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PCB temperature controller for automated soldering

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***Abstract*— This paper presents the design and layout of a PCB that implements a closed-loop temperature control system for automated soldering. The PID control algorithm can adjust the power delivered to a heating element represented by a meander copper track embedded in the PCB using feedback from a thermocouple. This enables the system to follow the thermal profile of the solder paste, ensuring optimal results with no soldering skills required from the user. The end product resembles a commercial hot-plate but is also equipped with a connector for PCBs with a segmented copper plane on layer 2 as a heating element, creating self-soldering PCBs.**

***Keywords*— PCB, soldering, PID temperature control**

I. Introduction

Advancements in technology have led to increasingly compact Surface-Mount Device (SMD) packages, including Ball Grid Array (BGA), with a growing number of pins. This poses challenges for manual soldering [1], especially for hobbyists and amateur PCB designers who may lack access to expensive assembly equipment utilized in professional factories, such as reflow ovens and wave soldering machines.

While soldering irons and heat guns remain viable options for many applications, they demand a high level of skill, particularly when dealing with fine-pitch components and small packages like 0201. Recognizing this gap, this paper aims to document the development of an embedded system designed to deliver consistent and replicable soldering results without requiring extensive soldering expertise from the user.

The paper's structure is outlined as follows: Section II explains the working principles, Section III presents the schematic and component selection, Section IV details the PCB layout, Section V illustrates the software design and Section VI displays the experimental results.

II. Working Principles

The core working principle of the proposed PCB temperature controller lies in its closed-loop temperature control system. This system ensures precise regulation of the heating area temperature, crucial for achieving optimal soldering results. The copper meander track embedded within the PCB serves as the primary heating element, controlled by a MOSFET-driven circuit.

The temperature control algorithm continuously monitors the temperature of the hot-plate using feedback from integrated sensors. By comparing the measured temperature with a predefined setpoint, the Proportional-Integral-Derivative (PID) controller [2] adjusts the power supplied to the heating element to maintain the desired temperature. This closed-loop control mechanism ensures consistent and stable thermal performance.

Moreover, the inclusion of a connector for external boards enhances the versatility of the system. Daughter PCBs containing a segmented copper plane as a heating element on an inner layer can be easily attached and soldered by the mother PCB. A user interface composed of 2 buttons and a display lets the user select the maximum temperature and which MOSFET to drive. The system's blocks are represented in Fig. 1.

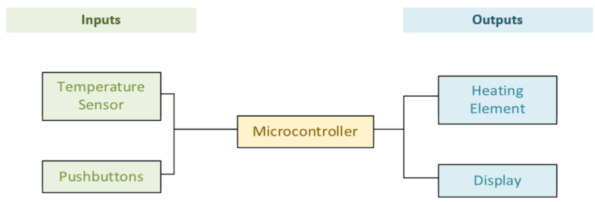

Fig. 1. Block diagram of the system

III. Schematic and Component Selection

Fig. 2 details the schematic design and component selection, focusing on the integration of critical elements within the temperature control circuitry. The schematic encompasses various components, including the MOSFET drivers, a thermocouple interfaced with an integrated circuit (IC), a microcontroller unit (MCU) with an In-Circuit-Serial-Programming (ICSP) header, essential power supply components, and a display with 2 pushbuttons.

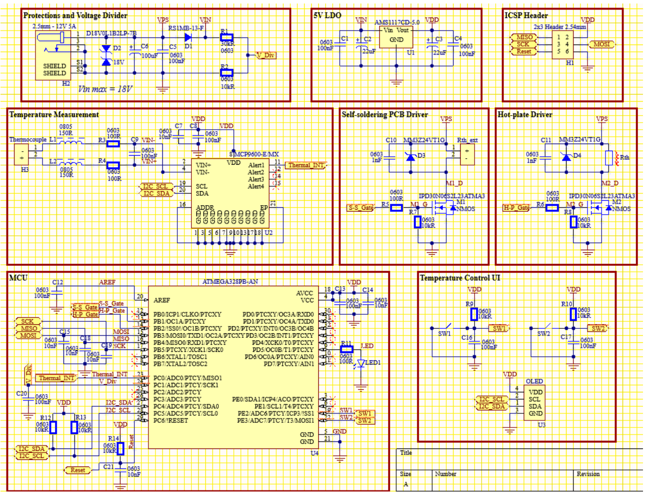

Fig. 2. Circuit schematic

Particular emphasis is placed on the selection of the temperature sensor, ensuring a wide range, high accuracy and rapid response times to facilitate precise temperature measurement and control. The MCP9600 IC serves to condition the thermocouple signal and convert it to a digital format after cold-junction compensation, amplification and filtering, enabling easy communication with the MCU via the Inter-Integrated Circuit (I2C) protocol.

