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AN EFFICIENT AIOT FRAMEWORK FOR IMAGE-BASED BEHAVIOR MONITORING IN DAIRY CALVES

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Abstract: Monitoring behaviors in dairy cattle is crucial for efficient livestock management and welfare enhancement, as variations in behavioral patterns often signal health issues. Image-based behavior monitoring systems are non-invasive and suitable for automated dairy farming practices, while these intelligent systems require substantial computational resources to process consecutive video frames, which makes it challenging to deploy behavioral recognition models on edge devices in dairy farms. Therefore, our objective is to develop an efficient AIoT framework for image-based behavior monitoring system for dairy calves, which balances computational demands with reliable recognition performance. In this study, several MoViNet models for dairy calf behavior recognition were compared and evaluated based on their predictive performance and hardware efficiency on Raspberry Pi 4. The analysis revealed that MoViNet-A0 with Float16 Quantization achieved the best performance in behavior recognition, with a 47ms latency and a 0.916 F1-score. Additionally, long-term behavior monitoring at the National Taiwan University's experimental dairy farm was conducted to assess the effectiveness of our AIoT dairy calf behavior monitoring system in real-world settings. The experiment demonstrated that our threshold-based calibration approach effectively enhanced model predictions, with a decrease in MAPE from 60.1% to 10.4% and RMSE from 82.4 to 13.1 in behavior monitoring in dairy calves.

Key Words: Behavior Monitoring, Image Recognition, Deep Learning, Edge Computing

INTRODUCTION

Behaviors reflect health conditions, and behavior monitoring in dairy cattle is essential for assessing their health status. This is particularly critical for newborn dairy calves, whose immune and digestive systems are not yet fully developed, making them susceptible to conditions such as neonatal calf diarrhea (NCD), which accounts for 75% of losses within their first month. Dairy calves suffering from the disease have been reported to exhibit reduced milk intake, slower drinking rates, decreased lying time, and more frequent lying bouts (Knauer et al., 2017; Swartz, 2020). Early detection of these abnormal behavioral characteristics can significantly aid in preventing severe health issues in dairy calves. Compared to human observation, automatic behavior monitoring systems provide efficient, objective measurements that facilitate efficient data-driven management in dairy farms. Studies have explored wearable devices with sensors such as accelerometers (Li et al., 2022) and GPS for accurate measurements and real-time monitoring in dairy cattle. Despite their precision and variety, these technologies cause potential stress, especially for neonatal dairy calves. Recently, rapid advancements in deep learning and computer vision have made image-based solutions viable for monitoring behaviors in dairy cattle. These methods capture data from multiple animals at once, allowing them for large-scale livestock monitoring. Additionally, unlike wearable sensor-based monitoring, this non-contact approach prevents potential disturbance to the easily frightened dairy calves. To support the well-being of the calves and dairy farm management practices, this research aims to develop an efficient AIoT framework for image-based behavior monitoring system specifically designed for dairy calves.

MATERIALS AND METHODS

Fig. 1 illustrates our AIoT behavior monitoring framework, encompassing model development, automated behavior recognition, and long-term cloud-based monitoring. This study conducted a comparative analysis to explore the impacts of various factors on predictive performance and hardware efficiency of the models and the effectiveness of long-term behavior monitoring.

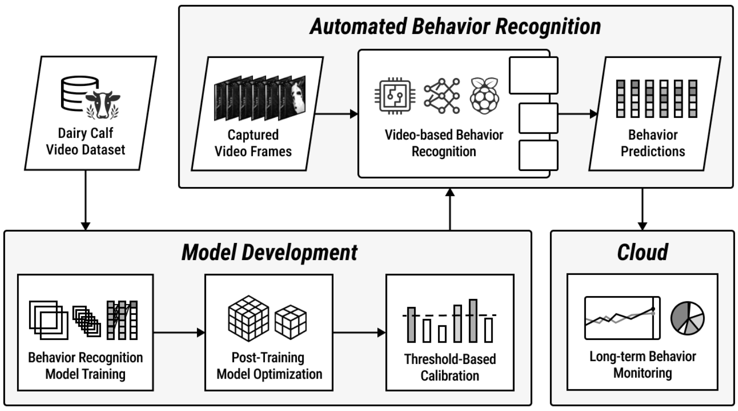


Fig.1 System overview of the AIoT dairy calf behavior monitoring framework.

IMAGING SYSTEM FOR BEHAVIOR MONITORING

In this study, an imaging system was designed for efficient behavior monitoring in dairy calves. The setup consisted of a Raspberry Pi 4 Model B with a Logitech webcam, supporting real-time image transmission over Wi-Fi using ZeroMQ and SFTP. Installed on the crossbeam at the NTU’s experimental dairy farm, this system enables continuous 24-hour monitoring.

DAIRY CALF BEHAVIOR RECOGNITION

This study focuses on seven behaviors in dairy calves: non-active lying, active lying, non-active standing, active standing, feeding, drinking, and ruminating. To efficiently recognize these behaviors, the MoViNet-Stream deep learning models were employed for real-time inference on streaming video (Kondratyuk et al., 2021). Various MoViNet-Stream models of varying complexities, including A0, A1, and A2 were compared. Their predictive performance was evaluated by average F_1-score, while hardware efficiency was assessed by inference latency and peak memory usage on Raspberry Pi 4.

