Machine Learning based Real Time UAV Detection using Smartphone

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Real-time UAV Detection using Smartphones

Introduction

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Introduction

Acronyms

- **ML : M**achine **L**earning
- **CNN : C**onvolutional **N**eural **N**etworks
- **RF : R**adio **F**requency
- **YOLO : Y**ou **O**nly **L**ook **O**nce
- **MFCC : M**el **F**requency **C**epstral **C**oefficient
- **NN : N**eural **N**etwork
- **GNB : G**aussian **N**aïve **B**ayes algorithm
- **KNN : K N**earest **N**eighbor algorithm
- **SVM : S**upport **V**ector **M**achine algorithm
- **ReLU : Re**ctified **L**inear **U**nit
- **TCP: T**ransfer **C**ontrol **P**rotocol
- **UAV : U**nmanned **A**erial **V**ehicles
- **CAGR : C**ompound **A**nnual **G**rowth **R**ate

Introduction

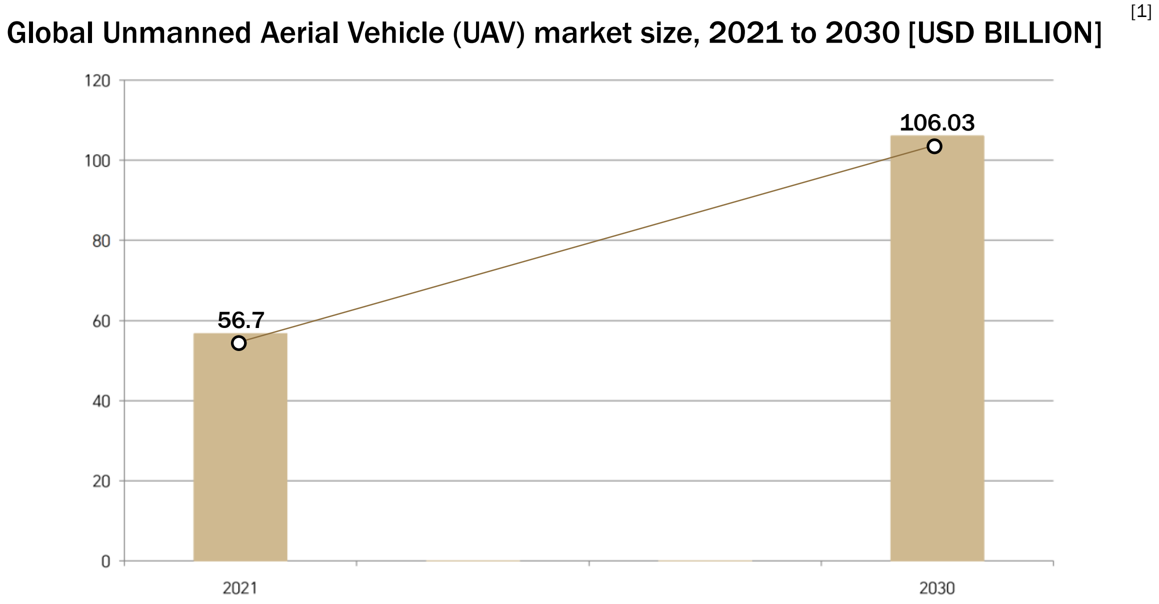
Project Motivation

Drone for delivery

Drone for photography

Introduction

Project Motivation



[1] B. Aamir, "Unmanned Aerial Vehicle (UAV) market are expected to reach US$ 106.03 billion by 2030 - astute analytica," GlobeNewswire News Room, 17-Nov-2022. [Online]. Available: https://www.globenewswire.com/en/news-release/2022/11/17/2558200/0/en/Unmanned-Aerial-Vehicle-UAV-Market-to-Reach-US-106-03-Billion-by-2030-Astute-Analytica.

