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Research Article

Design and Evaluation of a Cost-Effective Battery Management System for CERYAN Using Nuvoton

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Abstract

The development of Electric Vehicles (EVs) has accelerated advances in battery technology. A Battery Management System (BMS) is essential to use batteries in EVs safely and efficiently. The basic functions of a BMS include measurement, monitoring, and balancing. In the rapidly growing field of micromobility, achieving cost-effective balancing requires high-accuracy measurements. In this study, a BMS design was made with a Nuvoton NUC131 microcontroller for CERYAN, an L6e light electric vehicle, and was evaluated in terms of measurement, performance, and cost. As a result, the unit cost of the Nuvoton microcontroller is approximately 30% lower than that of STM32Fx, one of the most commonly used microcontrollers; therefore, the designed BMS prototype achieves a 27% cost reduction. In addition, the ADC measurement error is approximately 0.7 mV, which allows accurate measurement of cell voltages and efficient balancing.

Keywords: Battery management system, electric vehicle, microcontroller, Nuvoton, BMS

Nuvoton Kullanılarak CERYAN İçin Maliyet Etkin Bir BMS'nin Tasarımı ve Değerlendirilmesi

Öz

Elektrikli araçların (EA) gelişimi, pil teknolojisindeki ilerlemeleri hızlandırmıştır. Pil Yönetim Sistemi (PYS), pillerin EA'larda güvenli ve verimli kullanımı için olmazsa olmazdır. Bir PYS'nin temel işlevleri ölçüm, izleme ve dengeleme işlemlerini kapsar. Hızla büyüyen mikromobilite alanında, maliyet etkin dengeleme sağlamak yüksek doğruluklu ölçümler gerektirir. Bu çalışmada, L6e sınıfı hafif elektrikli araç olan CERYAN için Nuvoton NUC131 mikrodenetleyicisi kullanılarak bir PYS tasarımı gerçekleştirilmiş ve ölçüm, performans ve maliyet açısından değerlendirilmiştir. Sonuç olarak, Nuvoton mikrodenetleyicisinin birim maliyeti, en yaygın kullanılan mikrodenetleyicilerden biri olan STM32Fx'e kıyasla yaklaşık %30 daha düşük olduğundan, tasarlanan PYS prototipinin birim maliyeti %27 daha düşüktür. Ayrıca, ADC ölçüm hatası yaklaşık 0,7 mV olup, bu değer hücre voltajlarının doğru ölçümüne ve verimli dengelemeye olanak sağlamaktadır.

Anahtar Kelimeler: Pil yönetim sistemi, elektrikli araç, mikrodenetleyici, Nuvoton, BMS

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1. Introduction

Sustainable and environmentally friendly alternatives are becoming increasingly important in the rapidly evolving transportation sector. The most significant advances in these alternatives involve the development and design of electric vehicles (EVs). EVs are integral to the automotive economy and excel in sustainability due to their zero emissions, which aligns with essential goals in green energy transformation. On the other hand, storage systems should be considered in electric vehicle design, considering the entire life cycle of the EV [1].

Storage systems incorporate various battery types and capacities. Lithium-based batteries are the most widely used power source in EV technology due to their high energy density and long cycle life [2]. Battery Management System (BMS) monitors battery parameters for safe, reliable, and optimum operation of batteries, determines standard management intervals according to voltage levels, and determines the current operating conditions of the battery pack according to temperature readings [3].

The effective and safe operation of EVs depends on continuous BMS monitoring to ensure battery pack longevity and range [4], [5]. BMS maintenance involves temperature monitoring, cell balancing, State of Charge (SoC) management [6], [7], and optimization of battery life and performance during charge/discharge cycles. Battery Management Systems (BMS) are crucial for ensuring efficient and safe EV battery operation. Their primary responsibilities include accurate estimation of battery status parameters—State of Charge (SoC), State of Health (SoH), and State of Temperature (SoT)—which are essential for evaluating current battery conditions and predicting remaining driving range [8–10]. Given battery capacity variability, these estimations are vital for extending battery life and optimizing performance.

In addition to SoC, the accurate estimation of the State of Health (SoH) is also essential in predicting the long-term performance, safety, and reliability of batteries in electric vehicles. SoH provides insight into battery degradation patterns and capacity fade over time, which directly affect the vehicle's range and operational safety. Without reliable SoH estimation, it becomes difficult to detect early signs of aging or internal damage, potentially leading to unexpected battery failures in critical EV applications. Therefore, incorporating SoH monitoring into BMS design is a crucial step toward ensuring the overall robustness and lifecycle management of electric vehicle batteries [8–10].

