Self-sustainable Wearable IoT Devices: Energy Harvesting, Management and Consumption

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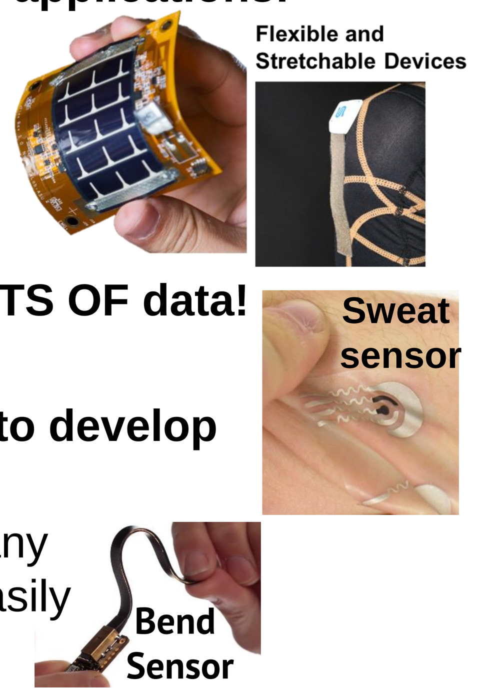
Motivation

- **Flexible and stretchable wearable devices open up novel and attractive applications!**
  - Patient rehabilitation
  - Fall detection
  - Physical activity promotion
  - Human activity recognition
- **Wearable devices collect LOTS OF data!**
  - Data is the new oil!
- **Strong and immediate need to develop open-source devices**
  - Open source will enable many researchers to contribute easily

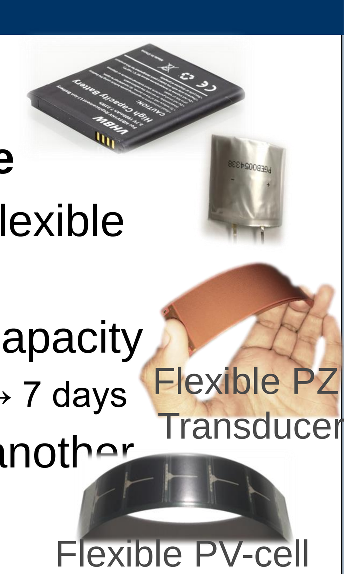


Applications

- **Human Activity Recognition [ACM TECS'19]**
  - Identifies activities (e.g. walking, sitting, jogging …)
- **Gait Analysis [ACM TIOT'21]**
  - Evaluates metrics, such as step length, stride length, and gait velocity
- **Freezing of Gait (FoG) Prediction in PD [BioCAS'21]**
  - Predicts potential FoG episodes using ML techniques
- Home-based Assistive Rehabilitation:
  - Assists patients with motor disorders
- Vital Signal Monitoring:
  - Collects electrophysiological signals (e.g., ECG, Galvanic Skin Response)

Challenge

- **Widespread adoption is hindered!**
- **IoT Devices have limited battery life**
  - Bulky batteries are inflexible, while flexible batteries have low capacity
  - Small form factor limits the battery capacity
    - E.g. Oura Ring: 22 mAh @ 3.7V battery → 7 days
- **Compliance:** Users do not want yet another device to manage and maintain!



