“On-sensor TinyML implementation: Advancing Neuroscience through Wearable Devices”

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January 19, 2023
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Muhammad Awais Bin Altaf (S’11–M’16) received a B.S. degree from the University of Engineering and Technology, Lahore, Pakistan, in 2008, and the M.Sc. and Ph.D. degrees in microsystems engineering and interdisciplinary engineering from the Masdar Institute of Science and Technology (MIST), Abu Dhabi, United Arab Emirates, in 2012 and 2016, respectively. Since 2016, he has been with the Electrical Engineering Department, Lahore University of Management Sciences (LUMS), Lahore, Pakistan, where he is currently an Assistant Professor. His current research interests include analog and digital IC design, energy-efficient applied AI, and the development of ultra-low-power circuits and systems for wearable bio-medical applications.
On-sensor TinyML implementation: Advancing Neuroscience through Wearable Devices

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Outline

- Motivation
- Big Data and Hardware: Challenges
- Example: Negative Emotion Outburst Detection
- Summary
Current Health Diagnostics Tools

- Hospital Environment
- Limited Capacity
- Operated by Clinician
- Human Errors

In Hospital Devices

Vital Signs Machine

ECG Recorder

EEG Acquisition
Current Health Diagnostics Tools

- Hospital Environment
- Limited Capacity
- Operated by Clinician
- Human Errors

In Hospital Devices
- Few Readings/day
- Not Wearable
- Limited Functionality
- Cost?

Portable Devices

- ECG Recorder
- Pulse Oximeter
- Wrist Blood Pressure
- Fetal Monitor
- Glucometer
- Vital Signs Machine
- EEG Acquisition

- Operated by Clinician

- Human Errors
Current Health Diagnostics Tools

- Hospital Environment
- Limited Capacity
- Operated by Clinician
- Human Errors

- Few Readings/day
- Not Wearable
- Limited Functionality
- Cost ?

- Hospital/Clinic
- Time Consuming
- Mostly Invasive
- Cost

In Hospital Devices
Portable Devices
Lab Tests

Vital Signs Machine
ECG Recorder
EEG Acquisition
Glucometer
Pulse Oximeter
Fetal Monitor
Wrist Blood Pressure
Proposed Health Diagnostics Tools

Benefits

😊 Physician Load ↓
😊 Human Error ↓
😊 Quick Response

Normal ▲ Abnormal ●

Challenges

(parentheses removed)

😢 Disease Requirements
😢 Patient Specific
😢 Data Availability

Patients need Intelligent Devices not just Artificial
Proposed Health Diagnostics Tools

**Benefits**

- 😊 Physician Load ↓
- 😊 Human Error ↓
- 😊 Quick Response

**Challenges**

- 😞 Disease Requirements
- 😞 Patient Specific
- 😞 Data Availability

Both LoC and Wearable Devices need to Operate ➔ Energy Harvesting

**Benefits**

- 😊 Long Life
- 😊 Patient Ease
- 😊 Reduce Cost

**Challenges**

- 😞 Weak & Unstable
- 😞 Efficiency
Outline

- Motivation
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- Summary
Big Data: Challenges and Opportunities

- Big Data Era ➔ Data created in last years
- **Exponential** Increase in the Sensors ➔ Zettabytes of data
- Automatic framework Required
  - Analyze this Data
  - Meaningful & Actionable information
- Challenges ➔ Significant Amount of Computation
  - Local Processing vs. Cloud Processing
  - Cost of Communication, Limited Bandwidth
  - Privacy, Latency and Security
- Applications ➔ Multimedia, Medical, Defense
Holistic View of Standard AI

- Simulation of Human Intelligence
  - Sense
  - Reason
  - Act
  - Adapt

- Subset of AI
  - Learn from previous occurrence
  - Adapt to new Data

- Subset of ML
  - Mimicking the human brain
  - Layers/Neurons

- Implementation of NN
  - Dense Architecture
  - More than three layers
Machine Learning

- Automatic Learning and Self-improvement
  - Training the systems to comprehend unfamiliar concepts
- Supervised Learning
  - Train algorithm using labeled data
  - Supervised Learning:
    - Naïve Bayes
    - LR
    - SVM
    - KNN
    - Random Forest
    - Neural Nets
- Unsupervised Learning
  - Hidden Patterns for identification
  - Unsupervised Learning:
    - K-Means
    - PCA
    - Density Estimation
- Semi-supervised Learning
  - Mix of above both
  - Semi-supervised Learning:
    - Learn Small Label data
    - Classify large unlabeled
    - Iterative process
    - Test Document
- Reinforcement Learning
  - Reward desired and push negative
  - Reinforcement Learning:
    - Optimization
    - Decision Making
    - Games, Robotics, Bot
- Relatively suited for wearable devices
Ultra-Low-Power Activity Profile

