EECE-4710 "IoT and TinyML"

KeyWord Spotting – Application Development, The Edge Impulse (EI) Approach

Cristinel Ababei

MARQUETTE UNIVERSITY

BE THE DIFFERENCE.

1

Create Your Own Audio Dataset

- Follow the steps in "Tutorial 12_2", Section 3 to create your own dataset.
- You must create a dataset to include (instead of "marquette", "engineering", and "silence") :
  1. Your First Name, e.g., "cris"
  2. Your Last Name, e.g., "ababei"
  3. Silence (with some background noise, such as a faucet running)
- Your audio files should be 1 second long
- Create 50 .wav files for each class

2

KWS Classifier Project
Audio Raw Data Analysis

audio_raw_data_analysis/audio_raw_data_analysis.ipynb
Read also “Tutorial 12_2”, Section 2

3

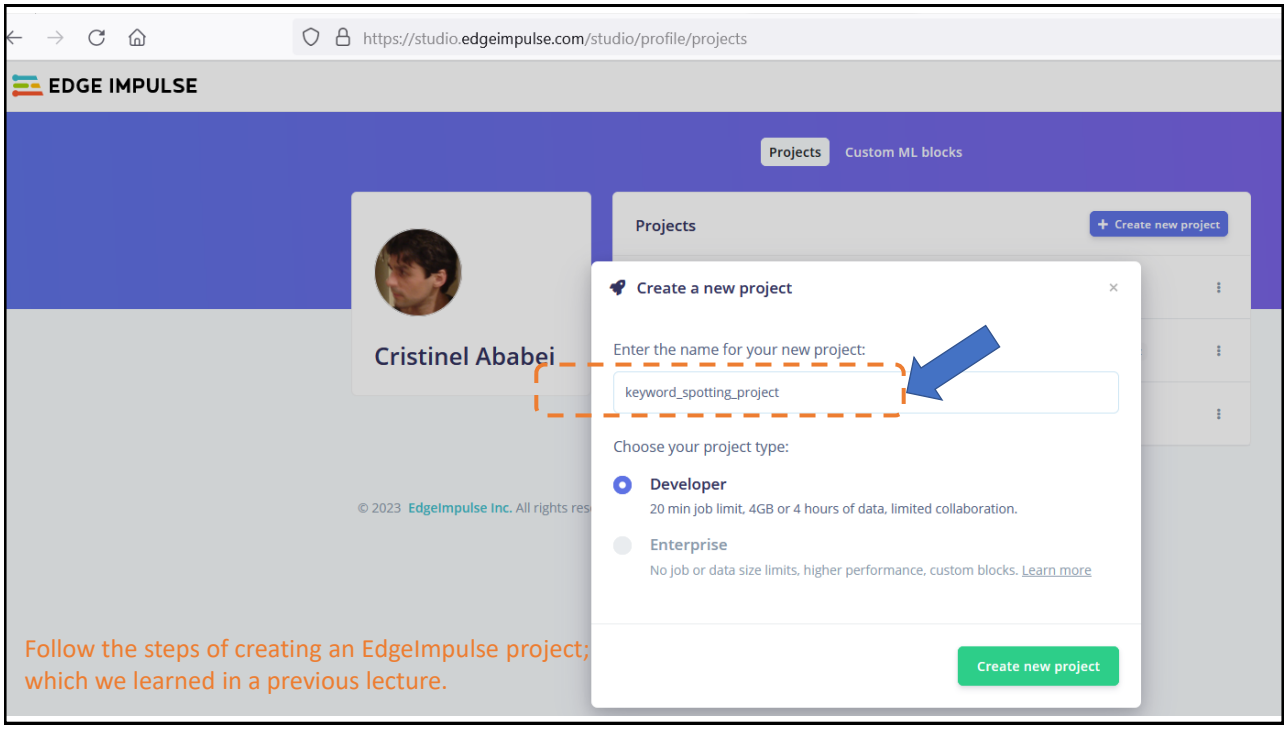
3

Nano-33 BLE
Keyword Spotting (KWS) Project

https://studio.edgeimpulse.com/public/209281/latest

4

4


https://studio.edgeimpulse.com/studio/profile/projects
EDGE IMPULSE
Projects
Custom ML blocks
Cristinel Ababei
Projects
+ Create new project
Create a new project
Enter the name for your new project:
keyword_spotting_project
Choose your project type:
Developer
20 min job limit, 4GB or 4 hours of data, limited collaboration.
Enterprise
No job or data size limits, higher performance, custom blocks. Learn more
Create new project
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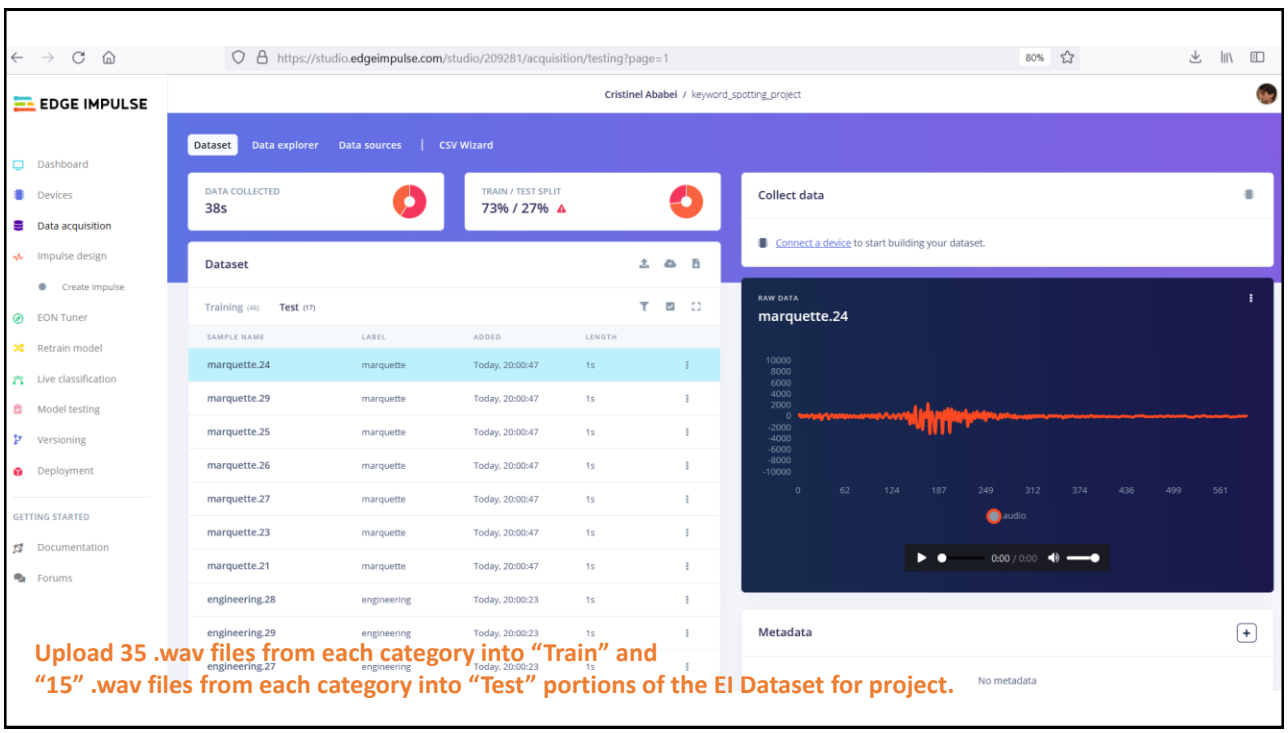
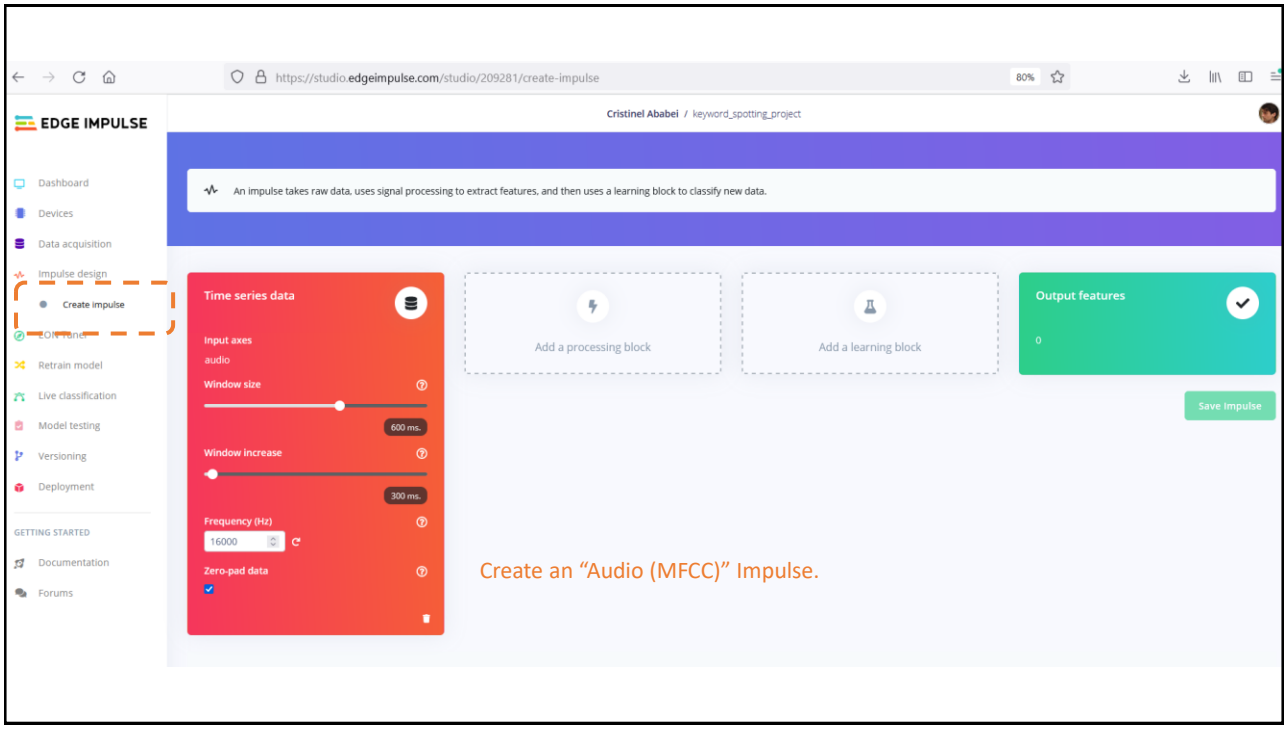
Follow the steps of creating an EdgeImpulse project;
which we learned in a previous lecture.

