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Design and Instrumentation of an Arduino-Based Temperature Measurement and Control Device by K-type Thermocouples

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Abstract

This study focuses on designing an Arduino-based temperature measurement and control device operating with K-type thermocouples. Cold junction compensation (CJC) is essential in temperature measurement by thermocouples. In our work, two user-selectable circuits were designed to measure and control the contact temperature, namely, the first one using the conventional MAX6675 module and the second one using the INA114AP instrumentation amplifier. The MAX6675 part in our design involves the MAX6675 module, which is a conventional "thermocouple to digital converter" where CJC is achieved internally by fabrication. On the other hand, the INA114AP part in our design involves external CJC through our Arduino codes. Our experimental setup to determine the accuracy of temperature measurements involves the Keithley-2182A Nanovoltmeter and a heated-cooled water bath. The accuracy of our setup was initially determined statistically by comparing the results of temperature-voltage measurements in our setup by the K and E-type thermocouples by using their table values. Performance and accuracy of our design have been determined statistically by comparing the measurement results of our two modules with the results of the direct measurements by Keithley-2182A, which was taken as the most accurate measurement through the tables of K-type thermocouples within our initially determined setup accuracy. The accuracy results of our measurements show that the INA114AP part in our design surpasses various conventional instruments, such as the RuoShui 97 Digital Multimeter, Fluke 17B+ Digital Multimeter and even the fabricated MAX6675 module between 0°C and 100°C. Finally, we present how to use our Arduino-based two modules (where INA114-part being the most accurate) for controlling load (i.e., running in 230V-AC) as a high precision temperature control device between 0°C and 100°C.

Keywords: Arduino based temperature measurement and control, cold junction compensation, control by temperature, INA114 instrumentation amplifier, MAX6675 module, temperature measurement, thermocouples.

1. Introduction

Thermocouples produced by connecting two different metal sticks physically from one of the ends are conventionally used in a wide range of temperature measurements, i.e., from -200°C to 1372°C for K-type thermocouples, as low-cost active sensors which act as active type circuit elements generating a dc voltage. Since the specific heats and atomic band structures of the two different metals in contact (at the measurement point - also called *hot junctions*) differ from each other, a temperature-dependent electromotive force (emf) at the unconnected ends (output terminals - also called *cold junctions*) is produced via the *Seebeck effect* characteristically [1-5]. Their nature of being a cheap means of temperature sensing with almost linear temperature-voltage characteristics over certain temperature ranges makes them popular for both temperature measurement and control in practical applications. The main types of thermocouples made up of certain metal or alloy stick pairs (and hence having a characteristic temperature-voltage relationship depending on the materials used) are classified and

standardized as J, K, E, T, N, B, R, and S-type thermocouples where K-type among which is widely used [6-10]. In this work, we study K-type thermocouple to design an Arduino-based hand device instrumented to measure the temperature and then control the load (i.e, running in 230V-AC) by comparing the measured temperature value with the user-selected temperature range. Consequently, a desired load running under 230V-AC will be enabled to work within the user-defined temperature values accurately.

Although the measurement principle by thermocouples involving *"measuring the produced emf at the thermocouple's output terminals and calculating the temperature from the (almost linear) temperature-emf characteristics of that thermocouple"* sounds quite simple, some certain problems like nonlinearity, signal amplification versus noise reduction, cold junction compensation (CJC), etc. requires careful treatment in the instrumentational design [11-23]. The CJC problem arises from the fact that temperature at the thermocouple's output terminals (cold junctions), just similar to the contact point (or measurement point or hot junction), generates thermoelectric-based emf via the Seebeck effect through each individual metal, causing an extra voltage at the thermocouple terminals. This extra voltage drop must be removed or compensated by an accurate temperature measurement and this phenomenon is known as the CJC in the thermocouple terminology [9-15].

Keithley 2182A is a modern laboratory-type nanovoltmeter which involves thermocouple inputs for temperature measurements by various standard thermocouple types, enabling users to test their CJC designs. Since it enables two-channel measurement via using all types of conventional thermocouples and its instantaneous measurement ability is more proper than most of its precedents [24,25], we selected it as a reference measurement tool in our experiments. Besides certain advanced lab devices like Keithley, Lake Shore, Omron, etc., some hand-type cheaper devices like multimeters (such as RuoShui 97 and Fluke 17B+) can also be used to measure temperature via their K-type thermocouples [26,27]. Table 1 below shows that both the accuracy and resolution of Keithley 2182A for K-type thermocouple measurement surpasses the other devices mentioned above, which also explains why we choose it as the reference (the most accurate) measurement device in this work.

Moreover, thermocouple to digital converter modules like MAX6675 to enable Arduino-based applications are widely available in today's electronics markets [28,29], though there is a wide range of efforts to increase their accuracy (i.e., from using a second sensor to application of Kalman filter) a in [30-35]. In this work, we designed an Arduino-based "hand-type temperature measurement and control device" involving two user-selectable circuits

to measure temperature and control the load by using K-type thermocouples. Our first user-selectable circuit involves MAX6675 module where internal CJC is achieved by fabrication [28,29]. Our second circuit, on the other hand, involves INA114 precision instrumentation amplifier [36]. In this part we suggest an external CJC via a voltage divider circuit and the Arduino codes to study it.

Our setup involves Keithley-2182A Nanovoltmeter (for obtaining the most accurate temperature measurements) and *heat-up/cool-down* water bath to change the contact temperature, namely, the temperature of the water bath-air-thermocouple system just in a thermal contact. By changing the temperature of the water bath, it excites the thin air around it and then terminates on the thermocouple, making up our measurement setup. The accuracy of this setup was initially determined statistically from voltage measurements across both K and E types of thermocouples (to increase the data number of the measurement) via Keithley-2182A and using their characteristic table values. Once we determine the accuracy of our setup (involving water bath-air-thermocouple's hot point mechanism), then we determine the accuracy of the two mentioned commercial hand-type devices (RuoShui 97, Fluke 17B+) and the mentioned two Arduino-based circuits in our design, namely, MAX6675 and INA114 circuits, for both heating-up and cooling-down experiments between 0°C and 100°C by using the same setup. These determined accuracy values are obviously within the pre-determined accuracy of our set-up. We then present the circuit diagram and the algorithm used in our Arduino code to control the load running in 230V-AC supply as a practical application by using the accurately measured temperature values in the mentioned range via these two user-selectable designs.

