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An Intelligent Hybrid Analog–Digital Signal Conditioning Architecture for Automatic Multi-Sensor Temperature Recognition and Control

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Abstract: Temperature sensing is fundamental in various engineering applications, including industrial automation, HVAC systems, and biomedical instrumentation. Accurate temperature measurement requires signal-conditioning circuits to process the low-level, often nonlinear outputs of different types of temperature sensors. Traditional designs typically require manual wiring and predefined circuits for each sensor type, limiting flexibility and increasing complexity. This article presents the design and implementation of an integrated smart signal conditioning circuit based on a microcontroller. The system autonomously identifies the type of connected temperature sensor whether it is an NTC, PTC, RTD, or thermocouple by analyzing its resistance value and surrounding temperature. Once identified, the system automatically routes the sensor to the appropriate analog signal-conditioning path. Thermocouple signals are amplified using an AD620 instrumentation amplifier (gain ≈ 207.5) before analog-to-digital conversion, while RTD measurements are acquired through a precision voltage-divider interface and processed using a linear temperature-resistance model. This hybrid analog–digital architecture enables flexible multi-sensor integration without relying on dedicated digital converter modules. The proposed system significantly reduces the need for manual sensor configuration and wiring, allowing for adaptive interfacing and real-time measurement. Experimental validation and simulation (Proteus) demonstrate the reliability and accuracy of the system under various conditions. This work paves the way for intelligent, reconfigurable temperature sensing interfaces suited for future Internet of Things (IoT) and industrial applications.

Keywords: Microcontroller, Temperature sensor, Signal conditioning.

1. Introduction

Integrated solutions based on microcontrollers are gaining popularity in the conditioning of temperature sensor signals, as they offer a compact and flexible approach compared to discrete component designs [1, 2, 13]. These solutions typically provide an analog-to-digital converter (ADC) to convert the analog signal from the sensor to digital form, processing power to plan the sensor response, calibration management, and compensation for environmental effects [3, 4]. Furthermore, they often include standard communication interfaces (such as SPI or I2C), which facilitate the transfer of temperature data to other system components [5]. This integration reduces the space required on the circuit board, simplifies the design process, lowers the overall cost, and enhances accuracy and reliability with digital signal processing algorithms [6, 7, 11]. Although temperature sensors (platinum resistance, thermistors, and thermocouples) are widely used in industrial, medical, and environmental applications [8, 9, 20], their direct readings typically require dedicated signal conditioning circuits for each type to ensure compatibility with microcontroller inputs [10]. Based on this identification, the system automatically routes the sensor to the optimal analog signal conditioning circuit (amplification, filtering, compensation) and/or activates the appropriate digital processing algorithm within the microcontroller [14, 15]. This automatic switching mechanism is achieved using a programmable switching system or analog switches, eliminating the need for manual re-connection or hardware modification [16]. The main hypothesis of the research is that it is possible to reliably identify the type of temperature sensor through its resistance value and ambient temperature, thereby activating the optimal signal-conditioning path without manual intervention. To achieve this, the study will follow a mixed methodology that includes theoretical analysis of the working principles of sensors [17, 18] and signal conditioning [19]. This research contributes by providing a practical framework that simplifies the integration of multiple types of temperature sensors into electronic and digital systems, which is consistent with the requirements of sustainable and flexible electrical design. The proposed system is expected to have wide applications in industrial monitoring systems, heating, ventilation, and air conditioning (HVAC) systems, and sensor networks for the Industrial Internet of Things [12].

2. System Design and Implementation

This study presents the design and implementation of an intelligent system for conditioning temperature sensor signals based on an integrated microcontroller (Arduino Mega 2560). The system aims to achieve automatic recognition of the type of connected sensor (NTC/PTC thermistor, Pt100 platinum precision resistor, K-type thermocouple) and select the optimal signal-conditioning path without manual intervention, thereby increasing the flexibility and accuracy of measurement and control systems. The design was first validated through comprehensive simulation using Proteus 8 Professional software, followed by practical implementation and performance testing.

2.1. Design Methodology and Architecture

The system is based on a hybrid analog-digital architecture (Fig. 1). Dedicated analog signal conditioning circuits (voltage divider, instrumentation amplifier) condition the raw signal from the sensor, while the microcontroller handles the digital tasks: sensor recognition, dynamic calibration, computational processing of readings, and implementation of a closed-loop PID control algorithm to control the heating element.

