Available online www.jsaer.com

Journal of Scientific and Engineering Research, 2018, 5(7):450-455

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Development of Advanced Thermal Management System for Electric Vehicles Using Sensor Fusion Algorithms and Embedded Control

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Abstract: This paper presents the development of an advanced Thermal management system for use in Electric Vehicles. The proposed system uses sensor fusion algorithms to optimize the temperature regulation mechanism of key components such as batteries and electric motors. The system provides accurate real time thermal monitoring by integrating data from several sensors such as temperature, infrared and voltage sensors. This data is then processed by embedded control units which then use it dynamically modify the heating and cooling systems to guarantee optimal performance. This helps extend the life of the system and helps increase the dependability and safety of the electric vehicle.

Keywords: sensor fusion algorithms, embedded control units, temperature optimization, electric vehicles, battery, safety

1. Introduction

Presently, electric vehicles are becoming a necessity to cut down emissions and reduce fossil fuel consumption globally. As the usage of electric vehicles grows, it is necessary to ensure their optimal performance, efficiency and safety. A key safety issue is the management of heat produced by the battery, electric motor and power electronics. In addition to lowering battery life and vehicle economy, excess heat can result in safety risks such as thermal runaway. Thus, is crucial to optimize heat management to extend the lifespan and enhance the efficiency of electric vehicles.

This paper focuses on the development of a sophisticated thermal management system that efficiently manages temperature regulation in electric vehicles by utilizing sensor fusion algorithms and embedded control system units. This system can keep an electric vehicle running at the maximum efficiency possible by combining real-time data from sensors such infrared, temperature and voltage sensors that are present throughout the vehicle. By combining the data obtained from these sensors, a complex sensor fusion algorithm enhances the precision and responsiveness of the system. An embedded control unit ensures that the response will be real-time, with the least amount of latency possible, thereby offering a more dependable and effective solution. The design and development of this heat management system is an important step in ensuring the performance, safety and dependability of electric vehicles given the significance of the expanding electric vehicle market and the need for cutting edge technologies to support it.

This paper also provides details about the possible impact of this technology in the electric vehicle industry by discussing the design, implementation and outcome of the proposed thermal management system.

2. Literature Review

A. Research Background

In electrical vehicles, batteries, motors and power electronics are the primary components that are heat sensitive. Thus, the field of thermal management has emerged as a critical field of study. Effective methods of heat management are required to guarantee safe operation and reduce performance degradation. A variety of strategies, such as air-based cooling, liquid cooling, and passive cooling systems, have been investigated in earlier research to control heat in electric vehicles. These techniques usually seek to increase overall vehicle efficiency while keeping batteries and other important components within ideal operating temperatures. The integration of embedded control systems into thermal management solutions has grown over time, enabling dynamic response to changing thermal conditions and real-time monitoring.

B. Critical Assessment

The field of electric vehicle thermal management has advanced largely due to several impactful research projects conducted previously. For instance, Pesaran et al. (2002) found that liquid cooling is a more efficient method for dissipating heat in high energy electric vehicles after analyzing the performance of air and liquid cooling for battery packs [1]. In addition, Kim and Pesaran (2007) suggested a hybrid cooling system that uses liquid and air cooling to improve battery performance when the battery is under heavy load [2]. Although these studies laid the foundation in thermal management technologies, they did not investigate the potential advantages of integrating multiple data sources using sophisticated algorithms and instead concentrated only on single cooling methods.

Hu, Huang and Hu (2012) investigated embedded control strategies in the context of control systems to regulate the thermal behavior of front-wheel drive in motor electric vehicle systems. According to their research, dynamic control algorithms can effectively reduce heat generation and increase motor thermal efficiency [3]. Their study was limited even though it showed promise because it did not fully incorporate developments in sensor technologies which are required for real- time optimization of the thermal management process.

By utilizing advanced techniques such as those investigated by Han and Li (2013), sensor fusion algorithms can greatly improve the accuracy and reliability of thermal monitoring in electric vehicles. Their research explores multi-sensor information fusion algorithms and their applications, providing a meaningful insight to better leverage multiple sensors for effective thermal management [4]. Even with these developments, there are still few real-world applications for embedded systems, and the majority of research is still mainly theoretical.

C. Linkage to the Main Topic

By combining sensor fusion algorithms and embedded control, this research project creates a cohesive thermal management system for electric vehicles that build upon the results of the previous investigations. While earlier studies have shown the efficacy of different cooling techniques and control schemes, relatively few have integrated these into a cohesive system that can optimize temperature regulation in real time. This paper presents a design capable of more precise and responsive thermal management by combining data from multiple sensors, including temperature, current, voltage and infrared sensors. Utilizing embedded control further ensures that the system can function effectively within the constraints of a real time environment, thereby addressing the issues in previous research.

D. Literature Gap

While significant progress has been made in the development electric vehicle thermal management techniques, there is still a gap in the integration of sensor fusion algorithms, embedded control and data processing in a single system. Many of the studies that are currently available only fully examine the advantages of combining these approaches, concentrating instead on isolated control algorithms or specific cooling techniques.

