Real-Time Keyword Recognition on STM32 using TensorFlow Lite

Stefan Gloor

ETH Zürich

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- Simple speech recognition
  - Wide range of applications
  - Simple and cheap user interface
  - Hands-free operation of devices
- Why on the edge?
  - Very cheap
  - Low latency
  - Data privacy

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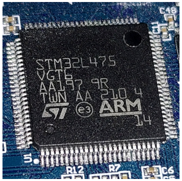
- Achieve simple speech recognition completely "on the edge", detect keywords such "left" and "right".
- Familiarize with available frameworks
- Demo project as a base for future applications



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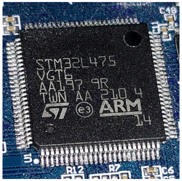

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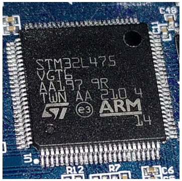

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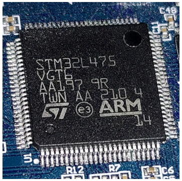
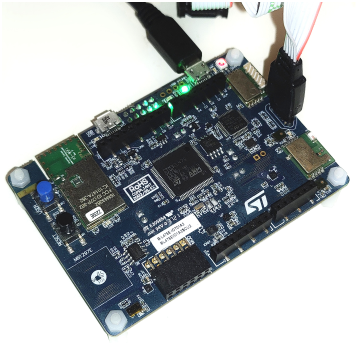


Hardware

- STM32L475VGT
  - General-purpose MCU
  - Industry-proven
  - Good availability
- Arm Cortex M4F @ 80 MHz
- 1 MB Flash
- 128 kB SRAM



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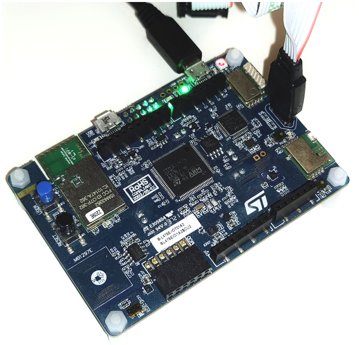

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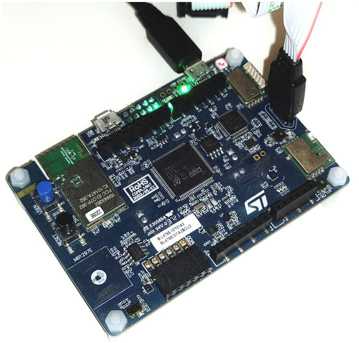

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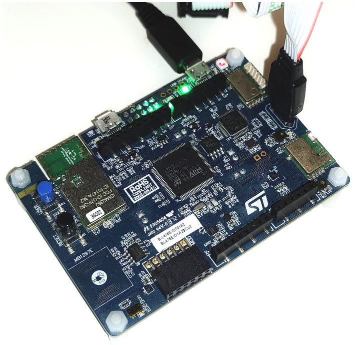

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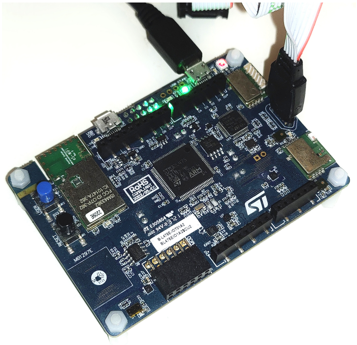

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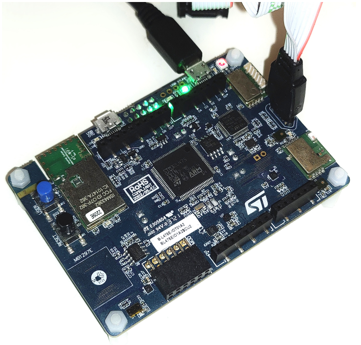

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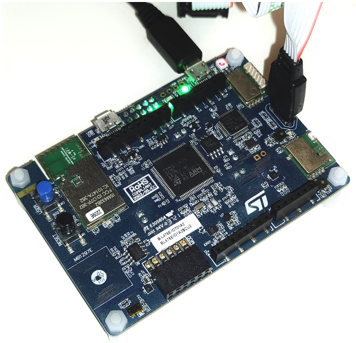

