CG4002: HARDWARE – SENSORS AND FPGA

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HARDWARE SENSORS REQUIREMENTS

- Detect Dance Moves!!!!!
- Design your own dance moves
- Design a Body Analytics System using EMG
- Power System Design

HUMAN MOVEMENT ESTIMATION

- What is motion capture?

- How do we do it?
  - Optical Systems
  - Non-Optical Systems

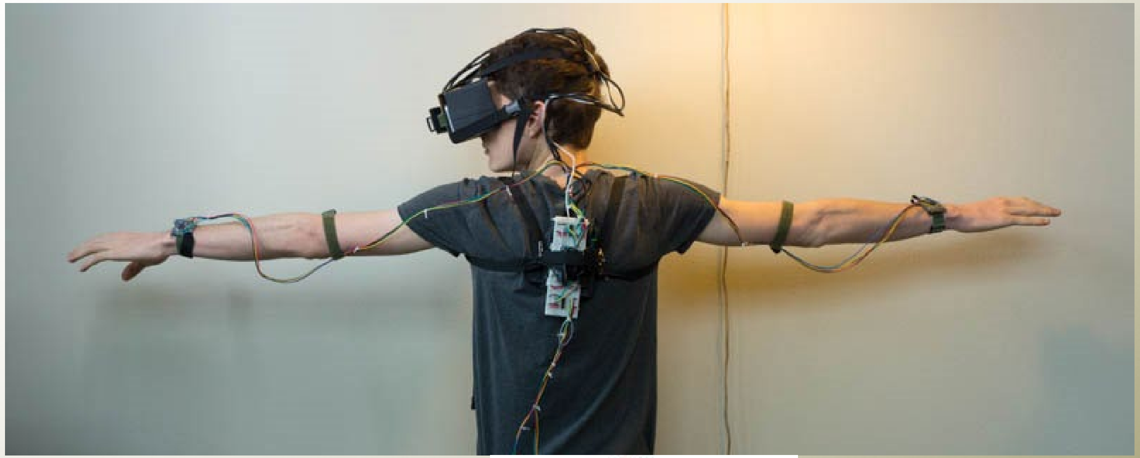
OPTICAL SYSTEMS

- Optical systems utilize data captured from image sensors to triangulate the 3D position of a subject between two or more cameras calibrated to provide overlapping projections
- Marker Based System

- Markerless System

NON-OPTICAL SYSTEMS

- Inertial Systems
  - miniature inertial sensors
  - biomechanical models
  - sensor fusion algorithms
  - $1,000 to $80,000 USD
- Mechanical motion
  - exoskeleton motion capture systems
  - $25,000 to $75,000 USD

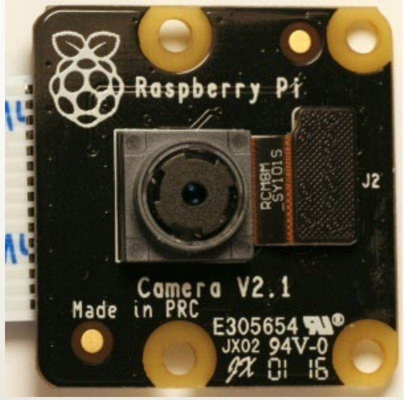


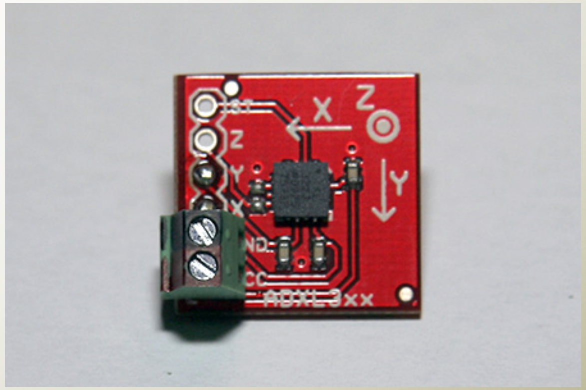
DETECT DANCE MOVES!!!

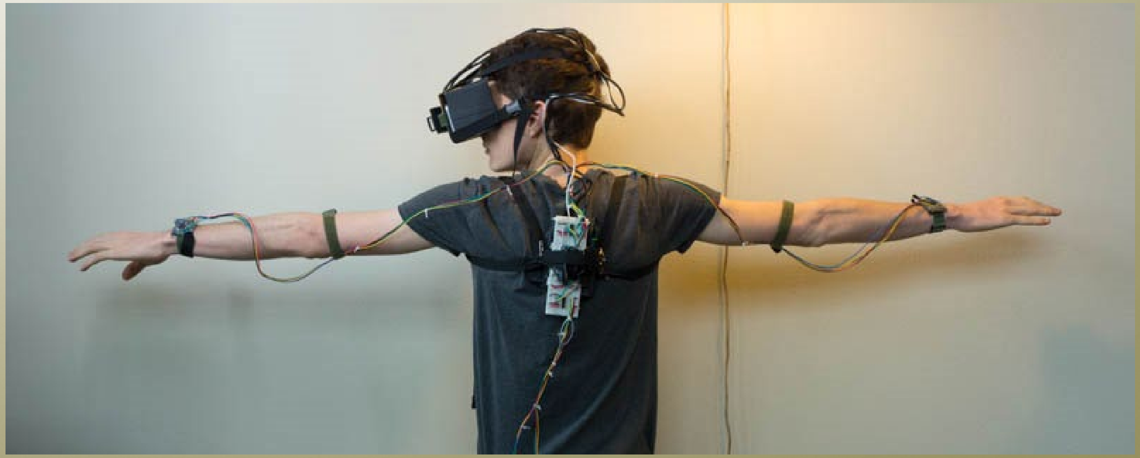
- What type of parameters need to be measured?
  - Hand movements
  - Leg movements
  - Body movements
  - Joint movements

DETECT DANCE MOVES!!!

- What type of sensors can we use?