Introduction

Project Motivation

Drone with bomb

Drone with gun

Introduction

Project Motivation

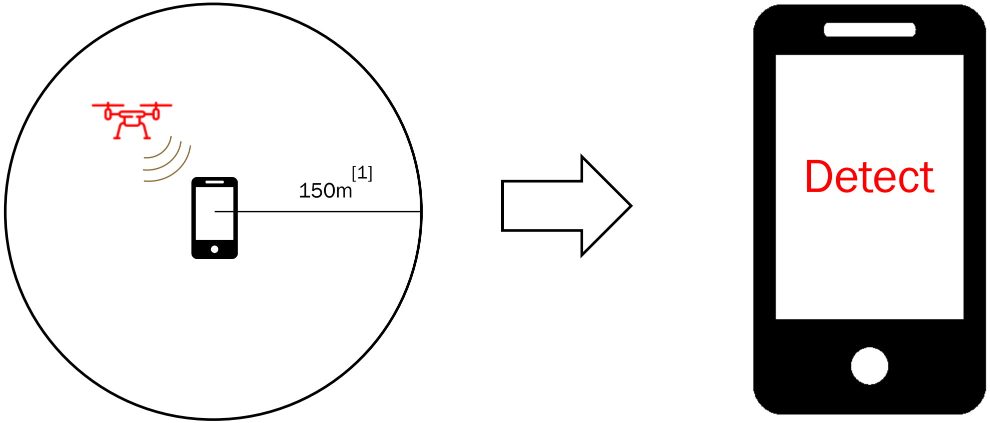
Drone assassination attempt on President

Drone attempts to smuggle out of prison

Introduction

Project Goal

- Real Time UAV Detection with Smartphone



[1] B. Taha and A. Shoufan, "Machine Learning-Based Drone Detection and Classification: State-of-the-Art in Research," in IEEE Access, vol. 7, pp. 138669-138682, 2019, doi: 10.1109/ACCESS.2019.2942944.

RELATED WORKS

Real-time UAV Detection using Smartphones

RELATED WORKS

Relevant literature for detecting Unmanned Aerial Systems

- **Vision based** UAV detection - B.-G. Han el al[1]. YOLO algorithm employs convolutional neural networks (CNN) to detect objects in real-time. This solution requires huge labeled datasets and have problem with visual data's noise.

- **Radar based** - B Torvik et al. [2] proposed 100% accuracy results by simple nearest neighbor approach for binary classification between UAVs and birds. However, this method has Radar Cross-Section and range limitation[3].

- **Radio frequency**-based UAV detection use RF signals from controller and achieved 80~95% accuracy with ML learning techniques. However, this solution fails when the drone is operated in autonomous mode[2].

[1] B. –G. Han et al. "Eesign of a Scalable and Fast YOLO for Edge –Computing Devices", Sensors, Bvol. 20, no. 23, 2020.
[2] B. Torvik, K. E. Olsen and H. Griffiths, "Classification of birds and uavs based on radar polarimetry", *IEEE geoscience and remote sensing letters* , vol. 13, no. 9, pp. 1305-1309, 2016.
[3] B. Taha and A. Shoufan, "Machine learning-based drone detection and classification: State-of-the-art in research", *IEEE Access*, vol. 7, pp. 138669-138682, 2019.

RELATED WORKS

Acoustic node for detecting Unmanned Aerial Systems

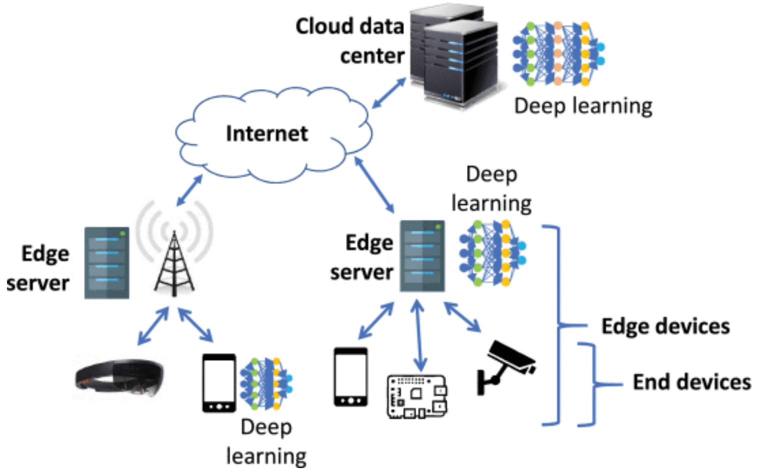
- The rotation of the drone’s **rotor blades produces a humming sound** that can be sensed and recorded, even within the range of human hearing.
- Y Wang *et al.*[1] Machine learning algorithm and **MFCC** were applied to detect UAVs.
- **Using features for classification** provide explanations for understanding how the ML classification was produced.
- This solution provided 78% accuracy and fewer computational resources than others.