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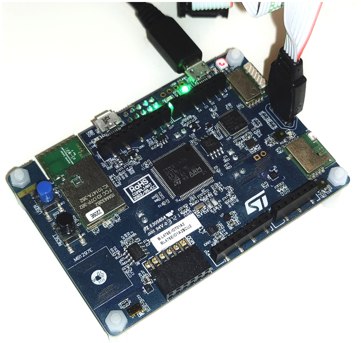
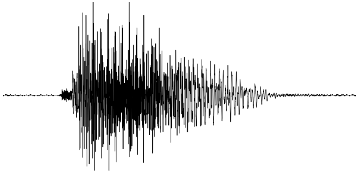


Dataset

speech_commands[1] by P. Warden at Google.

- Spoken keywords like "yes", "no", "up", "down", ...
- 1 second clips
- 16 kHz sampling rate
- 6:1:1 split



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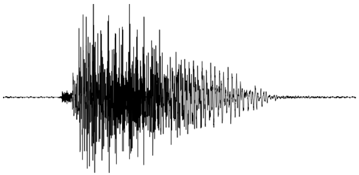

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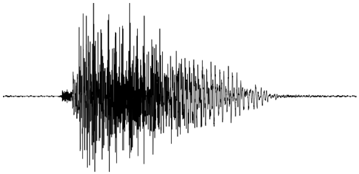

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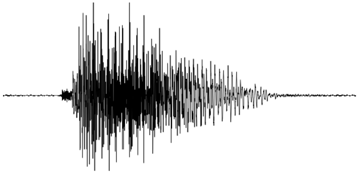

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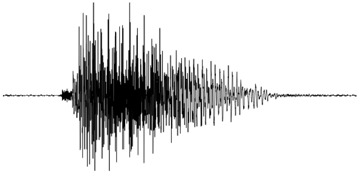

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Framework

TensorFlow Lite for Microcontrollers

- Easy to use
- Fully customizable
- Platform-independent

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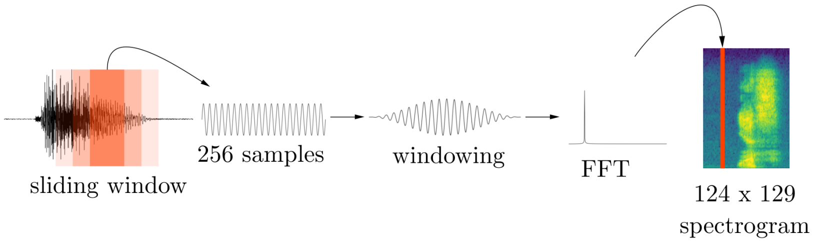
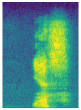
Preprocessing

Short-time fourier transform:

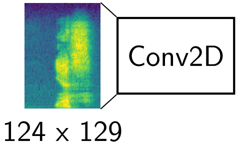
$$\mathbf{STFT}\{x[n]\}(m,\omega) \equiv X(m,\omega) = \sum_{n=-\infty}^{\infty} x[n]w[n-m]e^{-i\omega n}$$



Model


124 x 129

Model



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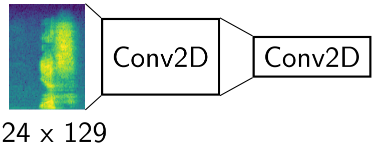

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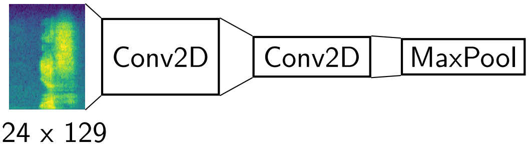

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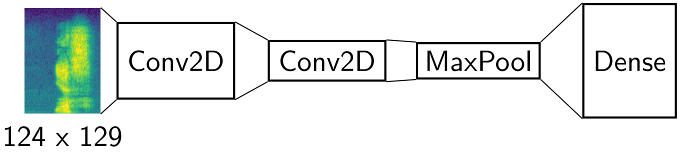