Additionally, the MOSFET driver is carefully chosen for its capability to efficiently regulate the power supplied to the heating element. This ensures swift temperature adjustments while maintaining stability during operation.

Furthermore, the heating element is equipped with protective components such as a Zener diode and a small capacitor placed in parallel. These components serve to mitigate voltage spikes that may occur during MOSFET switching, ensuring the longevity of the heating element and overall system integrity.

The power supply circuitry is designed with robust features, including bypass and decoupling capacitors, electrostatic discharge (ESD) protection, and reverse polarity protection. These measures safeguard the system against potential voltage fluctuations and ensure the voltage regulator works within the recommended operating intervals.

IV. PCB LAYOUT

The PCB layout is crucial in ensuring both the functionality and reliability of the temperature control system. This section uncovers techniques used in optimizing trace routing, component placement, and thermal management to achieve optimal performance. Fig. 3 illustrates the component placement and top layer routing.

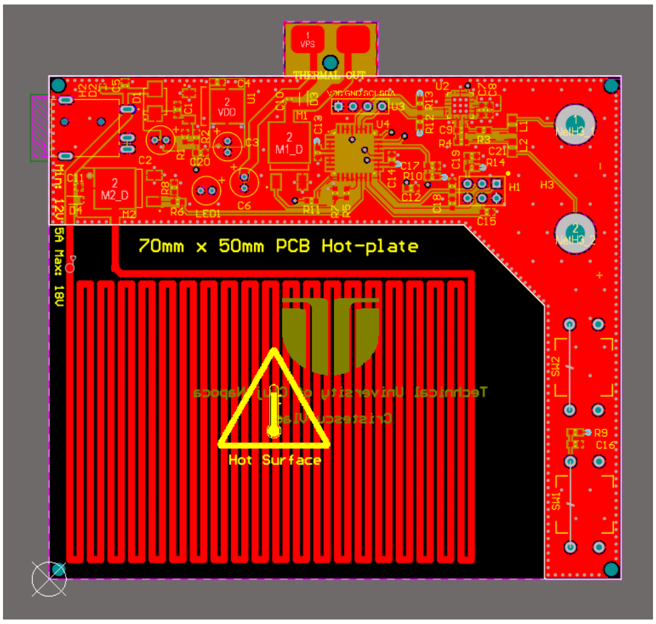

Fig. 3. Mother PCB layout

Special attention is dedicated to minimizing signal interference, establishing proper grounding techniques, and optimizing the layout for efficient heat dissipation. Notably, shielding techniques, along with stitching vias [3], are employed strategically to mitigate the heating element's antenna reception, minimizing electromagnetic interference (EMI) and ensuring signal integrity across the board.

All copper planes are intentionally isolated from the heating element to prevent unwanted heat transfer to adjacent components. Additionally, the top layer, designated as a signal layer, is poured with a ground plane to facilitate cold-junction compensation for the thermocouple IC, enhancing temperature measurement accuracy.

The resulting PCB layout culminates in a 100mm x 100mm 4-layer board with a 70mm x 50mm heating area as shown in Fig. 3. The heating element is a 1.4mm single ounce track over a length of 2000mm, laid out with 0.4mm spacing between lines. Based on these physical dimensions and knowing the resistivity (ρ) of copper is $1.72 \cdot 10^{-8} \Omega \cdot m$, the cold resistance (R) is computed in (1).

$$R = \frac{\rho \cdot l}{S} = \frac{1.72 \cdot 10^{-8} \Omega \cdot m \cdot 2m}{1.4mm \cdot 35\mu m} = 0.7\Omega \tag{1}$$

$$V = S \cdot l = 1.4\text{mm} \cdot 35\mu\text{m} \cdot 2000\text{mm} = 98\ mm^3 \tag{2}$$

The total volume of the heating element (V) can be used to calculate the mass (m), knowing the density of copper (ρ) is 8.96 g/cm^3 or mg/mm^3, which can then be used to calculate the heat capacity (C), knowing the specific heat capacity of copper (c) is 0.385 J/g·°C.

$$m = V \cdot \rho = 98\ mm^3 \cdot 8.96\ \text{mg}/mm^3 = 0.878\text{g} \tag{3}$$

$$C = m \cdot c = 0.878\text{g} \cdot 0.385\ \text{J/g}\cdot°\text{C} = 0.338\ \text{J/°C} \tag{4}$$

