EE 4065 – Embedded Digital Image Processing

Homework 4: Handwritten Digit Recognition

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1. Introduction

In this homework, handwritten digit recognition is studied using the MNIST dataset and two different neural network approaches. The implementations are based on Section 10.9 and Section 11.8 of the book "Embedded Machine Learning with Microcontrollers" by Ünsalan, Höke, and Atmaca. Hu Moments are used for feature extraction in both approaches. All training procedures are performed offline on a PC environment.

2. Q1 – Binary Classification with a Single Neuron

In the first part, the handwritten digit recognition problem is simplified into a binary classification task. The two classes are defined as digit "0" and "not zero" . A single neuron classifier with sigmoid activation is used.

2.1 Feature Extraction

For each MNIST image, seven Hu Moments are extracted using OpenCV. Hu Moments are invariant to translation, rotation, and scaling, making them suitable for embedded applications.

2.2 Normalization

The extracted features are normalized using the mean and standard deviation computed from the training set. The same normalization parameters are applied to the test set.

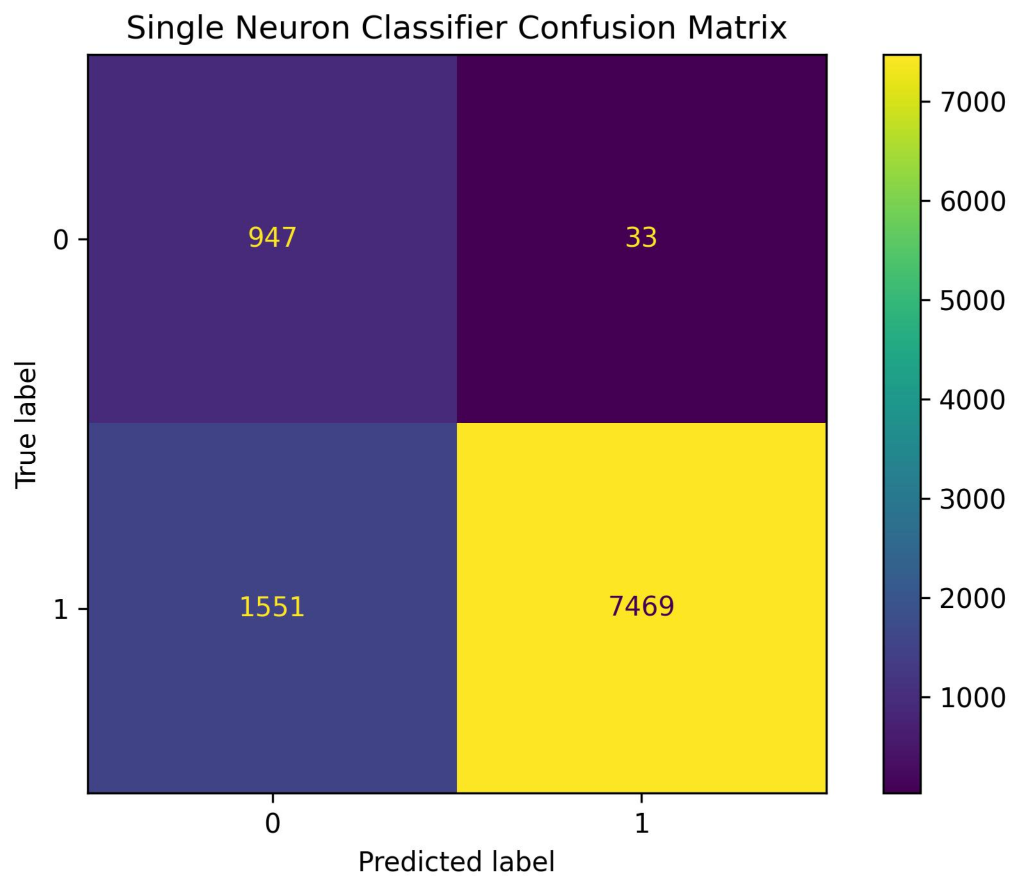
2.3 Model Architecture and Training

The classifier consists of a single dense layer with one neuron and sigmoid activation. The model is trained using the Adam optimizer and binary cross-entropy loss. Class weighting is applied to handle the imbalance between the classes.

2.4 Results

The confusion matrix obtained from the test set shows that most digits are classified correctly. The overall test accuracy is 84.47%.

The model achieves a high recall for digit zero, while some non-zero digits are incorrectly classified as zero. This behavior is expected due to the limited representational capacity of a single neuron and the heterogeneous nature of the non-zero class.




```
Model saved as 'mnist_single_neuron.h5'

Final Test Results:
Test Loss: 0.2942
Test Accuracy: 0.8438
```

3. Q2 – Multiclass Classification with a Multilayer Neural Network

In the second part, a multiclass classification problem is addressed, where digits from 0 to 9 are classified. A multilayer perceptron (MLP) is used to increase the model capacity.