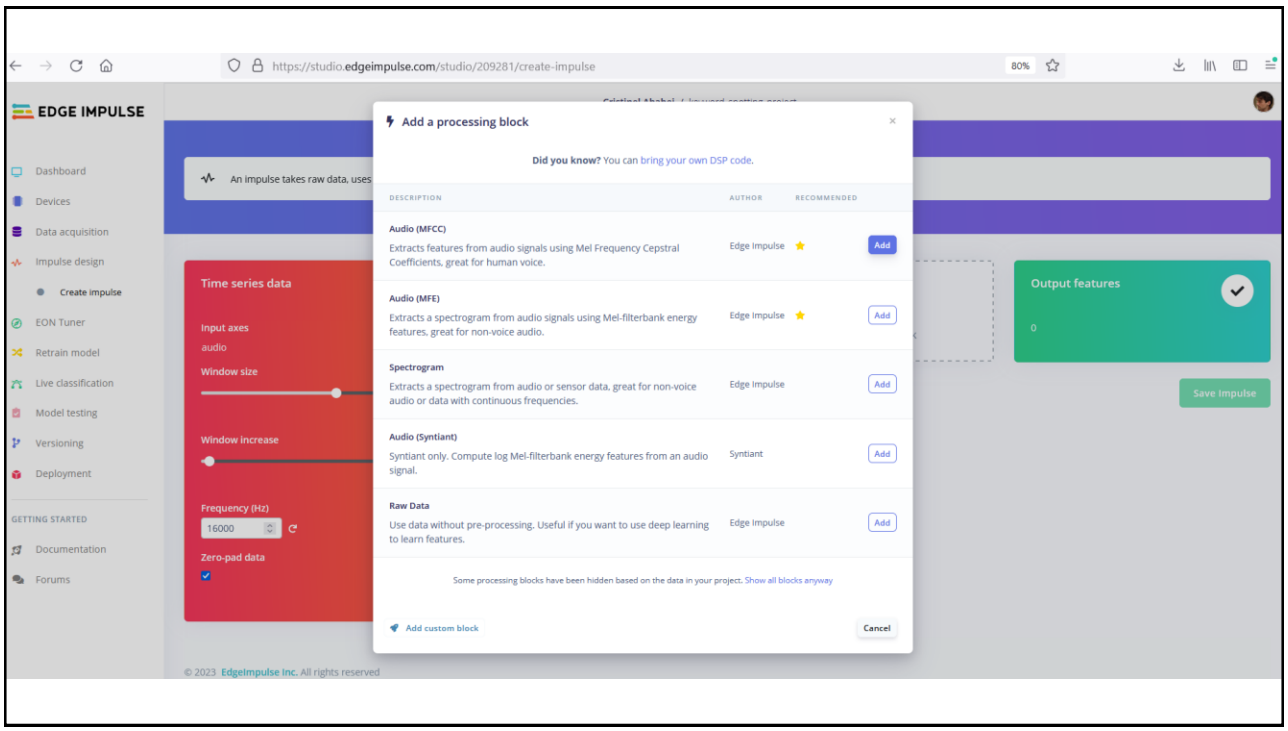
5


https://studio.edgeimpulse.com/studio/209281/acquisition/testing?page=1
EDGE IMPULSE
Cristinel Ababei / keyword_spotting_project
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
EON Tuner
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
Dataset
Data explorer
Data sources
CSV Wizard
DATA COLLECTED
38s
TRAIN / TEST SPLIT
73% / 27%
Collect data
Connect a device to start building your dataset.
Dataset
Training (46)
Test (17)
SAMPLE NAME
LABEL
ADDED
LENGTH
marquette.24 marquette Today, 20:00:47 1s
marquette.29 marquette Today, 20:00:47 1s
marquette.25 marquette Today, 20:00:47 1s
marquette.26 marquette Today, 20:00:47 1s
marquette.27 marquette Today, 20:00:47 1s
marquette.23 marquette Today, 20:00:47 1s
marquette.21 marquette Today, 20:00:47 1s
engineering.28 engineering Today, 20:00:23 1s
engineering.29 engineering Today, 20:00:23 1s
engineering.27 engineering Today, 20:00:23 1s
RAW DATA
marquette.24
audio
Metadata
No metadata
Upload 35 .wav files from each category into “Train” and
“15” .wav files from each category into “Test” portions of the EI Dataset for project.

6


https://studio.edgeimpulse.com/studio/209281/create-impulse
EDGE IMPULSE
Cristinel Ababei / keyword_spotting_project
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
EON Tuner
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
An impulse takes raw data, uses signal processing to extract features, and then uses a learning block to classify new data.
Time series data
Input axes
audio
Window size
600 ms.
Window increase
300 ms.
Frequency (Hz)
16000
Zero-pad data
Add a processing block
Add a learning block
Output features
0
Save Impulse
Create an “Audio (MFCC)” Impulse.