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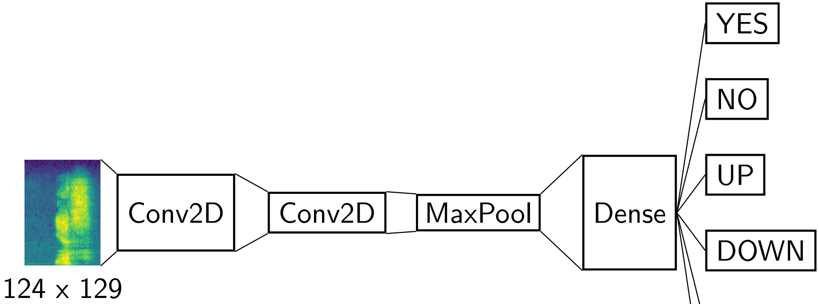
124 x 129
Conv2D
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MaxPool
Dense
YES
NO
UP
DOWN
LEFT
RIGHT

Microcontroller Implementation

- Full integer quantization of the model
- Implemented UART protocol with CRC32 checksum
- Preprocessing using CMSIS-DSP

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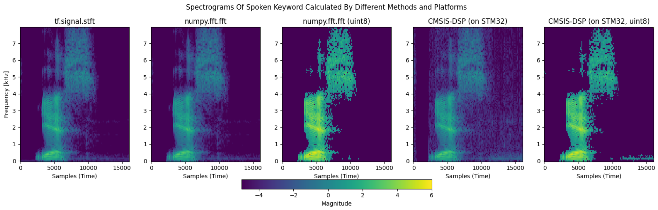
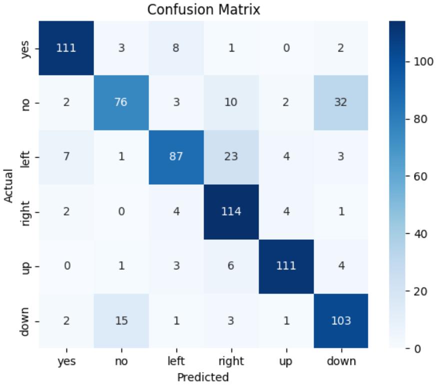


Performance Evaluation

- 80.27 % overall accuracy
- 180 ms per inference



Actual \ Predicted	yes	no	left	right	up	down
yes	111	3	8	1	0	2
no	2	76	3	10	2	32
left	7	1	87	23	4	3
right	2	0	4	114	4	1
up	0	1	3	6	111	4
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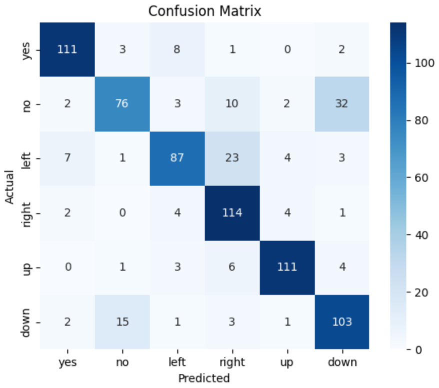

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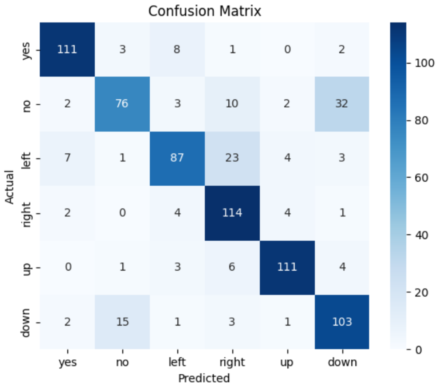

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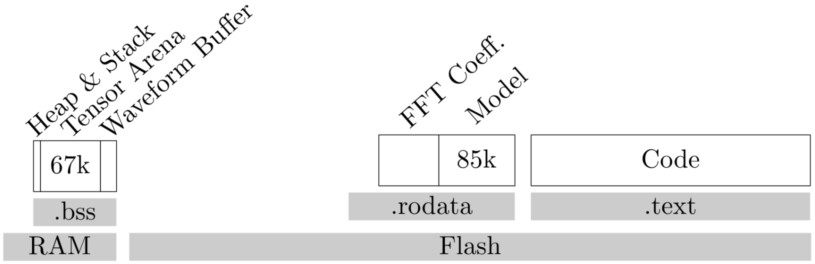
- Limiting factor is RAM for tensor arena
- 74.5 % SRAM used
- 45.9 % Flash used