Table 1. Manufacturer data of the temperature measurement devices used in this work.

Device	Temp. meas. range (°C)	Reso-lution (°C)	Accuracy
Keithley 2182A for K-type tc [24,25]	-200 to +1372	10^{-3}	± 0.2 °C
RuoShui97 [26]	-20 to 1000	10^{0}	$\pm(1.0\%+5)$ for t<400℃, $\pm(1.5\%+15)$ for t>400℃
Fluke 17B+ [27]	-55 to 400	10^{-1}	9% ± 2 °C for -55 °C <t< 0°C, ± 2 °C for 0 °C <t<50°C, 2% ± 1°C for 50°C<t<400°C

Normally, PID control circuits are used in such accurate measurement and control experiments [23, 37-39]. PID control consists of proportions (P), integral (I), and derivative (D) where u(t) input function is used in this control type. PID controllers are generally effective on both transient and steady state control criteria. Moreover, the relevant control parameter(s) can be reset and/or used

as a single PI or PD controller to maintain high accuracy. But in this work, we show that such a much cheaper hand-device can be instrumented by such a design in much modest and simpler laboratory conditions without using PID-controlled circuits or devices (such as in [39]) successfully with quite higher accuracy scores (in comparison to the commercially available precedents like RuoShui 97, Fluke 17B+, etc.) between 0°C and 100°C.

2. Materials and Methods

As mentioned above, we start with the determination of our experimental setup, whose general appearance is given in Figure 1. Also, a schematic sketch of the operation to determine the accuracy of our setup is given in Figure 2. Here, the first channel of Keithley 2182 measures the temperature of our water bath directly by selecting the correct thermocouple type used in its first channel (we used K-type here), whereas its second channel measures the produced emf in microvolts at the terminals of the second thermocouple.

Figure 1. A picture of our experimental setup

We performed it by using both K-type and E-type thermocouples as the second thermocouple (in Channel 2) to perform a wide range of measurements to determine the accuracy of the water-bath-based setup used. The setup involves a *"(water bath)-(thin air)-(thermocouple's hot point)"* mechanism in thermal contact. In each experiment, we obtained heat-up and cool-down curves by inputs of the materials (ice or hot water) through the neck of the water bath by stirring the mixture continuously, as shown in Figure 2.

After we determine the accuracy of our setup, we continue measurements to test the accuracy of the two conventional multimeter temperature measurements (RuoShui 97 and Fluke 17B+). Then we continued with our design which involves both MAX6675 and INA114 parts. The procedure is given in Figure 3 below schematically. In each experiment, since Keithley2182 is the most accurate lab device here (*See Table 1*), we take it as *the most accurate reference measurement* to compare with the other one under measurement. The measurement continues in pairs, namely, i-Keithley &

RuoShui, ii-Keithley & Fluke17B+, iii) Keithley & MAX6675-design, iv) Keithley & INA114-design, each time Keithley being one of the pairs (as the "reference" *or* "the most-accurate" measurement).

The measurement procedure of Keithley2182A is standard with the Keithley's probes as shown in Figure 2 and its accuracy calibration is guaranteed by Keithley Instruments with a signed certificate (fabricated calibration certificate) as shown in Table 1. Details of our design are given in the next section.
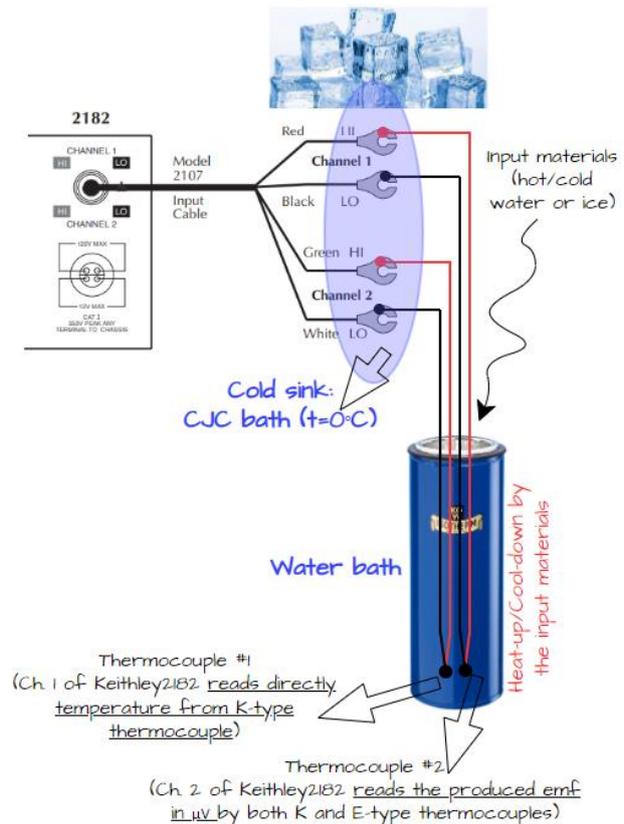

Figure 2. Determination of accuracy of our setup.

3. Our Design

An inner physical view of our design is given in Figure 4, and the circuit diagram of the MAX6675-part of our design, including the 230V-AC-load control, is given in Figure 5 below. Similarly, the circuit diagram of the INA114 part of our design, including the 230V-AC-load control, is given in Figure 6. Here, the MAX6675 part of our design involves its fabricated internal CJC inside MAX6675 as it was designed to achieve a digital temperature output [28-35]). As to the INA114 part, it involves the INA114 precision instrumentation amplifier. Here, we cope with the linearity problem (which also contributes to the CJC as explained below) by keeping the aimed measurement range smaller, namely, between 0°C to 100°C (in comparison to its full given measurement interval between -200°C and 1372°C). Consequently, an almost linear voltage-

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temperature relationship and hence quite constant CJC achievement can be applied. Moreover, by using the INA114 high precision instrumentation amplifier, we also aim to help solve problems associated with signal amplification versus noise reduction as the datasheet claims [36]. In both parts of our design, we use decoupling capacitors for noise reduction.