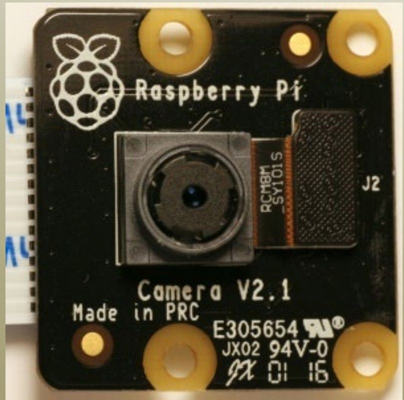






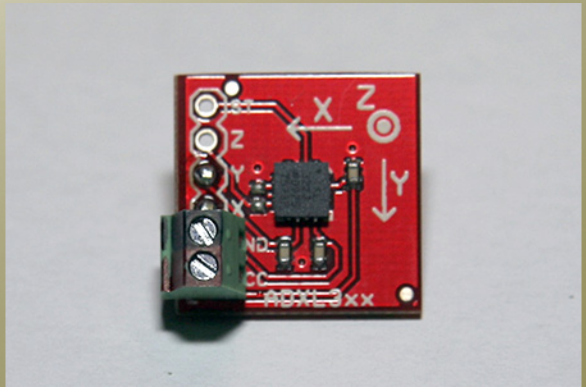
SENSORS- MOVEMENT DETECTION

- CAMERA
- Im ge Pro essing
- or
- noise
- depth ormation
- Visual Occlusion



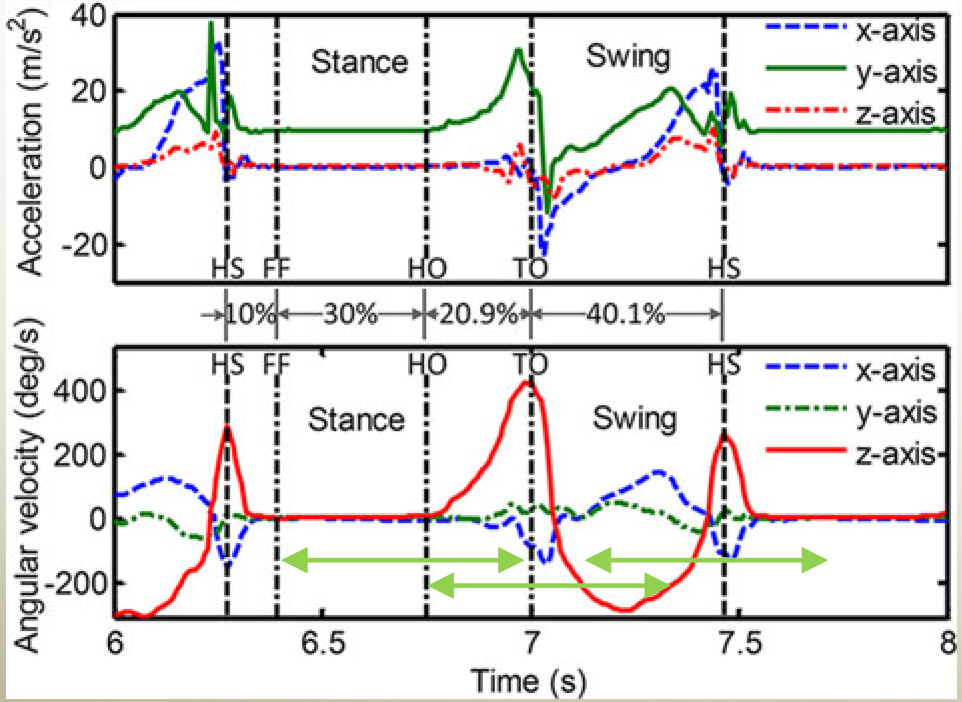
- FLEX SENSORS
- Joint angle
- Amateur processor
- Noise free data
- No other information
- 1 DOF

- IMU/ACCELEROMETER
- Acceleration, tilt, angles
- Good processor
- Some noise
- Holistic information
- 3/6/9 DOF



SENSOR MEASUREMENT PROTOCOL

- IMU Signal

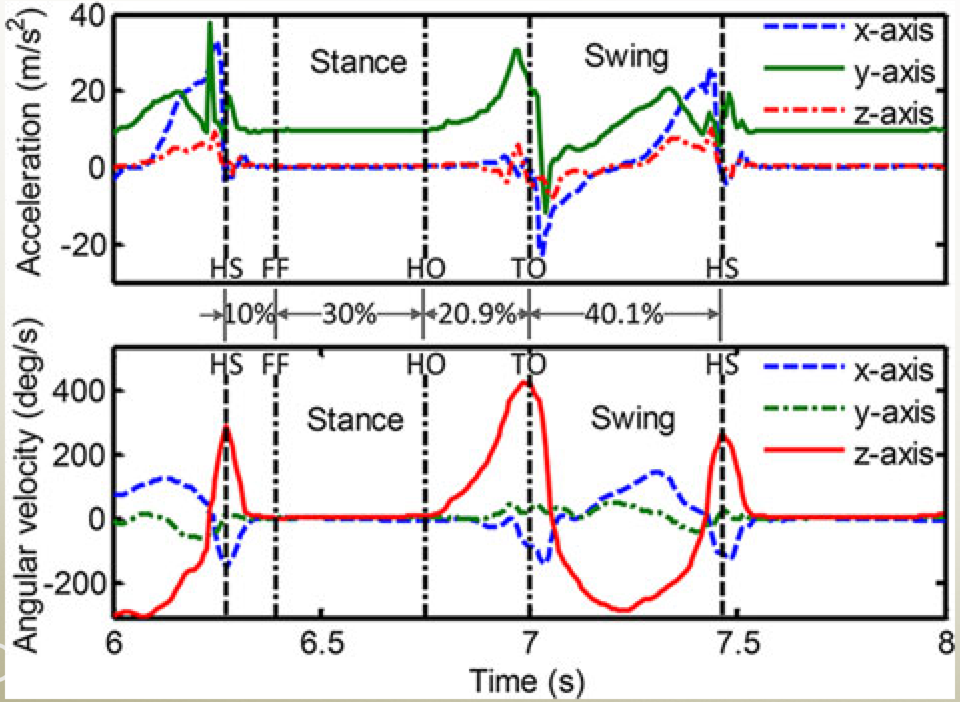


- Sampling – IMU Signal Processing
  - Filtering: Remove noise from the signal
  - Conversion of raw data to appropriate format (e.g. Hex value to m/s^2 for acceleration)
- Feature Extraction
  - Example Sampling Frequency: 5-50 Hz
  - Analysis Window: 250ms – 1000ms
  - 500 ms contains 25 samples per sensor
  - Use of sliding window ?

Image from Wang, ZHELONG & Zhao, Hong-Yu & Qiu, Sen & Gao, Qin. (2015). Stance-Phase Detection for ZUPT-Aided Foot-Mounted Pedestrian Navigation System. IEEE/ASME Transactions on Mechatronics. 20. 1-1. 10.1109/TMECH.2015.2430357.