7


https://studio.edgeimpulse.com/studio/209281/create-impulse
EDGE IMPULSE
Add a processing block
Did you know? You can bring your own DSP code.
DESCRIPTION
AUTHOR
RECOMMENDED
Audio (MFCC)
Extracts features from audio signals using Mel Frequency Cepstral Coefficients, great for human voice.
Edge Impulse
Add
Audio (MFE)
Extracts a spectrogram from audio signals using Mel-filterbank energy features, great for non-voice audio.
Edge Impulse
Add
Spectrogram
Extracts a spectrogram from audio or sensor data, great for non-voice audio or data with continuous frequencies.
Edge Impulse
Add
Audio (Syntiant)
Syntiant only. Compute log Mel-filterbank energy features from an audio signal.
Syntiant
Add
Raw Data
Use data without pre-processing. Useful if you want to use deep learning to learn features.
Edge Impulse
Add
Some processing blocks have been hidden based on the data in your project. Show all blocks anyway
Add custom block
Cancel
Time series data
Output features
Save Impulse
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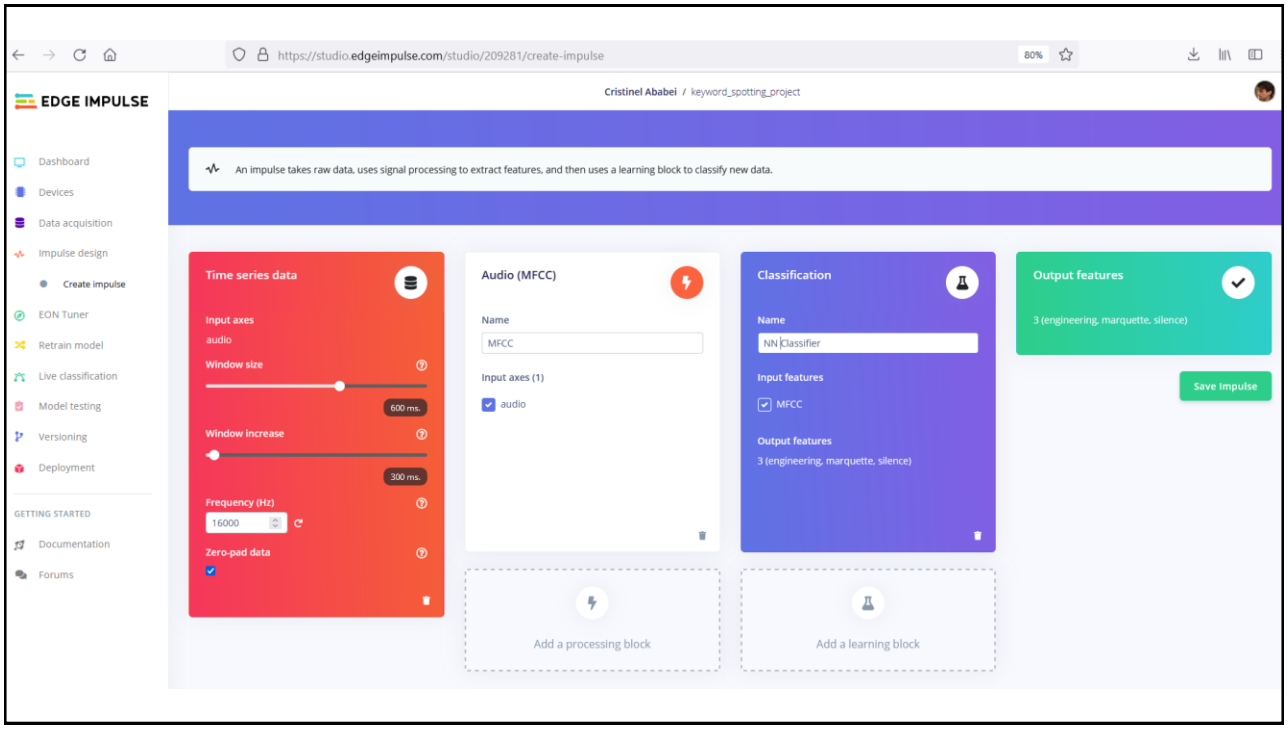
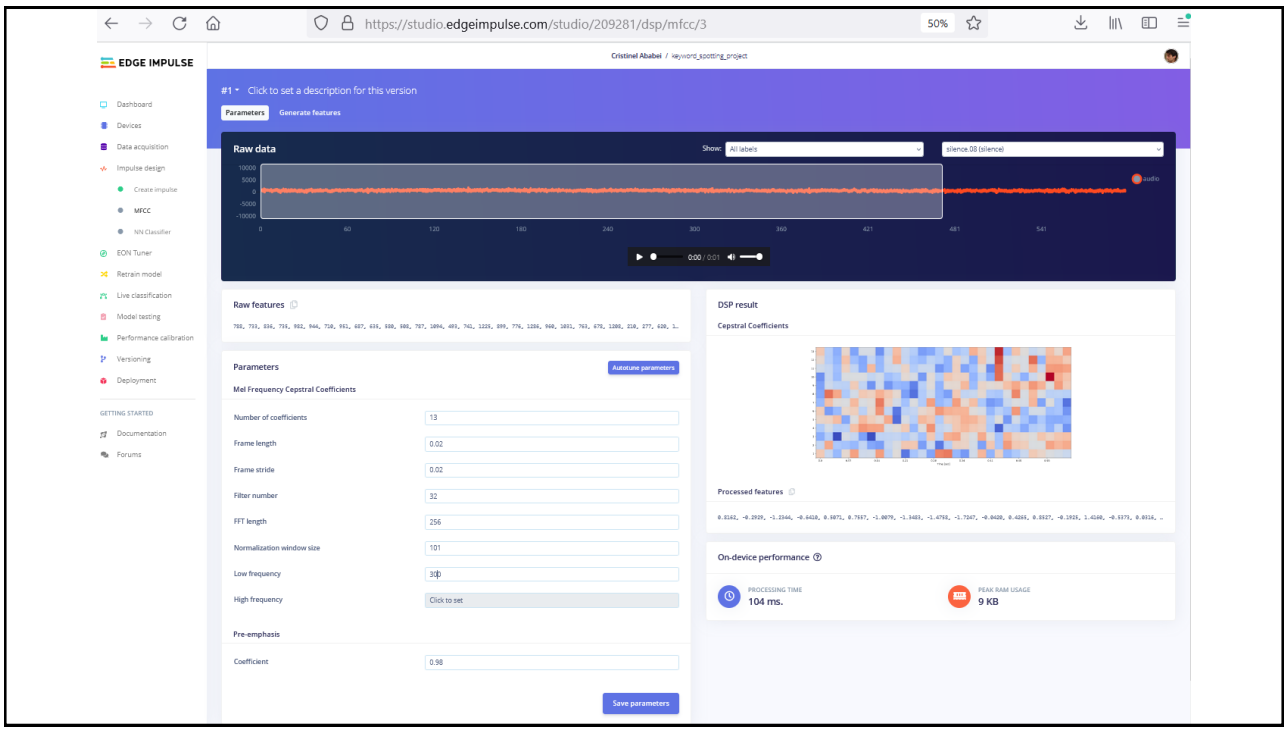
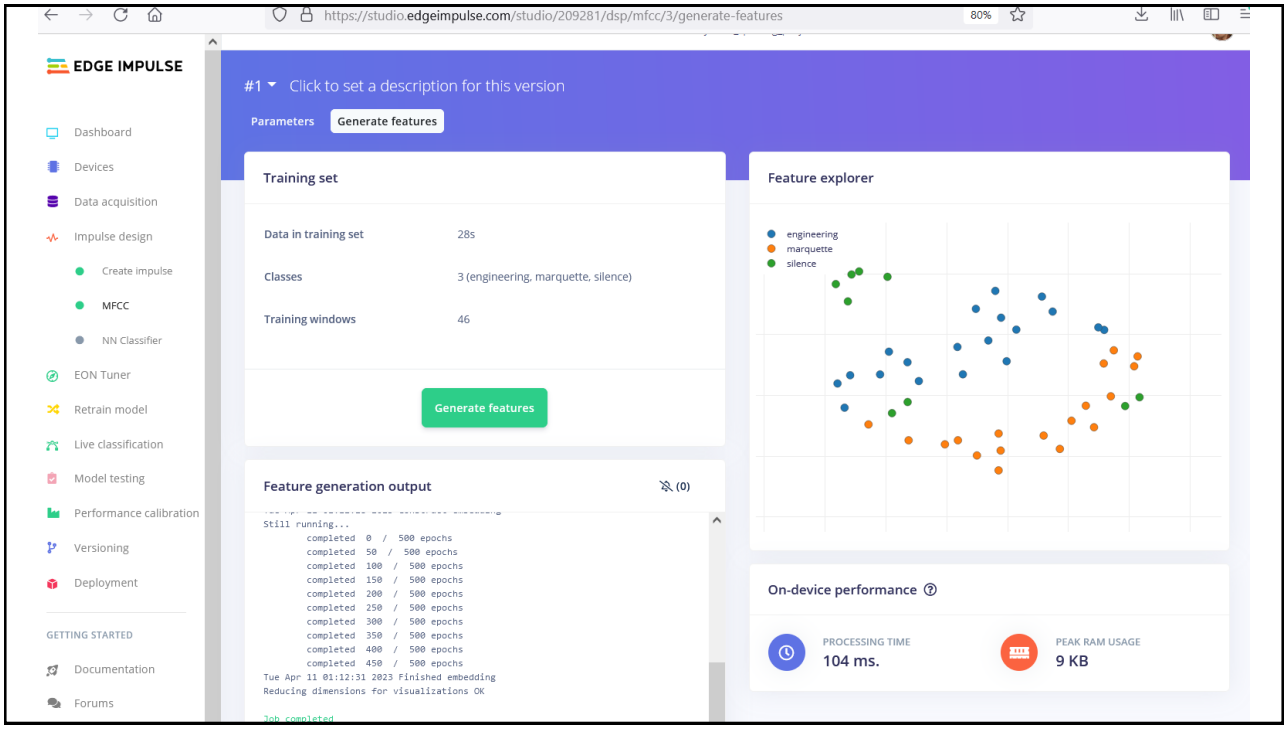
8


https://studio.edgeimpulse.com/studio/209281/create-impulse
80%
EDGE IMPULSE
Cristinel Ababei / keyword_spotting_project
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
EON Tuner
Retrain model
Live classification
Model testing
Versioning
Deployment
GETTING STARTED
Documentation
Forums
An impulse takes raw data, uses signal processing to extract features, and then uses a learning block to classify new data.
Time series data
Input axes
audio
Window size
600 ms.
Window increase
300 ms.
Frequency (Hz)
16000
Zero-pad data
Audio (MFCC)
Name
MFCC
Input axes (1)
audio
Classification
Name
NN Classifier
Input features
MFCC
Output features
3 (engineering, marquette, silence)
Output features
3 (engineering, marquette, silence)
Save Impulse
Add a processing block
Add a learning block