Now that it is known how much energy (C) it requires to heat the element by 1°C, energy (E) and power (P) requirements can be calculated. Let's assume a 100°C temperature increase.

$$E = C \cdot \Delta T = 0.338\ \text{J/°C} \cdot 100\ °\text{C} = 33.8\text{J} \tag{5}$$

$$P = R \cdot I^2 = 0.7\ \Omega \cdot 5^2\ \text{A} = 17.5\ \text{W} \tag{6}$$

$$t = \frac{E}{P} = \frac{33.8J}{17.5W} = 1.93\ \text{sec} \tag{7}$$

Equations (1)-(7) show that, in theory, the heating area is able to increase its temperature by 100°C in 1.93 seconds using a 12V 5A power supply. In practice, heat loss to the environment and other factors will affect this value.

Daughter PCBs can be connected to the exposed pads at the top of the board using a screw and a nut. These pads are connected as shown in the "Self-Soldering PCB Driver" section in Fig. 2. This design allows boards of bigger dimensions and irregular shapes to be soldered, as illustrated in Fig. 4. It also enables double-sided assembly with the use of component adhesive.

These boards can take advantage of all the existing circuitry and software on the mother PCB, so daughter PCBs are only required to implement a heating element on the second layer which runs under all SMD pads and a "thermal in" connector that is compatible with the "thermal out" connector on the mother PCB, as can be seen in Fig 4.

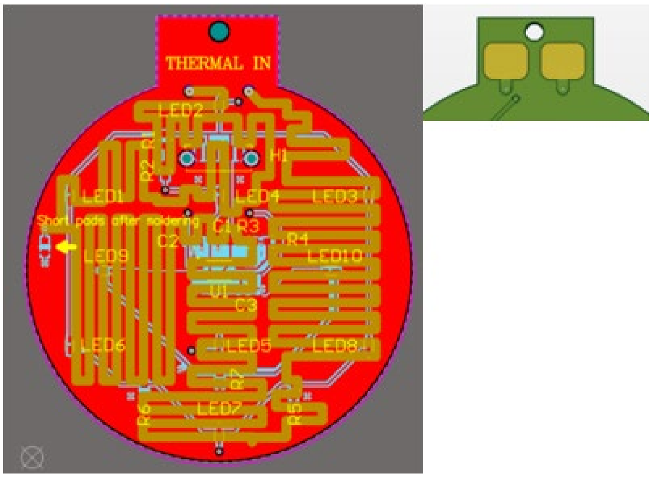

Fig. 4. Daughter PCB layout example and connector

V. Software Design

This section details the firmware that interfaces all the hardware components, as well as the software used to implement the control algorithm and manage interactions with the user. Upon power up, the system initializes all the necessary components and parameters and then enters the main menu, as shown in Fig.5.

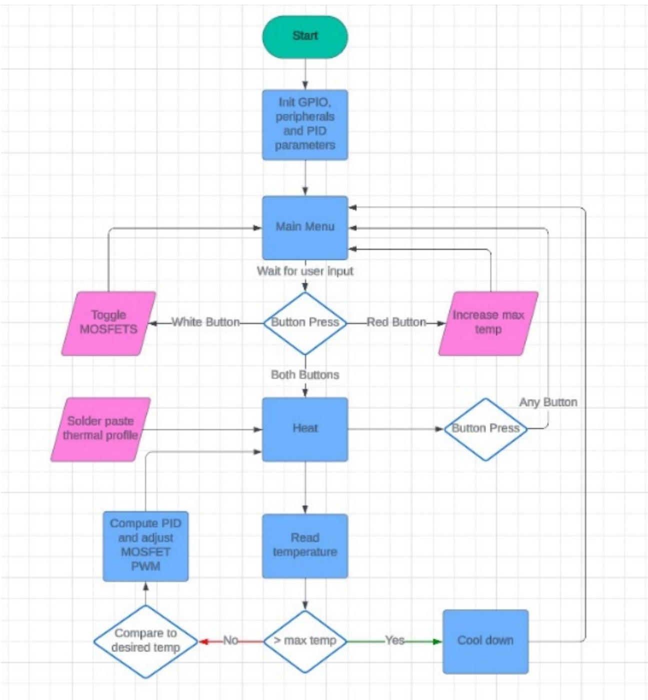

Fig. 5. Software flowchart

In the main menu state, the system simply waits for user input. By pressing the top (red) button, the user can toggle between an array of maximum temperatures. The available values are preprogrammed and range from 140°C to 180°C with 10°C resolution. The bottom (white) button toggles between the 2 MOSFETs. Every time one of the buttons is pressed the new values are updated in the memory. The soldering process starts when both buttons are pressed simultaneously.