SENSOR MEASUREMENT PROTOCOL

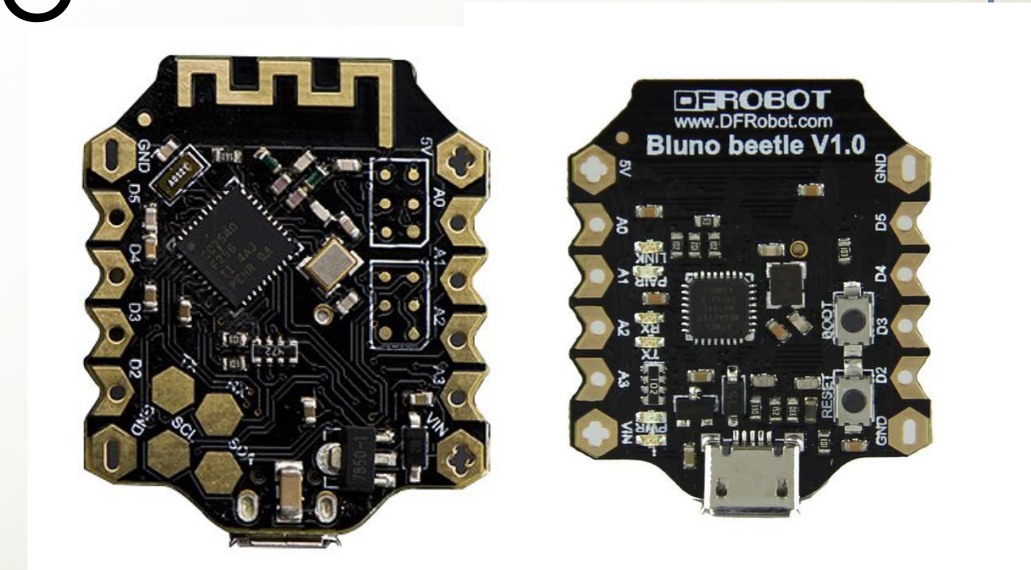
- Benefits of Feature Extraction on the Bluno



  - Communication protocol is simpler
    - 1 second window: 6 sensors/IMU * 2 IMUs per user* 50 samples/1 second = 600 samples
    - Extracting features: e.g. 6 features per sensor* 6 sensors/IMU* 2 IMUs per user = 72 features
  - Utilization of the Bluno resources
  - Decentralized Debugging of sensors and each body unit is easier and convenient

Image from Wang, ZHELONG & Zhao, Hong-Yu & Qiu, Sen & Gao, Qin. (2015). Stance-Phase Detection for ZUPT-Aided Foot-Mounted Pedestrian Navigation System. IEEE/ASME Transactions on Mechatronics. 20. 1-1. 10.1109/TMECH.2015.2430357.

BEETLE BLUNO



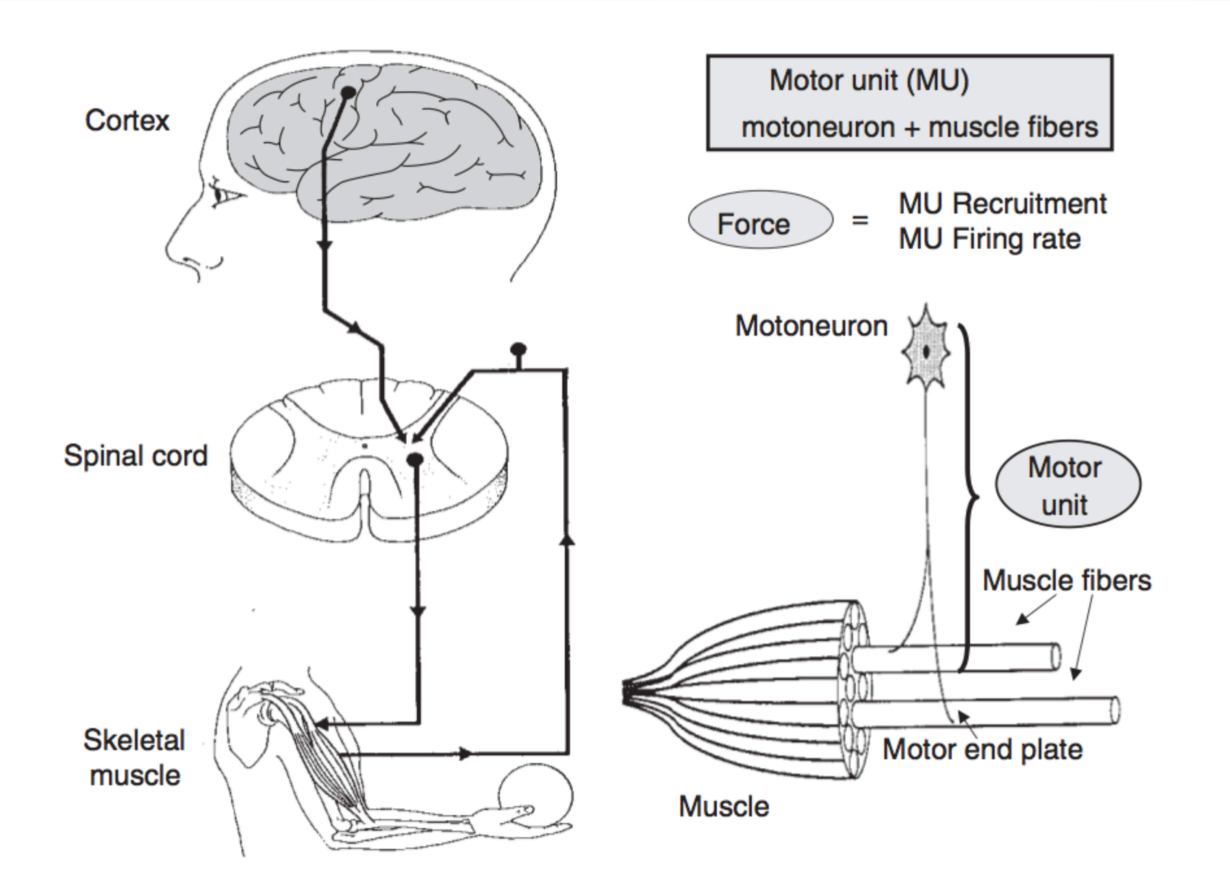
- The Beetle BLE (Former name as Bluno Beetle) is an Arduino Uno based board with bluetooth 4.0 (BLE)
- ATmega328@16MHz
- Bluetooth Low Energy (BT 4.0)
- Micro USB port
- Super Compact Size
- Support Bluetooth HID and ibeacon
- Support Wireless Programming