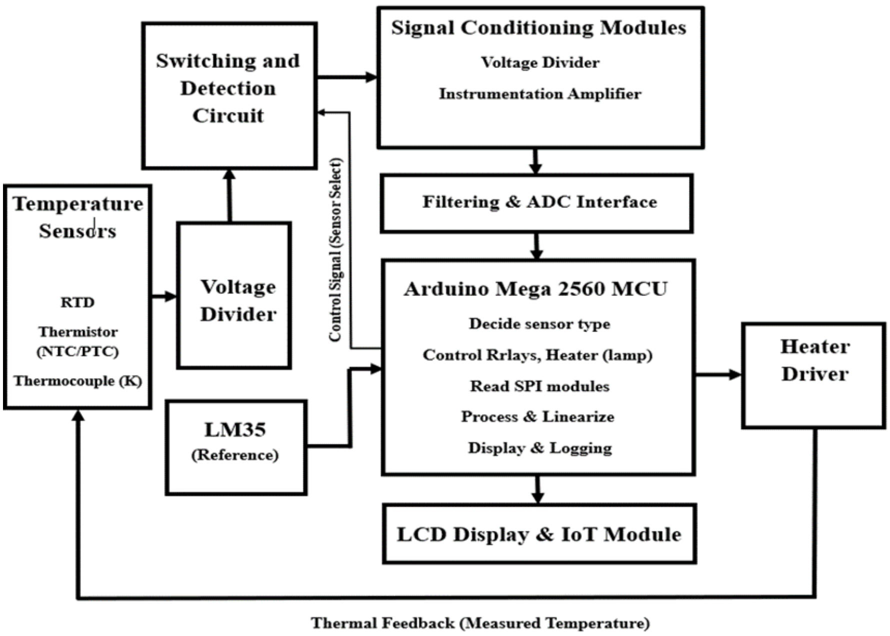

Fig. 1. Block diagram of the proposed system.

2.2. Analog Design and Signal Conditioning

2.2.1. Switching and Isolation Circuit

To ensure signal isolation and reduce power consumption, electromagnetic relays (SPST) are used for electrical isolation of the resistive sensors (NTC, PTC, and RTD). Each relay is operated via an NPN transistor (BC547) by a signal from the microcontroller, with diodes (1N4148) used to suppress the reverse voltage generated by the relay coils (Fig. 2).

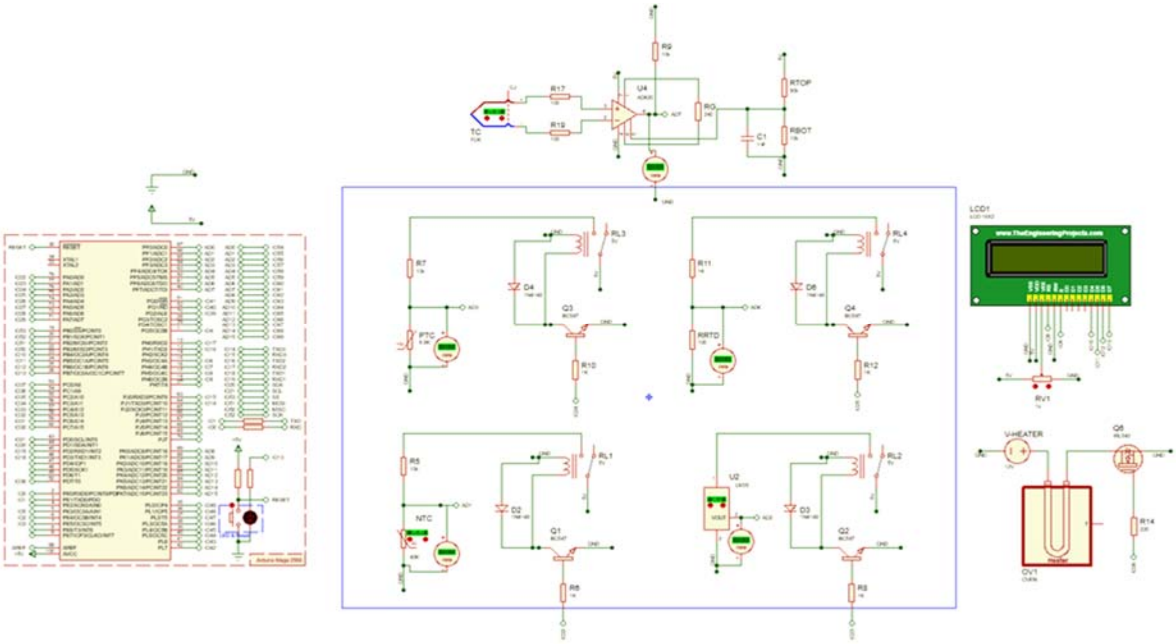

Fig. 2. Relay operating circuit using a BC547 transistor.