In addition, the BMS manages cell balancing and controls the charge/discharge operations of the battery pack to maintain uniformity among cells and prevent overcharging or deep discharging [8], [11]. Thermal management is another critical function, enabling the BMS to regulate the battery's temperature to prevent overheating and degradation, particularly under high-load or extreme environmental conditions [12], [13]. Furthermore, the system is responsible fo Furthermore, the system is responsible for detecting and diagnosing faults, allowing early identification of potential failures and enhancing operational safety [14], [15]. Finally, the BMS facilitates communication with the user and other vehicle systems through interfaces designed for data exchange and system monitoring [15].

In [16], issues such as the state of charge and the health status of existing BMSs that directly affect the battery's performance are discussed, and solutions are presented. In [17], the hardware concepts of BMS are discussed and evaluated in terms of EVs and other applications. The direct estimation method [18] used to calculate SOC has been widely preferred because it is easy to implement. The open-circuit Voltage (OCV) estimation method is one of them. Xing and colleagues [19] collected data by measuring open circuit voltage and created a lookup table for SOC estimation. Internal resistance [20] calculated using battery voltage and current values is another parameter other than OCV used in SOC estimation.

The BMS system uses microcontrollers to perform all the specified functions of the system controls. Therefore, the selection of battery status and life estimation methods, cost, and system performance are considered to be the most optimum design and design parameters [21]. Designers prioritize making products that are environmentally friendly, energy-efficient, and zero-energy [22], in addition to producing high-performance electric vehicles. In the literature, the most widely used microcontrollers in such BMS applications are the STM32Fx series microcontrollers of STMicroelectronics [23], [24]. Considering the time loss that may occur due to computational costs and the chip crisis, Nuvoton company was preferred due to its better price and performance and easy availability. Nuvoton has also been used in the BMS design of electric garbage compaction trucks [25].

Based on a comprehensive literature review and analysis of advantages and disadvantages, this study presents a cost-effective BMS design utilizing the Nuvoton microcontroller with passive balancing methodology. The SOC estimate was made using the ampere counting method.

In general, the contributions of this study to the literature can be summarized as follows:

Cost-effectiveness: The system is designed using microcontrollers and carefully selected components that offer an optimal balance between cost and performance, making it highly affordable for practical applications.

Modularity: The design supports integration into modular battery packs, allowing flexibility in adapting to various battery configurations.

Compact structure: Its space-efficient design enables easy integration, especially in systems with limited physical space.

Stackable architecture: Thanks to its compact and modular nature, combined with isolated SPI communication, the system supports stackable implementation, enabling scalability in larger battery systems.

Isolated communication: The use of isolated SPI interfaces ensures safe and reliable data exchange between modules, enhancing the system's robustness and safety.

The rest of the paper is organized as follows: Section 2 introduces the battery management system and experimental setup and modeling of the BMS system. Section 3 presents the results of the studies, and the conclusion part is given in Section 4.

2. Material and Methods

2.1. Battery Management Systems for EVs

Batteries are electrical energy storage systems that constitute one of the most critical EV components, capable of storing significant energy amounts over extended periods, with implications for both cost and design considerations. It is divided into primary and secondary batteries, which can be charged and non-chargeable. Secondary batteries, known as rechargeable batteries, are preferred, especially for EVs. EV batteries generally consist of Li-ion batteries [26]. The batteries used in EVs and their comparative features are detailed in [27].

These battery structures consist of cells, and any cell deterioration directly affects battery life and performance. Therefore, battery systems need to be monitored correctly and have a monitoring system. A battery management system (BMS) is required for this.

BMS is a management scheme that monitors the operating system and performance of the battery pack in the energy storage system, controls its separation from the system when necessary, and optimizes it. There are some requirements for managing and integrating batteries into the battery management system. The optimum levels of these requirements directly affect battery efficiency and life [28]. It is designed to control the most efficient operation of blocks with different functions required for energy management and security in EV applications. In addition, it controls many parameters, including State of Charge (SoC) estimation, overcurrent protection, cell balancing, and thermal monitoring of battery cells, to ensure the safe operation of Li-ion batteries, which are among the preferred ones [26]. Figure 1 shows the battery management system for EVs with the corresponding functional module.



Figure 1. Battery management system for EVs

Off-the-shelf Application Specific Integrated Circuits (ASICs) are used for basic monitoring and measurement functionality. For small personal electronic devices with one battery cell, simple fuel gauge ICs provide voltage monitoring, temperature measurement, current measurement, and SOC estimation. For higher-power applications with multiple cells, ICs provide monitoring and balancing tools for multiple cells simultaneously. Advanced functions such as SOC estimation and power estimation algorithms are implemented in a centralized

module known as BMS-Master. Current measurements can be done using two sensor technologies: galvanically or isolated and hall sensors [29].