The gain of the INA114 instrumentation amplifier in Figure 6 is given by $G = 1 + 5000/R_G$ where R_G is the resistor between its $R_{G\,1}$ and $R_{G\,2}$ pins [36], which is 100Ω in our design. Consequently, the gain of our circuit is $G = 1 + 50000/100 = 501$, which means K-type thermo-couple voltage sent between pins V_{+IN} and V_{-IN} is amplified 501 times at the output pin V_o.

As to the CJC in our design, we used the following conventional linearized approximation for the K-type thermocouples [6,7]:

$$v_{tc}(t) = S(t) \times t \qquad (1)$$

$$v_{tc}(t) \approx v_{app.}(t) = S \times t, for\ t_1 \le t \le t_2 \quad (2)$$

where t is the temperature at the hot point (contact/hot point or measurement point) of the thermocouple in °C, S is the Seebeck coefficient of the K—type thermocouple in $\mu V/°C$ (or in $mV/°C$) and $v_{tc}(t)$ is the generated thermocouple voltage in μV (or in mV— depending on the choice of the unit of S) at the thermocouple terminals.

As the temperature range gets smaller, this coefficient becomes almost constant ($S(t) \approx S = const.$) and the approximation becomes more accurate. For the measurement range of this work (between 0°C and 100°C), we selected $S = 40.00\mu V/°C = 0.04mV/°C$, namely,

$$v_{app.}(t) = 40.00 \times t\ (\mu V),$$
$$for\ t_1 = 0°C \le t \le t_2 = 100°C \quad (3)$$

We note here that considering the whole measurement range, as it is given $S = 41.00\mu V/°C$ in [7], it can be chosen as an appropriate approximate value considering the experimental measurement range as in [10-18]. Actually, the voltage generated between the terminals of a K-type thermocouple for 0°C≤t≤1372 (alternative to eqn. (1)) is given in the following polynomial form [6, Pg.157]:

$$v_{tc}(t) = \sum_{k=0}^{8} c_k t^k + \alpha_0 e^{\alpha_1 (t-126.9686)^2}\ (\mu V) \quad (4)$$

where coefficients are as follows:

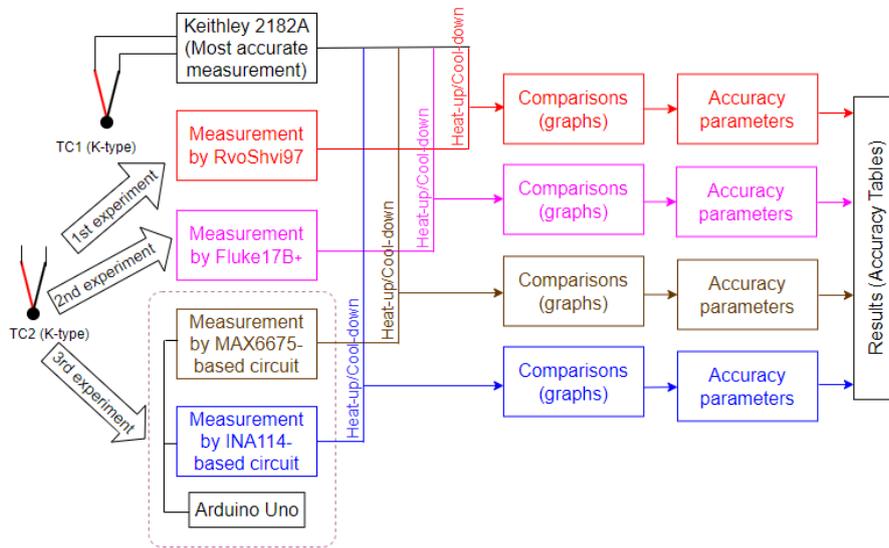|	
$c_0 = -1.7600413686 \times 10^1$	$c_1 = 3.8921204975 \times 10^1$
$c_2 = 1.8558770032 \times 10^{-2}$	$c_3 = -9.9457592874 \times 10^{-5}$
$c_4 = 3.1840945719 \times 10^{-7}$	$c_5 = -5.6072844889 \times 10^{-10}$
$c_6 = 5.6075059059 \times 10^{-13}$	$c_7 = -3.2020720003 \times 10^{-16}$
$c_8 = 9.7151147152 \times 10^{-20}$	$c_9 = -1.2104721275 \times 10^{-23}$
$\alpha_0 = 1.185976 \times 10^2$	$\alpha_1 = -1.183432 \times 10^{-4}$

Figure 3. A schematic sketch of our experimental procedure.

Eqn. (4) also shows the nonlinear relationship in (1) where the Seebeck coefficient S actually changes over temperature ($S \to S(t)$) [1,10]. Graphs of the generated voltage as a function of the hot point temperature (in other words, the measurement point temperature) for both the polynomial form in eqn. (4) and our approximated form in eqn. (3) along with the graph of

their difference (error graph), is given in Figure 7, which shows quite high accuracy in our approximation in the studied temperature interval.

Now the most essential point leading to the CJC concept is that this thermocouple voltage is valid *provided that the cold junctions (thermocouple terminals) are kept at*

0°C *[6,11-23]*, which is practically not possible in most of the measurement environment. We assume the temperature of the measurement environment (and hence the temperature at the thermocouple terminals) is equal to the conventional room temperature, namely, $t_{tc} = 25°C$ and this extra voltage is aimed to be compensated via the application of the CJC.

