Design of 6 ½ digit multimeter

Martin Petrek¹

¹Department of Electrical and Electronic Technology, Brno University of Technology, Czech Republic

E-mail: martin.petrek@vutbr.cz

Abstract—Paper summarizes individual parts of DMM (digital multimeter) and how they work. Design approach in comparison to commercial solution is in the thermal stabilization of the whole analog assembly. DMM has 8 custom designed PCBs (printed circuit board): Processor PCB, Keyboard and input backlit PCB, Analog PCB, Voltage reference PCB, Thermostat PCB, AC/DC PCB and LDO (Low dropout voltage regulator) PCB. User interface, program, thermal stabilization and mechanical construction are also described.

Keywords— 6 ½ digit multimeter, LTZ1000A, design, testing, bench multimeter, measuring device, ovenized multimeter, DMM, precise instrumentation

1. INTRODUCTION

In 2019 I decided to design and built a precise bench multimeter with thermal stabilization on budget, with parameters as in Table I: Projected parameters. After few design iterations and talks to experts I let out the budget limitation and continued designing. After a year of intermittent design, I started the process of gathering parts and finances to build the first prototype as you can see in the Figure 2: First prototype. In time of writing this paper, first prototype is built and now it is in process of programming and solving all problems which every first prototype has.

2. COMPONENTS AND PCB’S

Multimeter can be divided into block diagram showed in the Figure 1: Block diagram

User interface: Measured values are displayed on 3.5” Nextion touch screen [7]. It uses own 48 MHz microcontroller and data are transferred to it via serial bus at speed of 115200 baud. Display is programmed in its own language. For most used actions, such as change of measuring function or START/STOP of acquisition, there is membrane keyboard with custom backlit. Banana input is also backlit for visual representation of used input terminals.

Program: Microcontroller of DMM, two-core 32bit 240 MHz ESP32 is programmed in C/C++. First core is used for programming ADC (analog to digital converter) digital filter, starting conversions and reading its result. Result is in a format of 32-bit binary number which is converted to decimal number. Slope and offset are added according to measured function and range. Acquisition frequency can be determined either by NPLC (number of power line cycles) or Sa/s (Samples per second). When NPLC is higher or equal to one, then ADC will start new conversion on every rising and falling edge of mains sinus. After desired number of NPLC the results are averaged and displayed. There is also filtering which happens inside of ADC which can’t be explained due to size restrictions of this paper. Second core handle practically everything else: preparing and sending data to Nextion display as well as reading data from Nextion display, reading keyboard state, power button state, controlling input and keyboard backlight, changing ranges and controlling circuitry of Analog PCB. DMM can be also controlled through SCPI commands which are processed with second core. For now, it accepts commands via USB, but ESP32 has built in Wi-Fi and Bluetooth.

Thermal stabilization: Change in temperature can affect the parameters of all components. To fight this, DMM not only use stable resistors with very low thermal coefficient, but it also has ovenized analog PCB with reference PCB. This is done with fully analog thermostat regulator [1] with small processor cooler inside of thermally isolated 3D printed box where analog and reference board are located. This mean that maximum temperature of multimeter will by determined by oven temperature subtracted with temperature raise caused by self-heating of components. Minimum temperature, on the other hand, will be determined by isolation effectivity of box and power of heater which is about 30 W. To measure the

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temperature and its stability inside of oven, there is platinum resistance thermistor and 24-bit ADC on Analog PCB.

**Mechanical construction:** Whole body is assembled with laser cut and CNC bent 1 mm thick stainless steel. This 4-segment body holds all PCBs and acts as most outer EMI shield. Front and back of the multimeter are finished with 3D printed PLA panels. In the middle section of the multimeter a 3D printed containment with very low infill, acting like thermal insulation for proper working of thermostat. This middle section is also isolated with stainless steel sheets for EMI shielding.

**PCBs:** The multimeter has total of 8 PCBs with 2 and 4 layers.

**Processor PCB:** 2-layer PCB. It is an important part of user interface which controls all backlit LEDs with three eight-channel serial to parallel convertors [8] and drivers. Keyboard and power button presses are monitored with parallel to serial converter. Microcontroller is socketed for easy change. Buzzer is used for sound notification.

**Keyboard and input backlit PCB:** 2-layer boards for custom backlit of keyboard keys and input banana plugs. Keys are backlit with red/green and white color LEDs depending on key usage. Input banana plugs are backlit with green LEDs only.