Battery cells can show voltage level differences due to production, working conditions, and environmental factors. Over time, these differences can cause some batteries in the pack to charge or discharge quickly and thus cause capacity loss and rapid aging of these battery cells. This situation within the pack is referred to as an imbalance between batteries. If an imbalance occurs, it leads to inaccurate calculations in SOC estimation. Cell voltages are monitored to prevent imbalance, and cells with high voltage differences are identified. The resulting cell imbalance is compensated with one of the cell balancing methods—cell balancing methods, which are divided into active and passive [30], [31].

The main function of the BMS includes battery condition estimation [32]. A robust estimation of SOC [33] is crucial to provide the customer with an accurate indication of the remaining range. Battery SOC is defined as the ratio of the coulomb charge currently stored in the cell to the total charge capacity of the cell. SOC cannot be measured directly, as it depends on many dynamic parameters used in sensors. Prediction algorithms are used to estimate the SOC. Estimation algorithms include measurement-based, adaptive filter, observer-based, and data-driven-based algorithms. Measurement-based estimation algorithms include Coulomb-Counting[34], Open Circuit Voltage [35], [36], and electrochemical impedance stereoscopy methods that calculate SOC by measuring physical quantities directly related to SOC. The Coulomb-Counting way, which is the most widely used method, estimates SOC by integrating the battery current. The OCV method estimates SOC based on the battery's open circuit voltage obtained after a long resting period. Adaptive filter and observer methods estimate SOC as a function of cell current, voltage, and temperature.

2.2. Experimental Setup and Modeling of the System

This study designed the battery pack according to the voltage and capacity requirements for the L6e class light electric vehicle called CERYAN, developed by Solvaytech Engineering Company in Türkiye. Cylindrical 18650 Li-ion cells were preferred. The selected battery cell has a nominal voltage of 3.7 V, a maximum voltage of 4.2 V, and a capacity of 3500 mAh. It was configured with 12 series and 19 parallel cell connections, resulting in a nominal voltage of 48 V and a total capacity of 66.5 Ah. The charge temperature range is 0/50°C, the discharge temperature range is -30°C/+60°C and the maximum discharge current is 10 A. Figure 2 shows battery parameter testing within the vehicle's Digital Twin model range calculation module, developed in MATLAB/Simulink. The number of parallel cells was determined based on the battery capacity required to achieve the desired range.

