Enhanced Cooling with Peltier and Proprietary Coolant for Adaptive Thermal Management of Electronic Systems

Fakruddin Ahmed Bidiwale [1], Mohammed Tanzil Mestri[2], Amaan Ansari[3], Prof. Pavitra M. Badiger[4]

[1, 2, 3] Students, Department of Electronics and Communication Engineering
[4]Assistant Professor, Department of Electronics and Communication Engineering

KLS Vishwanathrao Deshpande Institute of Technology, Haliyal, Karnataka- 581329

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Abstract
Considering the explosive proliferation of small electronic devices, effective heat management now ceases to be an optional feature but a serious design requisite. Power electronic modules, IoT platforms, and modern embedded devices often operate continuously under severe heat stress, with limited airflow and physical space. These is difficult for conventional air-cooling methods to achieve which leads to decreased performance, thermal instability, and long-term reliability problems. This work describes a hybrid adaptive cooling system using a Peltier module for thermoelectric cooling, liquid-based heat extraction, and a proprietary coolant scientifically designed and managed by sophisticated PID and PWM algorithms. The system integrates relay-based fail-safe protection, optocoupler-isolated power electronics, and Bluetooth-enabled real-time telemetry for safe and dependable operation. In parallel, a novel Internet of Things (IoT)-based thermal conductivity testing device was developed to evaluate various distilled water–ethylene glycol (DW–EG) coolant combinations scientifically using Fourier's heat conduction concept. A 70:30 DW–EG mixture provides the optimal balance of thermal conductivity, viscosity, chemical stability, electrical safety, and pump efficiency, according to experimental results. This proposed system represents an advancement of the conventional concept of cooling. The new one offers tighter temperature control, more stability, and fewer operational costs, which make it perfect for compact embedded electronics.

Keywords Thermoelectric Cooling, Peltier Module, Liquid Cooling, PID Control, PWM Control, Thermal Conductivity, Proprietary Coolant, Embedded Systems & IoT Measurement

I. INTRODUCTION

Advances in semiconductor fabrication have pushed embedded controllers, IoT nodes, and power electronics into an interesting corner. A lot of processing power, packed into very small spaces. Impressive, yes. But the downside appears almost immediately. These devices are usually sealed inside tight, poorly ventilated enclosures, where heat has nowhere to escape. Thermal management, once just an afterthought, has quietly turned into a core design requirement. You can't ignore it anymore. Ignore it and the hardware responds. Leakage currents increase. Parameters drift. Components age faster than they should. And sometimes, things just fail. Permanently. At this point, temperature control is no longer only about performance—it's about reliability and safety too.

Air cooling still runs the show. Heat sinks, fans, basic airflow paths. Cheap. Familiar. Easy to deploy. But air is a weak medium for heat transfer, and that limitation shows up fast. Low thermal conductivity. Low heat capacity. In compact systems with restricted airflow, these weaknesses stop being theoretical and start becoming real problems.

Thermoelectric cooling offers another path. Built on the Peltier effect, it enables direct heat pumping without any moving parts. Solid-state. Compact. Precise. On paper, it sounds close to perfect. In practice, there's a catch. Everything depends on how well heat is removed from the hot side. Fail there, and the temperature gradient collapses. Cooling performance drops Quickly.

Liquid cooling shifts the balance again. Liquids move heat far more effectively than air, making them suitable for high heat-flux environments. But coolant selection is not trivial. Distilled water conducts heat well, no doubt about that. But over time it brings problems—evaporation, corrosion, even biological growth. Ethylene glycol is more chemically stable and offers freeze protection, yet its higher viscosity and lower thermal conductivity restrict heat transfer. One way or another, there's always a trade-off.

This project sits right at that intersection. It introduces an adaptive thermoelectric cooling system combined with a proprietary coolant whose composition is carefully tuned. Not assumed. Not copied. Tested and validated. A custom-built thermal conductivity testing device is used to refine the coolant formulation, ensuring efficient heat extraction and sustained Peltier performance. The objective is straightforward. Better cooling. Stable temperatures. And electronic systems that last longer than expected.