- Enormous bio signals Data to Process
- Major System Power consumed by Wireless Transmission
- Extended Ultra-Low-Power standby mode
- Minimum Active Duty Cycle

[Diagram showing power consumption and activity profile]

2. M. Altaf, et. al, IEEE TNSRE, 2019
Mixed Signal On-Chip AI for Healthcare

- AI can use sophisticated algorithms:
  - ‘Learn’ features from an **Enormous Data**
  - Assist Clinical practice

- My Goals:
  - Innovate Algorithms ➔ Disease detection
  - Hardware Realization ➔ Wearable devices

![Diagram of Medical Data, Feature Extraction, and ML/DL](image)
Wearables: Continuous Monitoring

- “Wearable” means whatever a subject can wear
- Helping People to better Monitor their Health status
- Self-health tracking at Home environment
- Providing more Data to Clinicians
- Earlier Diagnostic and Guidance

Current Wearables*
Outline

- Motivation
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Autism Spectrum Disorder

- Brain Development Condition
- Difficulty in communicating/socializing
- Can Affect whole life

- Affects differently
- No two cases are similar but they suffer
- 😞 Autism can be very difficult to diagnose

- Late ASD Detection ➔ 😞 Handicapped Life

- Early Detection ➔ Early Intervention ➔ Independent Life

- Conventional ASD Detection ➔ No Defined Biomarkers

Autism Spectrum Disorder

- Types of ASD
  - The oppositional Child
    - Slightest issue provocation
    - No one can be trusted
    - Hostile and aggressive actions
  - The unfocused Child
  - Daydreaming Child
  - Pessimistic Child

Autism Spectrum Disorder

- Types of ASD
  - The oppositional Child
  - The unfocused Child ➔ Difficult to process information ➔ Easily distracted
  - Daydreaming Child
  - Pessimistic Child
Autism Spectrum Disorder

- Types of ASD
  - The oppositional Child
  - The unfocused Child
  - Daydreaming Child
  - Pessimistic Child

- More focused on Fantasies
- Replays in his/her mind
- Reality is avoided

Autism Spectrum Disorder

- Types of ASD
  - The oppositional Child
  - The unfocused Child
  - Daydreaming Child
  - Pessimistic Child → More into preferred activities
  → Personal Benefit
  → Future depression

Diagnosis and Treatment

- Conventional Diagnosis
  - Child/Parent Interview
  - Behavior Monitoring
  - Late Diagnosis

- Conventional Treatment
  - Therapies/Specialized Schools

- Autism Patients Dilemma
  - Lack of Emotion Control
  - Evident Emotion Difference
  - Negative Emotions ➔ Suicide attempts

Suicide attempts are 28 times higher in ASD patients compared to normal children.

Treatment Cost:
- 2015: $268 billion
- 2025: $461 billion

~1.7X higher over 10 years.

Proposed Idea

[Image of a diagram with labeled parts]

Proposed Idea

- Avoid Emotion Outburst
- Assist in learning
- Regulate Emotions
- Home Environment
- Economical Burden

No EEG Processor [Confused] No/Mild Intervention

NeuroFeedback Intervention

Live Feedback
1. Learning Activity not helpful
2. Student distracted
3. Stimulation is required

EEG Recordings [Continuous feedback]
First SoC of NEOB Detection

- **AFE** = Analog Front End
- **DBE** = Digital Back End
- **NN** = Neural Network
- **EDL** = Emotion Detection Logic
- **C^2LNA** = Capacitive Coupled LNA
- **CTDC^2** = Continuous Time Digitally C^2
- **RRL** = Ripple Rejection Loop
- **ZC** = Zero Crossing
- **SKI** = Skewness

---

ML/DNN Processor: Channel Selection

- Efficient Channel Selection
- Comfortable to the wearer
- Overfitting across different datasets
- Maximize the information

DNN Based PS Classification Processor

- Preprocess
- ZCD
- SKEW
- FE Engine
- N1
- N2
- N8
- N1
- N2
- N16
- N1
- N2
- N32
- IL
- HL1
- HL2
- OL
- EDL
- Sel Chan EEG
- Valence PS Parameters 2x1 MUX
- Arousal PS Parameters

Efficient Channel Selection

Selecting K-Best Features
Sequential Forward Search


ML/DNN Processor: Feature Extraction

- Select the **best** subset of features
- Wrapper Method
- Large Scale Feature Extraction
- Analysis of Large Combination of features
- Experimentation of different features

