Detection of Black Ice in Autonomous Vehicles Using Inertial Measurement Based Binary Classification Neural Network

By Cooper Wang

ABSTRACT

Black ice poses significant challenges to driving, specifically autonomous driving, due to its difficulty to detect and its impacts on the vehicle safety. Present methods for detecting black ice, although accurate, are still vulnerable to external environmental influences and cannot function in certain environments. Therefore, the research looks into novel methods of all environment black ice detection, using inertial measurement data collected with a scale model of vehicles to train neural networks for binary classification of road conditions. The resulting method from two separate neural network structures are 98.8% and 99.5% accurate respectively, and deployment of the neural network onto Tensor Processing Units (TPU) is proved to be feasible with the average inference time being 0.75 milliseconds and the standard deviation being 0.13 milliseconds. A Two Proportions Z-Test also proves the method's improvement in accuracy to be statistically significant.

BACKGROUND AND RATIONALE

- Autonomous vehicles use is on the rise
  - **There are 31 million autonomous vehicles worldwide**
  - By this year, over 60 percent of new vehicles produced globally can drive autonomously under supervision of the driver
- Environmental factors remain a danger to autonomous driving
  - **Black ice is a thin and transparent sheet of ice that forms on roads**
  - **Over 116,800 people are injured and over 1300 are killed** in accidents on snowy or icy roads annually in America
  - More than 70 percent of Americans live in snowy regions

Figure 1. Image of Black Ice
Image taken from New York Times

- Present detection methods
  - Contact based methods
    - Conductivity
    - Temperature
    - Humidity
  - Remote sensing based methods
    - Cameras
    - mmWave
  - Both achieve high accuracies
- Challenges to present methods
  - **Visibility/Reflectivity**
    - Heavy fog, snow, rain, dust
    - Dark environments
    - Sun glares
    - Change in material
    - Change in temperature

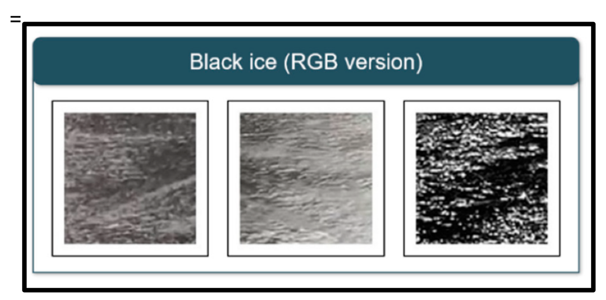

Figure 2. Image of Black Ice Used to Train the Neural Network in the FIrst Research
Image taken from doi.org/10.3390/electronics9122178

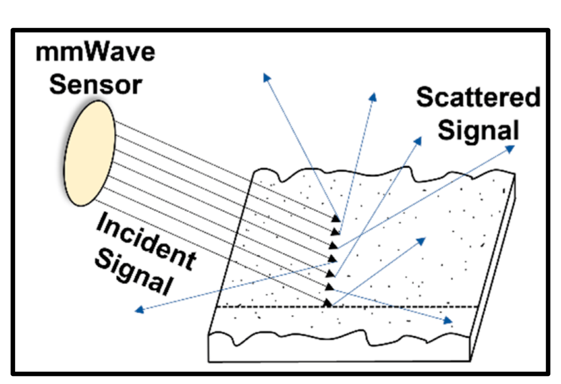

Figure 3. The Use of mmWave sensors to Detect Black Ice in the Second Research
Image taken from doi.org/10.3390/rs14205252

- Potential solutions
  - Enhanced sensors
  - Better neural network
  - **Different sensor based detection**
- **Inertial Measurement Unit (IMU)**
  - **3 Axis Accelerometer, Gyroscope**, and Magnetometer
  - High accuracy
  - Works under all conditions
  - Minimal application requirements
- **Neural Network**
  - Provides accurate classification
  - Takes in a range of data
  - Easily adaptable

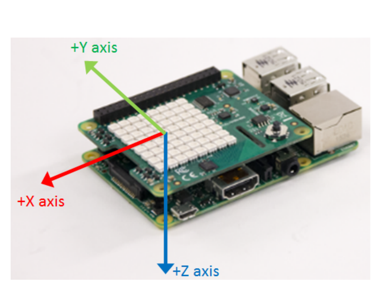

Figure 4. Diagram of how an IMU functions
Image taken from MathWorks

GOAL

The goal of the research is to train a **binary neural network that can classify road conditions** based on inertial measurement data in **all environments**, and can be deployed onto an autonomous car to yield accurate detection results with **minimal computational power** requirements.