POST-TRAINING MODEL OPTIMIZATION

Post-training optimization of the behavior recognition models on Raspberry Pi was achieved using TensorFlow Lite, which supports Raspberry Pi's quad-core ARM Cortex-A72 processor for efficient inference. In this research, post-training Float16 Quantization and Int8 Quantization were used to boost inference speeds by lowering the precision in the model's weights and activations. Float16 Quantization reduces the model's precision to 16-bit floating-point values, while Int8 Quantization further compresses the model's precision to 8-bit integers for smaller model size and faster computation. Through comparative analysis of different quantization techniques, we aim to identify the most suitable settings that minimize computations while maintaining reliable recognition performance.

THRESHOLD-BASED CALIBRATION

To enhance continuous monitoring performance, model outputs were further calibrated using thresholds obtained from the Precision-Recall curve to maximize F1-scores. The final predictions were determined by selecting the class with the highest probability above the thresholds, while predictions without exceeding these thresholds were discarded.

LONG-TERM DAIRY CALF BEHAVIOR MONITORING

At the National Taiwan University's experimental dairy farm, a long-term experiment was conducted to test the effectiveness our AIoT system. Daily predictions of multiple models were compared with actual behavioral observations, with performance evaluated by mean absolute percentage error (MAPE) and root mean squared error (RMSE).

RESULTS & DISCUSSION

BEHAVIOR RECOGNITION MODEL PERFORMANCE

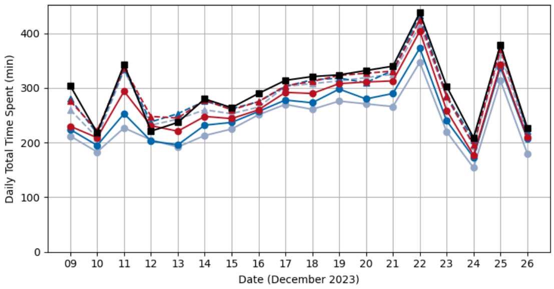
Table 1 compares the predictive performance and hardware efficiency of multiple model architectures and quantization techniques. While MoViNet-A2 Float32 and Float16 models achieved top F_1-scores of 0.929, their latencies are too high to meet the expected FPS of 10. Alternatively, the MoViNet-A0 Float16 model, with its low latency of 47ms and acceptable F_1-score of 0.916, stands out as the most suitable for dairy calf behavior monitoring.

Table 1 Comparative performance analysis of MoViNet architectures with different quantization techniques (*Float32: No Quantization).

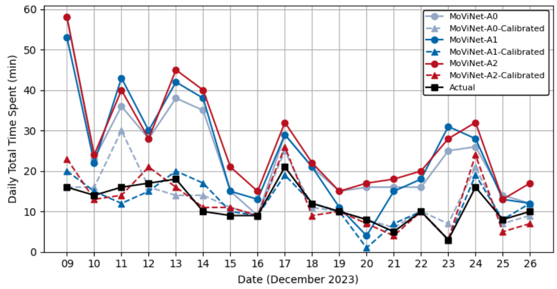
Model	Quantization	Latency (ms)	Peak Memory Usage (MB)	Average F_1-score
MoViNet-A0	Float32*	49	49	0.916
	Float16	47	58	0.916
	Int8	35	44	0.312
MoViNet-A1	Float32*	118	64	0.918
	Float16	98	86	0.918
	Int8	49	50	0.579
MoViNet-A2	Float32*	170	97	0.929
	Float16	154	120	0.929
	Int8	78	69	0.764

LONG-TERM DAIRY CALF BEHAVIOR MONITORING PERFORMANCE

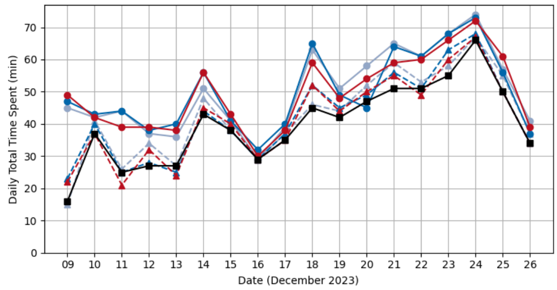
The long-term experiment at the NTU's experimental dairy farm demonstrated significant improvements through threshold-based calibration, as shown in Fig. 2 (a) through (d). This calibration effectively reduced the average MAPE from 60.1% to 10.4% and RMSE from 82.4 to 13.1, thus capturing accurate behavioral patterns during the calves' developmental stages.



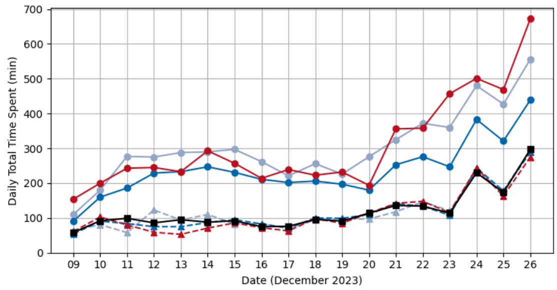
(a)



(b)



(c)



(d)

Fig. 2 Long-term behavior monitoring performance. (a) active standing, (b) drinking, (c) feeding, and (d) ruminating.

CONCLUSIONS

This study demonstrates the performance of our AIoT framework for image-based behavior monitoring in dairy calves. The comparative analysis reveals that MoViNet-A0 with Float16 Quantization, achieving a 47ms latency and a 0.916 F_1-score, is optimally suited for dairy calf behavior monitoring. Additionally, our long-term experiment at NTU's experimental dairy farm validates the effectiveness of the system and our calibration approach in improving model predictions, lowering the MAPE from 60.1% to 10.4% and RMSE from 82.4 to 13.1.

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