Optimizing LSTM for Low-Power SOC Estimation on ESP32 Using TinyML Techniques

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ABSTRACT

In this study, TinyML technology was applied to estimate the state-of-charge (SOC) of a lithium ion battery using ESP32, a memory limiting device. The algorithm used is LSTM (Long Short-Term Memory), which is quantized to be distributed to a microcontroller unit (MCU). Quantization is a technology that increases computational efficiency while reducing the memory requirements of the model. It enables machine learning models to run on devices such as ESP32 with limited memory. Through the LSTM model, complex temporal patterns that may occur at various charging stages of the battery were learned, and through this, high-accuracy SOC estimation was possible. In this paper, the effect of quantization on SOC estimation performance was evaluated by comparing and analyzing the accuracy (RMSE, MSE, etc.) of SOC estimation results before and after quantization.

1. Introduction

Lithium-ion batteries are the dominant energy storage solution in portable electronics, electric vehicles, and grid storage systems. Accurate state-of-charge (SOC) estimation is crucial for optimal battery performance, safety, and lifespan. Traditional methods for SOC estimation rely on voltage and current measurements[1]. However, these approaches suffer from limitations such as temperature dependency and aging effects, leading to inaccurate estimations, particularly during dynamic operating conditions[2].

Machine learning offers a promising alternative for accurate and robust SOC estimation. Several studies have demonstrated the effectiveness of machine learning techniques like support vector regression (SVR)[3] and artificial neural networks (ANNs)[4] for SOC estimation. However, deploying complex models on resource-constrained devices with limited memory and processing power remains a challenge. This is where TinyML emerges, focusing on training and deploying machine learning models on devices with minimal computational resources.

Recent research explores the application of TinyML for battery management tasks. Yahia et al.[5] implemented a lightweight 1D-CNN and GRU-recurrent neural network model for SOC estimation on an STM32 microcontroller. The study achieved promising results with low memory footprint and computational requirements.

This work builds upon this growing body of research by investigating the application of LSTM networks, a type of RNN well-suited for capturing long-term dependencies in sequential data, for SOC estimation on the ESP32 microcontroller. We further explore the use of model quantization to enable deployment on the memory-constrained ESP32 device while maintaining high accuracy.

2. Proposed Methodology

Our proposed methodology leverages a LSTM network for accurate SOC estimation on the memory-constrained ESP32 microcontroller. To achieve this, we first train an LSTM model on a dataset containing battery voltage, current, temperature, and corresponding SOC values. Following successful training, post-quantization is applied to the model. This technique reduces the precision of weights and activations within the LSTM network, significantly shrinking its memory footprint. Finally, the quantized model undergoes fine-tuning on a portion of the training data to minimize any potential performance degradation caused by quantization. This approach allows for deploying a complex LSTM model on the ESP32 while maintaining high accuracy in SOC estimation.

3. Results analysis

To achieve this, we first train an LSTM model on a specifically curated dataset. This dataset houses historical recordings of battery voltage, current, temperature, and their corresponding SOC values. However, directly deploying a complex LSTM model on the ESP32 presents a challenge due to its limited memory resources. Here's where post-quantization comes into play. This technique essentially reduces the model's size by lowering the precision of its internal data, specifically the weights and activations within the LSTM network.

Table 1 Per unit values of the system parameters

Reference	Model	RMSE (%)	MAE (%)
[5]	1D-CNN	2.691	2.249
	GRU	3.330	2.80
Proposed	LSTM	2.05	1.56

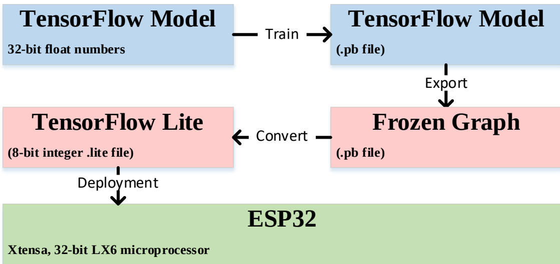


Fig.1 Block diagram depicting the tensorFlow steps used to convert proposed LSTM model into tflite format.

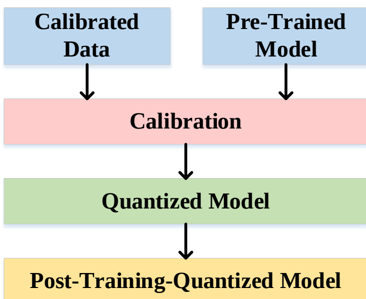
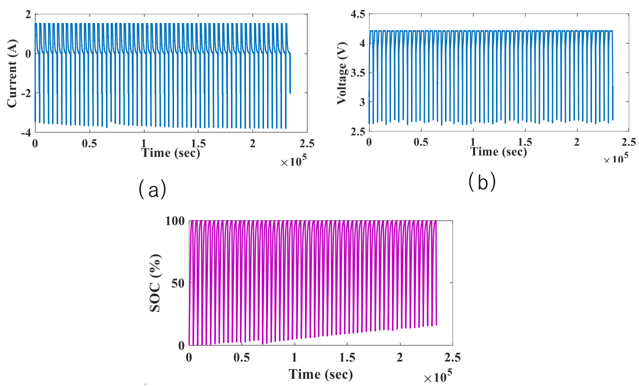


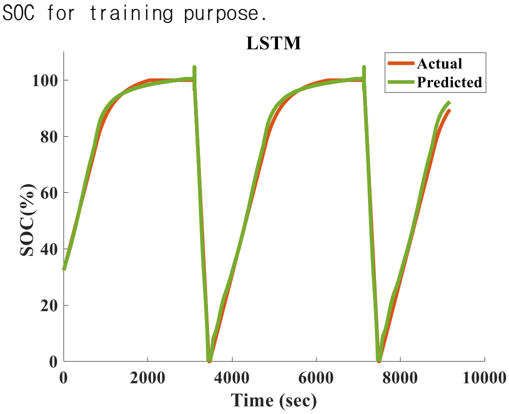
Fig. 2 Post quantization involves data calibration of the pre-trained model.



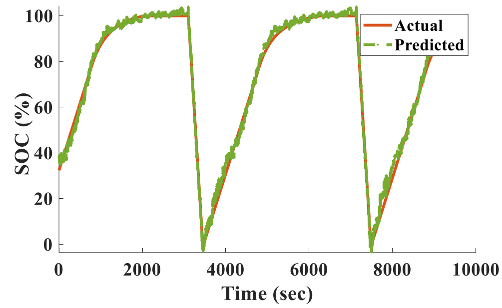
(a) (b)

(c)

Fig.3 Dataset illustration containing Current, Voltage and SOC for training purpose.



(a)



(b)

Fig. 4 SOC estimation results (a) before quantization, (b) after quantization.

4. Conclusion

This work demonstrates the feasibility of utilizing TinyML for high-accuracy SOC estimation on memory-constrained devices like the ESP32. By leveraging LSTM networks and model quantization, we achieve accurate battery monitoring suitable for resource-limited smart devices. Future work could explore further model optimizations, incorporate additional sensor data, and investigate real-world deployment in battery management systems.

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