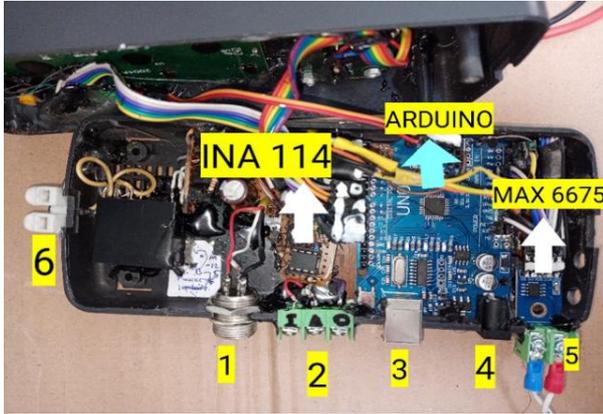**Figure 4.** An inner picture of our design (1: DC Power jack, 2: Thermocouple jacks, 3: Arduino uno port, 4: External DC supply of Arduino, 5: 230V-AC in, 6: 230V-AC out)

To achieve the CJC, we used voltage dividers via R1 and R2 resistors in the circuit in Figure 6 to feed the REF pin of INA114 with approximately 0.5V by considering the K-type thermocouple in the circuit having a thermocouple terminal temperature of 25°C as assumed. We note that the connection socket for the thermocouple terminals is shown with the abbreviation of "CJ" for "cold junction" in Figure 6. The corresponding CJC voltage is as follows: $V_{CJC}(25°C) = 0.040mV/°C \times 25°C = 1.00mV$ and this voltage is multiplied by gain (=501) giving $1.00mV \times 501 = 501.00mV \sim 0.5V$. In Figure 6, the voltage divider with resistors R_1 and R_2 provides this CJC voltage, namely, $V_{ref} = 5V \times [R_2/(R_1 + R_2)] = 5V \times [1k/(8.87k + 1k) = 0.507V$. Moreover, since the thermocouple connection terminals can also act as a kind of antenna, 0.1μF capacitor in Figure 5 and 0.01 μF capacitors (C_1&C_2) in Figure 6 are used for noise reduction.

Once the measurement of temperature has been achieved successfully, we can easily use these measured temperature values to control switching powers via relays. The success of our temperature measurement is given in the next section. We control the load running in 230V-AC power by setting limit temperature values t_1&t_2 (where $t_1 < t_2$) between 0°C and 100°C (as explained above for linearization and CJC issues) through Arduino code whose algorithm is given in Figure 8. We also use a buzzer to warn users about any deviation in temperature from set values (when it exceeds the temperature limits

t_1&t_2 at which it was set) and a relay for switching 230V-AC from 5V Arduino outputs as shown in Figure 5 and 6. In our design, we used digital pin #6 for the relay driver and digital pin#7 for the buzzer for both the MAX6675 and INA114-part as seen in Figure 5&6. Users can select the related part (MAX6675 part or INA114 part) from a user menu via Arduino codes in our designed "pocket-type measurement and control device" whose physical appearance is given above in Figure 4.
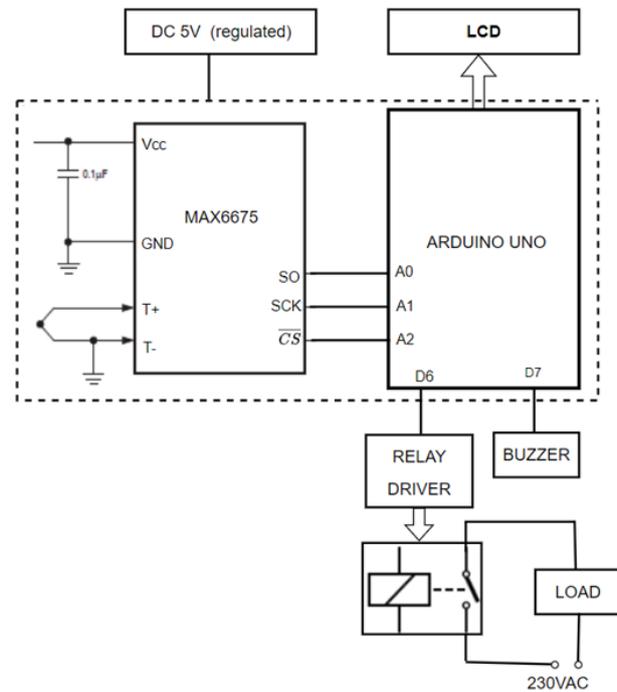

Figure 5. Our design for the MAX6675-part

As to the calibration of our INA114 part, we convert the maximum measurement temperature value (=100°C) from the Arduino's "analogRead" (via A3 pin, See Figure 6) as follows:

$$V_{+IN}(\max) = (0.040mV/°C) \times 100°C + V_{CJC}(25°C) = 4.00mV + 1.00mV = 5.00mV,$$

therefore,

$$V_o(\max) = V_A(\max) = G \times [V_{+IN}(\max) - V_{CJC}(25°C)]$$
$$= 501 \times (5.00 - 1.00)mV$$
$$= 2.004V \sim 2.00V.$$