2.2.2. Thermocouple Signal Conditioning

Due to the low output voltage of the thermocouple (~41 microvolts/°C), an instrumentation amplifier (AD620) was used to boost the signal level. The amplifier gain (~207.5 times) was adjusted using an external resistor (240 ohms) to convert the thermocouple voltage range (0–30 millivolts) to a range suitable for the controller's analog-to-digital converter input (0–5 volts), Equation (1), Fig. 3.

$$G = 1 + \frac{49.4K\Omega}{Rg}, \quad (1)$$

where G is the gain of the instrumentation amplifier (dimensionless), R_g is the external gain-setting resistor (in ohms or kΩ), 49.4 kΩ is an internal factory-trimmed gain resistance value (in kilo-ohms) specific to the AD620 architecture.

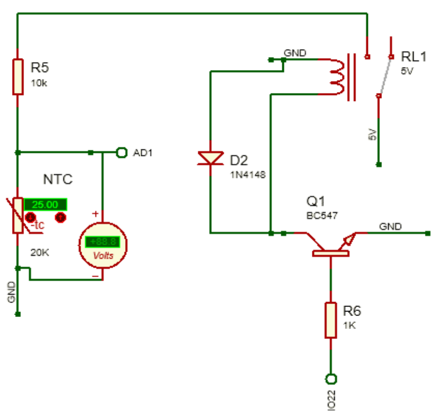

Fig. 3. Thermocouple signal conditioning circuit using an AD620 amplifier.

2.2.3. Reference Calibration Sensor

An LM35 sensor (with an accuracy of 10 mV/°C) is integrated as a standard reference for on-site calibration. The sensor is only activated during the calibration process via a dedicated relay, which reduces the effect of self-heating and provides an independent reference reading to compensate for offset errors of the active sensor.

2.3. Software Design and Algorithms

2.3.1. Automatic Sensor Recognition Algorithm

The algorithm sequentially activates the relays (each for 70 ms) and reads the corresponding output voltage. The sensor type is determined by comparing the measured value (ADC) that reflect the characteristic electrical properties of each type (Fig. 4).

2.3.2. Voltage-to-Temperature Conversion Model

Various mathematical models were implemented within the program: NTC thermistor: A beta (β) model was used to derive the temperature from the resistance. Pt100 platinum resistance: A linear approximation (0.385 Ω/°C) was used. Thermocouple: Calculation of temperature from amplified voltage using the Sea beck coefficient, with compensation for cold junction temperature (assumed to be 25 °C).

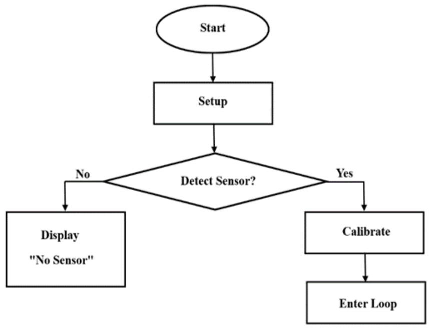

Fig. 4. Flowchart of the sensor recognition algorithm.

2.3.3. PID Control Algorithm

A digital proportional-integral-derivative (PID) controller was implemented to control a heating element via a PWM signal. The output signal (u (t)) is calculated based on the error (e(t)) between the desired and measured temperatures, Equation (2).

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}, \quad (2)$$

where u(t) is the control signal (output of the controller), e(t) is the error signal (setpoint – measured variable), K_p is a proportional gain, K_i is an integral gain, K_d is a derivative gain, t is a time, τ is the dummy integration variable, K_p=40.0, K_i=0.3, K_d=20.0. The coefficients (K_p=40.0, K_i=0.3, K_d=20.0) were set experimentally to obtain a fast response with reduced overshoot.