[1] Y. Wang et al. "A Feature Engineering Focused System for Acoustic UAV Detection", 2021 Fifth IEEE International Conference on Robotic Computing (IRC), 2022.

RELATED WORKS

Acoustic UAV detection on Edge device

- 3 Challenges : Latency, Scalability, and Privacy [1]
- TensorFlow Lite was proposed for mobile and embedded devices, with mobile GPU support.
- In contrast to cloud computing, edge computing's latency is significantly lower, as large quantities of data do not have to travel through a backhaul network to the cloud[2].



[Deep learning on edge devices and cloud data centers]

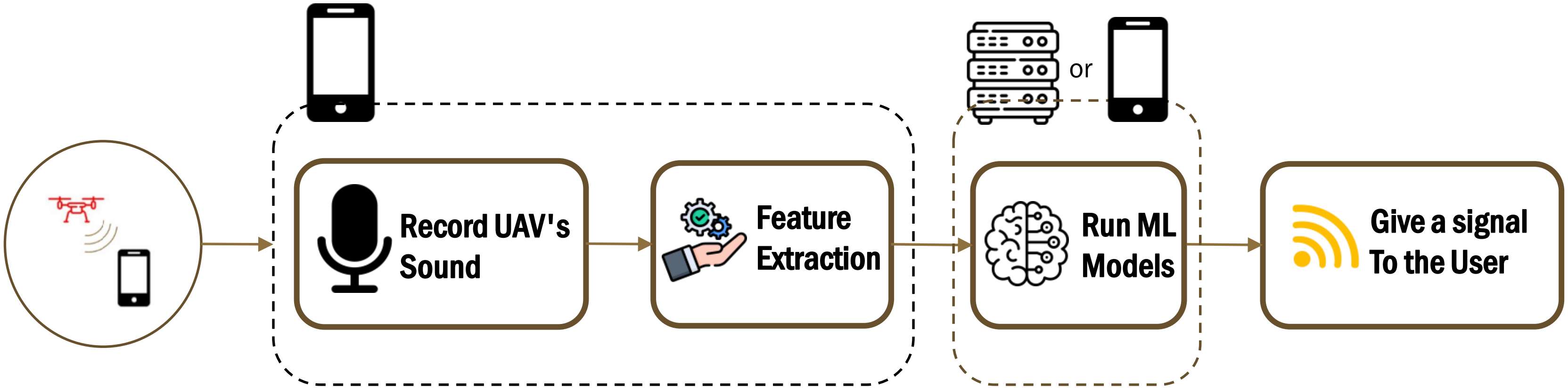
[1, Fig 1] J. Chen and X. Ran, "Deep learning with edge computing: A review", Proc. IEEE, vol. 107, no. 8, pp. 1655-1674, Jul. 2019.
[2] P. Joshi et al. "Enabling All In-Edge Deep Learning: A Literature Review" 2023, IEEE Access (Volume: 11)

Methodology

Real-time UAV Detection using Smartphones

Methodology

Overview of two methods for drone detection



Methodology

2.1 Drone Types

- **Autel Evo 2**
  - Weight : 1192 g
  - Max Speed : 20 m/s

- **DJI Phantom 4**
  - Weight : 1380 g
  - Max Speed : 20 m/s

Methodology

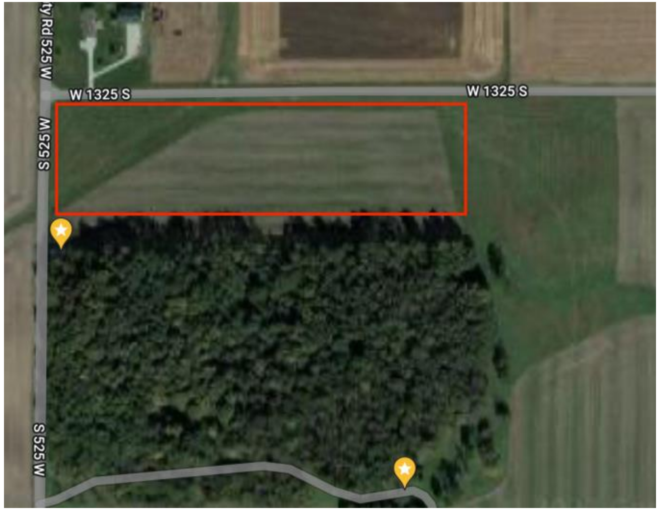
Location of data collection

- Location

  - New Richmond, Indiana,
    (40.2227062, -87.0000169)