---

DNN Based PS Classification Processor

Zero Crossing Detection (ZCD) ➔ Skewness

- Preprocess
- ZCD
- SKEW
- FE Engine

Deep Neural Network

- OL (32 x 1)
- HL2 (16 x 32)
- HL1 (8 x 16)
- IL (4 x 8)

Deep Neural Network

- VA PS Parameters 2x1 MUX
- Valence PS Parameters
- Arousal PS Parameters

Sel Chan EEG

- EDL

ML/DNN Processor: Classification

Sigmoid Activation Function \((SGM) = \frac{1}{1 + e^{-x}}\)
ML/DNN Processor: Classification

Feature Vector

IL (4x8) HL1(8 x16) HL2(16 x 32)

Weights

Linear Sigmoid RELU

0.98 0.5 -0.34

Deep Neural Network

Patient Specific DNN Emotion Classifier

DNN Control Unit

OPCODE

sig

X

rlu

ALU

(Controlled by FSM)
ML/DNN Processor: Classification

Deep Neural Network
Sigmoid
ReLU

Feature Vector
F_4 → F_3 → F_2 → F_1

IL (4x8) → HL1(8 x16) → HL2(16 x 32)

Weights
W_{IL} → W_{HL1} → W_{HL2} → W_{OL}

Patient Specific DNN Emotion Classifier

DNN Control Unit

ALU
(Controlled by FSM)

opcode

sig

X

+ rlu

Sigmoid

Feature Vector

F_4
F_3
F_2
F_1

IL (4x8)
NL (8 x16)
OL (32 x 1)

Deep Neural Network

Linear

Sigmoid

RELU

Weights

0.545
0.39
0.61

F_4
F_3
F_2
F_1
ML/DNN Processor: Classification

Feature Vector

Deep Neural Network

Linear

Sigmoid

RELU

Sigmoid

Weights

Linear

-0.128

0.13

0.24

Deep Neural Network

DNN Control Unit

Patient Specific DNN Emotion Classifier

opcode

sig

alu

(Controlled by FSM)

IL (4x8)

HL1 (8 x 16)

HL2 (16 x 32)

OL (32 x 1)

Deep Neural Network

Sigmoid

RELU

Sigmoid

Feature Vector

Weights

Linear

-0.128

0.13

0.24

Deep Neural Network

DNN Control Unit

Patient Specific DNN Emotion Classifier

opcode

sig

alu

(Controlled by FSM)
ML/DNN Processor: Classification

Deep Neural Network

Feature Vector

F_1 \rightarrow F_2 \rightarrow F_3 \rightarrow F_4

Weights

IL (4x8) \rightarrow HL1 (8 x 16) \rightarrow HL2 (16 x 32)

Patient Specific DNN Emotion Classifier

DNN Control Unit

Opcode

MUX (nx1)

X

sig

rlu

ALU (Controlled by FSM)
ML/DNN Processor: Classification

Feature Vector

IL (4x8) → HL1(8 x16) → HL2(16 x 32)

Deep Neural Network

- Linear
- Sigmoid
- RELU

OL (32 x 1)

Deep Neural Network

RELU

Weights

- Linear
- Sigmoid

Patient Specific DNN Emotion Classifier

- opcode
- sig
- rlu

ALU (Controlled by FSM)

DNN Control Unit

Weights

-0.87

N1

N1

N1

N1

N2

N2

N2

N8

N16

N32

-0.87

F1

F2

F3

F4

Feature Vector

Weights

-0.87
ML/DNN Processor: Classification

Deep Neural Network

Feature Vector

Patient Specific DNN Emotion Classifier

Weights

DNN Control Unit

ALU

opcode

sig

rlu

ML/DNN Processor: Classification
Measurement Results

- SoC is realized in 180nm CMOS \( \Rightarrow \) area of 16.0 mm\(^2\)
- 1.0V Supply \( \Rightarrow \) 10.13uJ/class
- RTI noise \( \Rightarrow \) 0.55uV\(_{\text{rms}}\) (0.5 – 100Hz)
- THD \( \Rightarrow \) -91dB
- NEF \( \Rightarrow \) 2.71
- No. of Classes \( \Rightarrow \) 4

- Processor verification on multiple databases \( \Rightarrow \) 85.2%
Prototype Ear-EEG
Outline

- Motivation
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- Summary
Objective: Early diagnosis of chronic neurological disorder

- Solving real-life health and beyond challenges
- Biggest Challenge is post-lab testing
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