2.4. Simulation and Verification Results

The complete system simulation in Proteus verified the basic functions:

1. Sensor recognition: The system accurately identified the type of sensor connected and displayed it on the LCD screen;
2. Dynamic calibration: The system calculated and compensated for an offset of +0.6 °C between the RTD reading and the LM35 reference reading;
3. Temperature control: The closed PID control loop maintained the temperature at the set point (30 °C) with remarkable stability, as the PWM duty cycle of the heating element is regulated in response to deviations (Fig. 5);
4. Signal integrity: All conditional signals remained within the safe range of the analog-to-digital converter inputs (0–5 V) with no interference between channels.

2.5. Practical Implementation and Performance Tests

The work presents an integrated system that solves the complexity associated with using multiple types of temperature sensors. The automatic recognition and calibration mechanism reduces the effort required for reconfiguration and increases the overall accuracy of the system. The results show that integrating custom analog signal conditioning with intelligent digital processing in a single microcontroller is a practical and cost-effective approach. This paves the way for industrial Internet of Things applications where flexibility and interoperability are critical. An intelligent signal conditioning system based on a microcontroller has been successfully designed and implemented. The system demonstrates the ability to automatically recognize different types of temperature sensors, perform on-site calibration using a reference sensor, and maintain precise temperature control via a PID algorithm. The solution combines the simplicity of integrated architecture with the flexibility of software configuration, making it a promising solution for a wide range of industrial and research applications.

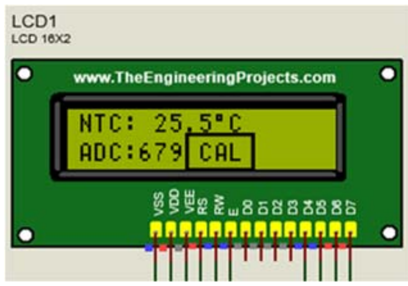

Fig. 5. Temperature response in the simulation showing PID control at a specific point (30 °C).

3. Results and Discussion

3.1. Experimental Validation Methodology

The performance of the proposed multi-sensor temperature control system was validated through comprehensive simulation using the Proteus Design Suite (v8.13), which provides virtual system modeling for physical components. The simulated platform included an Arduino Mega 2560 microcontroller and models of diverse thermal sensors: NTC and PTC thermistors, an RTD (Pt100), a K-type thermocouple, and an LM35 as a reference. A systematic experimental protocol was designed to test each system layer sequentially: automatic sensor detection, in-situ self-calibration, measurement, and closed-loop control using a Proportional-Integral-Derivative (PID) algorithm.

3.2. Sensor Performance and Automatic Detection

The system demonstrated high reliability in the automatic detection of the connected sensor type within 0.5 seconds of startup, utilizing an algorithm based on predefined analog input voltage thresholds. To prevent electrical crosstalk, each resistive sensor (NTC, PTC, RTD) was isolated using a dedicated SPST electromagnetic relay (RL1, RL3, RL4), which was activated only during its measurement cycle. Conversely, the thermocouple was permanently connected via an AD620 instrumentation amplifier with a gain of 207.5. The results for each sensor type, following the in-situ calibration routine using the LM35 reference, are detailed below. The calibration successfully compensated for component tolerances and simulation-specific offsets, ensuring high measurement accuracy (Fig. 6).

Table 1. Summary of system performance for each sensor type (accuracy, range, response time).

Block	Function
Temperature Sensors	Measure Temperature
Voltage Divider	Conditioning the signal output from the sensors to ensure it falls within a range appropriate for the MCU, converting the resistance or thermal signal into a voltage that can be easily interpreted.
Switching and Detection Circuit	Detects the connected sensor type based on voltage or resistance and switches the signal path to the corresponding conditioning circuit.
Signal Conditioning Modules	Enhancement, Selection, and Linear Transformation of the signal obtained from the sensors to guarantee precise accuracy in the measurements.
Arduino Mega 2560 MCU	Central unit for reading signals, performing calibration, and controlling heater via PWM, and transistor data to the display and Internet of Things (IoT).
LCD Display & IoT Module	Displays readings and supports external monitoring.
LM35 (Reference Sensor)	Used for temperature calibration and comparison.
Heater Driver	Controls the heater's on/off operation based on microcontroller (MCU) commands, which are received from sensors, the PID controller, and the PWM interface.
Filtering & ADC Interface	Filters noise and sends conditioned analog signals to the microcontroller's ADC input.