Aim

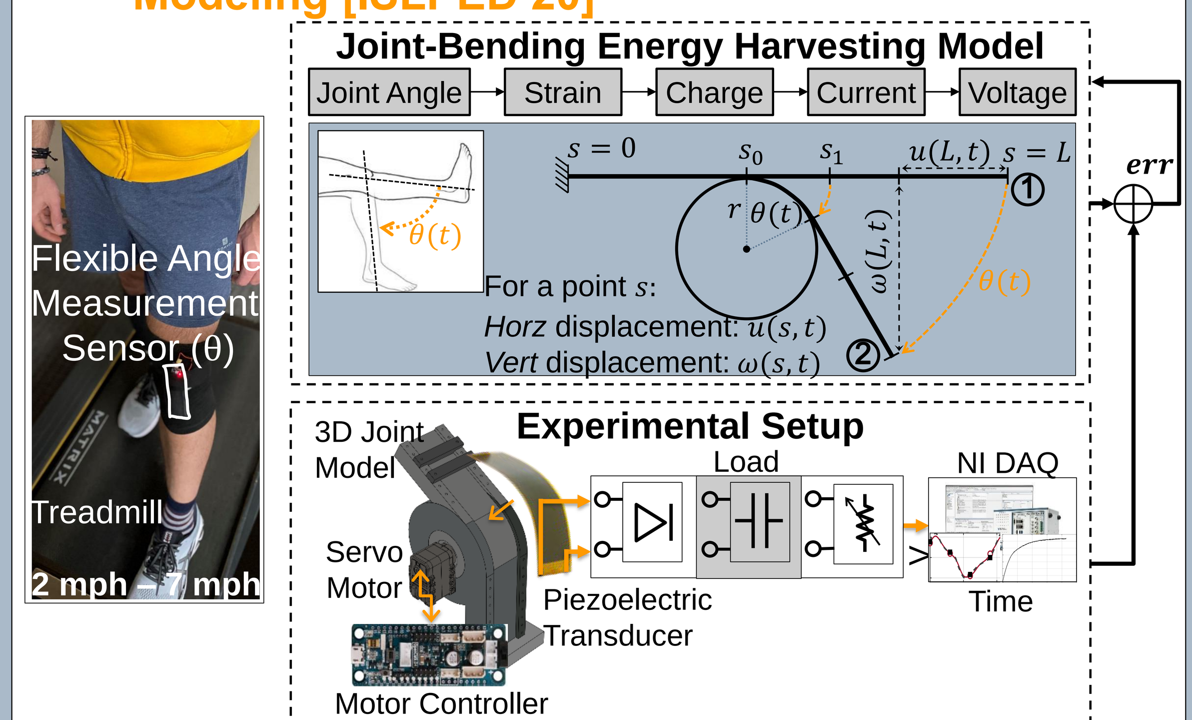
Address the compliance challenge with self-sustainability

3 Pillars

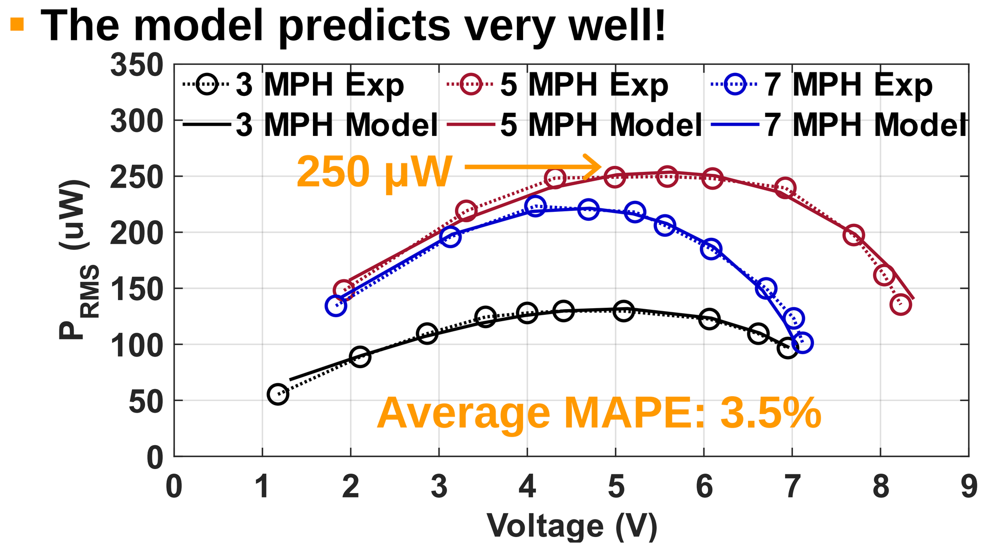
1- Energy Harvesting | **2- Energy Management** | **3- Energy Consumption**