- Digital Pin x4
- Analog Pin x4
- PWM Output x2
- UART interface x1
- I2C interface x1
- Micro USB interface x1
- Power port x2
- Weight： 10g

Source:https://www.dfrobot.com/index.php?route=product/product&product_id=1259&search=beetle&description=true&category_id=48&gclid=Cj0KCQiAsbrxBRDpARIsAAnnz_MokTwqL2LxM-OZI0JlZv2S_zNbUMkXhpnIkH734XtveQnhZ3dNI1MaAu-UEALw_wcB

EMG MEASUREMENT PROTOCOL

- ELECTROMYOGRAPHY (EMG)

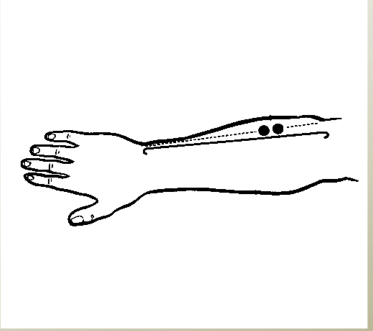


EMG MEASUREMENT PROTOCOL

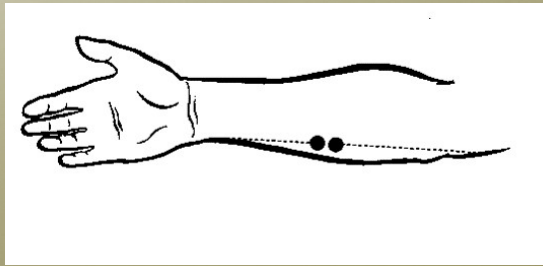
- Example Muscle Groups

Motion of the Hand	Associated Muscle Group
Elbow Flexion and Extension	*biceps brachii*
Wrist Flexion and Extension	*flexor carpi ulnaris*
Hand Grasp and Open	*flexor digitorum profundus* *flexor digitorum superficialis*

- Electrode Placement
  - *biceps brachii* : The midline of the muscle belly.
  - *flexor carpi ulnaris* :

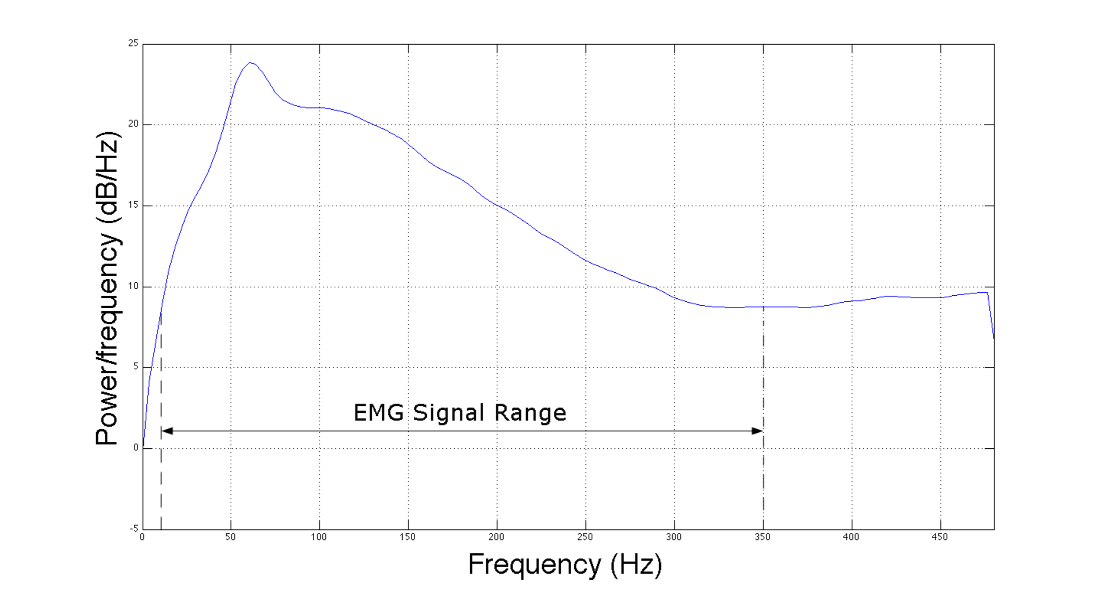


  - *flexors of the fingers* :



EMG MEASUREMENT PROTOCOL

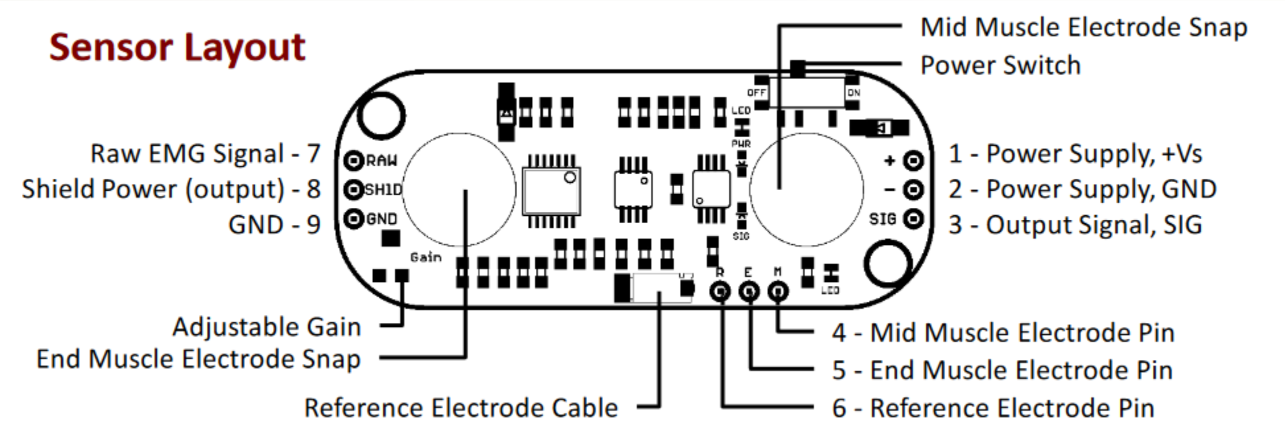
- EMG Signal Processing
  - Power Spectral Density



- Sample – EMG Signal Processing
  - Low Pass Filter:
    - Type: 2^{nd} Order Butterworth Filter
    - Cut-Off Frequency: 350 Hz
  - High Pass Filter:
    - Type: 2^{nd} order Butterworth Filter
    - Cut-Off Frequency: 10 Hz
  - Sampling Rate: > 2* Highest frequency in the signal
  - EMG Equipment: MyoWare Muscle Sensor