Consequently, ~2.00V being the maximum reading value, is (analog)read from pin A3 of Arduino-UNO and it is mapped to the desired maximum temperature value (=100°C) with the Arduino codes given in Figure 9. We also note that the pin numbers of the Arduino can be selected differently but the Arduino codes should match correctly as ours given in Figure 5&9 and in Figure 6&9.
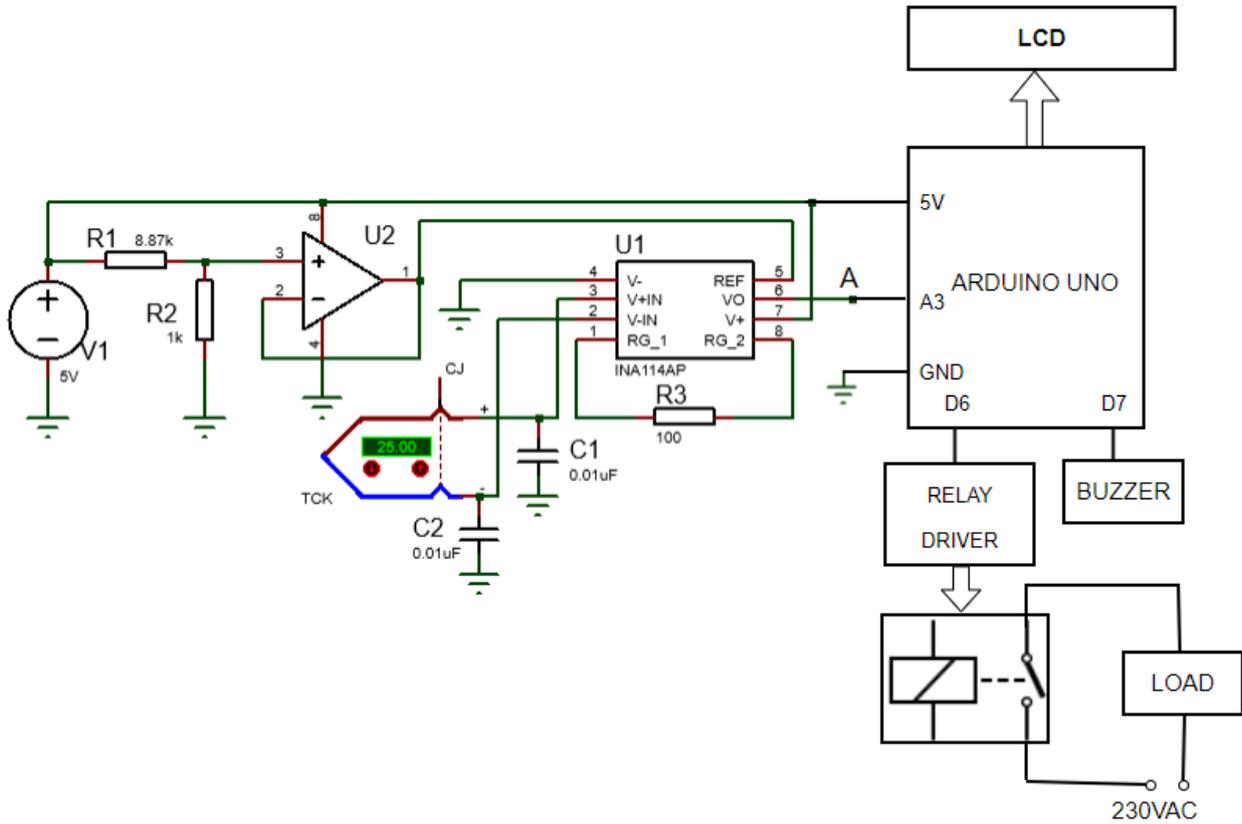
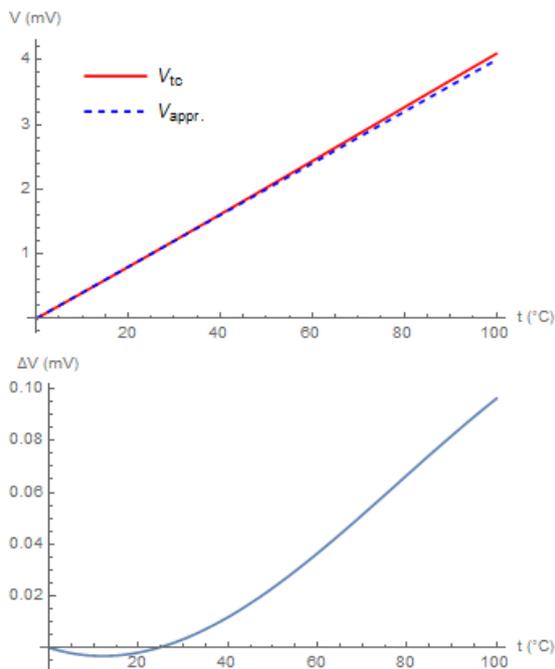**Figure 6.** Our design for the INA114-part.

Figure 7. Linear approximation we used for CJC in the measurement range: $0°C \leq t \leq 100°C$.

4. Results

Graphs of the measurements to determine the accuracy of our setup (for both heating up and cooling down processes by K-type and E-type thermocouples) are given in Figures 10-13 and their statistical accuracy results are given in Table 2. Similarly, graphs for the accuracy of our design (for heating up and cooling down processes by K-type thermocouples) along with the measurement of other devices mentioned above in comparison with the Keithley results (which are taken as the most accurate/reference measurement as mentioned above) are given in Figures 14-17. The statistical accuracy results of these measurements are given in Table 3. Graphs of heating and cooling experiments for all devices are given in Figure 18 and 19, respectively.

For the n numbers of measurements (with index i where $i = 1, 2, ..., n$), the statistical accuracy formulas used here are as follows:

$$\text{MAE} = \frac{1}{n} * \sum_{i=1}^{n} \left| x_{Keithley_i} - x_{others_i} \right|$$

$$\text{MSE} = \frac{1}{n} \sum_{i=1}^{n} \left| x_{Keithley_i} - x_{others_i} \right|^2$$

$$\text{RMSE} = \sqrt{MSE}$$

$$SD=\sqrt{\frac{\sum_{i=1}^{n}(x_i-x_{mean})^2}{n-1}}, x_{mean}=\frac{1}{n}\sum_{i=1}^{n}x_i$$