1- Energy Harvesting

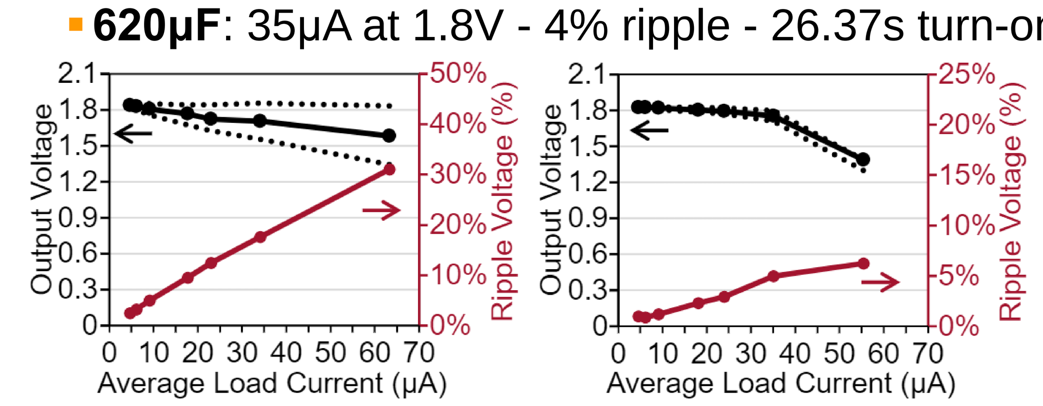
- **Wearable Energy Harvesting (EH) Modalities**
  - **Flexible Piezoelectric Transduction (PZT) Modeling [ISLPED'20]**