- Time

  - February 13, 06:00 A.M



Methodology

Sound data samples

Audio Type	Number of Samples	Total Time(sec)
UAV	200	500
Noise	200	500
Total	400	1000

5 seconds per each sample

Methodology

Feature extraction

TABLE II
DRONE ACOUSTIC FEATURE EXTRACTION METHOD

Feature	Shape
chroma_stft	12
chroma_cqt	12
chroma_vqt	12
mel	128
mfcc	40
rms	1
centroid	1
bandwidth	1
contrast	7
flatness	1
bandwidth	1
rolloff	1
poly_shape	2
tonnetz	6
zero_crossing	1

- Feature extraction methods

⇒ **Python library, Librosa**

→ Models can understand the sound through Feature extraction

Methodology

Selecting ML Algorithm

- Machine Learning is our main method of UAV detection.
- Using ML algorithms is suitable for audio classification.
- In another paper[1], 4 algorithms were selected.

Name of Algorithm	Hyperparameters
NN (**N**eural **N**etwork)	Learning rate = 0.001, epochs = 15
GNB (**G**aussian **N**aïve **B**ayes)	Default
KNN (**K**-**N**earest **N**eighbor)	N_neighbors = 6, others are default
SVM (**S**upport **V**ector **M**achine)	C = 10, kernel as linear

[1] Y. Wang et al, "A Feature Engineering Focused System for Acoustic UAV Detection," *2021 Fifth IEEE International Conference on Robotic Computing (IRC)*, Taichung, Taiwan, 2021, pp. 125-130

Methodology

Server Development

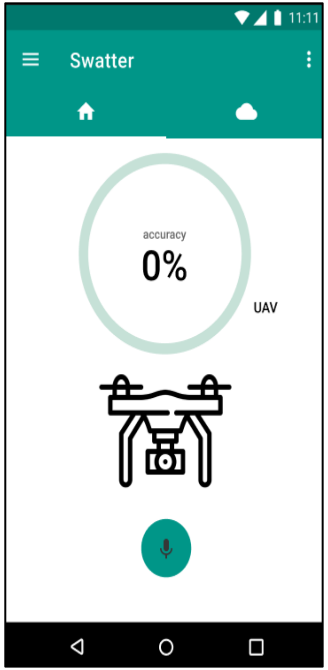
CentOS 7 | C++ 17 | Python/C API

1. Install CentOS 7 on VMWare 17
2. Implement server program
3. Embed Python inside a C++ program
4. Use Transmission Control Protocol (TCP)

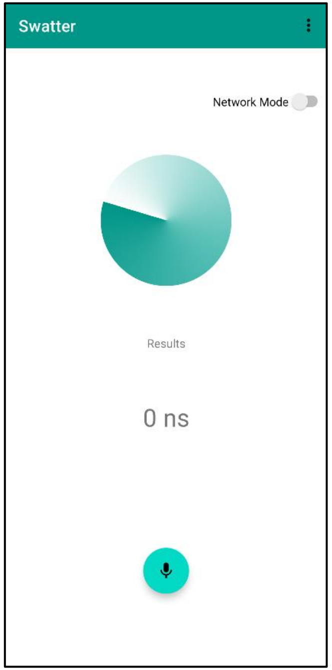
Methodology

Application Development

- Model converted using TensorFlow lite
- Program specifications
  - Kotlin (java), Android API 27
- Three main functions
  - Record sound
  - Draw result of UAV Inference
  - Transmit sound data to cloud server



[UI before Develop]



[UI after Develop]