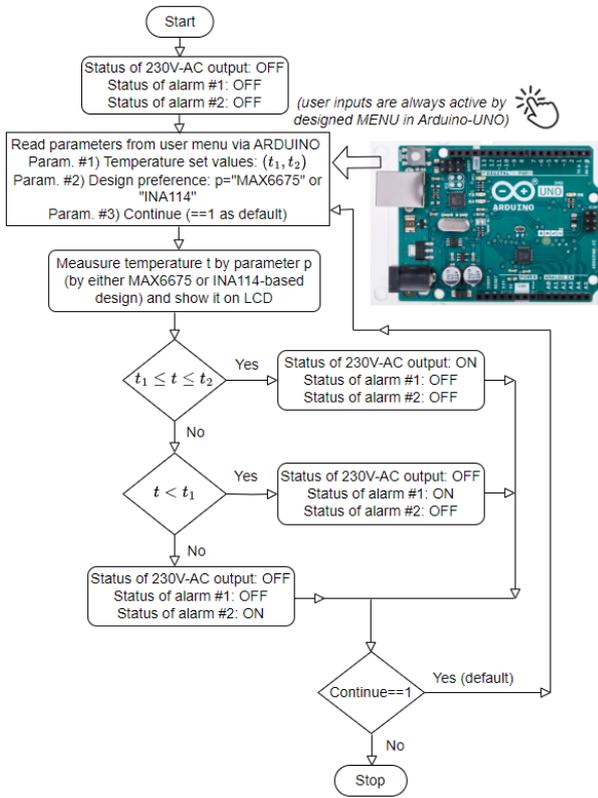(MAE: Mean absolute error, MSE: Mean squared error, RMSE: Root mean squared error, SD: Standard deviation)

```
void setup() {
Serial. begin(9600);   //  setup serial
… // with other initial definitions
;}
void loop() {
int INA114Pin = A3;
int INA114VoltageRead=AnalogRead(INA114Pin);
// it reads PWM value between 0 and 1023.
// Hence, a maximum integer value of
// 1023*2/5=409 for Vo=2 V (corresponding to
//100C)
Temp=map(int INA114VoltageRead, 0, 409, 0,
100)
// [0,409] mapped to [0,100]
//This mapped temperature value is sent to
the LCD
;}
```

Figure 9. Arduino codes for calibration of the INA114 part *(explanations are commented (by texts after "//") in the code, break control via Param. #3 is not shown for simplicity).*
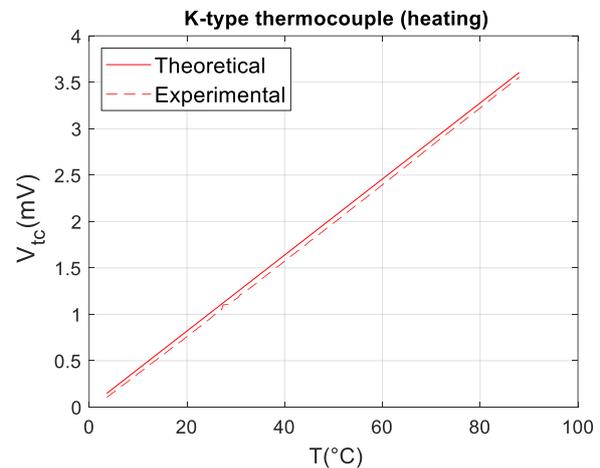

Figure 8. Algorithm for controlling load running in 230V-AC.

Table 2. Statistical accuracy results for the determination of accuracy of our setup with *"(water bath)-(thin air)-(thermocouple's hot point)"* mechanism

		Heat-up		Cool-down	
		°C	**mV**	**°C**	**mV**
K	MAE	0	0,0594	0	0,059728
	SD	20,22	0,8254	20,4	0,8361
	MSE	0,003601°C		0,0036436°C	
	RMSE	0,060008°C		0,060363 °C	
E	MAE	0	0,1371	0	0,14145
	SD	27,97	1,757	25,33	1,585
	MSE	0,019593		0,021099	
	RMSE	0,13997		0,14525	

Figure 10. Theoretical and experimental voltage-temperature graphs for the heating experiment (K-type).
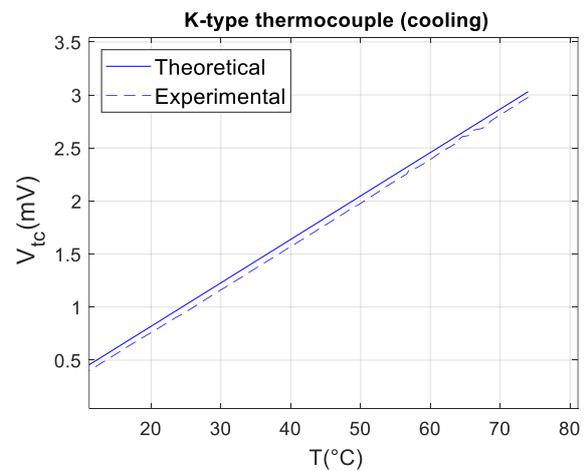

Figure 11. Theoretical and experimental voltage-temperature graphs for the cooling experiment (K-type).
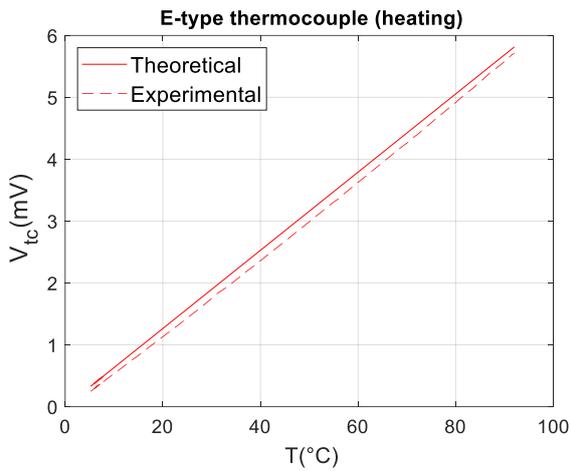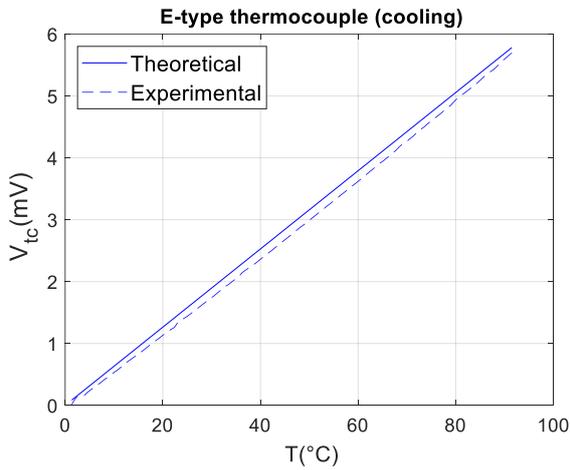
Figure 12. Theoretical and experimental voltage-temperature graphs for the heating experiment (E-type).

