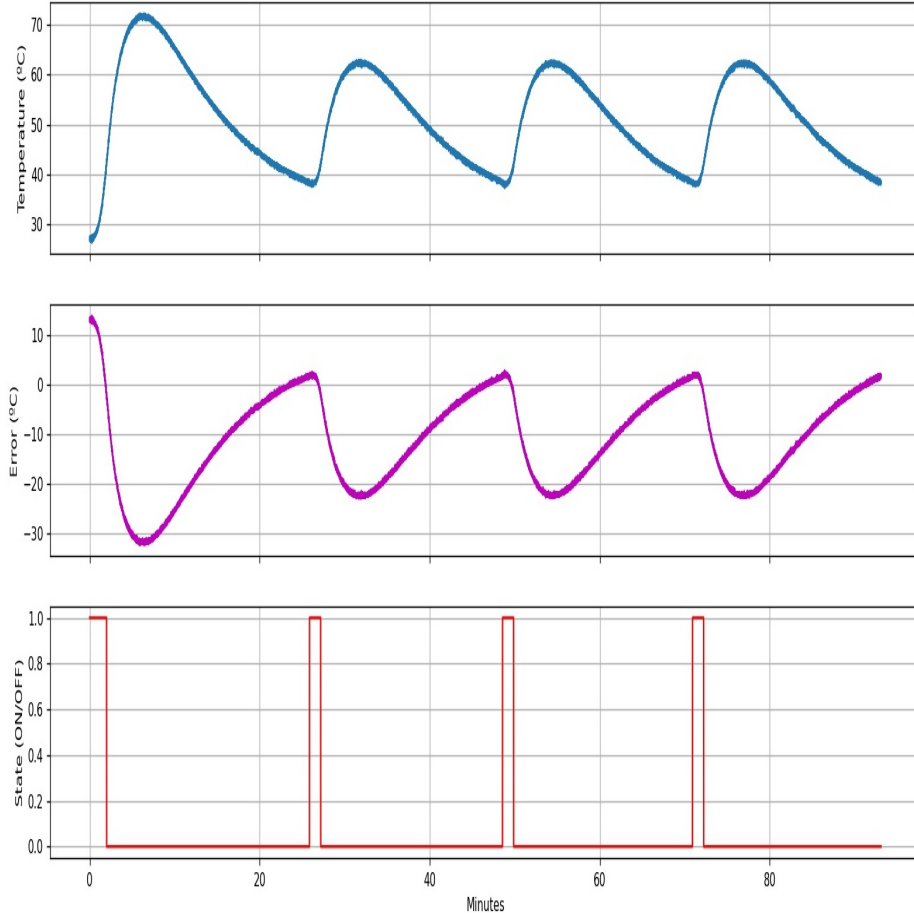


Fig. 5. Transient and steady state response at 40 C.

Figure ?? illustrate the result obtained for a 80 C step input. In this case, the system reaches a maximum temperature of 109 C and, when in steady-state, oscillates between 74 C and 101 C.

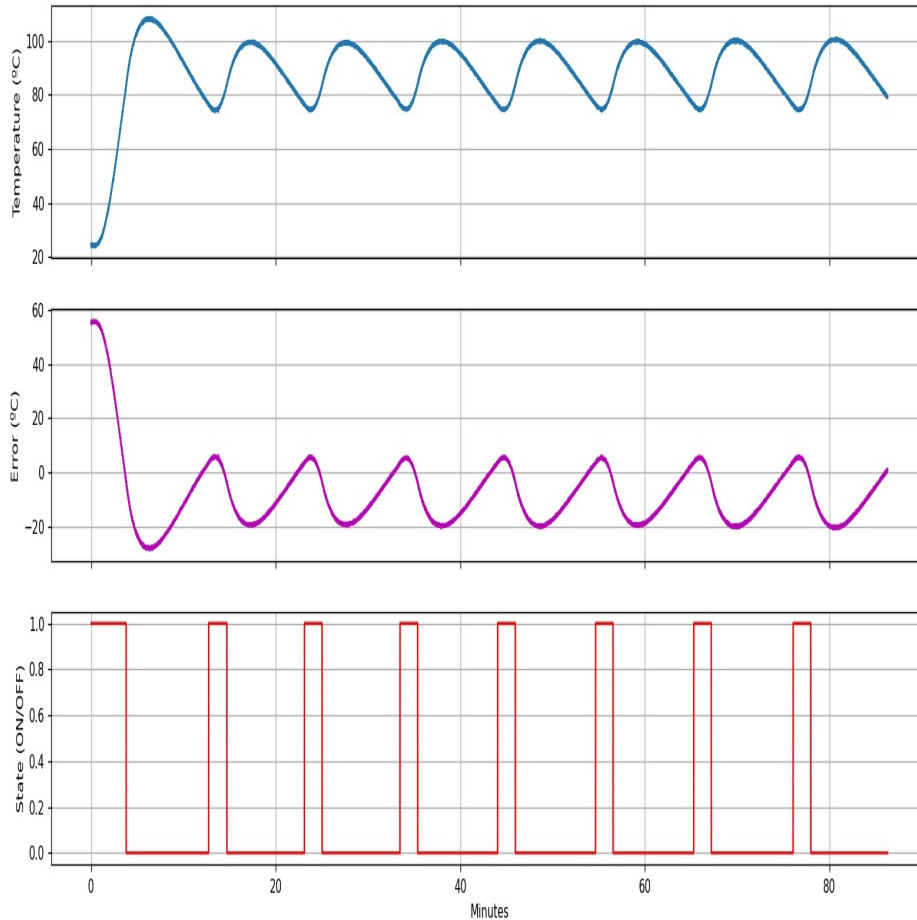


Fig. 6. Transient and steady state response at 80 C.