**Analog PCB:** 4-layer board. Board has four front ends for measuring voltage, voltage with high impedance, small currents (I <= 10 mA) and medium currents (I <= 1 A). Every front end has multiple protections in front and within it. First protections are high-energy fuses which are protecting against longer lasting overloads and are capable to safely disconnect multimeter from measured circuit. There is 440 mA fuse for small currents and all voltage measurement front ends and 3 A fuse for medium currents front end. MOV and gas discharge tube are also located in front of voltage measurement front ends. Schottky diodes, Zener diodes and TVS diodes are protecting sensitive component inside front ends. With combinations of front ends it is possible to measure: resistance in 2W or 4W mode, diode, continuity, temperature and capacitance. Signal from these front ends is switched with analog multiplexers, buffered, filtered and fed to 32-bit SAR Oversampling ADC LTC2500-32 [3] with configurable digital filter. In ADC is analog signal quantized to digital signal which is transmitted to MCU via optocoupler. Used ADC has fully differential inputs, but in effort to reduce noise, there is no circuitry to convert input signal to fully differential mode. Instead, negative input of ADC is connected to $V_{\text{REF}}/2$ and positive input of ADC is just buffered with op amp and is ranging from GND to $V_{\text{REF}}$. This lowers the resolution of ADC to 31-bits, which is still more than sufficient resolution for count of 1 000 000. Ranges are set with combination of analog multiplexers, relays and anti-serially connected P-Channel MOSFETs. All relays, MOSFETs and analog multiplexers are controlled though four eight-channels serial to parallel convertors. All digital signals are galvanically isolated from Processor PCB via two six-channel optocouplers.

**Voltage reference PCB:** 4-layer PCB with most stable, voltage reference on chip, which you can buy in quantity of one. LTZ1000A [2] is buried Zener diode with its own heater for lowering thermal coefficient to only 0.05 ppm/°C [2]. This is achieved by heating diode to stable temperature which do not change with ambient temperature. How stable the temperature will be is determined by resistors used in controlling circuitry. 0.02 ppm/°C foil resistor [6] and 8 ppm/°C resistor networks [5] are used in first prototype for setting temperature and current trough Zener diode and for lowering its output voltage from circa 7.2 V to 5 V.

**Thermostat PCB:** 4-layer PCB. Schematic from “Thermal compensation of the optical RF delay lines for SPS damper” [1] slightly modified by me. Used and modified with author's permission. Board is designed by me to fit inside the multimeter.

**AC/DC PCB:** 2-layer PCB. It takes mains AC 230 V and convert it to more manageable DC voltages. Transformer is used for processor board power supply because its sinus output is used for synchronizing a frequency of ADC conversions with mains to reduce noise. All AC/DC and DC/DC convertors are medical grade. Output from this PCB is 6 V 2 A AC, 3.3 V signal for mains frequency synchronization, +9 V 1670 mA DC, ±15 V 200 mA DC and +5 V 6 A DC with -5 V 200 mA DC for Thermostat PCB.

**LDO PCB:** 4-layer PCB. It uses Ultralow Noise, Ultrahigh PSRR Linear Regulators [4] to filter a voltage from AC/DC, DC/DC convertors and transformer. Output from this PCB is +5 V 1.5 A DC for Processor PCB and +0.5 V 10 mA DC, + 2.5 V 200 mA DC, +4.5 V 10 mA, +5 V 400 mA DC, +5V 1 A DC, 2x +14 V 200 mA DC, -5 V 200 mA DC, -14 V 200 mA DC for Analog board.
3. FIGURES AND TABLES

![Block diagram of the system](image1.png)

**Figure 1:** Block diagram

![First prototype of the system](image2.png)

**Figure 2:** First prototype
Table I: Projected parameters

<table>
<thead>
<tr>
<th>Count</th>
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<tbody>
<tr>
<td>Best accuracy</td>
<td>10 ppm</td>
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</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Range</th>
<th>Best resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Voltage</td>
<td>10 mV – 1 kV</td>
<td>10 nV</td>
</tr>
<tr>
<td>AC Voltage</td>
<td>10 mV_{pp} – 1 kV_{pp}</td>
<td>10 nV_{RMS}</td>
</tr>
<tr>
<td>DC Current</td>
<td>10 nA – 1A</td>
<td>10 fA</td>
</tr>
<tr>
<td>AC Current</td>
<td>10 nA_{pp} – 1 A_{pp}</td>
<td>10 fA_{RMS}</td>
</tr>
<tr>
<td>2W Resistance</td>
<td>1 Ω – 100 MΩ</td>
<td>1 μΩ</td>
</tr>
<tr>
<td>4W Resistance</td>
<td>1 Ω – 100 MΩ</td>
<td>1 μΩ</td>
</tr>
<tr>
<td>Diode</td>
<td>2 V, selectable current: 100 pA -10 mA</td>
<td>1 μV</td>
</tr>
<tr>
<td>Temperature</td>
<td>RTD – depends on type</td>
<td>100 μ°C</td>
</tr>
<tr>
<td>Continuity</td>
<td>Programable current</td>
<td>depends on frequency of ADC conversions</td>
</tr>
</tbody>
</table>

4. CONCLUSION

I’m only to see if I managed to complete all projected parameter with this first prototype. Right now, I’m in process of programming and multimeter works like it is designed. It was my most challenging and longest lasting project. My eventual goal is to make it my bachelor project, but for that I have more than a year.

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REFERENCES