Figure 13. Theoretical and experimental voltage-temperature graphs for the cooling experiment (E-type).
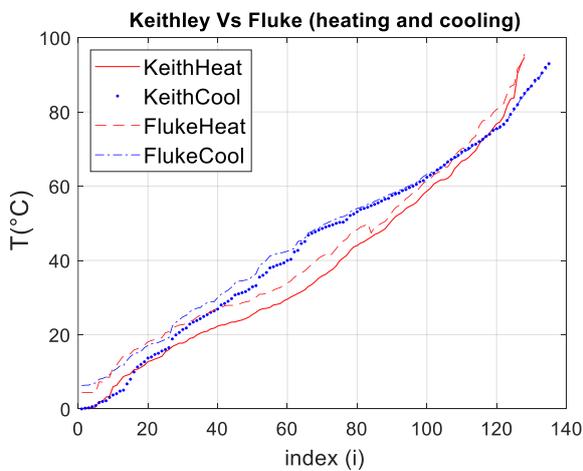
Figure 14. Comparison of measurements with *Keithley and Fluke pairs* for heating and cooling.

Figure 15. Comparison of measurements with *Keithley and MAX6675 pairs* for heating and cooling.
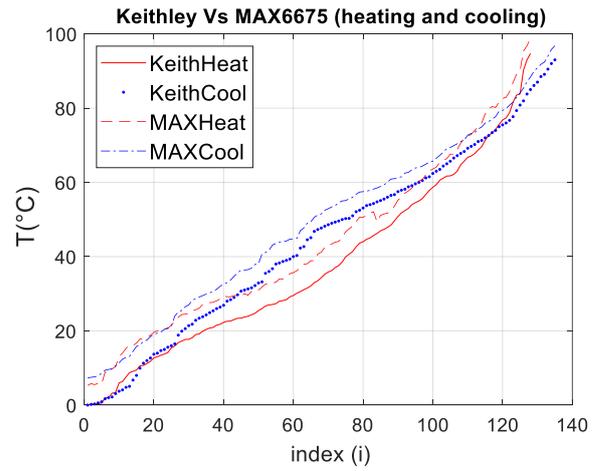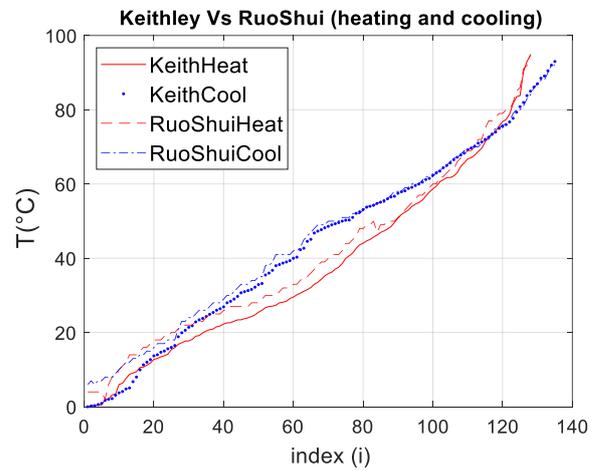

Figure 16. Comparison of measurements with *Keithley and RuoShui pairs* for heating and cooling.
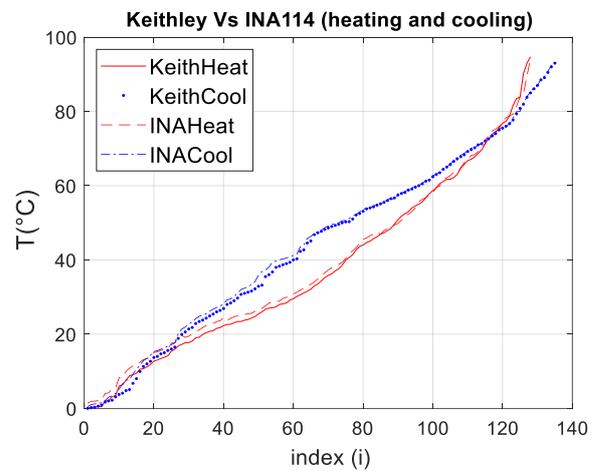

Figure 17. Comparison of measurements with *Keithley and INA114 pairs* for heating and cooling.
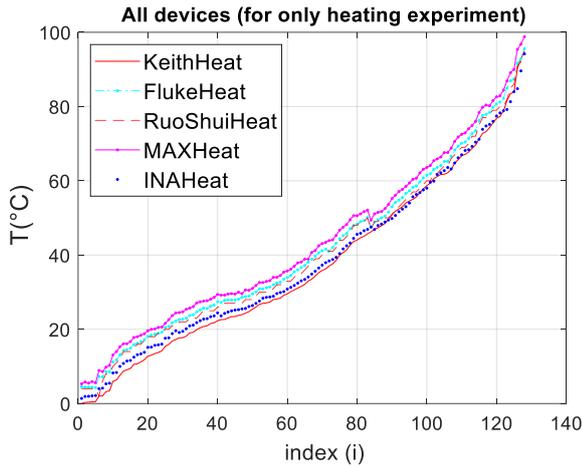
Figure 18. Comparison of measurement of *all devices* for
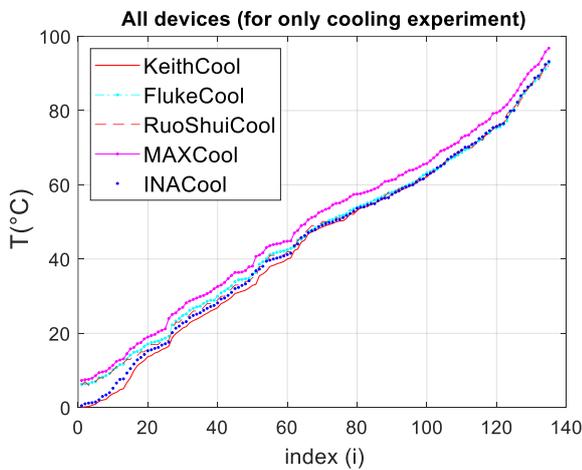<u>heating experiments</u> (plotted in the same graph).