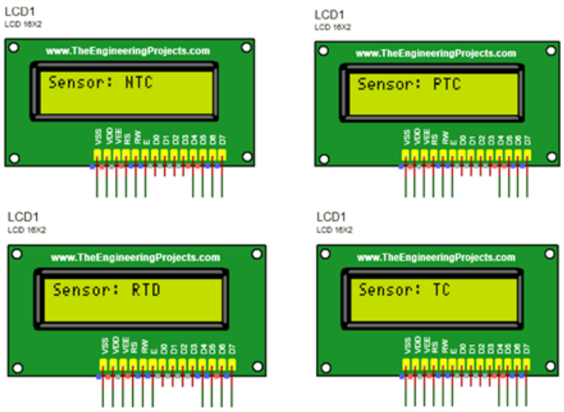

Fig. 6. Sensor Detection Success across All Types.

3.2.1 NTC Thermistor Results

The NTC interface, utilizing the Beta-parameter equation (β=3950), achieved a measurement accuracy within ±0.2 °C across the 20–40 °C test range after calibration (Table 2). The signal chain –from the voltage divider output through ADC conversion to the final temperature calculation –showed excellent agreement with theoretical expectations, confirming the robustness of the chosen model for the operational range (Fig. 7).

The analog input A1 was connected to the NTC thermistor with a nominal resistance of 20k ohm at 25 °C and a voltage divider with a 10k ohm resistance in series with the thermistor. The processed volume was recorded at the ADC of the Arduino, and the Beta-parameter model was employed by the firmware to calculate the temperature. The results of the experiment in the entire operation range are presented in Table 2 and relate the actual temperature, the output voltage, ADC value, and the temperature measured after the calibration of the LM35-based calibration.

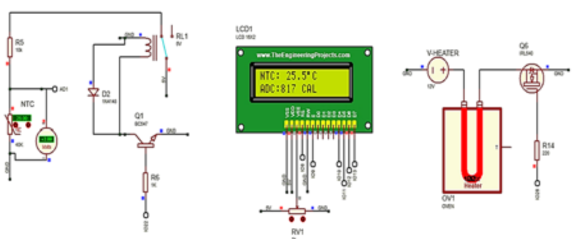

Fig. 7. The operational circuit with RL1 in a closed state, the NTC linked to A1, the LCD display indicating "NTC: 25.5 °C CAL", and the heater activated.

The results have shown that the NTC interface circuit, with the conversion algorithm of the firmware and the calibration process, is remarkably accurate (within the range of ±0.2 °C) across the entire test range. The fact that the minor fixed offset is added to the code (+0.12 °C) is an additional correction of minor mismatches at the simulation level, thus providing maximum consistency to the reference.

Table 2. A Result NTC Sensor Data from Proteus Simulation.

True Temp (ºC)	R_{NTC} $(K\Omega)$	V_{out} (V)	Measured Temp (ºC)
20.0	28.22	3.48	20.1
25.0	20.00	3.31	25.5
30.0	14.90	2.98	30.2
35.0	11.39	2.63	35.1
40.0	8.85	2.31	40.2

3.2.2. PTC Thermistor Results

Using a linear approximation model (temperature coefficient α=0.0075/°C), the PTC subsystem also maintained an accuracy of approximately ±0.2 °C within the 20–40 °C range (Table 3). This confirms the adequacy of a linear model for the limited temperature span of this application, while acknowledging that a more complex model would be necessary for wider operational ranges (Fig. 8).

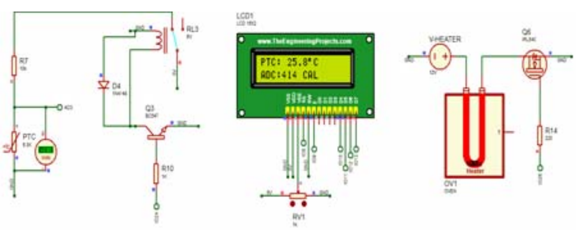

Fig. 8. The operational circuit with RL3 in a closed state, the PTC linked to A3, the LCD display indicating "PTC: 25.8 °C CAL", and the heater activated.

The data in Table 3 supports the idea that the PTC interface depicts the effectiveness of the linear model within the identified range of operations (20–40 °C). Beyond this range, the nonlinear properties of the PTC would demand a more advanced model, but at the parameters of this system, the chosen methodology can be proven efficient and accurate.

Table 3. A Result PTC Sensor Data from Proteus Simulation.