Progress

Real-time UAV Detection using Smartphones

Progress

Verifying Feature Extraction

- Feature extraction using sample data
  - Librosa built-in data is used
- Verified that shapes are matched with previous paper[1]

```python
## Verify shape of features
df = pd.DataFrame(index = ['MFCC','mel','chroma_stft','contrast','tonnetz']
                  ,columns = ['Shape'])
#df.index.name = 'Features'

## sample data
y, sr = librosa.load(librosa.ex('trumpet'))
print(y)

## MFCC
mfcc = librosa.feature.mfcc(y, sr=sr)
mfcc = np.mean(mfcc.T,axis=0)
# print(mfcc)
df.iloc[0] = mfcc.shape[0]

## mel
mel = librosa.feature.melspectrogram(y,sr=sr)
mel = np.mean(mel.T, axis=0)
df.iloc[1] = mel.shape[0]

## chroma_stft
chroma_stft = librosa.feature.chroma_stft(y,sr)
chroma_stft = np.mean(chroma_stft.T, axis=0)
df.iloc[2] = chroma_stft.shape[0]

## contrast
stft = np.abs(librosa.stft(y))
contrast = librosa.feature.spectral_contrast(S=stft,sr=sr)
contrast = np.mean(contrast.T, axis=0)
df.iloc[3] = contrast.shape[0]

## tonnetz
tonnetz = librosa.feature.tonnetz(y=librosa.effects.harmonic(y),sr=sr)
tonnetz = np.mean(tonnetz.T, axis=0)
df.iloc[4] = tonnetz.shape[0]

print(df)
```

[Program for verifying feature extraction]

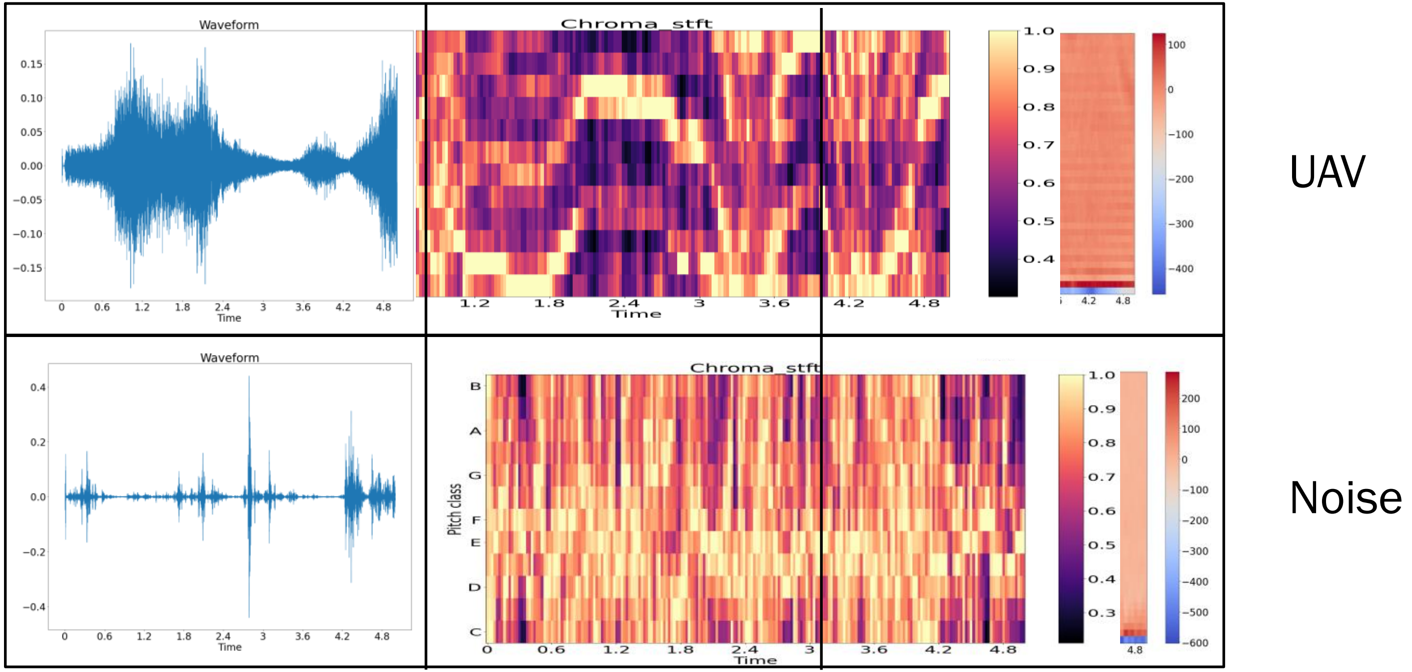
	Shape
MFCC	40
mel	128
chroma_stft	12
contrast	7
tonnetz	6

[Results of program]