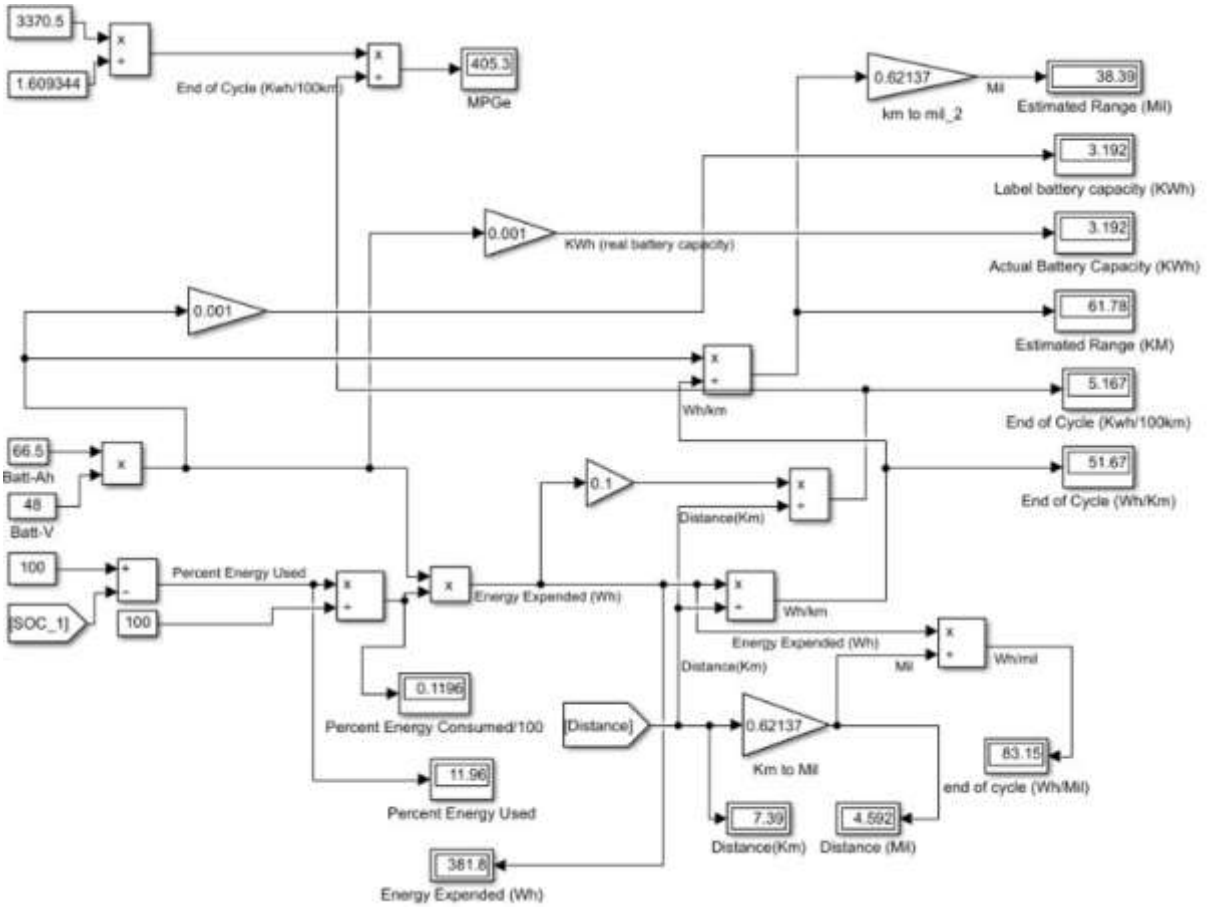


Figure 2. CERYAN Range Calculation based on the Battery capacity

Ensuring that the batteries operate within a safe range requires controlling them within specific limits. The safe operating range for the Li-ion batteries used in the CERYAN electric vehicle is specified in the manufacturer's information document as a voltage range of 2.5 V - 4.2 V and a temperature range of -30°C to +60°C. The BMS designed within this project's scope calculates the remaining energy based on the batteries' current, temperature, and voltage conditions, providing control and monitoring to ensure that the batteries operate within a safe range. Due to the chip crisis, sourcing off-the-shelf Application-Specific Integrated Circuits (ASICs) became difficult; therefore, monitoring and measurement circuit control was implemented using microcontrollers in master-slave topology. This study used the NUC131 microcontroller from Nuvoton as both the slave and master controller for BMS operations. The slave microcontrollers manage cell measurements and the balancing process, while the master microcontroller monitors the battery pack current and temperature. The master microcontroller receives cell voltage information from the slave microcontrollers via isolated SPI communication and, based on the collected data, activates the protection algorithm when necessary. The master also estimates the battery status using prediction algorithms and communicates it to the Electronic Control Unit (ECU) via CAN-Bus communication. Multiple slaves were used due to multiple battery packs in the CERYAN micro electric vehicle, providing the advantage of a stackable design, as shown in Figure 3. The BMS block diagram is provided in Figure 4, where the microcontrollers are represented as a single block.



a **b**

Figure 3. a) Block Diagram of BMS b) 3D CAD Design of Multiple Battery Pack

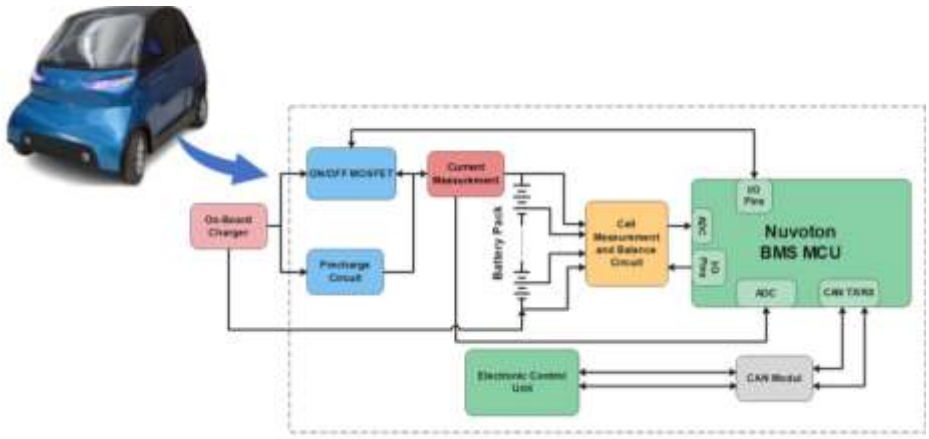


Figure 4. Block Diagram of BMS of CERYAN

Changing the differential Op-Amp gain with resistors reduced the cell voltages to suit the MCU ADC input voltage range. However, one advantage of the Nuvoton NUC131 microcontroller is that the ADC input voltage can be a maximum of 5.5 V. Thus since the battery cell voltage range is already between 2.5 V and 4.2 V, voltages can be measured directly without the need to halve the gain in the differential Op-Amp method. This has resulted in fewer components being used in the design and reduced PCB dimensions, thus reducing the cost. Cell voltage measurements are then performed by connecting the Op-Amp outputs to the ADC inputs.