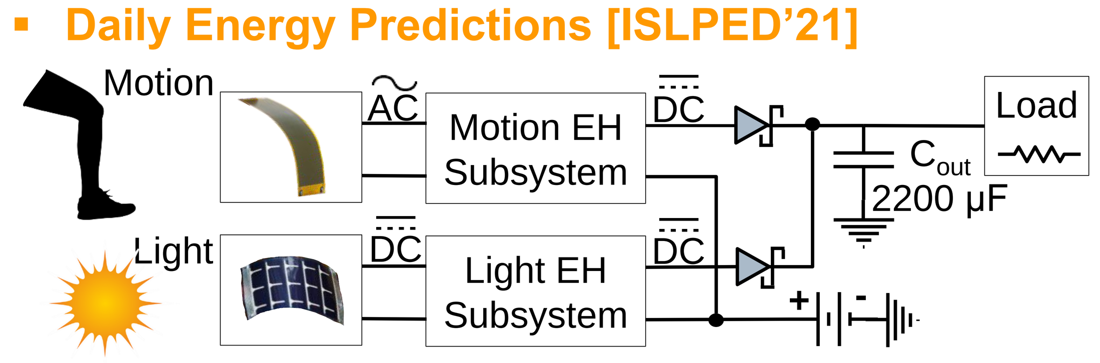
- **The model predicts very well!**



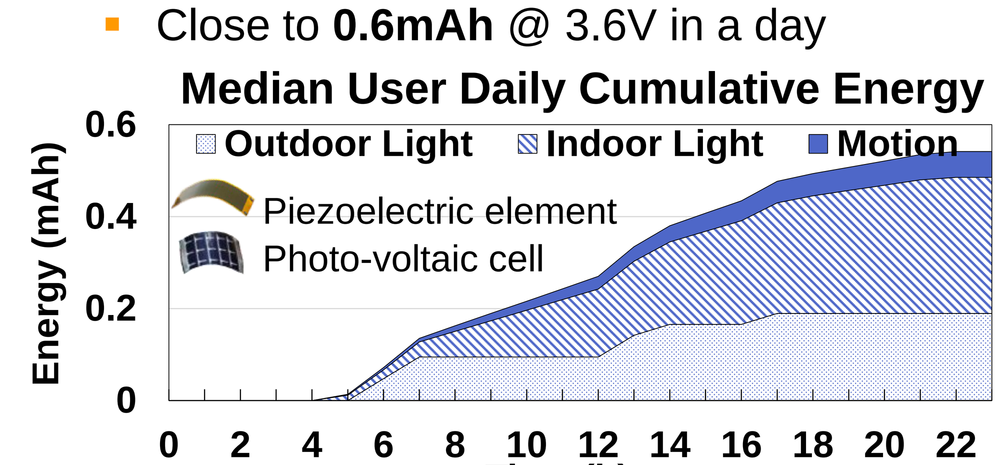
- **Choose the output capacitance carefully!**
  - **150μF**: 35μA at 1.7V - 20% ripple - 8.84s turn-on
  - **620μF**: 35μA at 1.8V - 4% ripple - 26.37s turn-on



- **Daily Energy Predictions [ISLPED'21]**

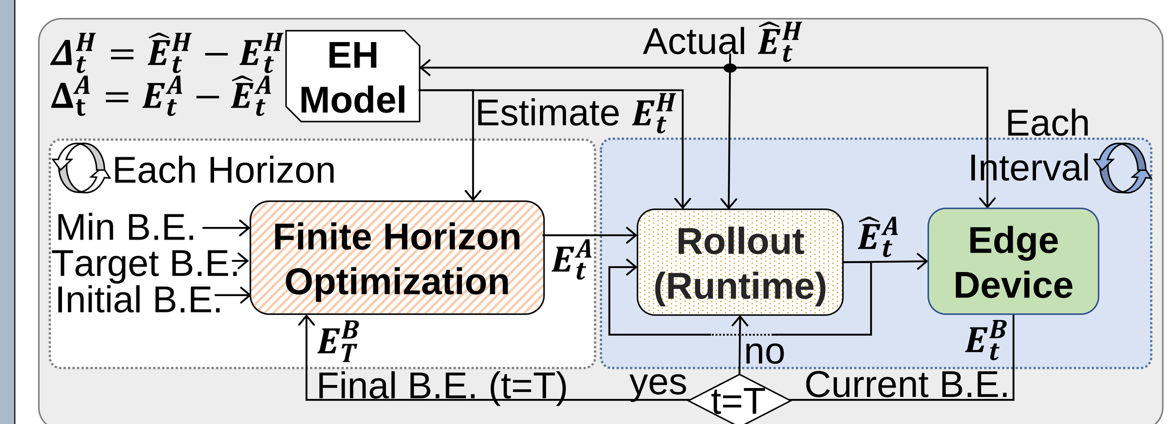


- **Daily EH potential using activity/location data from the American Time Use Survey**
  - Close to **0.6mAh** @ 3.6V in a day