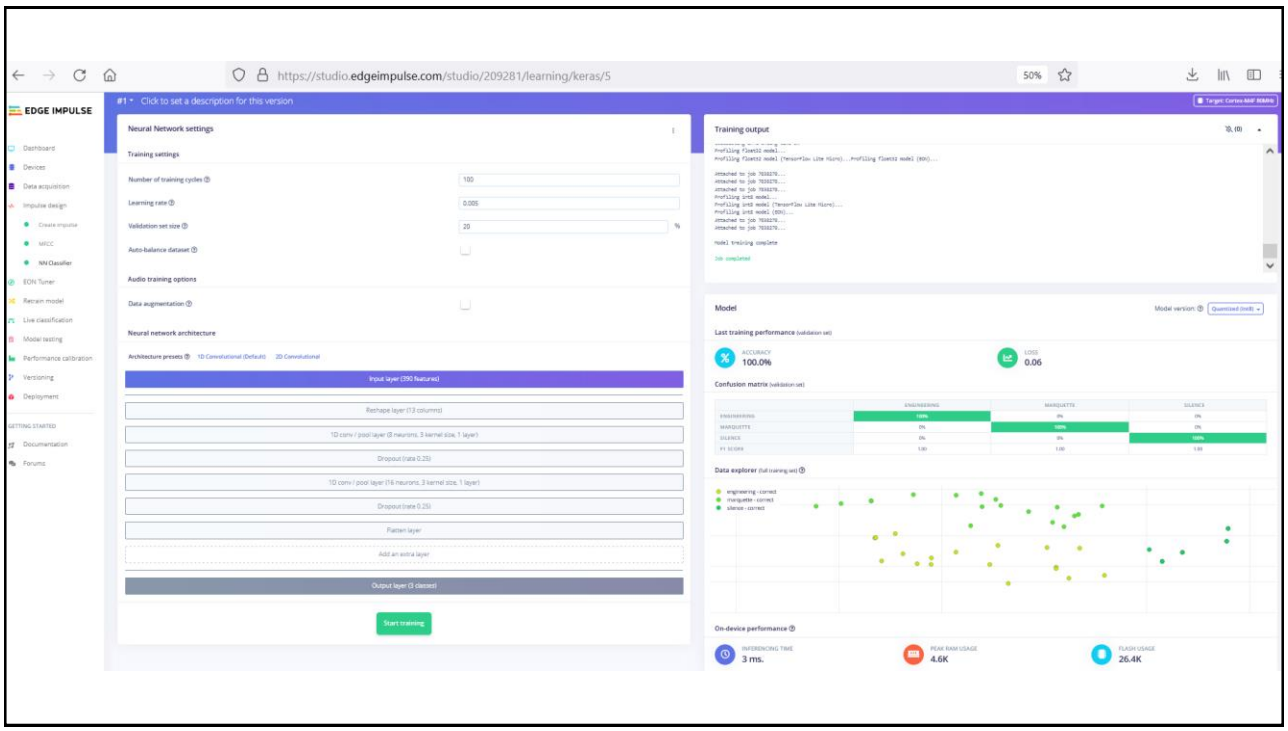
9


https://studio.edgeimpulse.com/studio/209281/dsp/mfcc/3
50%
EDGE IMPULSE
Cristinel Ababei / keyword_spotting_project
#1 Click to set a description for this version
Parameters
Generate features
Raw data
Show: All labels
silence.08 (silence)
0:00 / 0:01
Raw features
Parameters
Autotune parameters
Mel Frequency Cepstral Coefficients
Number of coefficients 13
Frame length 0.02
Frame stride 0.02
Filter number 32
FFT length 256
Normalization window size 101
Low frequency 300
High frequency Click to set
Pre-emphasis
Coefficient 0.98
Save parameters
DSP result
Cepstral Coefficients
Processed features
On-device performance
PROCESSING TIME
104 ms.
PEAK RAM USAGE
9 KB

10

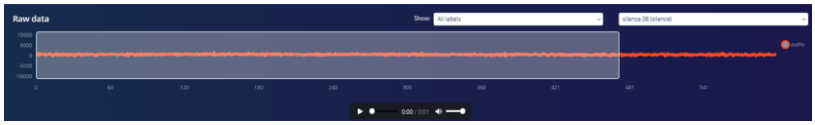

https://studio.edgeimpulse.com/studio/209281/dsp/mfcc/3/generate-features
80%
EDGE IMPULSE
#1 Click to set a description for this version
Parameters
Generate features
Dashboard
Devices
Data acquisition
Impulse design
Create impulse
MFCC
NN Classifier
EON Tuner
Retrain model
Live classification
Model testing
Performance calibration
Versioning
Deployment
GETTING STARTED
Documentation
Forums
Training set
Data in training set
28s
Classes
3 (engineering, marquette, silence)
Training windows
46
Generate features
Feature explorer
engineering
marquette
silence
Feature generation output
(0)
Still running...
completed 0 / 500 epochs
completed 50 / 500 epochs
completed 100 / 500 epochs
completed 150 / 500 epochs
completed 200 / 500 epochs
completed 250 / 500 epochs
completed 300 / 500 epochs
completed 350 / 500 epochs
completed 400 / 500 epochs
completed 450 / 500 epochs
Tue Apr 11 01:12:31 2023 Finished embedding
Reducing dimensions for visualizations OK
Job completed
On-device performance
PROCESSING TIME
104 ms.
PEAK RAM USAGE
9 KB

11


https://studio.edgeimpulse.com/studio/209281/learning/keras/5
50%
EDGE IMPULSE
#1 Click to set a description for this version
Neural Network settings
Training settings
Number of training cycles
100
Learning rate
0.005
Validation set size
20
Auto-balance dataset
Audio training options
Data augmentation
Neural network architecture
Architecture presets
1D Convolutional (Default)
2D Convolutional
Input layer (390 features)
Reshape layer (13 columns)
Dropout (rate 0.25)
Dropout (rate 0.25)
Flatten layer
Add an extra layer
Output layer (3 classes)
Start training
Training output
Model
Last training performance
ACCURACY
100.0%
LOSS
0.06
Confusion matrix
Data explorer
On-device performance
3 ms.
4.6K
26.4K

12

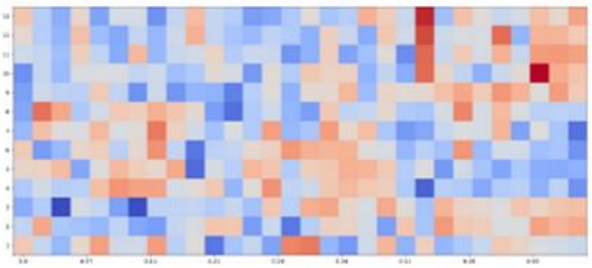
Raw data:



1000 ms of Sound Raw Data

MFCC

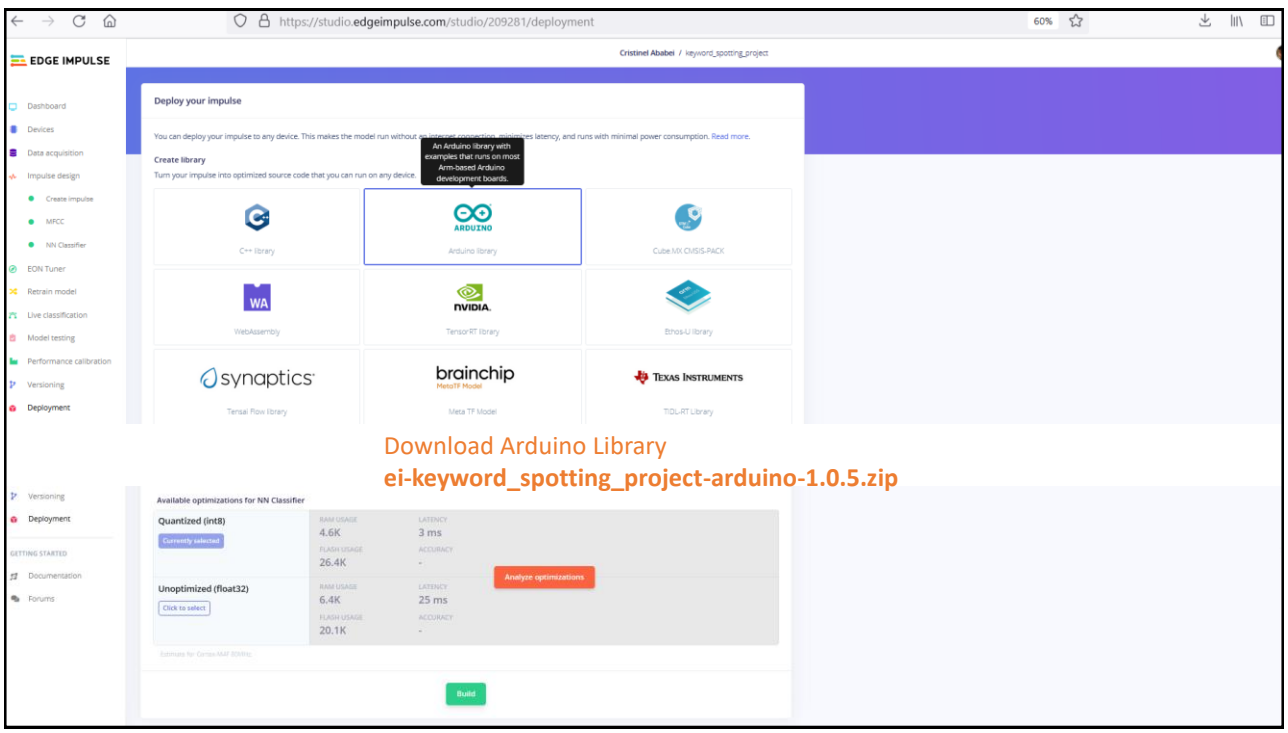
13 Coef.