Engineering Process

Step 1: Data Collection

- Model vehicle construction
  - **Ackerman steering**
  - Twin rear motor drive
  - One servo steering mechanism
  - **Raspberry Pi control functionality**
  - IMU connection
  - Controller connection
  - Data collection ability
- Model vehicle building problems
  - Proprietary software
  - Controller connection issue
  - IMU connection issue
- Location selection
  - Ice rink for ice simulation
  - Indoor floor for normal road data

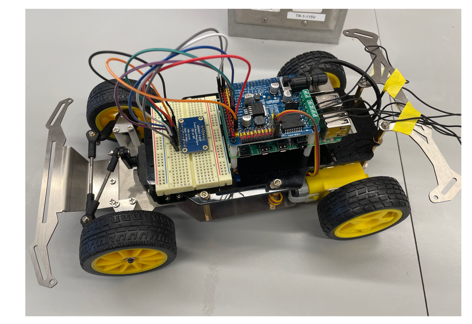

Figure 5. Completed Model Vehicle for Data Collection

Figure 7. Edge TPU Equipped Model Vehicle

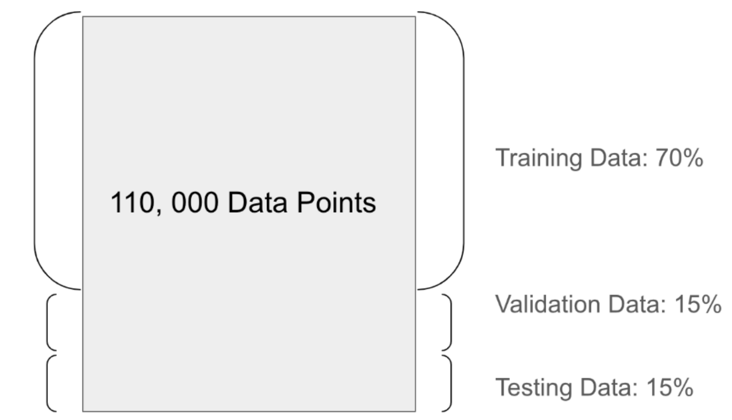

Figure 6. Grouping of the Dataset

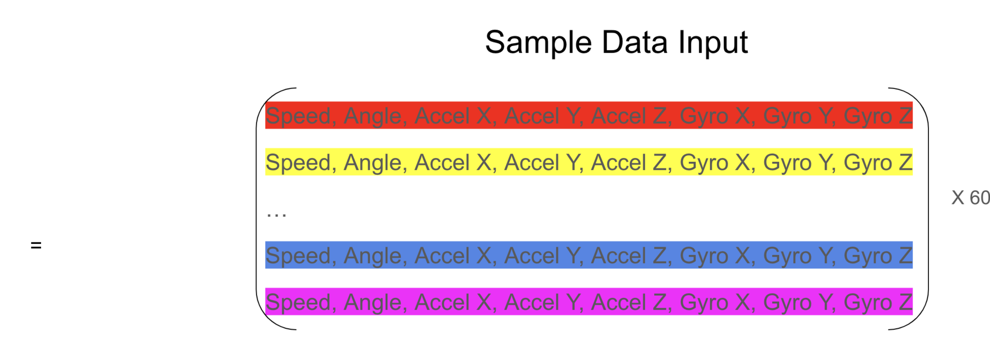

Figure 8. Input of the Neural Network

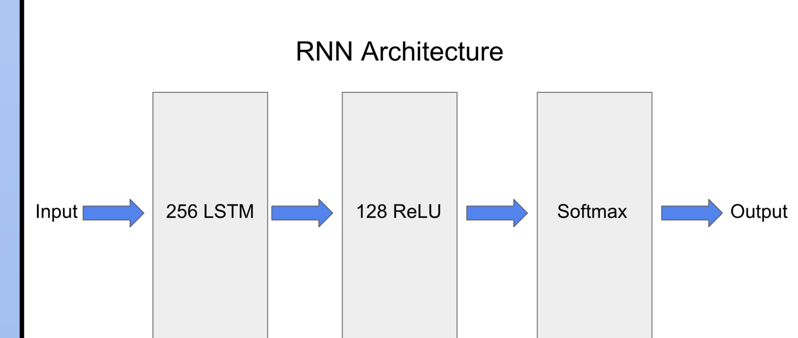

Figure 9. RNN Architecture

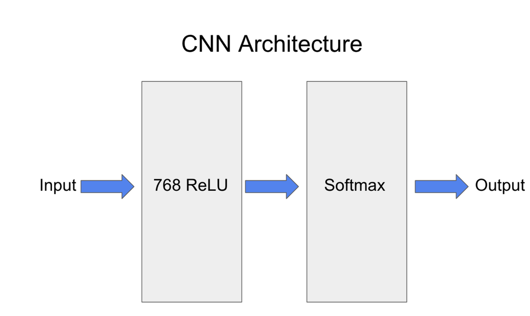

Figure 10. CNN Architecture

Step 2: Neural Network Design

- Data Input
  - Data collection at 60 Hz
  - Consideration for speed and angle
  - Accelerometer and gyroscope values