EMG MEASUREMENT PROTOCOL

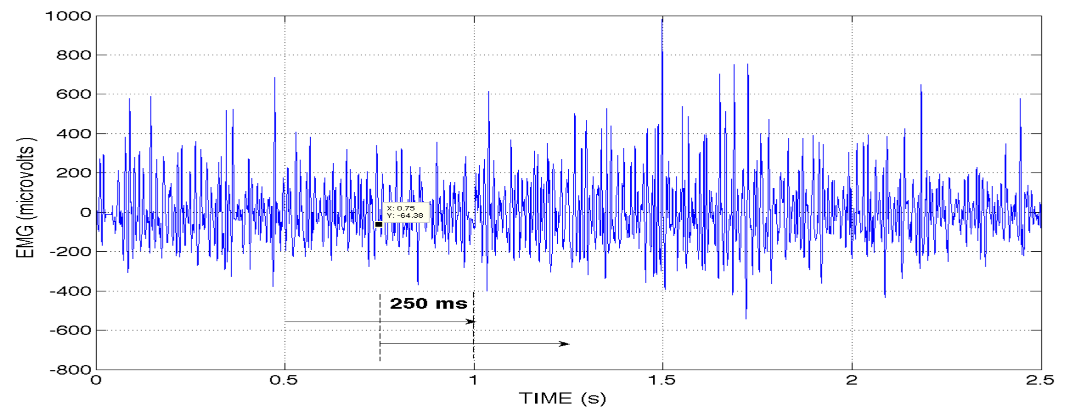
- MyoWare Muscle Sensor (Source- Sparkfun)



EMG MEASUREMENT PROTOCOL

- EMG MEASUREMENT
  - Skin Preparation → Alcohol Swabs to clear the skin of dirt and debris
  - Electrode Configuration:
    - Bipolar Electrode Configuration with Ground Electrode
    - Eg. - Ground Electrode Site: Elbow Joint

- Feature Extraction
  - Example Sampling Frequency – 1000 Hz
  - Analysis Window→ 500 ms
  - 500 ms containing 500 Samples
  - Moving Window → 250 ms



METHODOLOGY

- Feature Set of Tim-Frequency Features
  - Mean Absolute Value → $\overline{x_i} = \frac{1}{N}\sum_{k=1}^{N} |x_k|$
  - Mean Absolute Value Slope → $\Delta\overline{x_i} = \overline{x_i} - \overline{x_{i-1}}$
  - Zero Crossings
  - Slope Sign Changes
  - Waveform Length → $l_0 = \sum_{k-1}^{N} \Delta x_k$ where,

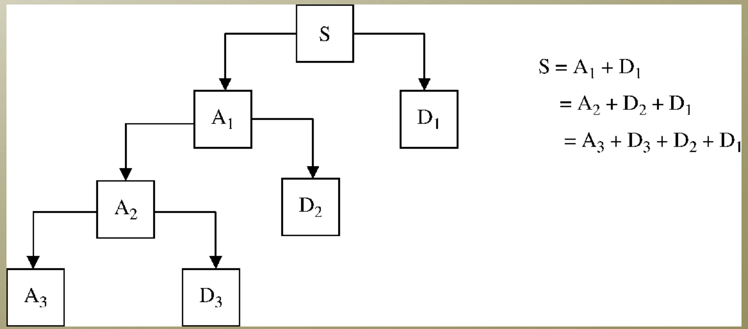
$$\Delta x_k = x_k - x_{k-1}$$

- Feature set using Wavelet Analysis
  - Wavelet Decomposition

V_j	=	W_{j+1}	$\oplus$	V_{j+1}		
	=	W_{j+1}	$\oplus$	W_{j+2}	$\oplus$	V_{j+2}
	=	…..				

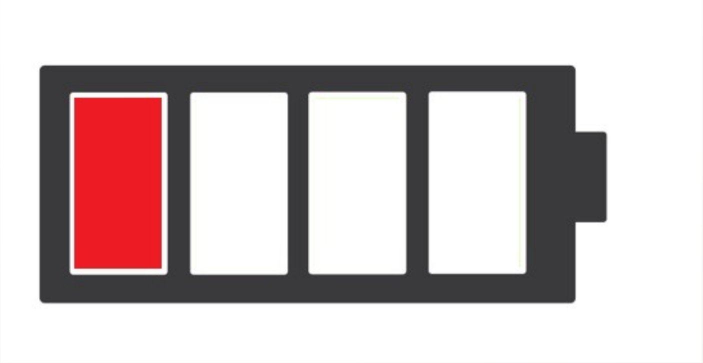
  - Wavelet Entropy → $E = \sum_{j=1}^{L} |d_j(k)|^2$