The soldering state is a continuous loop where on every iteration the MCU reads the elapsed time since the heating started, checks the thermocouple reading and subtracts it from the desired temperature in that moment, which varies according to the thermal profile of the solder paste, detailed in Fig. 6.

Recommended process parameters

Temperature rise speed	The time taken to get to 110 ℃	Constant temperature of 110 – 138 ℃	Peak temperature	> 138℃	Cooling speed
1-3 ℃/sec	< 60-90 sec	60-100 sec	175±5 ℃	< 30-60 sec	< 4 ℃/sec

Fig. 6. Sn42Bi58 recommended temperature profile

Then it applies a correction to this error variable based on proportional, integral and derivative terms and computes a process control variable, the Pulse Width Modulation (PWM) signal for the MOSFET.

The heating process can be stopped at any time by the user by pressing any of the 2 pushbuttons, or it will stop automatically if the thermocouple reading exceeds the maximum temperature set by the user in the beginning by a predefined value. These are safety measures in case the system performs unexpectedly for any reason. During normal operation, the system automatically goes to the main menu when the last setpoint of the PID controller is reached.

VI. Experimental Results

This section seeks to evaluate the board's electrical and thermal performance, as well as its soldering capabilities.

The first step is to test the heating element and check the power requirements. After setting the current limit on the power supply to 5A and turning the MOSFET fully on (100% duty cycle), the supply voltage is represented in Fig. 7.

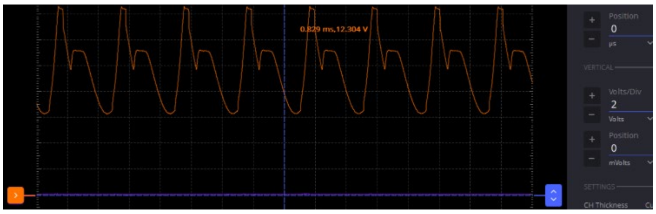

Fig. 7. Supply voltage for 100% duty cycle PWM with 5A limit

The voltage drops from 12V to as low as 6V, this means that a 5A power supply does not suffice to turn the transistor fully on. Since the PCB is not allowed to increase its temperature with more than 3°C/sec to respect the thermal profile, it is actually not necessary to ever apply a PWM with 100% duty cycle as this leads to a too sudden increase in temperature. A compromise is required to find a solution: increase the current limit and clamp the duty cycle in software to prevent overshooting, the result of which is represented in Fig. 8.

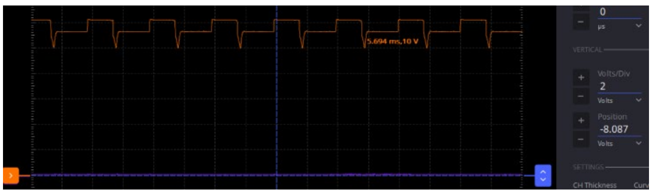

Fig. 8. Supply voltage for 60% duty cycle PWM with 8A limit

If the current limit is increased to 8A and the PWM signal is clamped between 0-60%, the supply voltage only drops to

10V, which is more acceptable. Even with this limitation, the heating area is capable of exceeding 100°C in less than 30 seconds.

After successfully fine-tuning each PID constant individually, the system presents an adequate response to a fixed setpoint, shown in Fig. 9.

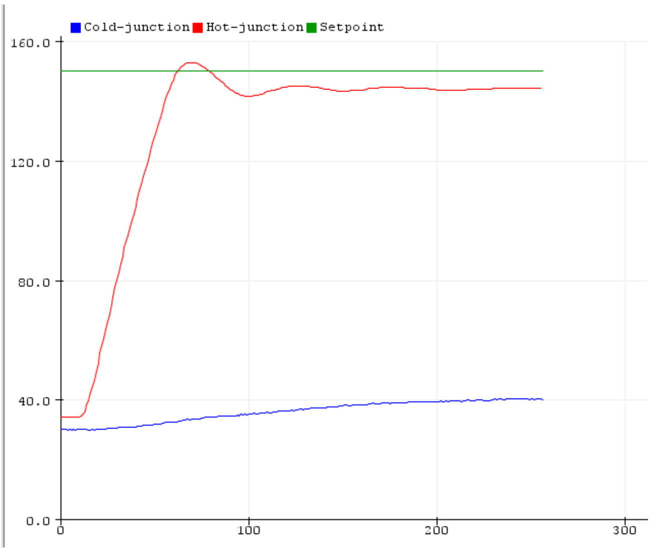

Fig. 9. PID fixed setpoint response

Even though there is still a small steady-state error present, it will not represent a problem for the system during normal operation due to thermal inertia, as proven in Fig 11.