3.1 Model Architecture

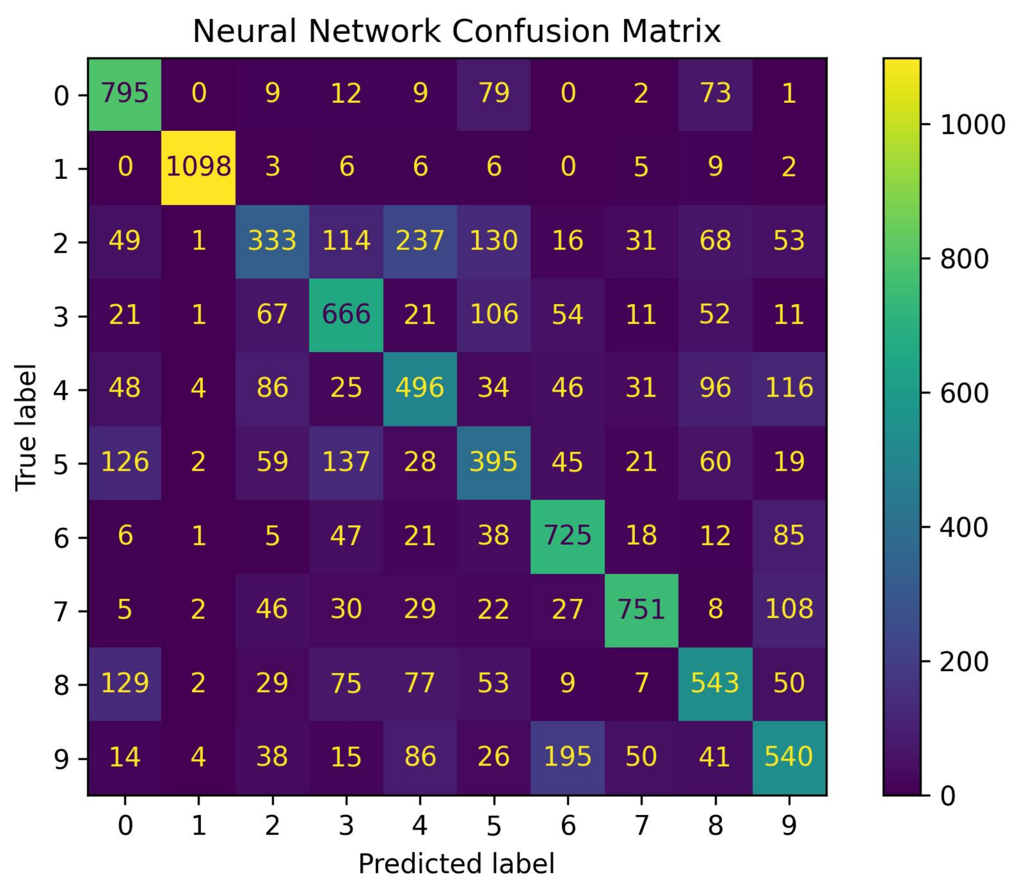
The MLP consists of two hidden layers with ReLU activation functions and an output layer with softmax activation. This architecture allows the model to learn more complex decision boundaries compared to the single neuron model.

3.2 Training Strategy

The model is trained using the Adam optimizer and sparse categorical cross-entropy loss. Early stopping is applied to prevent overfitting.

3.3 Confusion Matrix Analysis and Results

The 10×10 confusion matrix reveals that visually similar digits such as 2–4, 3–5, 8–0, and 9–7 are occasionally confused. These errors indicate the limitations of Hu Moments in capturing fine-grained structural details.



```
Test Accuracy: 0.6342 (63.42%)

Confusion matrix saved as 'q2_confusion_matrix.png'

Per-class Accuracy:
Class 0: 795/980 = 0.8112 (81.12%)
Class 1: 1098/1135 = 0.9674 (96.74%)
Class 2: 333/1032 = 0.3227 (32.27%)
Class 3: 666/1010 = 0.6594 (65.94%)
Class 4: 496/982 = 0.5051 (50.51%)
Class 5: 395/892 = 0.4428 (44.28%)
Class 6: 725/958 = 0.7568 (75.68%)
Class 7: 751/1028 = 0.7305 (73.05%)
Class 8: 543/974 = 0.5575 (55.75%)
Class 9: 540/1009 = 0.5352 (53.52%)

Model saved as 'mlp_mnist_model.h5'
Training completed!
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4. Comparison of Q1 and Q2

The single neuron model offers low computational complexity and is suitable for embedded systems with limited resources. However, its classification capability is limited. The multilayer neural network achieves better discrimination among digits at the cost of increased model complexity.

5. Conclusion

In this homework, handwritten digit recognition was implemented using Hu Moment features and two different neural network models. The single neuron classifier achieved reasonable performance for the binary classification task with low computational cost. The multilayer neural network provided better discrimination for multiclass digit recognition, although some visually similar digits were still confused. The results demonstrate the trade-off between model simplicity and classification accuracy, especially for embedded system applications.

6. References

1. C. Ünsalan, B. Höke, and E. Atmaca, Embedded Machine Learning with Microcontrollers, Springer, 2025.
2. MNIST Handwritten Digit Database, Yann LeCun.
3. TensorFlow and Keras Documentation.
4. OpenCV Documentation.