  where $d_j(k)$ *is the wavelet coefficient*



POWER SYSTEM DESIGN

- Why Power System Design



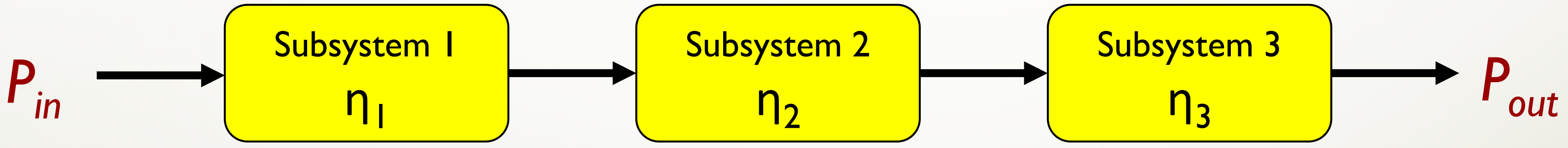
VS

VS

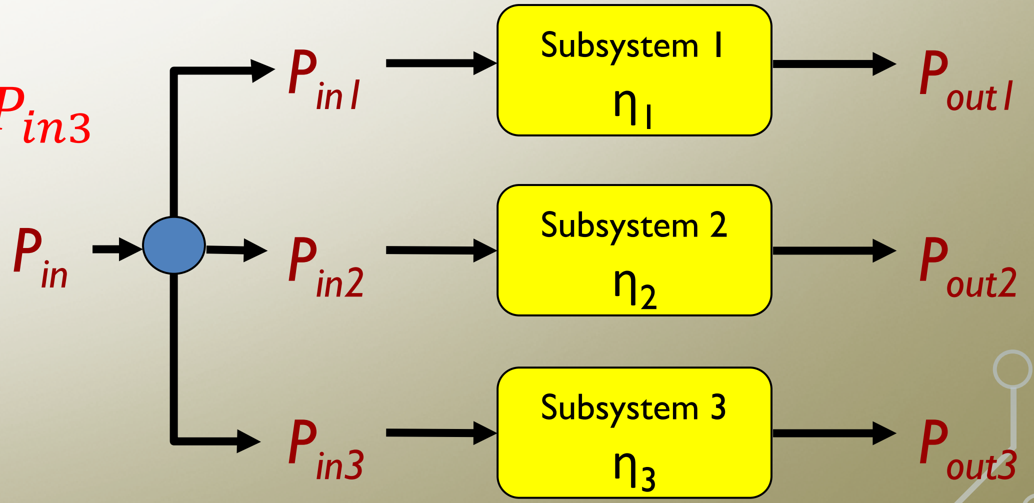
- How Big a Battery do you actually need?

POWER BUDGET AND BATTERY DESIGN

- Subsystems in Series $P_{in} = \frac{P_{out}}{\eta_1 . \eta_2 . \eta_3}$



- Subsystems in Parallel $P_{in} = P_{in1} + P_{in2} + P_{in3}$



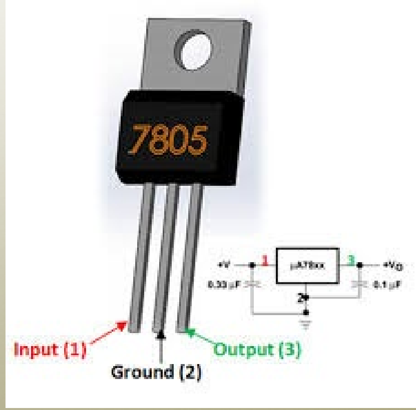
- Subsystems in Series and Parallel

PS: Sample battery design video also has been uploaded

BEETLE POWER OPTIONS

- Button Cell Battery
  - Small, Portable, Lightweight
  - High running cost, does not last long

- AA Battery
  - Relatively small, can be integrated to the body sensor system, rechargeable
  - Unregulated voltage, requires voltage regulator or DC-DC convertor



INTERFACING INFO - GPIO, I2C, UART

- General Purpose Input/Output (GPIO) – configure a pin as output / input and write/read digital data to the pin

  Eg : simple devices such as ultrasound, IR, 2-line LCD display

- Inter-integrated circuit (I2C) – 2 wire, synchronous, serial, master-slave, half-duplex, in-band addressing using 7-bit addresses (+read/write bit), short-distance [Arduino Library : Wire]

  Eg : Slower devices such as accelerometer, gyro, compass etc.

- Universal asynchronous receiver/transmitter (UART, also simply called serial) – 2 non-shared wires, asynchronous, serial, full-duplex, longer distance (using a physical layer) [Library : Serial]

  Eg : Between computers / microcontrollers, RFID modules, GSM modules

INTERFACING INFO

- Take note of the voltage levels of each device and component(3.3V / 5V/12V etc)
  - Do you require level shifting between 3.3V sensors and 5V Blunos?
- Take note of the max. current supplied by each pin of the device
- Read the datasheet carefully for such info
- Damaged Ultra96 / Bluno will be replaced, but the cost will be deducted from your budget !!
- You have to be careful about endianness* used by the two devices being interfaced

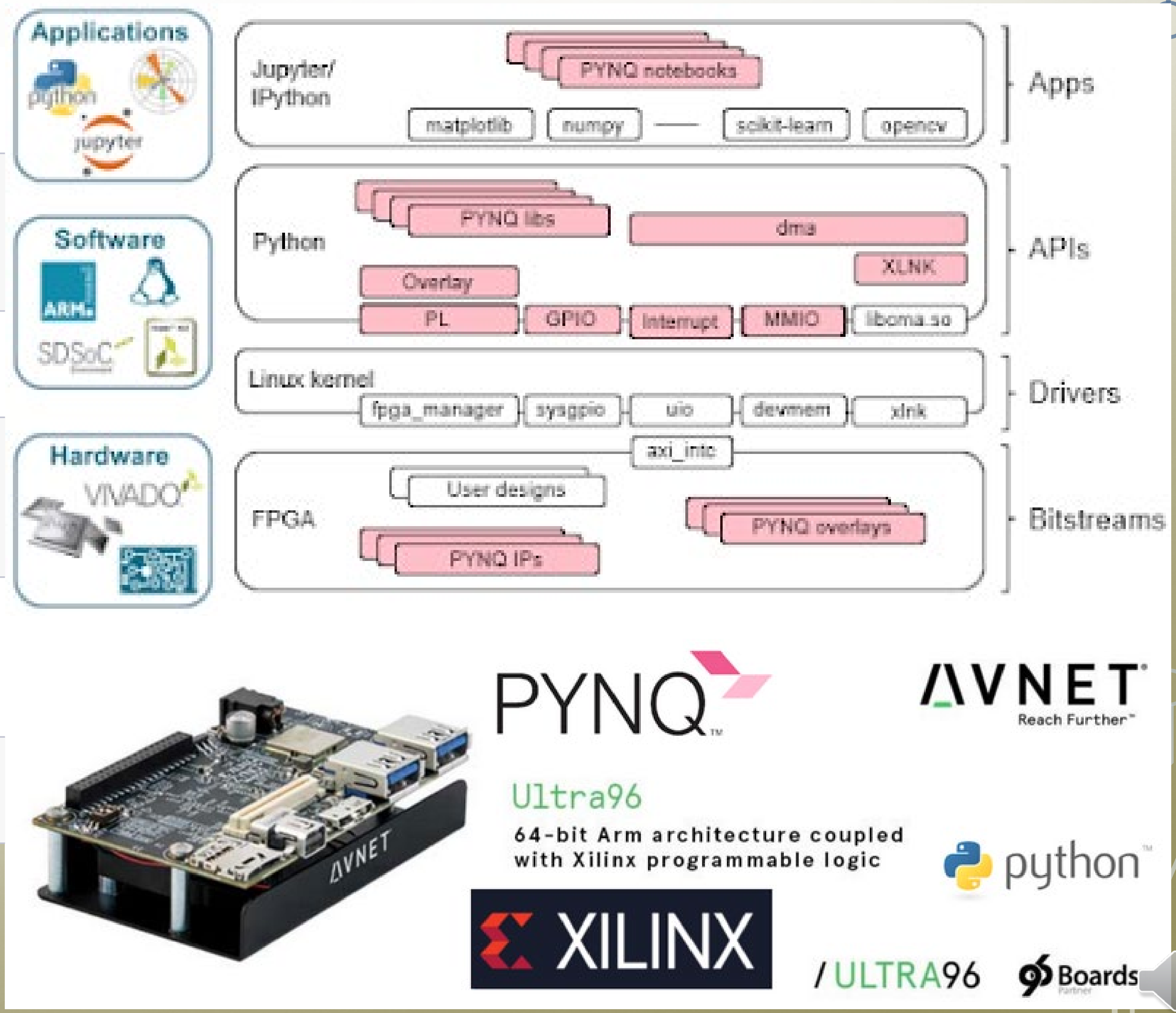
*If **L**east significant byte occupies the **L**owest address, it's **L**ittle-endian