  - Taking in a segment of data
  - **60 rows, each row with 8 numbers**
- Data Output
  - Binary classification
  - **0 for normal, 1 for icy**
- Data Split
  - **110,000 total data points**
  - 70% for training
  - 15% for validation
  - 15% for testing
- Structures
  - **Recurrent neural networks (RNN)**
    - One 256 node LSTM layer
    - One 128 node ReLU layer
    - One Softmax layer
    - Accounts for time sequence
  - **Convolutional neural networks (CNN)**
    - Three 768 node ReLU layers
    - One Softmax layer
    - Easier application
- Design problems
  - Network architecture
  - Learning rate
  - Batch size
  - Training epochs
  - Dataset separation

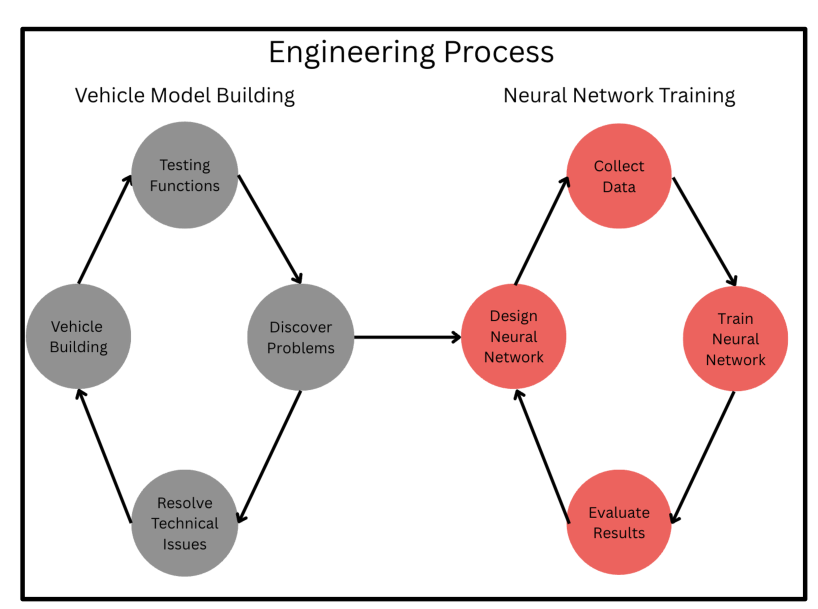

Figure 11. Overview of Project Engineering Process

Step 3: Implementation

- Google Coral Tensor Processing Unit (TPU)
- **Real time classification**

Results

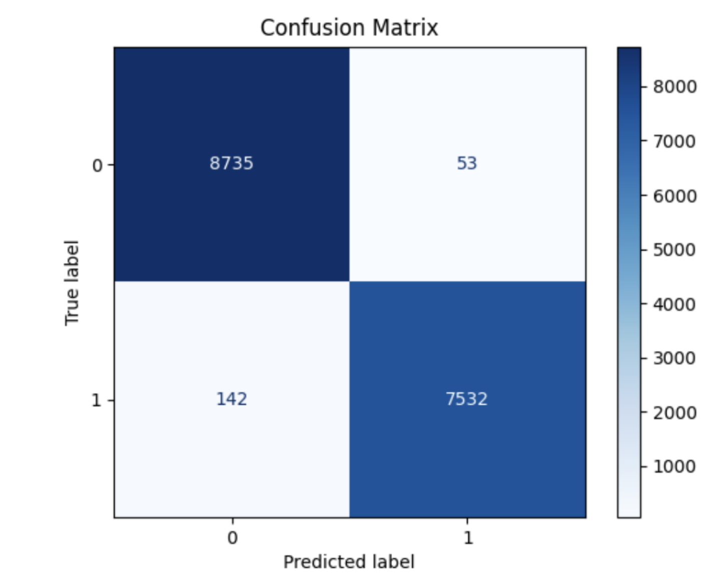

Figure 12. Finalized recurrent neural network model with 110,000 datapoint dataset and 10 epochs of training yields **98.8% accuracy** on the 16,500 datapoint testing dataset.