The Hall effect current sensor measures the current drawing from/flowing into the battery pack. Temperature measurement is obtained using the DS18B20 temperature sensor. DS18B20 sensor is a digital temperature sensor that measures between -55 $°C$ / +125 $°C$ with 9–12-bit resolution. The sensor, which communicates using the One-Wire communication protocol, is a device communications bus system that can connect multiple temperature sensors to a single I/O pin.

The minimum and maximum voltage values set for batteries operating within certain limits are 2,7 V and 4,1 V, respectively. Current limits were determined by applying the World Motorcycle Test Cycle (WMTC) to the battery pack specified in the Digital Twin model. In this cycle, as seen in Figure 5, a maximum instantaneous current of 254 A is drawn from the battery. Considering the batteries' thermal management, the microcontroller's current limit was

determined as 200 A, as it would be more suitable for the efficiency of the battery pack. For the temperature, a maximum of 60 degrees during discharge and a maximum of 45 degrees during charge is chosen.

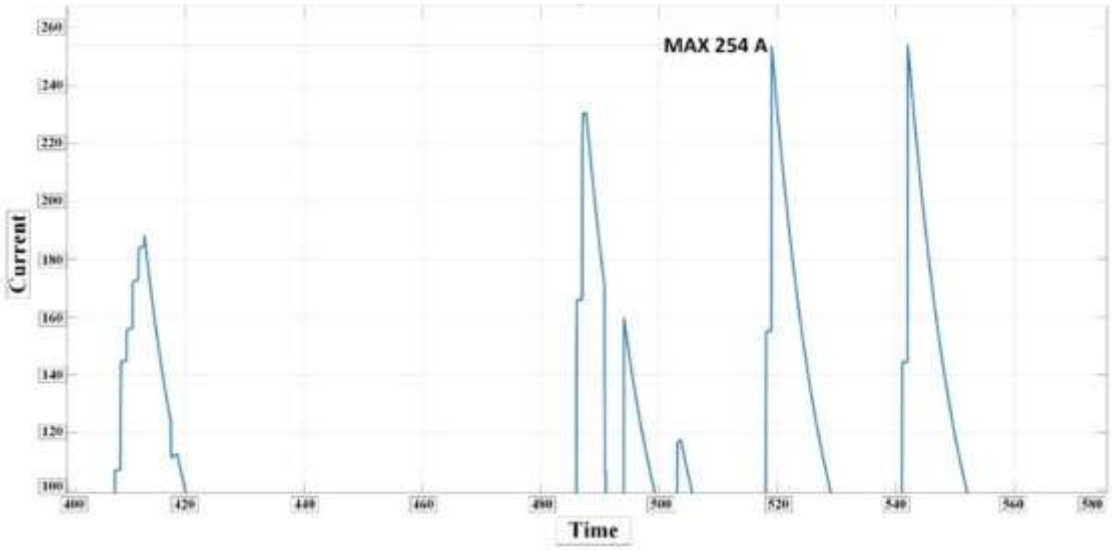


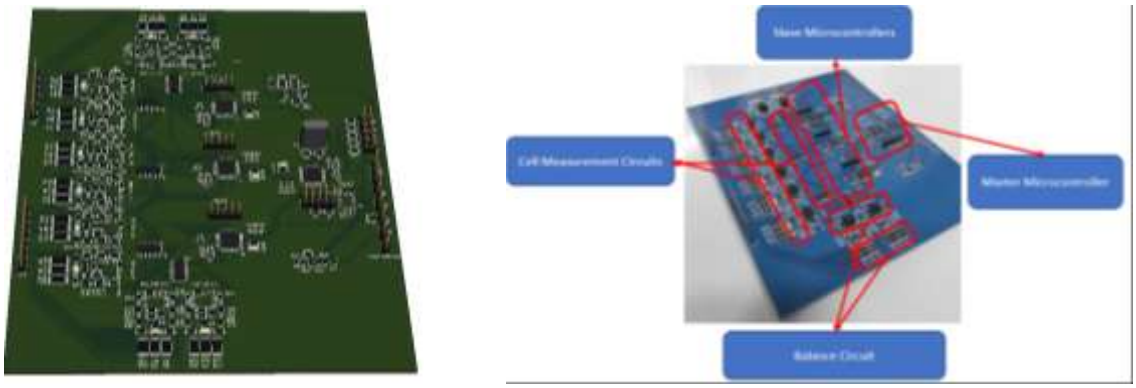
Figure 5. WMTC Cycle test on the battery pack