Dim = 13 x 50
= 650

50 slots

13



Download Arduino Library
ei-keyword_spotting_project-arduino-1.0.5.zip

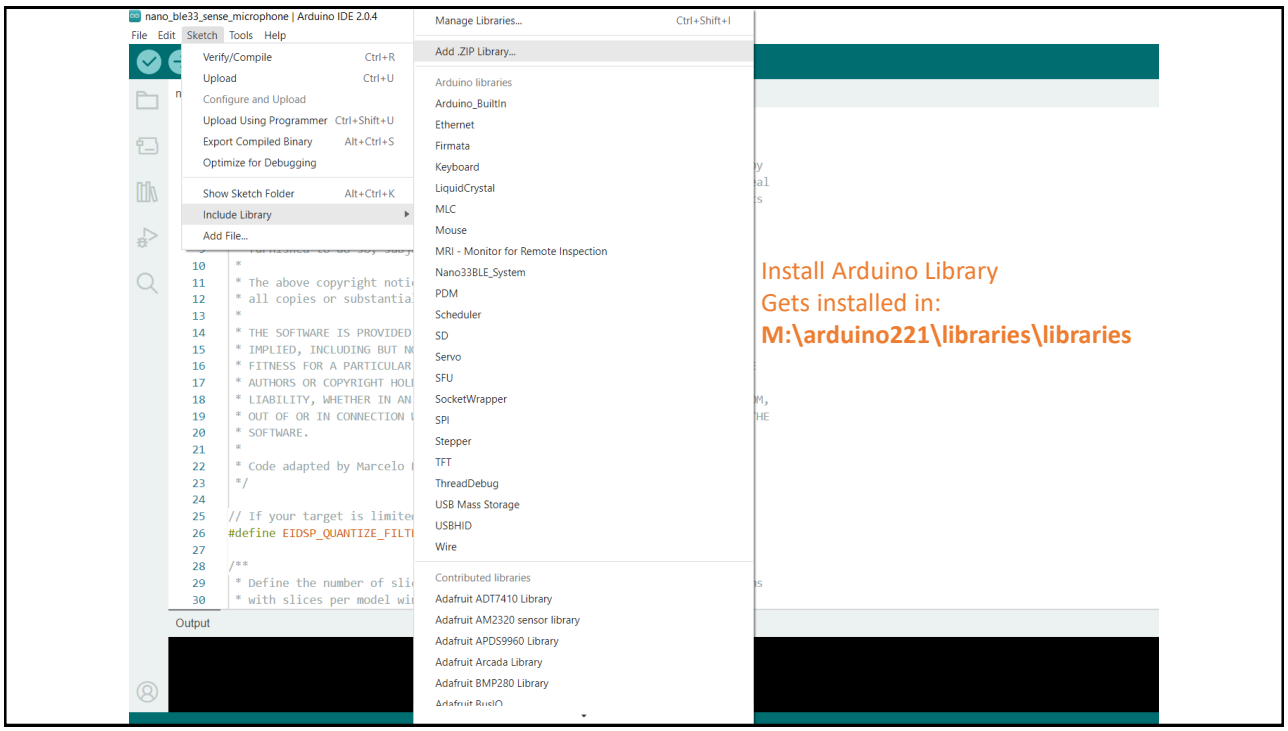
14

KWS Application
Running it on Arduino!

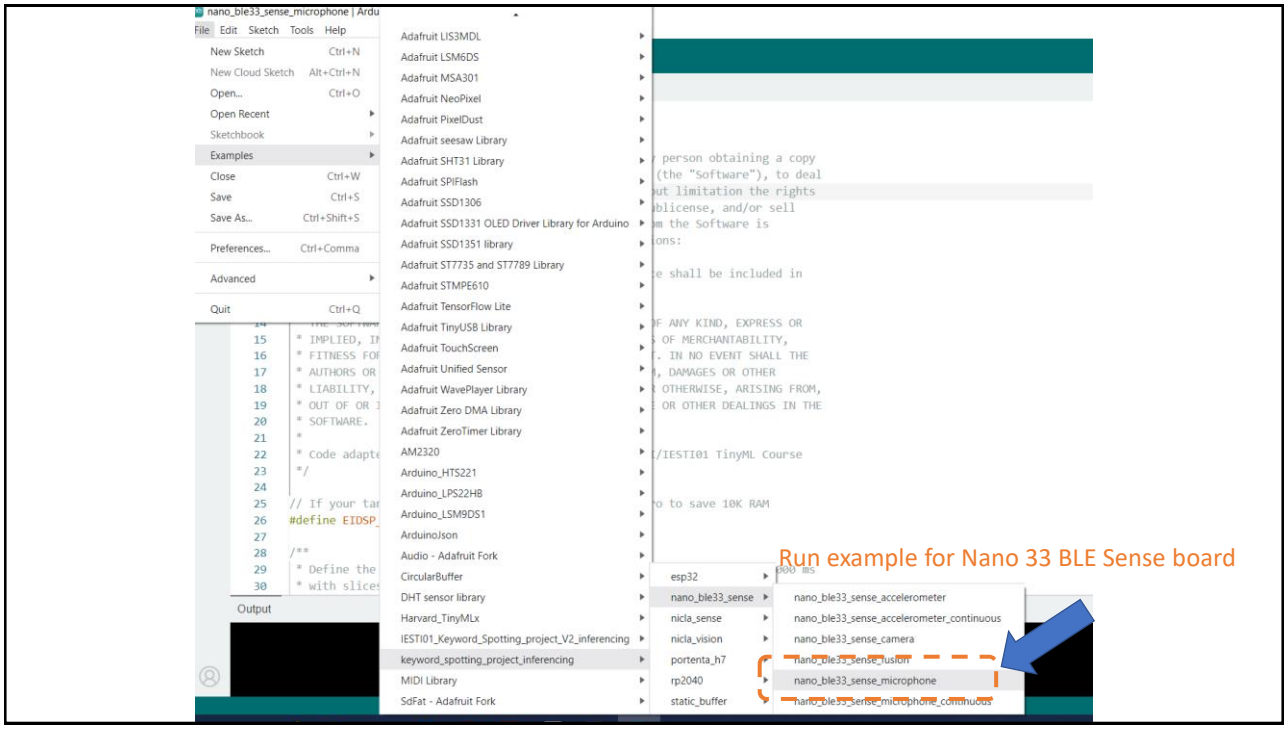
keyword_spotting_example\keyword_spotting_project_inferencing\...\nano_ble33_sense_microphone.ino

