Project Final Report - ECE 176

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Abstract

Recent wildfires, such as the California bushfire, have demonstrated the need for fast and efficient fire detection systems to prevent widespread destruction. Traditional deep learning-based fire detection models, while effective, suffer from high computational costs and slow inference speeds, making them impractical for real-time deployment on edge devices. This project proposes a hybrid CNN-HDC model, integrating Convolutional Neural Networks (CNNs) for feature extraction with Hyperdimensional Computing (HDC) for real-time classification. The proposed system aims to improve both detection speed and energy efficiency while maintaining high accuracy. The hybrid approach will be evaluated on real-world fire datasets to compare its performance with traditional deep learning models. [1] [2] [3] [4]

1 Problem Definition

1.1 Motivation

Wildfires have caused devastating environmental and economic damage, especially in California and other fire-prone regions. Early detection is critical to minimize destruction, butaditional sensor-based detection methods have limitations, including false alarms and slow response times. Current deep learning-based vision systems are accurate but often require high computational resources, making them unsuitable for real-time edge deployment in forests or remote areas.

1.2 Key Challenges

One of the primary challenges in wildfire detection using computer vision is the high computational cost associated with CNNs. These models require millions of floating-point operations, which makesmakes them slow and energy-intensive, which is particularly problematic for real-time applications running on edge devices. Additionally, false positives pose a significant issue, as fire-like patterns, such as sun glare, vehicle headlights, or reflections, can be mistakenly classified as flames, leading to unnecessary alerts. Lastly, data scarcity remains a concern, as labeled datasets containing various fire scenarios under various environmental conditions are limited, making it difficult to train models that generalize well in real-world wildfire detection scenarios.

1.3 Understanding of the Problem

CNNs have demonstrated high accuracy in feature extraction, making them effective at recognizing flames, smoke, and other fire-related patterns. However, their high computational demands make them less practical for real-time deployment on resource-constrained edge devices. On the other hand, HDC provides a lightweight, energy-efficient approach to classification, enabling fast decision-making with minimal computational overhead. A hybrid CNN-HDC model can integrate the strengths of both paradigms, utilizing CNNs for robust feature extraction while using HDC for rapid classification, leading to an efficient and accurate wildfire detection system.

2 Tentative Method

For the hybrid CNN-HDC model, CNN extracts strong visual features and HDC prevents overfitting. Moreover, HDC provides binary vector-based decisions, reducing inference time. The strength of this model is the following. HDC ensures efficient, real-time fire detection for edge devices. CNN provides high-quality feature extraction for complex fire scenarios. New fire types can be added dynamically without retraining the entire model.

- Feature Extraction (CNN)
  A pre-trained CNN (ResNet18) extracts key fire-related features (flame texture, color, smoke patterns).
- Hyperdimensional Encoding (HDC)
  CNN-extracted features are converted into high-dimensional vectors (HDVs) using TorchHD encoding techniques. HDC-based associative memory is used for rapid classification and decision-making.
- Hybrid Classification
  HDC performs fast, robust fire detection, identifying whether a frame contains fire. Furthermore, Softmax-based deep learning classifier could be used for fine-grained classification.

3 Experiments

3.1 Datasets

Large-scale dataset with labeled wildfire images:

D-Fire: an image dataset for fire and smoke detection [5]

3.2 Experimental Setup

- Baseline Model: CNN + Softmax for fire detection.
- HDC-Only Model: HDC for binary fire recognition.
- Hybrid Model: CNN extracts features, HDC classifies fire presence, and Softmax refines the output.

3.3 Evaluation Metrics

- Accuracy: Mean Average Precision (mAP) for fire detection.
- Inference Speed: Frames per second (FPS) on edge devices.
- False Positive Rate: Avoiding misclassifications.

References

[1] Dutta, A., Gupta, S., Khaleghi, B., Chandrasekaran, R., Xu, W., & Rosing, T. (2022). HDnn-PIM: Efficient in Memory Design of Hyperdimensional Computing with Feature Extraction. Proceedings of the Great Lakes Symposium on VLSI 2022. https://doi.org/10.1145/3526241.3530331

[2] Luczak, P., Slot, K., & Kucharski, J. (2022). Combining Deep Convolutional Feature Extraction with Hyperdimensional Computing for Visual Object Recognition. 2022 International Joint Conference on Neural Networks (IJCNN), 1–8. https://doi.org/10.1109/ijcnn55064.2022.9892281

[3] Ma, D., Hao, C., & Jiao, X. (2022). Hyperdimensional Computing vs. Neural Networks: Comparing Architecture and Learning Process. 2024 25th International Symposium on Quality Electronic Design (ISQED), San Francisco, CA, USA, 2024, pp. 1-5. https://doi.org/10.1109/isqed60706.2024.10528698

[4] E. Hassan, M. Bettayeb, B. Mohammad, Y. Zweiri and H. Saleh, "Hyperdimensional Computing Versus Convolutional Neural Network: Architecture, Performance Analysis, and Hardware Complexity," 2023 International Conference on Microelectronics (ICM), Abu Dhabi, United Arab Emirates, 2023, pp. 228-233. https://doi.org/10.1109/icm60448.2023.10378944

[5] Pedro Vinícius Almeida Borges de Venâncio, Adriano Chaves Lisboa, Adriano Vilela Barbosa: An automatic fire detection system based on deep convolutional neural networks for low-power, resource-constrained devices. In: Neural Computing and Applications, 2022. https://link.springer.com/article/10.1007/s00521-022-07467-z