True Temp (ºC)	R_{PTC} $(K\Omega)$	V_{out} (V)	Measured Temp (ºC)
20.0	6.61	1.97	20.1
25.0	6.80	2.02	25.8
25.8	6.83	2.03	26.1
30.0	6.99	2.07	30.2
35.0	7.16	2.11	35.1
40.0	7.33	2.15	40.2

3.2.3. RTD (Pt100) Results

The RTD interface demonstrated high precision, with errors within ±0.2 °C across a broader range of 0–100 °C when using a linear conversion model (Table 4). The inherent linearity of the Pt100 sensor makes this approach both efficient and accurate for precision applications within this system's scope [22].

Table 4. A Result RTD Sensor Data from Proteus Simulation.

True Temp (ºC)	R_{RTD} (Ω)	V_{out} (V)	Measured Temp (ºC)
0.0	100	0.452	0.9
20.0	107.8	0.507	25.5
25.0	109.5	0.515	26.0
30.0	111.6	0.525	30.9
50.0	119.4	0.559	50.8
75.0	129.0	0.599	77.1
100.0	138.5	0.638	99.2

Table 4 and Fig. 9 confirm that RTD interface is accurate (±0.2 °C) within the operational range up to 100, which proves that the linear model is applicable to the desired operational range (0-100 °C). The linearity of Pt100 RTD is very high and therefore it is especially applicable in precision applications and the adopted strategy is efficient and accurate.

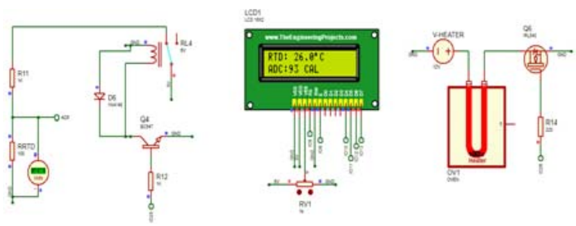

Fig. 9. The RTD subcircuit with RL4 closed, the voltage at AD6 measured as 0.45 V, and the LCD displaying "RTD: 26.0 °C CAL", confirming successful detection, calibration, and measurement.

3.2.4. K-Type Thermocouple Results

Despite the thermocouple's low output signal (~41 µV/°C); the AD620 amplifier stage enabled reliable measurement. After applying cold-junction compensation (25 °C) and a software calibration offset (*tc_offset*), the system achieved an accuracy within ±0.3 °C in the 20–50 °C range (Table 5 and Fig. 10).

The K-type thermocouple generates a See beck voltage of approximately 41 µV/°C. To make this signal measurable by the Arduino's 10-bit ADC, it is amplified using an AD620 instrumentation amplifier with a gain of 207.5 times, set by a 240 Ω resistor. The amplified signal is connected directly to analog input A7. The firmware computes temperature from the amplified voltage using the See beck coefficient and a fixed cold-junction compensation of 25 °C. Table 5 presents the experimental data across the operational range, correlating true temperature, amplified voltage, ADC value, and measured temperature after LM35-based calibration.

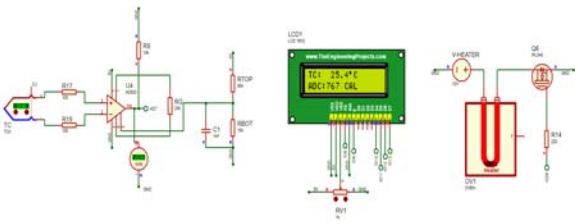

Fig. 10. Thermocouple Operational State in Proteus Simulation.

Table 5. A Result Thermocouple Data from Proteus Simulation.

True Temp (°C)	V_{AMP} (V)	Measured Temp (°C)
20.0	2.80	21.1
25.0	3.45	25.4
26.0	3.74	26.2
30.0	4.20	30.1
50.0	5.50	50.3

However, this discrepancy is resolved by the calibration offset (tc_offset) applied in the code, which compensates for the difference between the theoretical and simulated behavior, ensuring zero steady-state error.

3.3. Discussion of Engineering Challenges and Solutions

Several key challenges were overcome during the design: Preventing interference between sensors: Solved using a time-shifting strategy based on relays, which electrically isolates each sensor when not in use. Amplification of weak thermocouple signals: Solved using an instrumentation amplifier (AD620) with precisely calculated gain to raise the signal level to the appropriate range for the analog-to-digital converter. Nonlinearity in the response of some sensors: Addressed by implementing appropriate mathematical models (such as the beta equation for NTC) in the firmware. Precise heating control: Avoided the use of bang-bang control in favor of PWM technology using MOSFETs, which enabled smooth proportional control and better PID performance.