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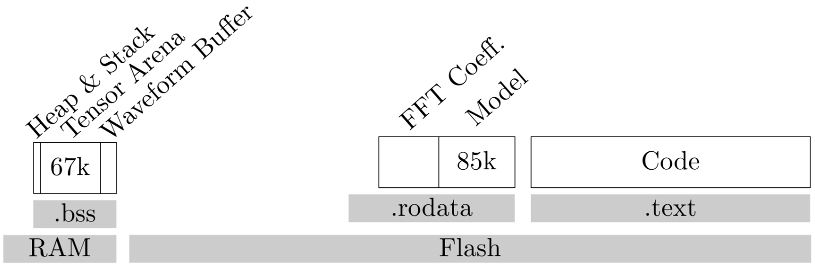

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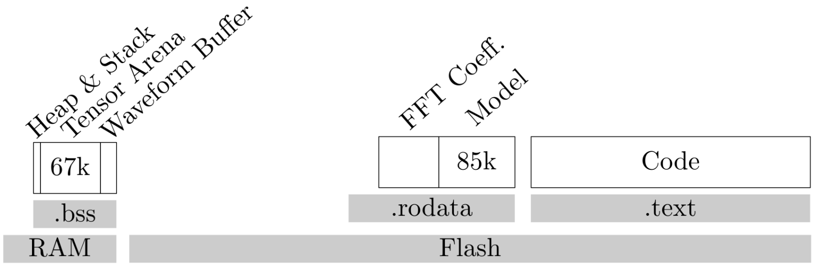

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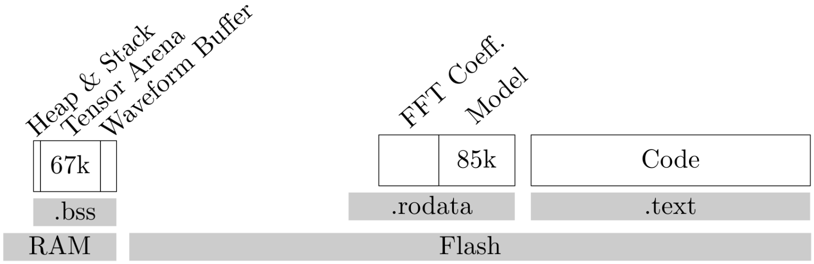
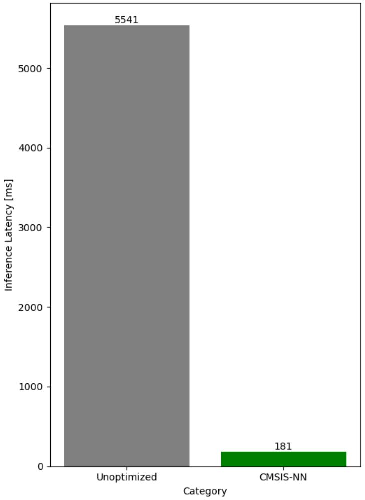


Optimized TFLite Kernel (using CMSIS-NN)

- Inference latency decreases by a factor of 30
- Program size increases by 37 kiB



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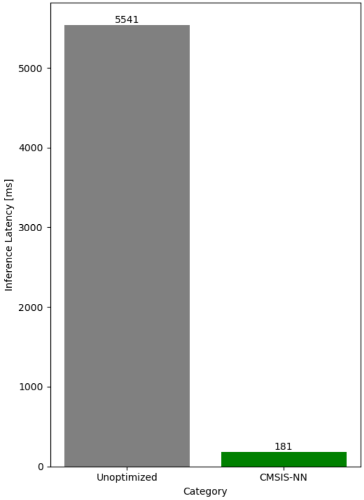