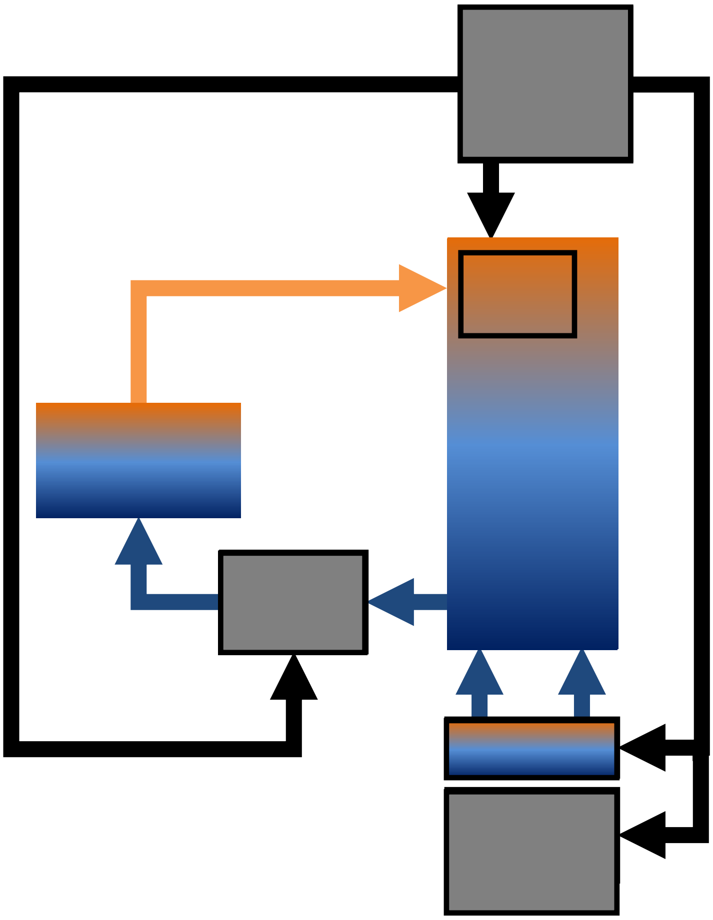

Fig. 1 - Overall System Block Diagram

II. REVIEW

Previous thermoelectric cooling research has been more focused on the refinement of control mechanisms, including PID controlled feedback loops and PWM-based regulation. According to literature, PID control helps much in improving temperature stability by reducing oscillations and overshoot. Still, most of these systems are susceptible to electrical noise and issues of a ground loop when operating in high-current environments, due to lack of proper electrical isolation. Liquid cooling research has involved a range of coolants, such as water-based mixtures, dielectric fluids, and mineral oils. Water is an exceptionally good heat transfer medium because of its high specific heat capacity and its reasonably high thermal conductivity of ~0.6 W/m·K; however, its chemical instability usually limits its long-term use in closed-loop systems. Ethylene glycol is normally added in automotive applications for its antifreeze effect and to prevent corrosion; it has a higher viscosity and lower thermal conductivity, which can reduce the overall cooling efficiency. A key knowledge gap in the existing literature is experimental validation of coolants that is explicitly coupled to system performance. Additionally, testing thermal conductivity usually requires costly laboratory equipment, complicating student-level research and smaller-scale studies. intelligent software control, and adaptive cooling hardware into a single integrated framework, this work closes these gaps.

III. PROBLEM STATEMENT

Compact electronic systems still struggle with thermal instability. Even today. And it's not because cooling methods don't exist. The problems are more basic than that. Heat is often not removed effectively from thermoelectric devices, especially from the hot side. Adaptive control is missing in many designs, so the system cannot respond when conditions change. Electrical isolation and fail-safe protection are frequently overlooked, which makes the setup risky under fault conditions. And then there's the coolant choice—picked almost at random, with little scientific validation to back it up. Put all this together and the result is predictable. Unstable temperatures. Reduced efficiency. Shortened hardware life. Compact electronic environments, by their nature, demand something better. A cooling system that is safe. Adaptive. And, most importantly, empirically tested rather than assumed to work.

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IV. PROPOSED SYSTEM ARCHITECTURE

Two interrelated subsystems make up the suggested system: A. System of Adaptive Thermoelectric Cooling: This subsystem incorporates a liquid cooling loop with a pump and a Peltier module for active cooling. Relay-controlled fail-safe power management; optocoupler-based electrical isolation; MOSFET-based high-current switching; and a fan for hot-side heat dissipation

B. Subsystem for Coolant Development and Testing Multiple DW–EG coolant mixtures may be prepared, heat-flow production can be controlled using a Peltier module, dual-point temperature measurement can be done, and IoT-based real-time visualization and logging are all made possible by this subsystem.