15

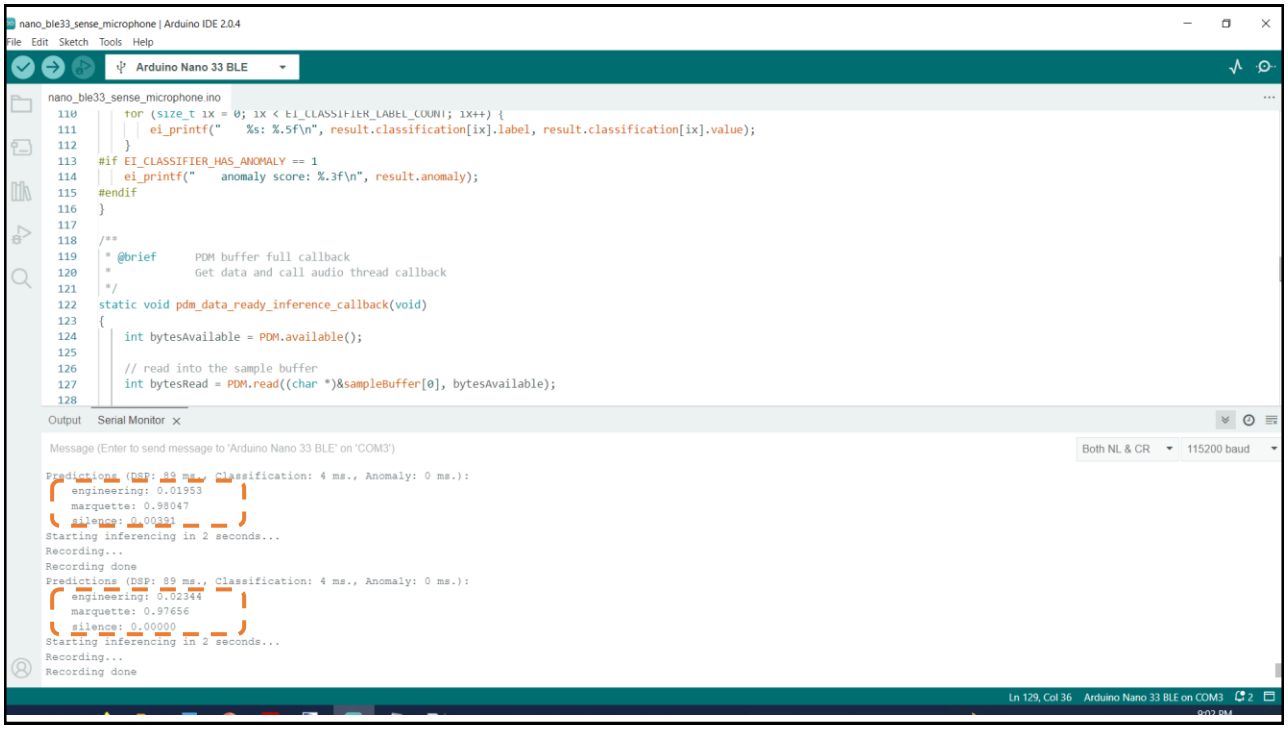
15



16


File Edit Sketch Tools Help
New Sketch Ctrl+N
New Cloud Sketch Alt+Ctrl+N
Open... Ctrl+O
Open Recent
Sketchbook
Examples
Close Ctrl+W
Save Ctrl+S
Save As... Ctrl+Shift+S
Preferences... Ctrl+Comma
Advanced
Quit Ctrl+Q
Adafruit LIS3MDL
Adafruit LSM6DS
Adafruit MSA301
Adafruit NeoPixel
Adafruit PixelDust
Adafruit seesaw Library
Adafruit SHT31 Library
Adafruit SPIFlash
Adafruit SSD1306
Adafruit SSD1331 OLED Driver Library for Arduino
Adafruit SSD1351 library
Adafruit ST7735 and ST7789 Library
Adafruit STMPE610
Adafruit TensorFlow Lite
Adafruit TinyUSB Library
Adafruit TouchScreen
Adafruit Unified Sensor
Adafruit WavePlayer Library
Adafruit Zero DMA Library
Adafruit ZeroTimer Library
AM2320
Arduino_HTS221
Arduino_LPS22HB
Arduino_LSM9DS1
ArduinoJson
Audio - Adafruit Fork
CircularBuffer
DHT sensor library
Harvard_TinyMLx
IESTI01_Keyword_Spotting_project_V2_inferencing
keyword_spotting_project_inferencing
MIDI Library
SdFat - Adafruit Fork
esp32
nano_ble33_sense
nicla_sense
nicla_vision
portenta_h7
rp2040
static_buffer
nano_ble33_sense_accelerometer
nano_ble33_sense_accelerometer_continuous
nano_ble33_sense_camera
nano_ble33_sense_fusion
nano_ble33_sense_microphone
nano_ble33_sense_microphone_continuous
Output
Run example for Nano 33 BLE Sense board

17


nano_ble33_sense_microphone | Arduino IDE 2.0.4
File Edit Sketch Tools Help
Arduino Nano 33 BLE
nano_ble33_sense_microphone.ino
for (size_t ix = 0; ix < EI_CLASSIFIER_LABEL_COUNT; ix++) {
ei_printf(" %s: %.5f\n", result.classification[ix].label, result.classification[ix].value);
}
#if EI_CLASSIFIER_HAS_ANOMALY == 1
ei_printf(" anomaly score: %.3f\n", result.anomaly);
#endif
}
/**
* @brief PDM buffer full callback
* Get data and call audio thread callback
*/
static void pdm_data_ready_inference_callback(void)
{
int bytesAvailable = PDM.available();
// read into the sample buffer
int bytesRead = PDM.read((char *)&sampleBuffer[0], bytesAvailable);
Output Serial Monitor
Message (Enter to send message to 'Arduino Nano 33 BLE' on 'COM3')
Both NL & CR
115200 baud
Predictions (DSP: 89 ms., Classification: 4 ms., Anomaly: 0 ms.):
engineering: 0.01953
marquette: 0.98047
silence: 0.00391
Starting inferencing in 2 seconds...
Recording...
Recording done
Predictions (DSP: 89 ms., Classification: 4 ms., Anomaly: 0 ms.):
engineering: 0.02344
marquette: 0.97656
silence: 0.00000
Starting inferencing in 2 seconds...
Recording...
Recording done
Ln 129, Col 36 Arduino Nano 33 BLE on COM3

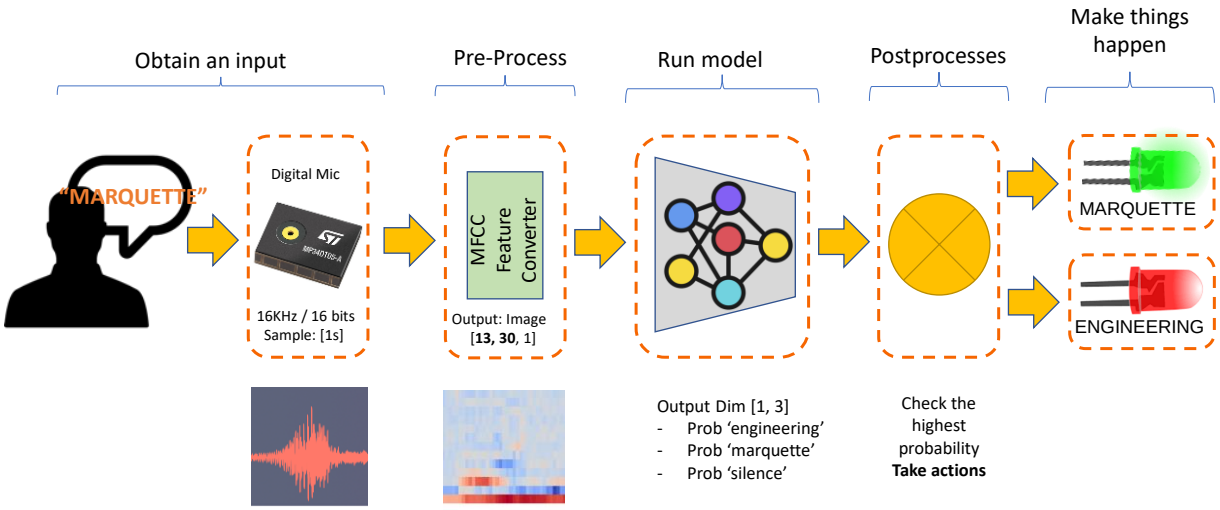
18

Change Arduino Application to Drive RGB LEDs

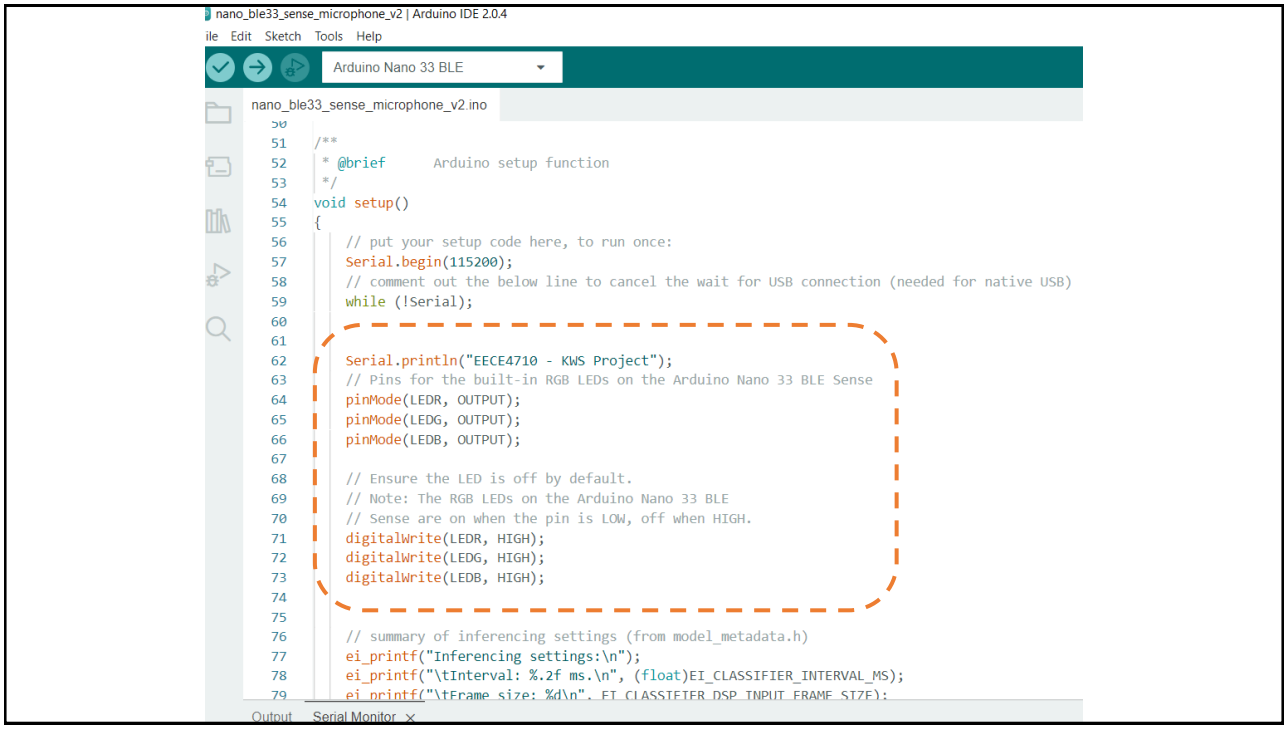
- Create a copy of the Arduino Application:
  - keyword_spotting_example\keyword_spotting_project_inferencing\examples\nano_ble33_sense\nano_ble33_sense_microphone
- as:
  - keyword_spotting_example\keyword_spotting_project_inferencing\examples\nano_ble33_sense\nano_ble33_sense_microphone_v2
- And, modify nano_ble33_sense_microphone_v2.ino to control the RGB LEDs such that:
  - **LEDG** is turn on when “marquette” is detected
  - **LEDR** is turn on when “engineering” is detected