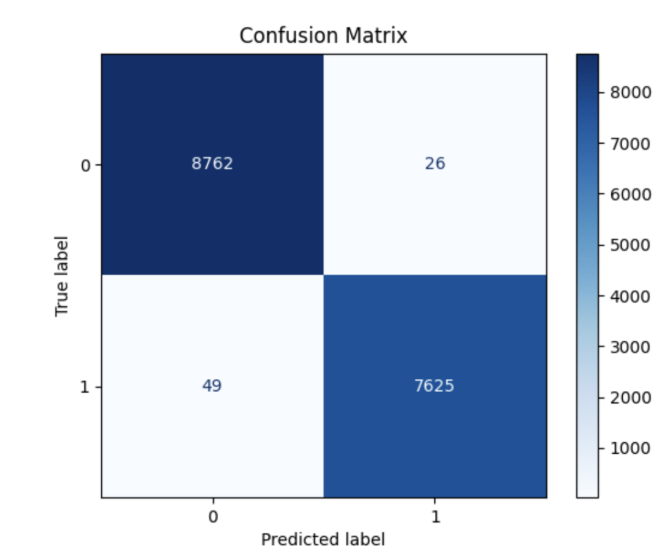

Figure 13. Finalized convolutional neural network model with 110,000 datapoint dataset and 15 epochs of training yields **99.5% accuracy** on the 16,500 datapoint testing dataset.

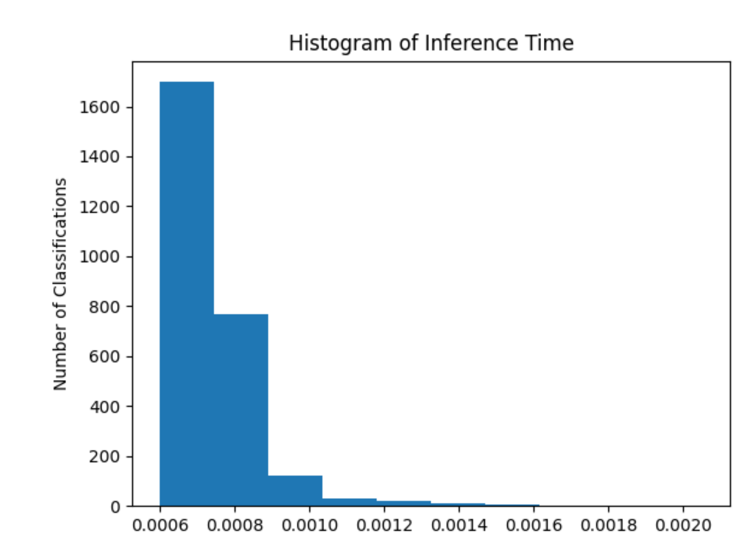

Figure 14. Average inference time of the deployed convolutional neural network on the vehicle is **0.75 milliseconds,** with a standard deviation of **0.13 milliseconds**

DATA ANALYSIS & Conclusion

Hypothesis:

- H_0: $P_{BI}=P_I$ or $P_{BN}=P_N$
- H_A: $P_{BI}>P_I$ and $P_{BN}>P_N$
- P_{BI} = Baseline for icy
- P_{BN} = Baseline for normal
- P_I = Result for icy
- P_N = Result for normal

Two Proportions Z Test:

- α = 0.05
- Baseline = mmWave sensor based classification method
- Baseline Icy Accuracy = 98.62%
- Baseline Normal Accuracy = 98.31%
- Result Icy Accuracy = 99.36%
- Result Normal Accuracy = 99.70%

Results:

- **Icy Classification**
  - **P = 0.0228**
  - 95% CI = 0.0786% to 1.90%
- **Normal Classification**
  - **P < 0.0001**
  - 95% CI = 0.467% to 3.34%
- $P_I < \alpha$ and $P_N < \alpha$

Conclusion:

- Reject null hypothesis and accept alternative hypothesis
- The accuracy improvement is **statistically significant**
- Accurate method with **all environment support**
- **Minimal computation** required

FUTURE DIRECTION OF RESEARCH

- Collecting more data and improving overall classification accuracy
- Include testing conditions that include partially icy, snowy, and wet road environments
- Develop a Multi-Axis Inertial Grouping Operation (MAIGO) that classifies all terrains using their inertial properties
- Implement control methods to adjust for driving on ice and help stabilize the vehicle

All images, charts, and graphs are created by the researcher unless otherwise stated.