[1] Y. Wang et al, "A Feature Engineering Focused System for Acoustic UAV Detection," *2021 Fifth IEEE International Conference on Robotic Computing (IRC)*, Taichung, Taiwan, 2021, pp. 125-130

Progress

Feature Visualization



Progress

Model training

- **Models**
  - NN (Tensorflow)
  - SVM, KNN, GNB (scikit-learn)

- **Data**
  - X (Predictor Variable) : Extracted feature
  - Y (Outcome Variable) : Autel Evo2 (0)

    DJI Phantom4 (1)

    Noise (2)

- **Train vs Test**
  - 0.8 : 0.2 ratio

- **Computing Power**
  - Laptop (Ryzen 5 5625U)

Progress

Testing Result

Feature	Accuracy	Recall	Precision	F1 Score
1. chroma_stft	0.81	0.81	0.83	0.80
2. mel	**0.89**	**0.89**	**0.89**	**0.88**
3. mfcc	0.86	0.86	0.88	0.86
4. contrast	0.76	0.76	0.75	0.75
5. tonnetz	0.78	0.78	0.79	0.76

[NN model Benchmark]

Feature	Accuracy	Recall	Precision	F1 Score
1. chroma_stft	0.86	0.86	0.86	0.86
2. mel	0.86	0.86	0.87	0.86
3. mfcc	**0.96**	**0.96**	**0.96**	**0.96**
4. contrast	0.76	0.76	0.77	0.75
5. tonnetz	0.79	0.79	0.81	0.78

[SVM model Benchmark]

- NN model
- SVM model

Progress

Testing Result

Feature	Accuracy	Recall	Precision	F1 Score
1. chroma_stft	0.80	0.80	0.81	0.79
2. mel	0.85	0.85	0.85	0.85
3. mfcc	**0.93**	**0.93**	**0.93**	**0.92**
4. contrast	0.82	0.82	0.84	0.82
5. tonnetz	0.80	0.80	0.80	0.79

[KNN model Benchmark]

- KNN model

Feature	Accuracy	Recall	Precision	F1 Score
1. chroma_stft	**0.91**	**0.91**	**0.91**	**0.91**
2. mel	0.66	0.66	0.77	0.67
3. mfcc	0.88	0.88	0.88	0.87
4. contrast	0.84	0.84	0.86	0.83
5. tonnetz	0.89	0.89	0.89	0.89

[GNB model Benchmark]

- GNB model

Progress

Model Conversion

- To implement models into Android

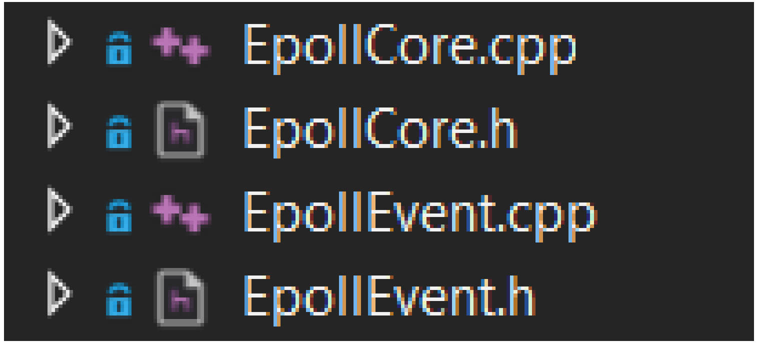
- HDF5 (Hierarchical Data Format 5)
- PB (Protocol Buffer)
- TFLITE (Tensorflow Lite)

Progress

Server program

```
for (int32 i = 0; i < 5; i++)
{
    GThreadManager->Launch([&service]()
        {
            DoWorkerJob(service);
        });
}
```

[Multiple threads start in main function]



[Classes to control epoll]

- Use Multithreading for smooth service
- Share the jobs to be processed to each thread
- Epoll is used for reducing waste and increasing performance

Packet protocol

```cpp
enum PacketNum : uint16
{
    C_LOGIN = 1000,
    S_LOGIN = 1001,
    C_AUDIO_DATA = 1002,
    S_DETECTION_RESULT = 1003,
};
```

- Received byte data is converted to packet
- Two protocols are used for the service

```cpp
struct PKT_C_AUDIO_DATA
{

    uint16 packetSize; // Common header,
    uint16 packetId; // Common header,
    uint16 featureOffset; // Address of
    uint16 featureCount = 40;
```