19

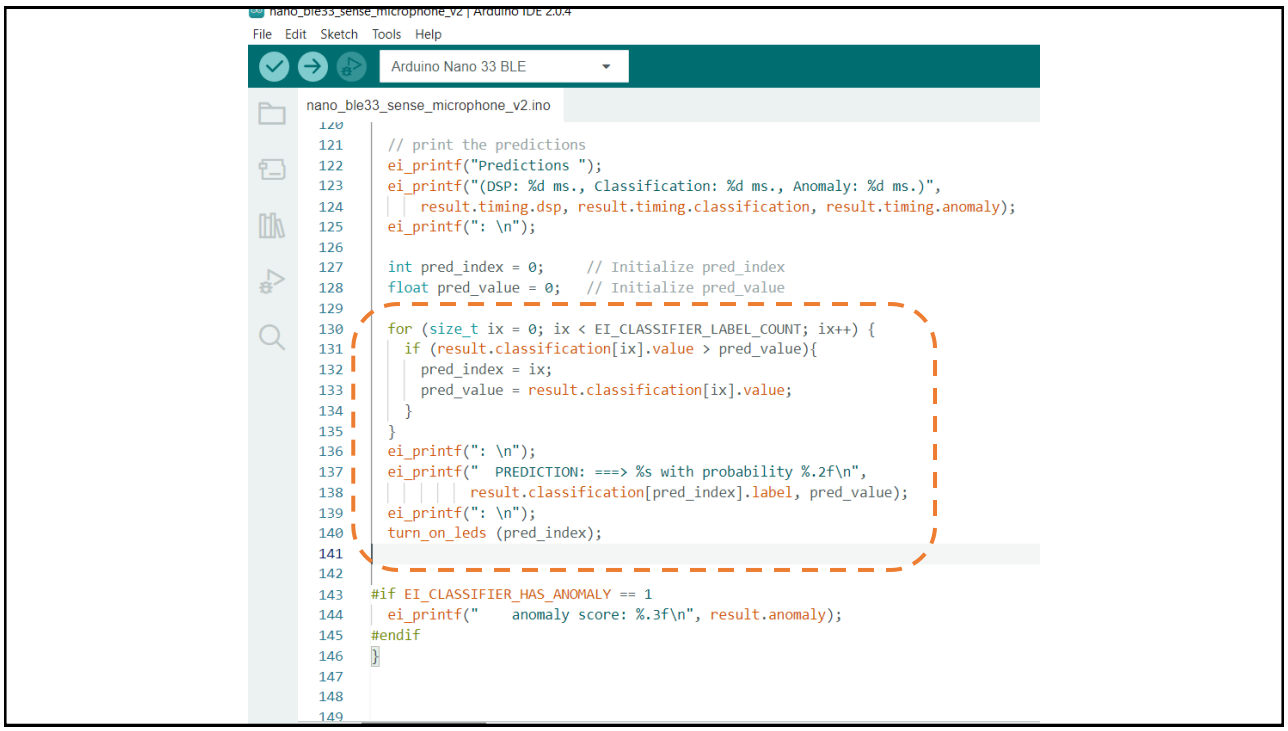
KeyWord Spotting (KWS) - Inference



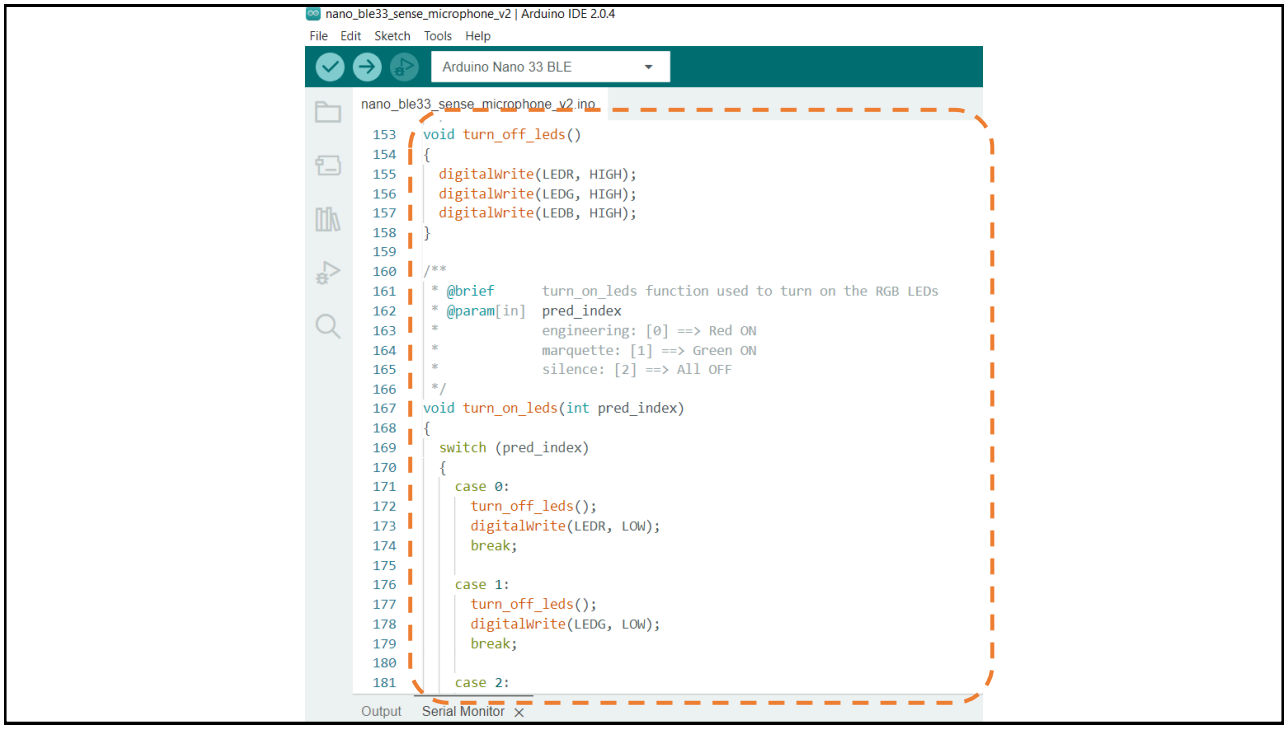
20


nano_ble33_sense_microphone_v2 | Arduino IDE 2.0.4
ile Edit Sketch Tools Help
Arduino Nano 33 BLE
nano_ble33_sense_microphone_v2.ino
/**
* @brief Arduino setup function
*/
void setup()
{
// put your setup code here, to run once:
Serial.begin(115200);
// comment out the below line to cancel the wait for USB connection (needed for native USB)
while (!Serial);
Serial.println("EECE4710 - KWS Project");
// Pins for the built-in RGB LEDs on the Arduino Nano 33 BLE Sense
pinMode(LEDR, OUTPUT);
pinMode(LEDG, OUTPUT);
pinMode(LEDB, OUTPUT);
// Ensure the LED is off by default.
// Note: The RGB LEDs on the Arduino Nano 33 BLE
// Sense are on when the pin is LOW, off when HIGH.
digitalWrite(LEDR, HIGH);
digitalWrite(LEDG, HIGH);
digitalWrite(LEDB, HIGH);
// summary of inferencing settings (from model_metadata.h)
ei_printf("Inferencing settings:\n");
ei_printf("\tInterval: %.2f ms.\n", (float)EI_CLASSIFIER_INTERVAL_MS);
Output Serial Monitor