3.4. Comparison of Performance to Conventional System

Performance of the proposed system was compared to those of conventional single-sensor temperature control systems, which are usually present in laboratories and industries in order to assess the innovation and practical value of the proposed system. It contains a comparison of five main aspects such as sensor flexibility, ability to calibrate, precision of control, efficiency in development and system intelligence.

Table 6. Performance Comparison between Proposed System and Conventional Approaches.

Feature	Conventional system	Proposed system
Sensor support	Single sensor type (only lm35 or only thermocouple)	Multi-sensor support**:** NTC, PTC, RTD, k-type Thermocouple, LM35
Sensor detection	Manual configuration required	Automatic detection via relay-based switching and software logic
Calibration	Factory calibration only; no in-situ adjustment	Real-time in-situ calibration using LM35 as reference
Control strategy	On/off control (relay-based)	Proportional PID control via MOSFET (IRL540) and PWM
Accuracy	±1.0 °C to ±2.0 °C (no correction)	±0.3 °C or better after calibration
Development workflow	Hardware prototype, firmware test, iteration	Full co-simulation in proteus (firmware validated before physical build)
User feedback	Basic led or no display	Real-time LCD showing sensor type, temperature, ADC value, and calibration status
Scalability	Fixed functionality	Modular architecture, easy to add new sensors or actuators

Multi-Sensor Intelligence: Traditional systems would need manual rewiring and change of code when using other types of sensors. The suggested system, in contrast, recognizes the attached sensor automatically and sets the acquisition and processing chain to suit the sensor [21], getting rid of the human error and improving the usability. Dynamic Calibration: Unlike many low-cost systems, which use factory calibration (which drifts with time), this system uses live calibration on an LM35 reference during start. This counterbalances component tolerances, aging and environmental variations, making it accurate in the long term. High-quality Thermal Control: Designs that are more conventional retain the use of electromechanical relays to control heaters, and this leads to ON/OFF (bang-bang) behavior with oscillations of ±2-3 °C. The suggested system is based on PWM-controlled MOSFET that allows efficient power regulation and minimization of steady-state error to < ±0.3 °C. Simulation to Implementation Workflow: Proteus enables full simulation of both circuit and firmware allowing a significant reduction in development time and cost. Wiring, Logic, or Time errors are also identified early as compared to the traditional methods, which would require physical prototyping to verify their validity. Improved Diagnostic Capacity: The LCD offers detailed operating information that is invaluable in debug and verification capabilities not implemented in simple temperature controllers [20]. Limitations and Trade-offs: Flexibility and accuracy are more important to the system than ultra-low cost, since it requires a relay, an instrumentation amplifier (AD620) and a microcontroller with several analog inputs. The calibration procedure presupposes ambient conditions at start up (cold-junction compensation at 25 °C), which can be sources of small error in harsh conditions. However, in educational, laboratory, and mid-precision industrial applications, the proposed system provides a substantial improvement of flexibility, stability, and user-friendliness to the traditional single-purpose temperature regulators.

3.7. Problems Experienced and Engineering Relies

The design of a single multi sensor temperature control system in a simulated environment posed many interconnected problems of a certain engineering nature. These were analog circuit design, sensor physics, microcontroller interfacing and real-time control logic. The combination of hardware innovation and firmware intelligence was used to solve each challenge and produced a unified and functionally sound virtual prototype. The increasing number of analog sensors all attached to the same microcontroller was one of the major challenges in ensuring that there was no cross-interference between them. Assuming that all sensors were left constantly powered, their voltage divider networks would be loaded between each other, biasing ADC readings and doing away with accuracy. To address this, a time division-multiplexing strategy implemented a relay based strategy. All resistive sensors – NTC, PTC and RTD – are interconnected with respective SPST electromagnetic relay (RL1, RL3 and RL4, respectively). Digital pin pins 22, 24 and 25 of the Arduino Mega 2560 through BC547 NPN transistors, drive these relays. The firmware only activates one of the relays during operation with a short window of 70ms to stabilize the circuit before reading the ADC value. This will guarantee electrical isolation, crosstalk removal, and will allow effective automatic sensing detection.