Figure 19. Comparison of measurement of *all devices* for
<u>cooling experiments</u> (plotted in the same graph).

5. Conclusion

From Figures 10-13 and Table 2, we see that we have great accuracy scores in our measurement setup, namely, an MSE score of around 0.03 and an RMSE score of around 0.06 for both heating and cooling experiments with K-type and E-type thermocouples (and similar small values for the E-type thermocouple experiments). In all measurements here, we take the Keithley's temperature measurement as the most accurate/reference measurement as mentioned above (See Table 1 above). Results given in Table 2 show that our experimental setup involving the *"(water bath)-(thin air)-(thermocouple's hot point)"* mechanism has high accuracy scores, and therefore it can be used for testing devices. If we perform a series of temperature measurements with both Keithley and another device under test simultaneously, the accuracy of that device can be calculated by taking Keithley's corresponding measurements as the most accurate values (reference measurements) within the pre-determined accuracy of the setup. Consequently, we performed the experiments

similarly in pairs, each time the Keithley's measurement was taken as the reference/correct temperature values.

As to the accuracy in temperature measurement with various devices in pairs along with our design, we can see from Figure 14-17 and Table 3 that our INA114-based design gives the most accurate temperature measurement surpassing the other devices, namely, RuoShui 97, Fluke 17B+, and MAX6675-based design, in both heating and cooling experiments. Figure 18 and 19 also verify that curves of our INA114-based design are the closest to the Keithley's curves in both heating and cooling. In our INA114-based design, we considered that the connection terminals of the K-type thermocouple under measurement are kept at the room temperature (around 25°C) to maintain a 0.5V at the reference terminal of INA114 via linearization approximation in eqn. (3) with the corresponding CJC as explained above. Results show that our INA114-based design surpasses even the fabricated MAX6675 *(shown in blue and red in Table 3 for comparison)*. Low accuracy of MAX6675 applications is due to its fabricated internal CJC, ADC, nonlinearity of K-type thermocouple, etc. and a wide range of suggestions for enhancement techniques are reported in the literature [30-35]. Thanks to the use of a precision instrumentation amplifier similar to [12,13] and a well-achieved CJC, the INA114-part of our design in Figure 6 with the related Arduino codes given in Figure 9 gives the highest accurate scores. At this point, it can also be noted that various CJC techniques other than ours are possible in such microcontroller-used applications and further development may enable the system to work with also other types of thermocouples. It would be important to underline here that MAX6675 involves CJC for only K-type thermocouples and it is not designed for other types of thermocouples. But the INA114-part we present here (or any equivalent or precedent) is versatile in this respect. Our preference in eqn. (3) and successful CJC gives very accurate results for the target measurement range between 0°C and 100°C as aimed (exceeding temperature values seen in the graphs were also measured but we focus between 0°C and 100°C as discussed above). For the other measurement ranges, appropriate linearization of the Seebeck coefficient and the necessary CJC can be achieved, as we did here, but as the measurement ranges get larger, it is obvious that the linearized approximation gets worse and other advanced techniques, including the use of artificial neural networks, as in [11-19] could be required.

Table 3. Measurement accuracies of measurements made with 4 instruments in the 2nd experiment

		Heat-up(°C)	Cool-down(°C)
Ruoshui	MAE	3,1147	1,6083
	S. D.	23	23,7
	MSE	11,5946	6,4624
	RMSE	3,4051	2,5421
	Min	2	6
	Max	95	92
	Mean	40,38	45,81

	Median	35,5	49
	Mode	27	41
	Range	93	86
Fluke17B	MAE	4,1234	1,9856
	S. D.	23,14	23,48
	MSE	18,2710	8,2
	RMSE	4,2745	2,8636
	Min	4,3	6,3
	Max	95,6	92,8
	Mean	41,38	46,19
	Median	36,9	48,4
	Mode	4,4	6,4
	Range	91,3	86,5
MAX6675	MAE	6.0944	4,9246
	S. D.	23,44	24,22
	MSE	38,0624	26,0197
	RMSE	6,1695	5,1009
	Min	5,3	7,3
	Max	98,8	96,8
	Mean	43,35	49,13
	Median	38,5	51,5
	Mode	16,1	36,4
	Range	93,5	89,5
INA114	MAE	1,0128	0,8431
	S. D.	23,02	24,89
	MSE	2,3808	1,2951
	RMSE	1,5430	1,1380
	Min	1,38	0,5
	Max	94,2	93,2
	Mean	38,27	45,05
	Median	33,24	47,95
	Mode	23,61	0,5
	Range	92,82	92,7

Our methodology also presents a cheap means of determination of accuracy of temperature measurement by thermocouples without using any PID control in a simple, cheap, and modest lab environment. By using the desired high accuracy result of temperature measurement by our suggested compensation via INA114 precision instrumentation amplifier, we also presented a practical application regarding temperature-controlled switching (controlling load running in 230V-AC by temperature set values) by using the relay circuitry in Figures 5&6 and the Arduino-implemented algorithm shown in Figure 8. We also note that Arduino's typical void loop shown in Figure 9 is normally an infinite loop running as the continuously user interactive inputs as long as Arduino-UNO is powered. So, a user controllable parameter (Param. #3: Continue) to enable a break of the execution by the user is added as shown in Figure 8 (it is predefined as 1 by default for running continuously). During measurements, total power consumption of our design is measured to be between 40mW to 210mW depending on some parameters like LCD screen light intensity settings, selected part (MAX6675-part or INA114-part), external source ratings, whether buzzer and relay activated or not, etc.

Author's Contributions

Burak Buran: Performed the experiments, reported the results, drafted and wrote the manuscript.

Coşkun Deniz: Supervised the design of the set-ups, the experiments' progress, interpretation of the results, and preparation of the manuscript.

Ethics

There are no ethical issues after the publication of this manuscript.

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