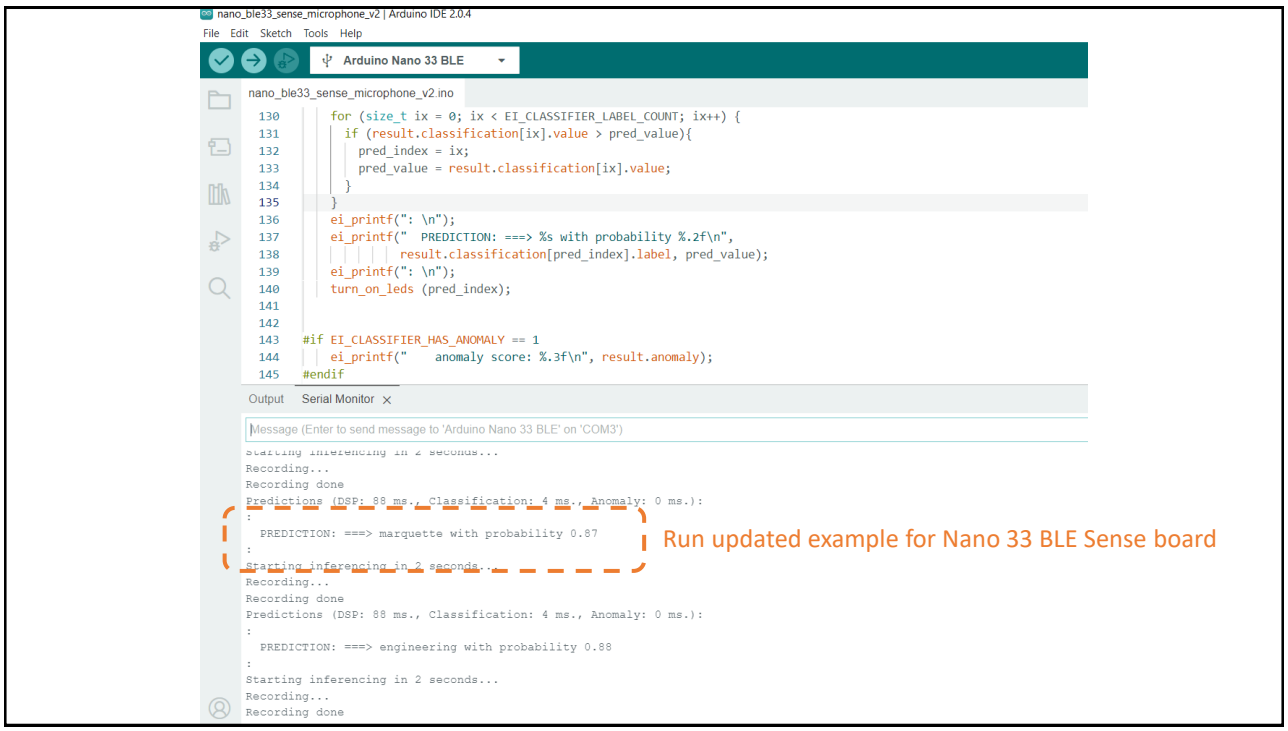
21


File Edit Sketch Tools Help
Arduino Nano 33 BLE
nano_ble33_sense_microphone_v2.ino
// print the predictions
ei_printf("Predictions ");
ei_printf("(DSP: %d ms., Classification: %d ms., Anomaly: %d ms.)",
result.timing.dsp, result.timing.classification, result.timing.anomaly);
ei_printf(": \n");
int pred_index = 0; // Initialize pred_index
float pred_value = 0; // Initialize pred_value
for (size_t ix = 0; ix < EI_CLASSIFIER_LABEL_COUNT; ix++) {
if (result.classification[ix].value > pred_value){
pred_index = ix;
pred_value = result.classification[ix].value;
}
}
ei_printf(": \n");
ei_printf(" PREDICTION: ===> %s with probability %.2f\n",
result.classification[pred_index].label, pred_value);
ei_printf(": \n");
turn_on_leds (pred_index);
#if EI_CLASSIFIER_HAS_ANOMALY == 1
ei_printf(" anomaly score: %.3f\n", result.anomaly);
#endif
}

22


nano_ble33_sense_microphone_v2 | Arduino IDE 2.0.4
File Edit Sketch Tools Help
Arduino Nano 33 BLE
nano_ble33_sense_microphone_v2.ino
153 void turn_off_leds()
154 {
155 digitalWrite(LEDR, HIGH);
156 digitalWrite(LEDG, HIGH);
157 digitalWrite(LEDB, HIGH);
158 }
159
160 /**
161 * @brief turn_on_leds function used to turn on the RGB LEDs
162 * @param[in] pred_index
163 * engineering: [0] ==> Red ON
164 * marquette: [1] ==> Green ON
165 * silence: [2] ==> All OFF
166 */
167 void turn_on_leds(int pred_index)
168 {
169 switch (pred_index)
170 {
171 case 0:
172 turn_off_leds();
173 digitalWrite(LEDR, LOW);
174 break;
175
176 case 1:
177 turn_off_leds();
178 digitalWrite(LEDG, LOW);
179 break;
180
181 case 2:
Output Serial Monitor

23


nano_ble33_sense_microphone_v2 | Arduino IDE 2.0.4
File Edit Sketch Tools Help
Arduino Nano 33 BLE
nano_ble33_sense_microphone_v2.ino
130 for (size_t ix = 0; ix < EI_CLASSIFIER_LABEL_COUNT; ix++) {
131 if (result.classification[ix].value > pred_value){
132 pred_index = ix;
133 pred_value = result.classification[ix].value;
134 }
135 }
136 ei_printf(": \n");
137 ei_printf(" PREDICTION: ===> %s with probability %.2f\n",
138 result.classification[pred_index].label, pred_value);
139 ei_printf(": \n");
140 turn_on_leds (pred_index);
141
142
143 #if EI_CLASSIFIER_HAS_ANOMALY == 1
144 ei_printf(" anomaly score: %.3f\n", result.anomaly);
145 #endif
Output Serial Monitor
Message (Enter to send message to 'Arduino Nano 33 BLE' on 'COM3')
Recording...
Recording done
Predictions (DSP: 88 ms., Classification: 4 ms., Anomaly: 0 ms.):
:
PREDICTION: ===> marquette with probability 0.87
:
Starting inferencing in 2 seconds...
Recording...
Recording done
Predictions (DSP: 88 ms., Classification: 4 ms., Anomaly: 0 ms.):
:
PREDICTION: ===> engineering with probability 0.88
:
Starting inferencing in 2 seconds...
Recording...
Recording done
Run updated example for Nano 33 BLE Sense board

24

KWS Classifier Project
Looking "Under the Hood"

keyword_spotting_example\
keyword_spotting_project_nn_classifier.ipynb

25

Credits

- A previous edition of this course was developed in collaboration with Dr. Susan C. Schneider of Marquette University.
- We are very grateful and thank all the following professors, researchers, and practitioners for jump-starting courses on TinyML and for sharing their teaching materials:

- Prof. Marcelo Rovai - TinyML - Machine Learning for Embedding Devices, UNIFEI
  - https://github.com/Mjrovai/UNIFEI-IESTI01-TinyML-2022.1
- Prof. Vijay Janapa Reddi - CS249r: Tiny Machine Learning, Applied Machine Learning on Embedded IoT Devices, Harvard
  - https://sites.google.com/g.harvard.edu/tinyml/home
- Prof. Rahul Mangharam – ESE3600: Tiny Machine Learning, Univ. of Pennsylvania
  - https://tinyml.seas.upenn.edu/#
- Prof. Brian Plancher - Harvard CS249r: Tiny Machine Learning (TinyML), Barnard College, Columbia University
  - https://a2r-lab.org/courses/cs249r_tinyml/

26

References

- Additional references from where information and other teaching materials were gathered include:

- Applications & Deploy textbook: “TinyML” by Pete Warden, Daniel Situnayake
  - https://www.oreilly.com/library/view/tinyml/9781492052036/
- Deploy textbook “TinyML Cookbook” by Gian Marco Iodice
  - https://github.com/PacktPublishing/TinyML-Cookbook
- Jason Brownlee
  - https://machinelearningmastery.com/
- TinyMLedu
  - https://tinyml.seas.harvard.edu/
- Professional Certificate in Tiny Machine Learning (TinyML) – edX/Harvard
  - https://www.edx.org/professional-certificate/harvardx-tiny-machine-learning
- Introduction to Embedded Machine Learning - Coursera/Edge Impulse
  - https://www.coursera.org/learn/introduction-to-embedded-machine-learning
- Computer Vision with Embedded Machine Learning - Coursera/Edge Impulse
  - https://www.coursera.org/learn/computer-vision-with-embedded-machine-learning

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