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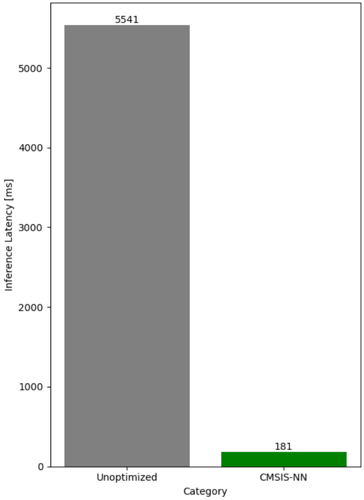

Limitations

- Accuracy could be better
- “Spotting” of keywords in background noise
- Microphone acquisition not working
  - Started to read out on-board PDM microphone
  - No support for 8-bit output with DMA
  - Amplitude and sampling rate seem off
- Optimize code, refactoring

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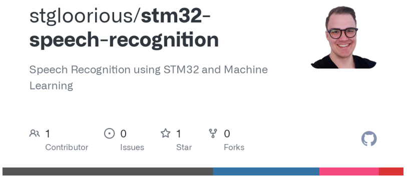
- Easy to reproduce, CMake-based build
- CI Pipeline
- Dependencies cleanly separated in Git submodules



stgloorious/**stm32-speech-recognition**

Speech Recognition using STM32 and Machine Learning

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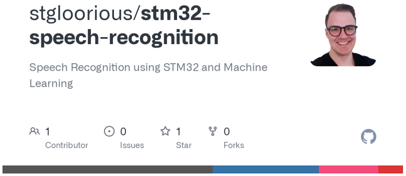
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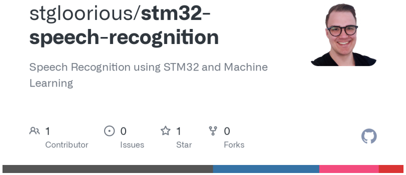

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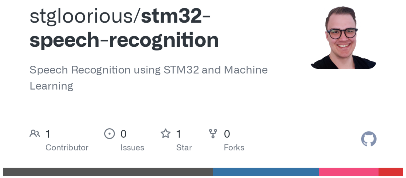

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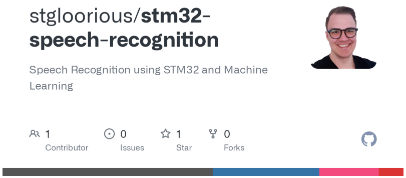

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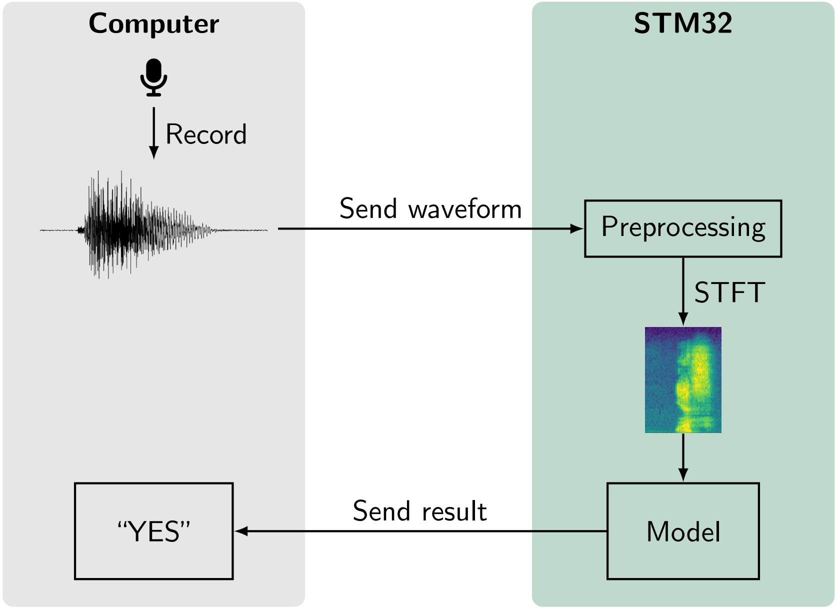
Computer
STM32
Record
Send waveform
Preprocessing
STFT
Send result
Model
"YES"

Real-Time Keyword Recognition on STM32 using TensorFlow Lite

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ETH Zürich

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