The microcontroller evaluates the values obtained from the measurement circuits. If it is detected that the limit values have been exceeded, the protection circuit is activated. One of the limit values is set as the upper voltage limit. During charging, when the battery pack reaches the upper limit value of 49.2 V, the protection circuit terminates the charging process. Another limit value is the lower voltage limit. During discharge, when a voltage of 32.4 V is measured, the BMS issues an over-discharge warning on the display and gradually stops the discharge process at the voltage level specified by the manufacturer. The current limit, another critical threshold, is monitored by the Hall effect sensor. If the sensor detects current values exceeding the set limit, the system disconnects the relay between the load/charger and the battery pack.

Over time, due to production and usage conditions, voltage differences may develop between the cells in the battery pack, limiting the batteries' long-term usability. The previously mentioned passive cell balancing method is employed to correct cell imbalance.

Using the passive balancing method, the BMS prevents further charging of cells that reach the voltage limit of 4.1 V during charging and waits for the other cells to reach the 4.1 V level. In the balancing process, a certain current is passed through the bleeder resistors connected to each series cell in a switching manner, generating heat. This process dissipates energy in the fully charged cells and brings them to the same level as the others. The passive balancing operation is controlled by the microcontroller in the system, as seen in Fig. 6. The microcontroller averages the incoming cell data. The average value is subtracted from each cell voltage, and if the resulting value exceeds 50 mV, the microcontroller sends a signal to the MOSFETs used as switching elements. This allows current to pass through the resistors via the MOSFET, dissipating the excess charge in the cell. This process is continuously repeated during charging.

High-power Surface Mount Device (SMD) resistors are used as bleeder resistors, with their values determined based on the balancing current.



a b

Figure 6. A) BMS Board 3D View and b) PCB view with parts

3. Results And Discussion

In this study, a cost-effective Battery Management System (BMS) was designed for use in L6e class light electric vehicles. The primary reason for selecting the Nuvoton M0 series microcontroller is its specific design for high-temperature and harsh operating conditions. The microcontroller's features, including 17 ADC channels, 6 PWM channels, and four timers, have proven effective in ensuring the precise monitoring and control functions required by the BMS, as seen in Fig. 7. Additionally, its support for various communication protocols such as UART, SPI, I2C, and CAN-Bus enhances system flexibility. It enables the design of multi-battery pack systems. Furthermore, another significant advantage is including the CAN-Bus protocol, which is essential for communication in automotive electronics.

Results demonstrate that the Nuvoton microcontroller offers high performance with a unit cost approximately 80% lower than the STM32Fx series. This cost advantage, combined with production continuity during periods of battery-integrated circuit market unavailability, demonstrates Nuvoton's viability as a commercially attractive alternative, particularly for cost-sensitive light electric vehicle applications. The growing popularity and accessibility of Nuvoton microcontrollers may further promote the adoption of this technology in future applications.

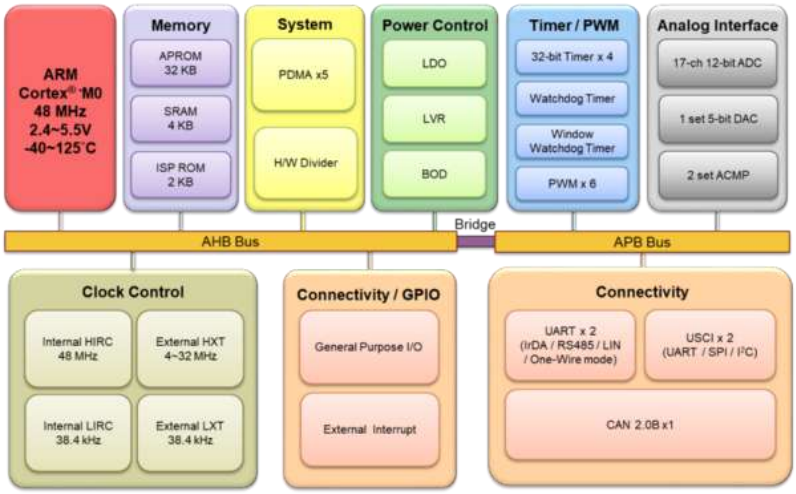


Figure 7. Nuvoton NUC131 Microcontroller Block Diagram

The battery pack was formed according to the specifications of the CERYAN EV. As seen in Table 1, it is calculated that for CERYAN with a 48 V 3 kW motor, battery cells with a nominal voltage of 3.7 V and a rated capacity of 3500 mAh should be used in 12 series and 19 parallel using the digital twin model for a range of 60 km.