The temperature of the cold junction is also displayed to check the effectiveness of the thermal management techniques implemented in the layout. Even after almost 5 minutes in which the hot junction is submitted to 150°C, the cold junction barely reaches 40°C.

This is also illustrated in Fig. 10, which is an image captured during operation using an infrared (IR) thermovision camera. This also shows there are no hotspots, i.e., the heat is distributed evenly and contained to the heating area.

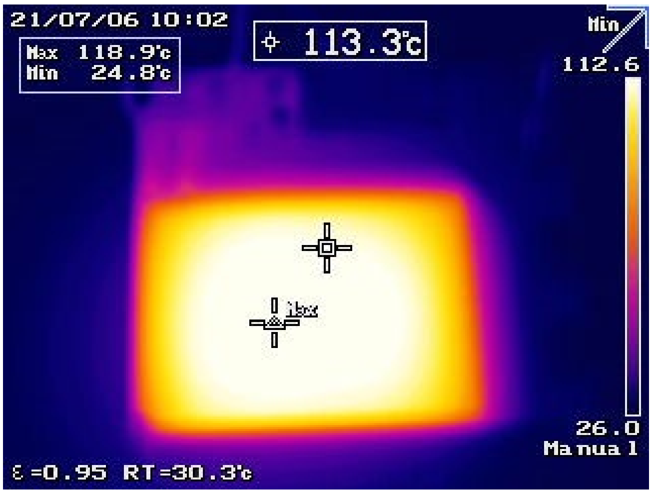

Fig. 10. IR image

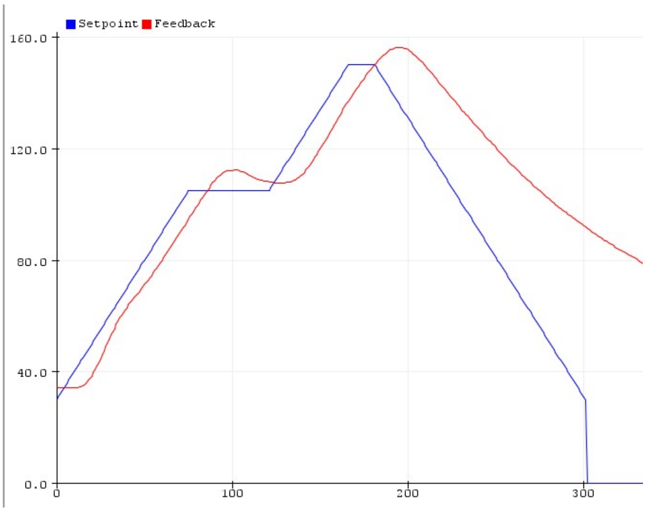

Fig. 11. PID variable setpoint response

After defining in software the reflow curve described in Fig. 6, which will guarantee optimal and replicable soldering results, it is now clear that the system can successfully follow it and respect the thermal profile of the solder paste. A small delay is noticeable, along with the fact that the feedback can not follow the setpoint during the cooling off. Both of these are not actual problems for the system since a delay will not affect the quality of the process and the cooling gradient's only requirement is to not exceed 4°C/sec. The board is not able to drop more than 1-2°C/sec, which is well within the accepted interval.

VII. CONCLUSIONS

The PCB Temperature Controller for Automated Soldering offers a practical solution to the challenges faced by hobbyists and amateur PCB designers in achieving consistent soldering results with SMDs. By integrating a closed-loop temperature control system and user-friendly interface, this embedded system provides accessible and reliable soldering capabilities, excellent for prototyping PCBs.

With its MOSFET-driven heating element, thermocouple and PID controller, the system ensures precise temperature regulation for optimal soldering conditions. The inclusion of a connector for external boards enhances versatility, enabling easy expansion and customization.

While the heating element can reach temperatures of more than 200°C with a 100W power supply, it is advisable to operate at lower temperatures and utilize low melting point solder paste. This approach helps extend the lifespan of components and avoids reaching the glass transition temperature of the PCB.

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