HW FPGA REQUIREMENTS

- HW FPGA to do inference while SW ML to take care of training
- Implement 1 specific neural network inference model onto the FPGA
- Run the model with the test data provided
- Evaluate the hardware utilization, timing and power requirements
- Use C++ High Level Synthesis (HLS)

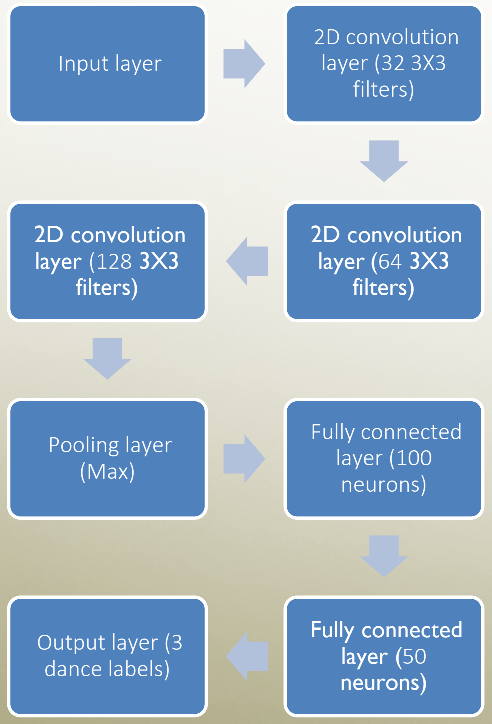
ULTRA96 - FEATURES

SoC	Xilinx Zynq UltraScale+ MPSoC ZU3EG A484
RAM	Micron LPDDR4 memory provides 2 GB of RAM in a 512M x 32 configuration
Storage	Delkin 16 GB microSD card + adapter
Wireless	802.11b/g/n Wi-Fi and Bluetooth 4.2 (provides both Bluetooth Classic and Low Energy (BLE))
USB	1x USB 3.0 Type Micro-B upstream port 2x USB 3.0, 1x USB 2.0 Type A downstream ports
Display	Mini DisplayPort (MiniDP or mDP)