Table 1. Specifications of CERYAN and BMS

Parameter	*CERYAN*	*Battery*
Voltage	48V	3,6 V – 3500 mAh
Power	3kW	12Series 48 V
Range	60km	19 Parallel 66,5 Ah

For BMS and microcontroller testing, battery cell voltages were initially recorded. After the connection between the BMS and the battery pack, the microcontroller ADC measurement accuracy was checked from the microcontroller interface. The differential Op-Amp output in the measurement circuit and the MCU ADC measurement results were compared with the noted voltage values. As a result of the comparison, it was observed that the voltages were measured with an average error of ±0.7mV in the microcontroller. This result satisfies the minimum error requirement for the BMS's measurement and SOC estimation functions.

During charging, the BMS passive balancing algorithm was activated in the battery pack. According to the algorithm, after the cell voltages are measured, they are averaged, and the difference between the average and each cell voltage is calculated. If the resulting value exceeds 50 mV, a signal is sent to the bleeding resistor switch to stabilize that cell. As shown in Figure 8, cells with significant initial voltage differences achieved balance by the end of the charging process.

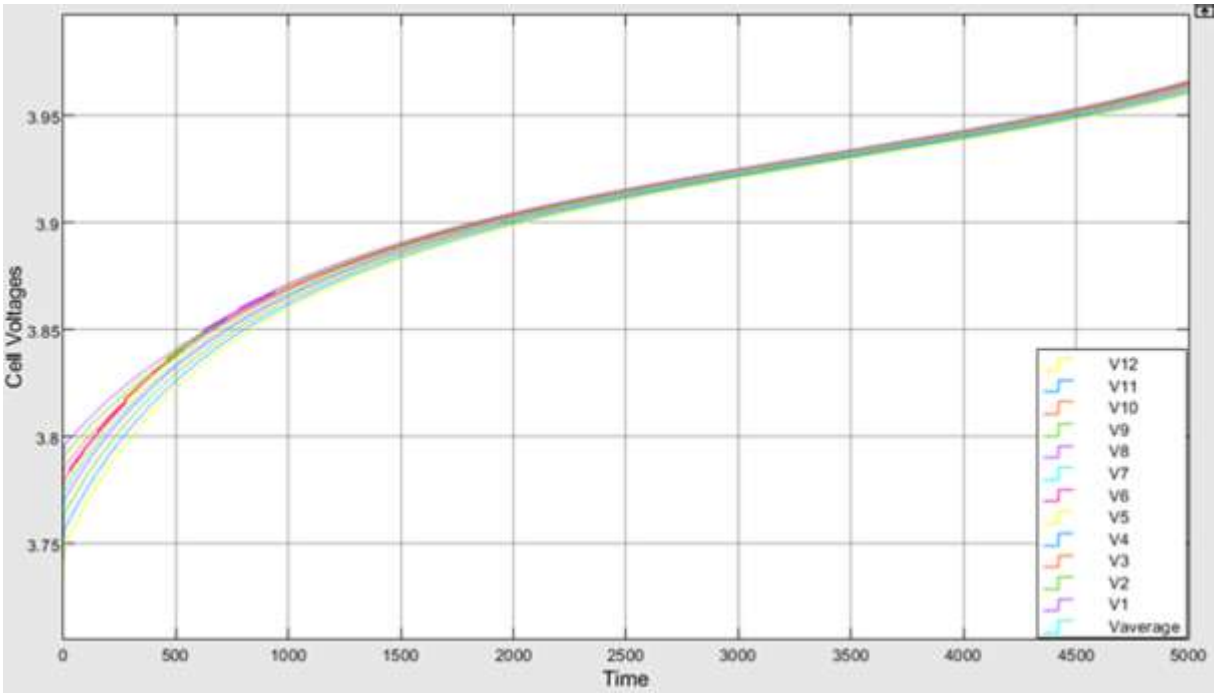


Figure 8. Balance Algorithm Results

Table 2 shows that both microcontrollers are suitable for automotive applications; however, the NUC131 is more specifically designed for certain automotive environments, such as BMS and motor control, while the STM32F042 provides a more general-purpose automotive solution with the added feature of USB connectivity.

The NUC131 may offer a more appropriate solution for specific automotive applications like BMS and motor drivers. In contrast, the STM32F042, with its USB connectivity, offers a broader range of features and support, making it more versatile across various applications.