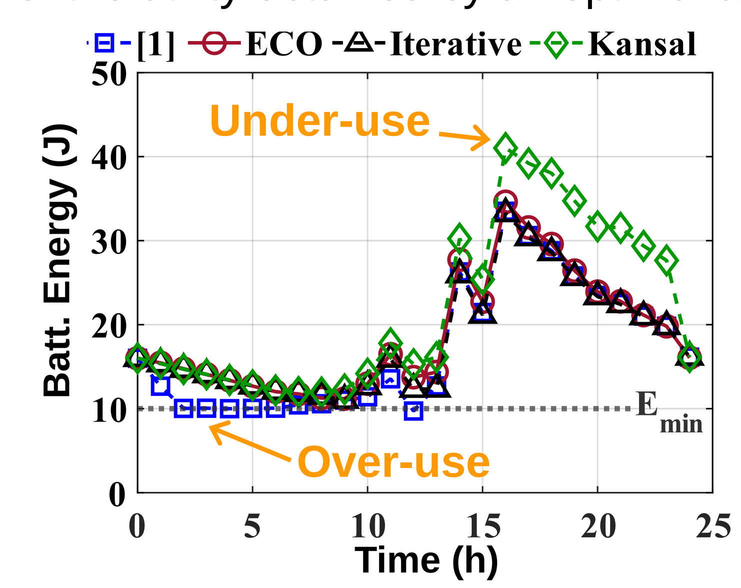


2- Energy Management

- **Allocate the energy in the battery such that**
  - Device utilization is maximized
  - Device is energy-neutral
- **Two main approaches:**
  - Prediction-based vs. prediction-free
- **ECO: Runtime Allocation of Harvested Energy [IEEE IoTJ'21]**



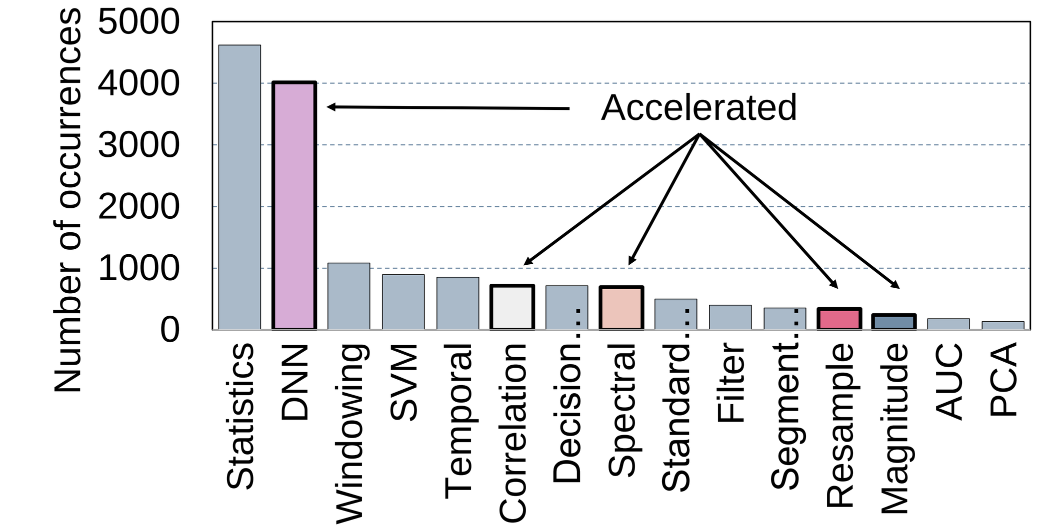
- Finite horizon near optimal algorithm
  - Inputs: Expected energy harvesting pattern and initial battery energy
  - Objective: Optimize the utility by the device
    - Quantified by an arbitrary utility function (e.g. accuracy, throughput)
- Lightweight and Realtime – 87.5 $\frac{\mu J}{hr}$ overhead
- 98% of the utility obtained by an optimal algorithm