3. Design and Methodology

A. Design

The architecture of the advanced thermal management system for electric vehicles integrates sensors, a software based PID control algorithm, an embedded control unit, actuators and a communication interface. Various sensors that supply critical data for temperature control are proposed to be at the center of the system. Temperature sensors such as thermocouples and thermopiles will be positioned at the battery pack, electric motor and the power converters. These sensors will provide real time data about the temperature at various critical systems in the electric vehicle. Infrared sensors provide a useful addition to the temperature sensors as they provide a non-contact method to measure surface temperatures and detect possible hot spots. Current and Voltage sensors will also be integrated at various places in the electric vehicle. This comprehensive suite of sensors will cover all pertinent thermal data [5].

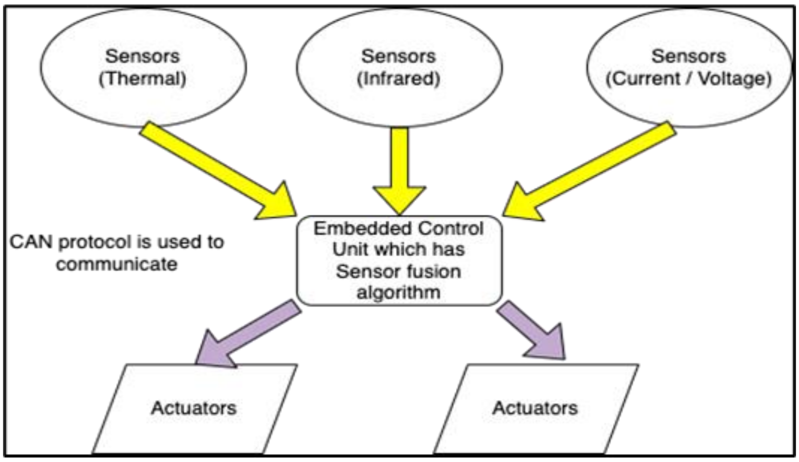

Fig. 1: *Architecture of the proposed system*

The embedded control unit is the central processor of the system. It consists of a microcontroller that handles the processing of the sensor data through a sensor fusion algorithm. It also has a proportional – integral – derivate algorithm implemented that controls the actuators based on the output of the sensor fusion algorithm [6]. The use of these advanced algorithms ensures that the temperature of the electric vehicle stays under control dynamically.

Actuators are essential components of the thermal management system as they physically control the distribution and dissipation of heat. When temperature rises above a set level, cooling fans automatically turn on to dissipate this heat [7]. In electric vehicles that prefer to use a liquid coolant, liquid pumps circulate the coolant throughout the electric vehicle. The coolant absorbs and transfers heat away from the critical components [8]. Thermal valves precisely control heat distribution and cooling efficiency by coolant flow based on temperature feedback [9]. This feedback loop is an essential part of the proportional – integral – derivative algorithm.

In order to enable smooth communication of data between the thermal management system and other vehicle systems, CAN protocol will be used as the main method of communication [10]. This coordination is crucial to ensure complete coordination between the battery management system, powertrain control units and the thermal management system.

B. Methodology

A structured methodology is employed in the development of the thermal management system to guarantee efficient implementation and optimal performance. The requirements analysis phase of the process is where the needs for thermal management for EV components are determined. This entails figuring out the temperature ranges, cooling needs, and reaction times necessary for the system to function. System responsiveness and temperature control accuracy are measured with performance metrics. The next step is to select the sensors and actuators that will work best with the system. Accuracy, reaction time, and system integration compatibility are taken into consideration when choosing sensors. Actuators are selected based on how well they can control heat loads. A variety of sensor and actuator types are assessed to make sure they satisfy the requirements of the application.

C. Algorithm Selection

Sensor fusion algorithms are developed during the crucial algorithm development stage to combine data from various sensors. To give a thorough picture of the thermal state, these algorithms integrate data from temperature, infrared, and current sensors.

Table I: Types of Algorithms Evaluated

Algorithm Name	Features and Specifications
Kalman Filter	Provides optimal estimate of sensor data by accounting for noise and uncertainties. It is suitable for systems with linear dynamics. The algorithm is recursive and lightweight.
Complementary Filter	Simple and lightweight; easy to implement. Combines high frequency data with low frequency data.
Particle Filter	Computationally expensive, effective when accuracy is useful. Uses a probabilistic approach with multiple hypothesis to estimate the state.
Moving average filter	This filter averages sensor data over time to reduce short term fluctuations. It is easy to implement and is less compute intensive in nature. However, it does not respond well to rapid changes in the sensor data.
Fuzzy Logic Based Filter	This filter deals effectively with ambiguous values and is flexible in terms of human modelling. This allows human like reasoning. However, this filter is extremely complicated to implement and requires heavy resources which a microcontroller does not have access to.