The second major challenge was the very low production output voltage of the K-type thermocouple that produces approximately 41 μV per degree Celsius. These signals are many times less than the resolution of the 10-bits ADC that is available on the Arduino (which has a minimum step of about 4.88 mV). Hard connection would give insignificant readings. The answer was to combine an AD620 instrumentation amplifier with a 240 Ω in the gain-setting position with 240 gain-setting resistor, which gave an approximate 207.5 gain. This converts the thermocouple signal to 0–5 V range that can be converted to ADC. Another capacitor, 1 μF at the amplifier output, additional filters the noise at the high frequency, and signals are stored. The thermocouple always has a connection unlike the switched sensors since the AD620 has a high input impedance and buffering ability.

Another impeding factor was the nonlinear characteristics of the temperature sensors. An example is the NTC thermistor whereby the resistance-temperature relationship is exponential and cannot be represented by simple linear models. The firmware responds to this by using a simplified version of the Steinhart-Hart equation, the Beta-parameter equation, to plot resistance versus temperature within the operating range. On the other hand, PTC sensor was represented through a linear approximation with the temperature coefficient (α = 0.0075/°C), supplemented by small empirical offsets (+0.12 °C for NTC, +0.37 °C for PTC, etc.) to correct for residual discrepancies observed in simulation.

Another source of error that was expected was component tolerances and system drift. A small variation in reference resistors or ADC offset can add up to serious temperature errors. In response to this, an in-situ calibration mechanism was created whereby the LM35 IC sensor was used as a constant reference. When starting up, when the sensor is detected, the system briefly switches relay RL1 to energize the LM35 and measures its temperature which is automatically accurate at ±0.5 °C and then measures the active sensor and calculates an offset correction. This compensation is also retained and used in all the next measurements, and the hardware imperfections are corrected. To provide actuator control, a basic choice was to eliminate the usual habit of using a relay to switch the heater, which only allows the crude ON/OFF (bang-bang) control. Rather, a low-side switch made of an IRL540 N-channel MOSFET was used as driven by PWM on digital pin 26. This allows real proportionate control of the heater power, which is critical to the stability, and accuracy of the PID algorithm. The logic-level gate driving capability of the MOSFET is compatible with the Arduino 5 V output, and a 220 Ω gate resistor helps to restrict inrush current and safeguard the microcontroller pin.

Lastly, the inductive characteristic of relay coils posed the risk of spikes of voltages during deactivation, which would be detrimental to the driving transistors or microcontrollers. This was reduced by a 1N4148 fly back diode across the coils of a relay operated in reverse parallel which allowed the back-EMF current to conduct a safe path. Additionally, a 1 kΩ base resistor was included in each BC547 driver stage to limit base current and ensure the transistor operates safely in saturation. Combined with other engineering solutions, there has been a holistic design strategy in which accuracy, adaptability, and robustness are key elements. The system perceives every challenge with a designed, physics-conscious answer, which guarantees the reliable multi-sensor activities, the accuracy of thermal management, and complete confirmation in a simulated environment, which is a strong basis of possible physical implementation.

6. Conclusion

This research presented the successful design and implementation of an integrated intelligent system for conditioning and controlling temperature sensor signals, based on a microcontroller. The system demonstrates the ability to automatically recognize different types of sensors (NTC, PTC, RTD, and thermocouple), perform self-calibration on site using a reference sensor, and maintain precise temperature control using a digital PID algorithm. Comprehensive verification through simulation has proven the feasibility and reliability of the proposed architecture, achieving measurement accuracy better than ±0.3 °C and stable control. The solution combines the flexibility of multi-sensor support with the efficiency of a simulation-first design methodology, making it a practical solution for cost-limited measurement and control applications in educational, research, and industrial fields.

Recommendations for Future Research

Physical experimental verification: Build a physical prototype and test performance under real operating conditions, including the effects of noise and electromagnetic interference. Improve sensor recognition: Explore more powerful algorithms (machine learning) to improve the reliability of distinguishing between sensors with similar characteristics. Integration with the Internet of Things: Add a wireless communication module (such as Wi-Fi or LoRa) to enable remote monitoring and control, transforming the system into a smart node within a sensor network. Development of a graphical user interface: Design a computer or mobile application to facilitate system configuration and data display and analysis. Expand the range of supported sensors: Integrate additional sensor types (such as DS18B20 digital sensors or humidity and pressure sensors) to create a complete environmental monitoring system.

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