The last trial regards a set-point of 180 C. The results are presented in Figure ?? and measurements show that the maximum temperature achieved by the system is near 189 C. During steady-state, temperature oscillates between a maximum of 187 C and a minimum of 172 C.

As can be seen, the relative ripple due to the switching behaviour of the bang-bang controller diminishes with the increase of the set-point amplitude. For the trials that involve the lower temperature set-point, a ripple of 25 C leads to a relative value of 62.5%. Applying the same idea to the other two trials lead

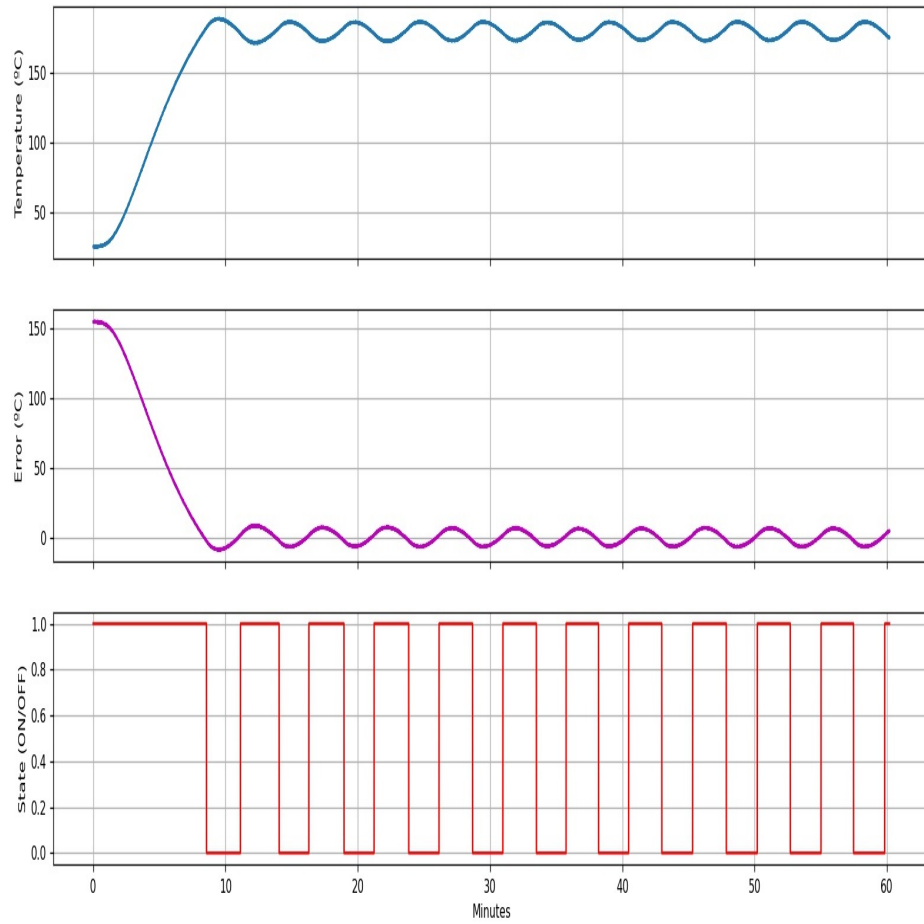


Fig. 7. Transient and steady state response at 180 C.

to a value of 33.8% for the case where the set-point has an amplitude of 80 C and just 8.3% for the higher temperature situation. Those results suggest that a bang-bang controller does not possess enough set-point accuracy to be used as the control strategy for the reflow oven. For this reason, other approaches must be explored such as the use of PID control.

5 Conclusion and further work

Being able to solder SMD devices into printed circuit boards requires the use of reflow ovens which can be expensive. For this reason, this paper deals with the preliminary results of retrofitting an off-the-shelf electric oven into an SMD reflow oven. Besides the economic motivation, the process of repurposing any machine is always an excellent way to apply many of the concepts taught during engineering courses.

Along with this paper, results regarding the open-loop step response were presented. It was shown that a simple first-order plus dead time transfer function can be used to capture the overall system dynamics.

Experiments with a feedback controller based on a bang-bang strategy were carried out. The obtained results point-out large ripple and poor set-point tracking for lower temperatures. Moreover, and even for higher temperatures, zero steady-state error is impossible to achieve using this method.

For this reason, more complex control systems must be implemented and evaluated regarding their set-point tracking performance. PID control is a good candidate and will be the next strategy to be evaluated. The design of PID controllers is more challenging and frequently relies on the system model to compute its gains. For this reason, obtaining a more accurate model for the reflow oven will also be investigated. In particular, using system identification techniques based on empirical data obtained from the system response. Optimisation algorithms, such as genetic algorithms, will be employed to derive the best parameters and structure for the model.