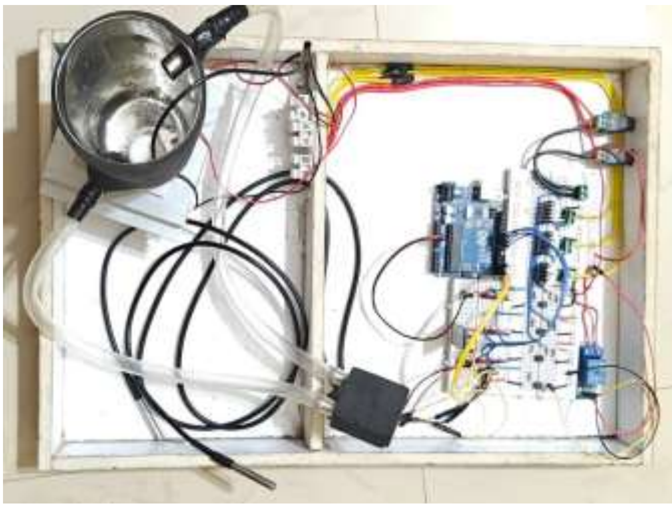

Fig. 2 - System Architecture Overview

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V. HARDWARD DESIGN

A. Power Supply Architecture

Table I – Power Supply Configuration

Source	Rating	Loads	Purpose
USB Power	5V	MCU, Sensors, Bluetooth	Stable logic supply
5V SMPS	5V / 1A	Relay, Pump	Isolated low-current loads
12V SMPS	12V / 5A	Peltier, Fan, Gate Pull-ups	High-power cooling

Electrical isolation between domains ensures noise immunity and protects sensitive electronics.

B. Temperature Sensing and Feedback

Table II – Temperature Sensor Placement

Sensor	Location	Function
DS18B20 (Hot)	Near Peltier hot side	Heat rejection monitoring
DS18B20 (Cold)	Coolant block	Cooling effectiveness

Digital sensing ensures high accuracy and immunity to electrical noise.

C. Switching, Isolation, and Protection

Table III – Power Switching and Isolation Components

Component	Role
PC817 Optocoupler	Logic–power isolation
IRFZ44N MOSFET	High-current switching
Relay	Fail-safe power cutoff

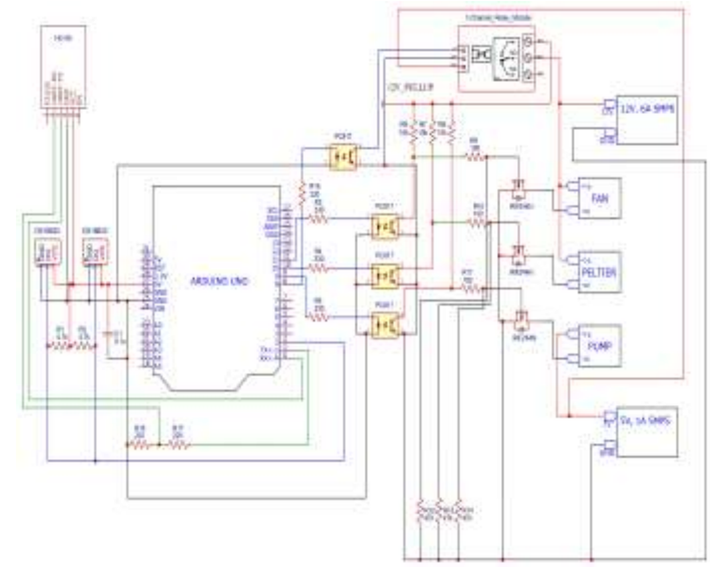

Fig. 3 - Hardware Circuit Diagram

VI. SOFTWARE DESIGN

A. Dual-Mode Cooling Control

Table IV – Cooling Modes

Mode	Description
PID Mode	Closed-loop precision control
PWM Mode	Rule-based stage control

PID mode provides fine temperature regulation, while PWM mode ensures rapid response during predictable thermal loads.

B. Safety and Telemetry

Multiple layers of protection are implemented:

- Over-temperature shutdown
- Sensor failure detection
- Emergency shutdown via Bluetooth
- Relay-based hardware isolation

Real-time telemetry provides continuous insight into system behavior.