[Packet from a client to the server]

```cpp
struct PKT_S_DETECTION_RESULT
{
    uint16 packetSize; // Common header
    uint16 packetId; // Common header
    uint8 result;
};
```

[Packet from the server to the client]

Progress

Embedding Python program

```
#define PY_SSIZE_T_CLEAN
#include <python3.9/Python.h>

class MLManager
{
public:
    MLManager();
    ~MLManager();

    void Init();
    int8 RunModel(const float features[], uint16 featureCount);
```

[A class for call ML model written in python]

Progress

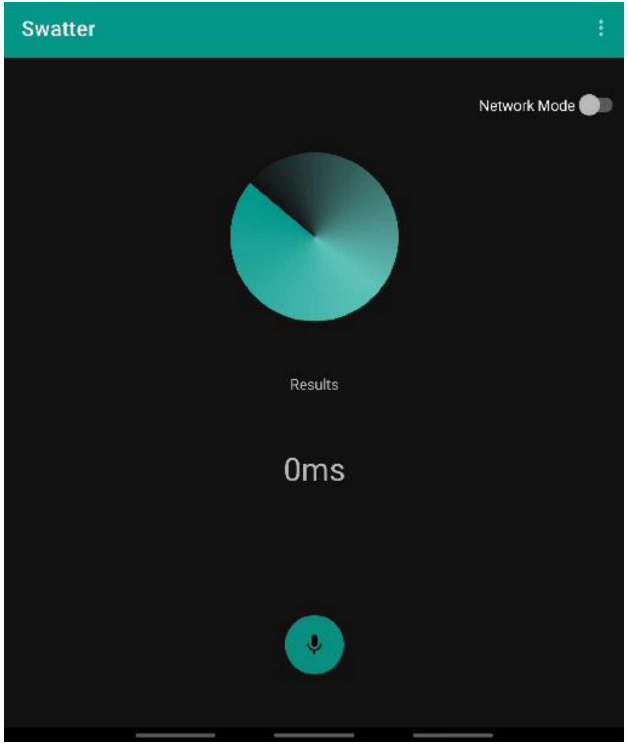
Application

- **Implementation**

  - Record Audio with Uncompressed Audio File

  - MFCC feature extraction

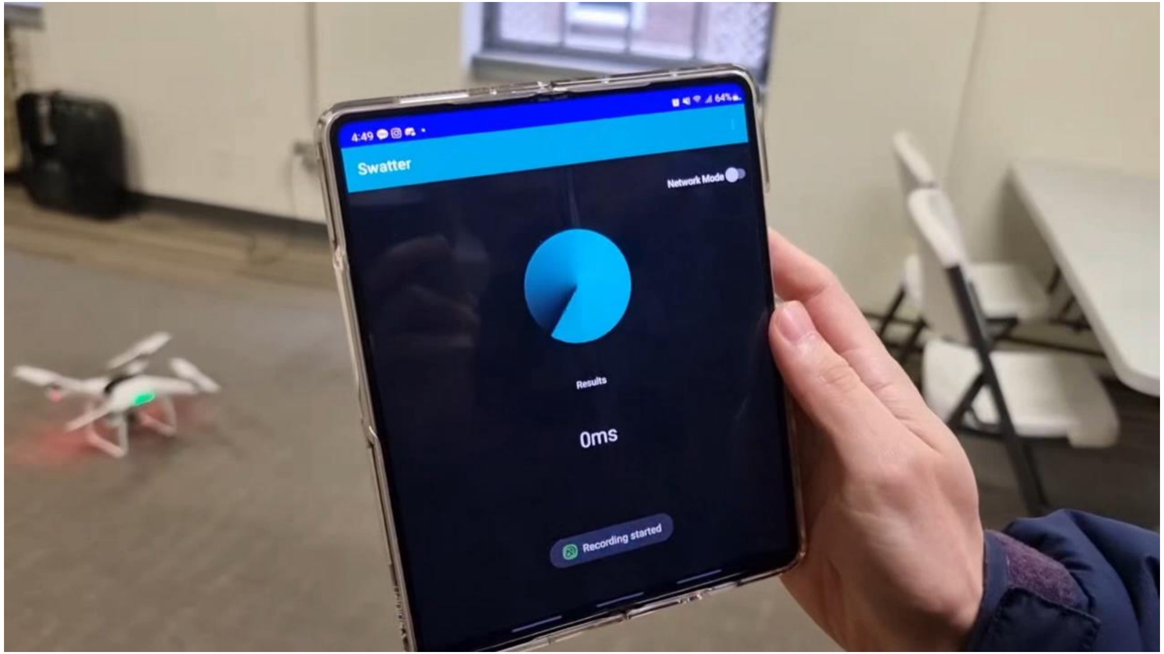
  - TensorFlow Lite Interpreter



[Application]