Table 2. Comparison of STM32F0xx and Nuvoton NUC131

	STM32F0xx	*Nuvoton NUC131*
Core	ARM Cortex-M0	ARM Cortex-M0
Clock Speed	Up to 48 MHz	Up to 50 MHz
Flash Memory	32 KB	32 KB to 128 KB
RAM	6 KB	4 KB to 16 KB
Operating Voltage	2.0V to 3.6V	2.5V to 5.5V
ADC	12-bit ADC with up to 10 channels	12-bit ADC with 17 channels
Timers	Up to 5 (16-bit)	Multiple 16-bit
Communication Interfaces	USART, SPI, I2C, CAN	UART, SPI, I2C, CAN
Price	★	★★

This study eradicates microcontroller-based measurement errors due to the Nuvoton microcontroller's low ADC measurement errors. As a result of the experiment, it was observed

that measurements were taken with an error of 0.7 mV. In addition, the microcontroller software interface is straightforward to use with NuLink on-board debugger and programmer. Another advantage of the microcontroller is the broad ADC input voltage range. Since the ADC input voltage range of other microcontrollers is usually a maximum of 3.6 V, the ADC output is perceived as maximum for cell voltages of 3.6 V and above. When using a differential Op-Amp, the circuit should be designed so that the Op-Amp gain is 0.5 V/V. This can be solved by using an extra resistor in the design. The extra resistor increases the cost. At the same time, it increases the design cost, and the PCB manufacturing cost as it causes the PCB dimensions to become more prominent. Table 3 shows the cost analyses of the STM32Fx microcontroller, frequently used in the literature, and the Nuvoton microcontroller used in the Solvaytech BMS design. As seen in the table, the unit cost of the Nuvoton microcontroller is approximately 30% cheaper than the STM32Fx microcontroller. The unit cost of the BMS designed with a Nuvoton microcontroller is 27% cheaper, as shown in the table.

Table 3. Cost Analysis of BMS with Two Different Microcontrollers

	MicroController Price			*Active and Passive Components*			*BMS Unit Price*		
	Quantity			*Quantity*			*Quantity*		
	1	10	1000	1	10	1000	1	10	1000
12S19P BMS (STM Controller)	$2,78	$1,75	$1,51	$ 35,25	$28,50	$20,81	$38,03	$30,25	$ 22,32
12S19P BMS (Nuvoton Controller)	$2,01	$1,75	$1,33	$ 27,50	$23,25	$16,25	$29,51	$25,00	$17,58

4. Conclusions

With the development of Electric Vehicles (EVs), the advancement of battery technology has also accelerated. A Battery Management System (BMS) is essential for using batteries safely and efficiently in EVs. The basic functions of a BMS include measurement, monitoring, and balancing. In the rapidly growing field of micromobility, achieving cost-effective balancing requires high-accuracy measurements. This can be achieved by using high-quality ASICs or microcontrollers for measurement. In this study, ASICs could not be used due to accessibility issues, so the measurement circuit was designed using the differential Op-Amp method. The measurements were performed with a Nuvoton M0 series microcontroller. The measurement, performance, and cost values of the BMS prepared with the Nuvoton NUC131 microcontroller were discussed. Since the unit cost of the Nuvoton microcontroller is approximately 30% lower than that of STM32Fx (one of the most commonly used microcontrollers), the designed BMS

prototype unit cost is 27% lower. The Nuvoton M0 series microcontroller provides a cost advantage in design due to its wide ADC input voltage range. In addition, the ADC measurement error is approximately 0.7 mV, allowing for accurate measurement of cell voltages and efficient balancing. Future work will use this microcontroller to estimate the remaining healthy life of batteries using artificial neural networks. However, given potential uncertainties in long-term availability and supply chain stability of the Nuvoton NUC131 microcontroller, future work will explore alternative microcontrollers with similar cost-performance characteristics to ensure BMS scalability and commercial viability. In this context, cross-platform compatibility and firmware portability will be prioritized to enable seamless transitions between different microcontroller families in case of supply disruptions.

Although the proposed passive balancing method offers a cost-effective solution, it inherently results in heat dissipation during the balancing process. This heat can negatively impact battery performance and accelerate aging, particularly under high-current discharge conditions. To address these thermal concerns, future studies will focus on optimizing the balancing algorithm to reduce unnecessary energy loss and improve thermal efficiency. Additionally, alternative strategies such as semi-passive or active balancing methods will be evaluated to achieve a better balance between cost, efficiency, and thermal safety.

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

Author Contributions

S.K; Designing the study, evaluating the results, writing

A.O.P; Prototip desing, evaluating the result, collecting data

S.Y; Prototip desing, writing, evaluating the result

S.A.C; writing, evaluating the result

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