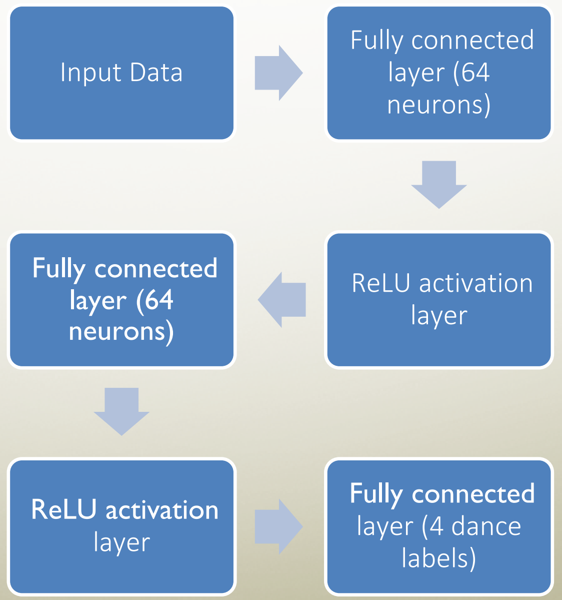


NEURAL NETWORKS ON FPGA – SAMPLE IMPLEMENTATIONS

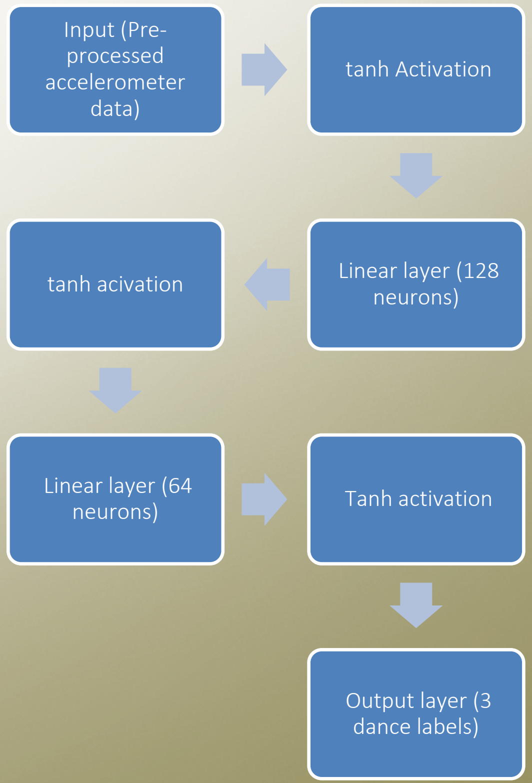
CNN on FPGA



MLP with ReLU activation function

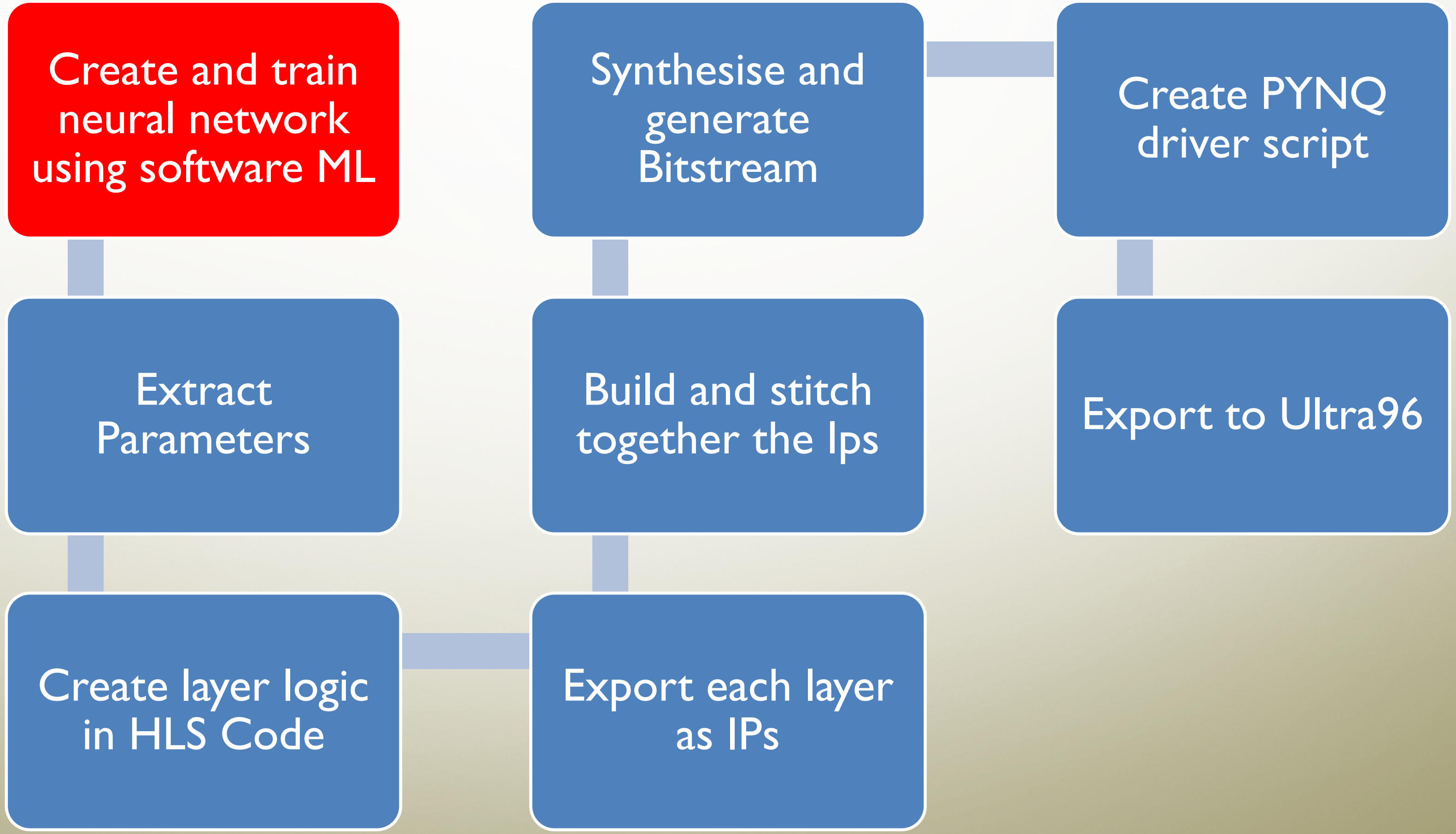


MLP with tanh activation function



CNN: https://github.com/mfarhadi/CNNIOT

HARDWARE FPGA DESIGN



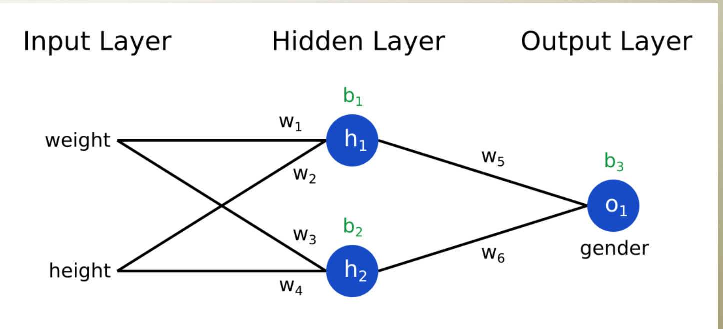
NEURAL NETWORK IMPLEMENTATION

- Convolution and Linear Layer

$$Output = bias + (input \cdot weight)$$

where;

- $input = 1 \times i\ vector\ of\ input\ features$
- $weight = i \times j\ vector\ of\ weights$
- $bias = 1 \times j\ vector\ of\ biases$
- $output = 1 \times j\ vector\ of\ neuron\ outputs$



➔Matrix multiplication

ACTIVATION FUNCTION: RELU FUNCTION

- ReLU : Rectified Linear Unit
- Simple Calculation:

$$\begin{array}{l} if\ input > 0: \\ \quad return\ input \\ else: \\ \quad return\ 0 \end{array}$$

- Can be implemented in the FPGA using Look Up Tables (LUTs)

FIXED POINT DATA TYPE

- IPs data streams are 32-bit floats → compiler needs to synthesise hardware for floating point operations
- Vivado HLS has "ap_fixed" data type for fixed point conversion and quantisation of data
- Fixed point Conversion: Requires checking for absolute maxima and minima of all the data
- Quantisation: reduces the precision of the data→ may affect prediction accuracy
- Precision loss is evaluated at each layer level and at the model level to find a small enough bit-width

EVALUATION

- Evaluation of the inference model and its comparison to the software ML implementation
- Hardware co-simulation at the HLS stage
- Optimization of the design using parallelization and pipelining
- Hardware Utilization: BRAM, DSP, FF, LUT
- Ultra96 Power Consumption Measurement: https://github.com/Avnet/Ultra96-PYNQ/blob/master/Ultra96/notebooks/common/ultra96_pmbus.ipynb

IMPORTANT SAFETY INFO

- Follow all the lab safety rules (non-negotiable)
- Be responsible for your own safety as well as that of people around you
- Always use a regulated, fused power source to power your project
- You need a battery to power the final system (for it to be wearable)
  - The battery specs would depend on the components you are using
  - If possible, try and use NiMH battery packs
  - Be VERY VERY careful with Li-ion / LiPo batteries
    - They can explode if you overcharge, charge faster than the recommended rate/current, charge using a charger not designed for it, draw excessive current, subject it to mechanical stress
    - Use it only if you are very careful and confident. Never charge unattended or attempt disassembly

DOCUMENTATION

- A proper documentation is very useful in debugging
- Document everything in a wiki / knowledge bank (eg: NUS wiki, GIT, Microsoft Teams)
  - Include the links. Always have wiki open whenever you google
  - Save all the datasheets, libraries you used (you need to specify the library source in your code clearly)
- Will help you in final documentation. It will also serve as a learning journal
- “Oh, I had seen it somewhere, can’t recall where” issues can be minimized

THANK YOU