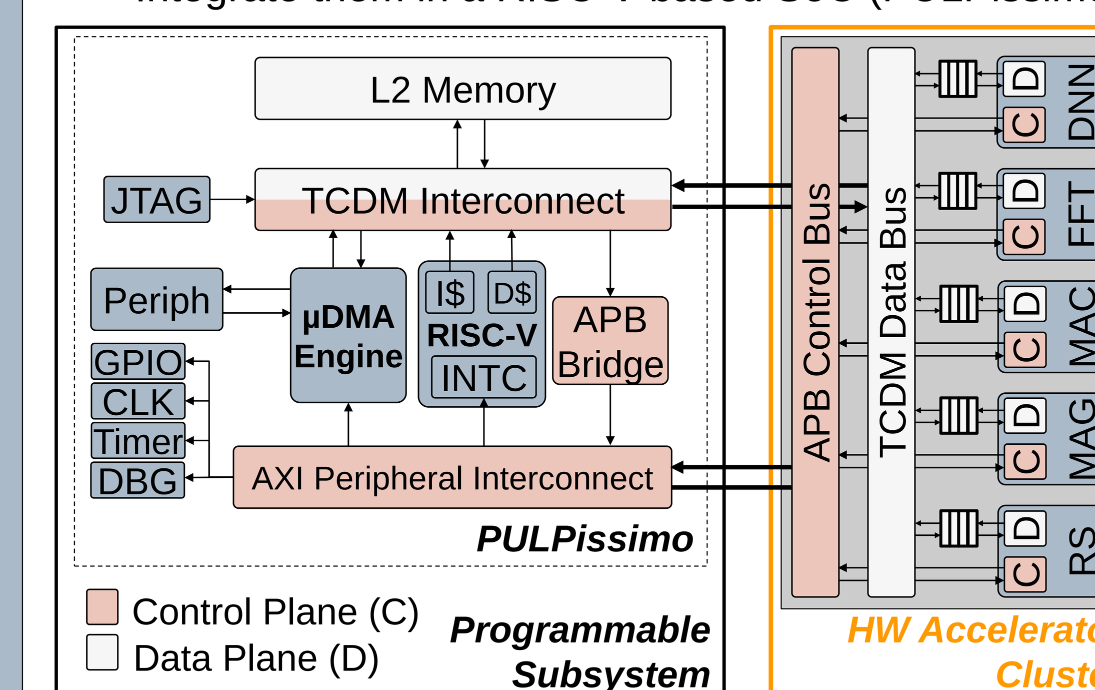
- **tinyMAN: RL-based Lightweight Energy Manager [tinyML'22]**
  - Finite horizon RL-based algorithm
    - Discrete State Space: $\{E_t^B, E_{t-1}^H, E_0^B, t, \sum_\tau^{t-1} E_\tau^H\}$
    - Continuous Action Space: $E_t^A \in [E_{min}^A, E_t^B]$
    - Objective: Optimize the utility by the device
      - Quantified by an arbitrary utility function
  - Lightweight and Realtime – 27.8 $\frac{\mu J}{hr}$ overhead (inference only)
  - 86% of the utility obtained by an optimal algorithm

3- Energy Consumption

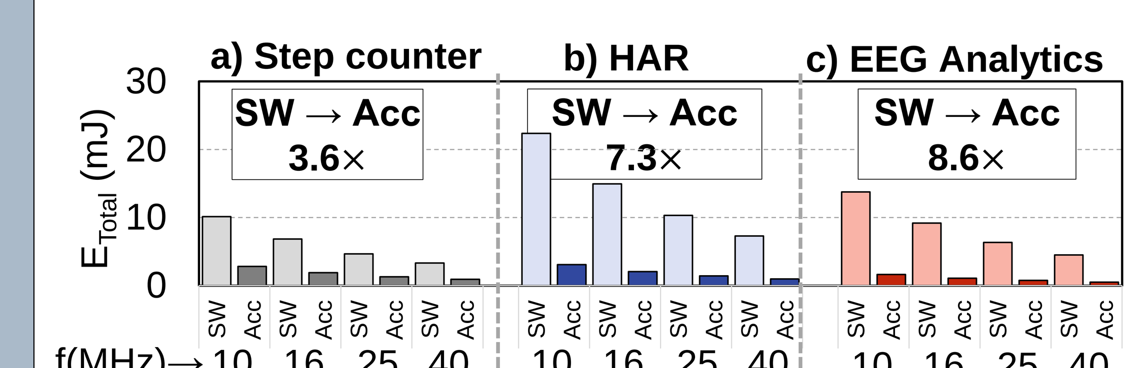
- **System-On-Chip Design for Wearable Devices [*Submitted*]**
  - Identify most common tasks in wearable apps
  - Time-profile the exec times and choose costliest 5



- Design HW accelerators for these tasks
- Integrate them in a RISC-V based SoC (PULPissimo)



- Evaluate the performance on three apps on FPGA



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