Progress

Demo video



Progress

Test between smartphones and server

	Smartphone	Server
Average of inference time	0.90525 ms	5270 ms

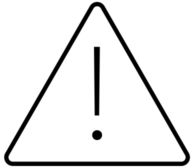
- Compare inference time.
- Using only smartphones more faster than using Server.

Future work

Real-time UAV Detection using Smartphones

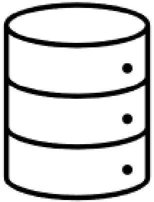
Future Work

Developing various functions on smartphone



- **Warning UAV's appearance**

  - Save GPS location
  - Share appearance to security



- **Collecting UAV's sound**

  - Restore audio file
  - Send to database

Reference

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Thank you

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Q&A

Real-time UAV Detection using Smartphones

Appendix

Real-time UAV Detection using Smartphones

Structure of Neural Network Model

- Neural network model structure
- High flexibility, depends on usage.
- 3 Dense layers
  - 128 nodes for 2 layers, 1 node for output
- 2 Activation layers
  - 'ReLU' function
- 2 Dropout layers
  - Dropout rate : 0.1

```
Layer (type)                 Output Shape              Param #
=================================================================
input_2 (InputLayer)         [(None, 128)]             0

dense_3 (Dense)              (None, 128)               16512

activation_2 (Activation)    (None, 128)               0

dropout_2 (Dropout)          (None, 128)               0

dense_4 (Dense)              (None, 128)               16512

activation_3 (Activation)    (None, 128)               0

dropout_3 (Dropout)          (None, 128)               0

dense_5 (Dense)              (None, 1)                 129

=================================================================
Total params: 33,153
Trainable params: 33,153
Non-trainable params: 0
_________________________________________________________________
```

[Structure for NN model]

Appendix

Server program

- Epoll can notify to users when monitored file descriptor is ready
- On each call to select() or poll(), the kernel must check all of the specified file descriptors to see if they are ready.

-> When monitoring a large number of file descriptors that are in a densely packed range, the timed required for this operation greatly outweights [the rest of the stuff they have to do]

- The 3 system calls that let you ask Linux to monitor lots of file descriptors are poll, epoll and select.

Appendix

Server program

```
bool ClientPacketHandler::Handle_C_AUDIO_DATA(PacketSessionRef & session, BYTE * buffer, int32 len)
{
    // TODO
    BufferReader br(buffer, len);

    PKT_C_AUDIO_DATA* pkt = reinterpret_cast<PKT_C_AUDIO_DATA*>(buffer);

    if (pkt->Validate() == false)
        return false;

    float* features = pkt->GetFeatures();

    int8 result = GMLManager.RunModel(features, pkt->featureCount);

    cout << "Handle_C_Audio, Result: " << result << endl;
    return true;
}
```

[Handle the packet from and do follow-up]

Server program

```cpp
class Lock
{
    enum : uint32
    {
        ACQUIRE_TIMEOUT_TICK = 10000,
        MAX_SPIN_COUNT = 5000,
        WRITE_THREAD_MASK = 0xFFFF'0000,
        READ_COUNT_MASK = 0x0000'FFFF,
        EMPTY_FLAG = 0x0000'0000
    };

public:
    void WriteLock(const char* name);
    void WriteUnlock(const char* name);
    void ReadLock(const char* name);
    void ReadUnlock(const char* name);

private:
    Atomic<uint32> _lockFlag = EMPTY_FLAG;
    uint16 _writeCount = 0;
};
```

```
ClientPacketHandler.cpp
ClientPacketHandler.h
DetectingSession.cpp
DetectingSession.h
DetectingSessionManager.cpp
DetectingSessionManager.h
MLManager.cpp
MLManager.h
```

- Offer the detection operation
- Call ML model to classify and send results to client