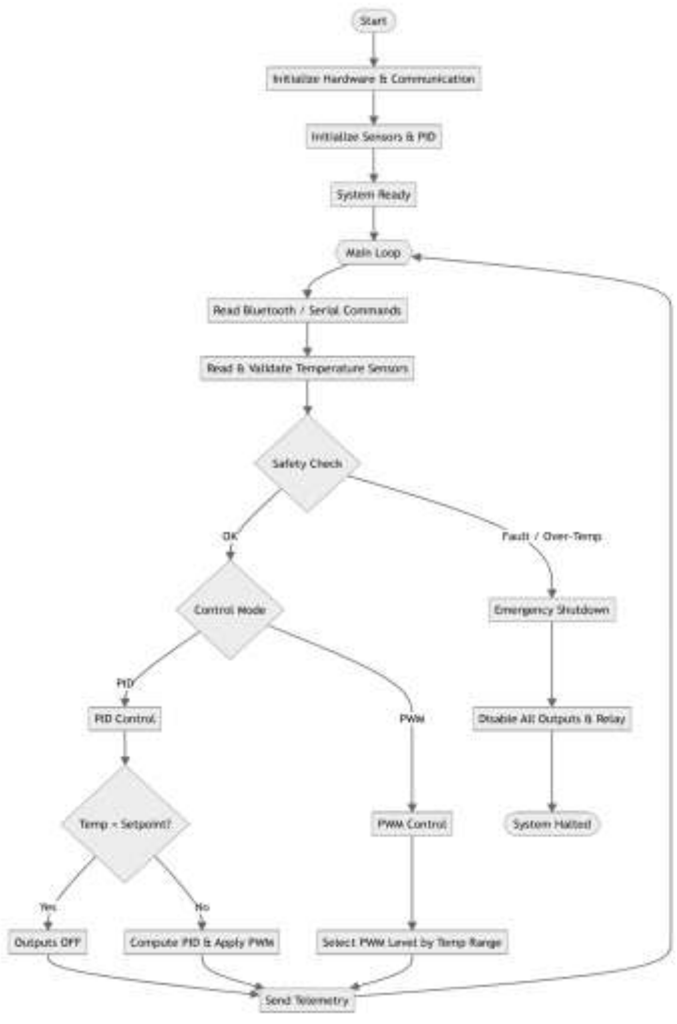

Fig. 4 - Software Flowchart

VII. COOLANT DEVELOPMENT

A. Coolant Preparation

Table V – Coolant Mixtures Tested

Sample	DW (%)	EG (%)
S1	90	10
S2	80	20
S3	70	30
S4	60	40
S5	50	50
S6	40	60

B. Thermal Conductivity

Thermal conductivity was calculated using Fourier's law:

$$K = Q \cdot L / A \cdot (T1 - T2)$$

Fig. 5 - Thermal Conductivity Test Setup

VIII. RESULTS

Table VI – Experimental Results Summary

DW:EG	Conductivity (W/m·K)	Stability	Overall Assessment
90:10	0.613	Low	High conductivity, unstable
80:20	0.596	Low	Peak but unreliable
70:30	0.528	Excellent	Best overall
60:40	0.504	Good	Increased viscosity
50:50	0.471	Excellent	Poor flow
40:60	0.580	High	Too viscous
30:70	0.618	Low	Too viscous

Fig. 6 - Conductivity vs Coolant Ratio Graph

The 70:30 mixture consistently delivered the most stable and efficient cooling behavior under long-duration tests.

IX. CONCLUSION

This study presents an adaptive thermal management system built for small electronic devices, where space is tight and heat rises fast. It combines liquid-based heat extraction, thermoelectric cooling, intelligent control logic, and coolant optimization that is actually tested. Not assumed. The idea came from a simple realization—cooling solutions exist, but they rarely work well together. The hardware is designed with safety at the center. Always. Relay-based fail-safe protection steps in when conditions go wrong. MOSFET-based power switching handles high-current loads efficiently. Optocoupler-isolated PWM control keeps noisy power stages away from sensitive electronics. Together, these choices lead to dependable operation, even under high thermal stress. Which is usually where systems fail. On the software side, control stays flexible. And fast. A dual mode framework using PID and staged PWM control enables precise temperature regulation, quick response to sudden thermal changes, and energy-efficient operation. The system doesn't just react. It adapts. That part matters. A key contribution of this work is the development of a custom IoT-based thermal conductivity testing apparatus. Instead of trusting predefined commercial coolants or datasheet numbers, coolant performance is evaluated scientifically, under real conditions. Experiments indicate that a 70:30 distilled water ethylene glycol (DW–EG) mixture offers the best overall balance. Good thermal conductivity. Acceptable viscosity. Chemical stability. Efficient pump operation. Not perfect, but close enough to ideal. Overall, the proposed solution shows improved thermal stability, operational safety, and cost-effectiveness. It fits well into embedded systems, IoT devices, power electronics, and even laboratory-scale thermal research. Small systems. Serious cooling.

X. FUTURE SCOPE

There is still clear room to push the system further. And in meaningful ways. Future improvements could start with the integration of boron nitride (BN) nanoparticles, forming nanofluids with higher thermal conductivity. Better heat transfer, right at the fluid level. Adaptive pump speed control is another natural step, allowing real-time flow optimization while cutting down unnecessary power consumption. Small change. Noticeable impact. Peltier efficiency could also be improved through closed-loop optimization, using real-time monitoring of the coefficient of performance (COP). Instead of fixed operation, the system would continuously tune itself. Cloud-based monitoring opens up a different dimension altogether—long-term thermal analytics, fault tracking, and predictive maintenance. Data that actually helps. Further miniaturization is possible through PCB-level integration, reducing system size and improving reliability at the same time. And finally, machine learning-based thermal prediction could be introduced to anticipate heat buildup before it happens, enabling proactive cooling rather than reactive correction. Taken together, these enhancements would move the proposed framework closer to high-performance, industrial-grade thermal management solutions. Not a jump. A steady evolution.

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