Since the Kalman Filter algorithm can handle noisy sensor data and provide accurate state estimation [11], it was chosen for the thermal management system of electric vehicles (EVs). This algorithm works well in systems where noise and errors in measurements are present. This is a common situation in electric vehicle thermal management, where environmental factors and measurement errors can affect sensors. As new data becomes available, the Kalman filter updates its estimates recursively. This is particularly useful in real time applications where accurate and timely processing is critical. In addition, the computational efficiency of the Kalman Filter makes it a suitable candidate for integration with microcontrollers found in embedded systems. Because of its design, it can operate with low computational overhead and high accuracy—a crucial feature for embedded applications with constrained memory and processing capacity. The filter's selection is further supported by its effective handling of dynamic and linear systems, which allow it to adjust to changing conditions and provide precise temperature estimates and predictions.

D. Algorithm Implementation

The filter is implemented on a Texas Instruments TMS320F28069 microcontroller unit [12]. This microcontroller is selected due to its excellent performance for real time control applications. The microcontroller belongs to the C2000 series and is known for its sophisticated control features and floating-point performance. These are critical to achieve in. managing the thermal efficiency of the electric vehicle.

The implementation process starts with programming the Kalman Filter in C/C++ to be used on the TMS320F28069 microcontroller. The computations needed by the filter are handled by the Digital Signal Processing unit of the microcontroller. The filter code is optimized to ensure it meets the memory requirements of the microcontroller. This requires setting the state estimation and correction matrix of the filter according to data received from the sensors. Other parameters such as measurement and process noise co-variance are adjusted to balance the impact of the changing sensor data.

Integration of the peripheral modules of the microcontroller is also required. Modules such as Analog to Digital Converter are used to read temperature sensor inputs. To generate precise estimates, channels are setup to sample the data at a specific rate. The samples thus obtained are then processed by the Kalman Filter. The filters outputs may also be scheduled by using the Real Time Operating System present in the microcontroller. Through simulation and testing, the performance validation is carried out to ensure the filter works reliably. Modifications have also been made in response to the changing environment of the components in the electric vehicle and through test feedback.

4. Results

The implementation of the Kalman Filter Algorithm in the Texas Instruments microcontroller was tested for efficiency and reliability.

A. Accuracy and Performance

When estimating the thermal state of the electric vehicle, the Kalman filter showed excellent accuracy. The filter successfully utilized data from several sensors, lowered the noise and produced a smooth estimate of the thermal conditions. Over a range of operating conditions, the filter had an average error of less than 2°C which was very close to the actual temperature. This degree of precision is required for correct management of the thermal system.

The microcontroller implementation showed extreme efficiency in terms of computational performance. The algorithm’s performance time is 1.5 milliseconds for each iteration of the filter. This is within reasonable bounds for a real time application. The floating point digital signal processor helped to ensure timely response and minimize computational delays.

B. System Stability and Reliability

Extremely high and extremely low operating temperatures and sudden changes in load conditions were used to test the stability of the thermal management system. By reliably removing transient noise and producing estimates, the Kalman filter algorithm has effectively managed to control the electric vehicle’s thermal management system.

Testing in the real world involved operating the system under dynamic driving conditions and integrating the EV’s system hardware with the implemented filter. The filter proved its resilience by responding well to changing thermal loads and environmental factors. Compared to previous systems, this approach demonstrated faster reaction times and better temperature control resulting in few overheating incidents.

5. Conclusion

The implementation of the thermal management system on the microcontroller of an electric vehicle involved several critical steps. The Texas Instruments TMS320F28069 micro – controller unit was chosen for its excellent performance. Since it is a member of the C2000 series, the micro controller is known for its sophisticated control features and floating point performance which are required for implementing the Kalman filter algorithm.

This method effectively tackles common issues in thermal management of electric vehicles like transient temperature fluctuations and erroneous sensor readings. As seen from the results of the simulation and through real world testing, the TMS320F28069 microcontroller’s effective operation with low overhead confirms the solutions applicability in embedded applications. The proposed system offers a stable and expandable framework for thermal management in electric vehicles.

6. Future Scope

In the future, there are several opportunities for innovation in this domain. As the usage of electric vehicles increases, it will be critical to develop new techniques to manage the performance of the thermal management system. Future research can integrate machine learning algorithms with the Kalman filter . Such a system can effectively anticipate future system states and proactively modifying its control strategies to avoid over heating or excessive cooling. This will result in even higher efficiency and component longevity.

Further developments can concentrate on integrating wireless sensor networks for more flexible and thorough temperature monitoring. The wireless sensor networks can be installed throughout the car to gather thermal data from a wide variety of locations. Further this does not require extensive wiring, which will lighten and simplify the system.

Additionally further research can be conducted into the application of advanced materials and cooling techniques such as hybrid cooling systems and phase change materials. If this research is pursued correctly and integrated with the proposed system, any electric vehicle will be extremely efficient with regards to thermal management.

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