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Integrated Systems Laboratory

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Computer Engineering and
Networks Laboratory

Wearable, Energy Opportunistic Vision Sensing for Walking Speed Estimation

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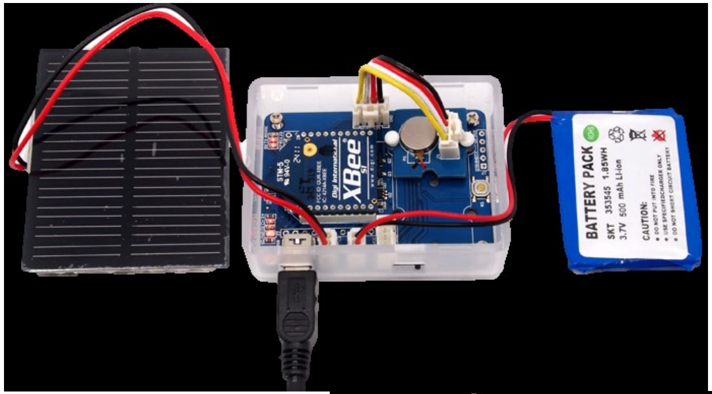
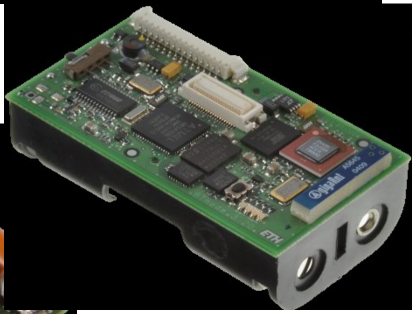
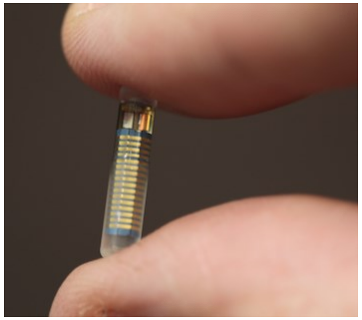
Sensor Application Symposium
Glassboro, NJ, USA

Design Trends

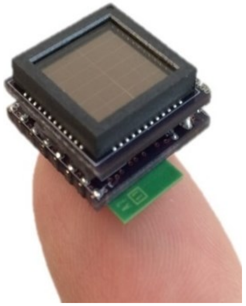
Battery-based → Batteryless

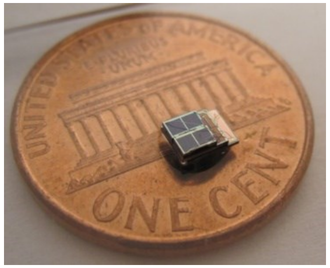






http://senseonics.com/product/the-sensor





http://www.electronicsweekly.com/news

When is a system “batteryless”?

If it can buffer, *at most*, the energy required for <u>one atomic operation</u>

Why minimize storage?

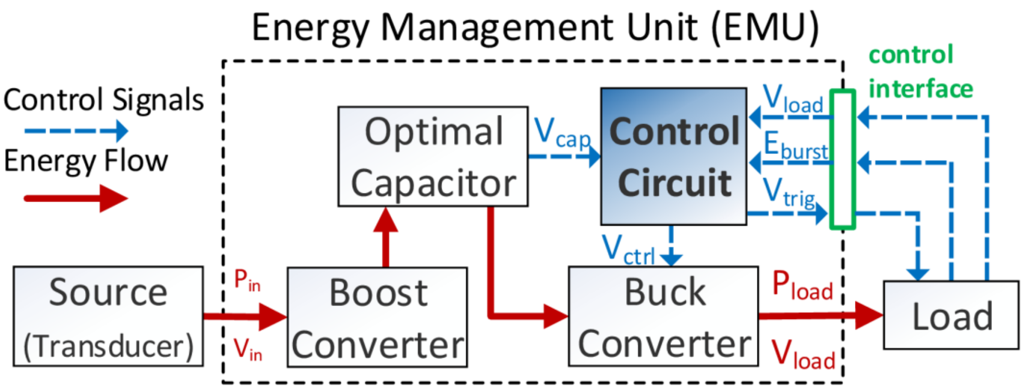
- Storage is expensive (cost, form factor, self-discharge, limited cycles)
- Storage requires energy surplus

Where does the energy come from?

- Harvesting from surroundings (light, temperature, vibration, movement)
    - Low-cost, long-term, environmentally friendly
- Energy harvesting suffers from volatile / low power levels

Transiently Powered Sensor Node

Input Power:
100's µW



Load Power:
100's mW

First published at DATE '16:

- Based on the Boost-Buck topology
- Optimized storage element
  - Minimized wake-up time, cold-start energy
- Tracks load's optimal operating point
  - Feedback-based Dynamic Energy Burst Scaling (**DEBS**)

Challenges for Transiently Powered Logging Applications

1. Minimum Energy Guarantee
   - Atomic task execution
2. Temporal Independence
   - Application correctness
3. Non-Volatility
   - Long-term logging

Single Burst Application:

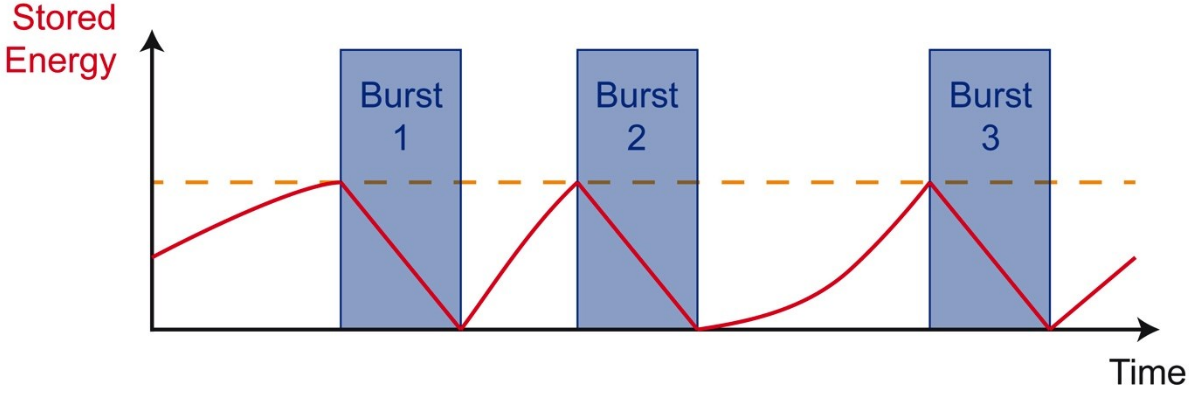
Burst 1: Sense + Store

Burst 2: Sense + Store

Multi-Burst Application:

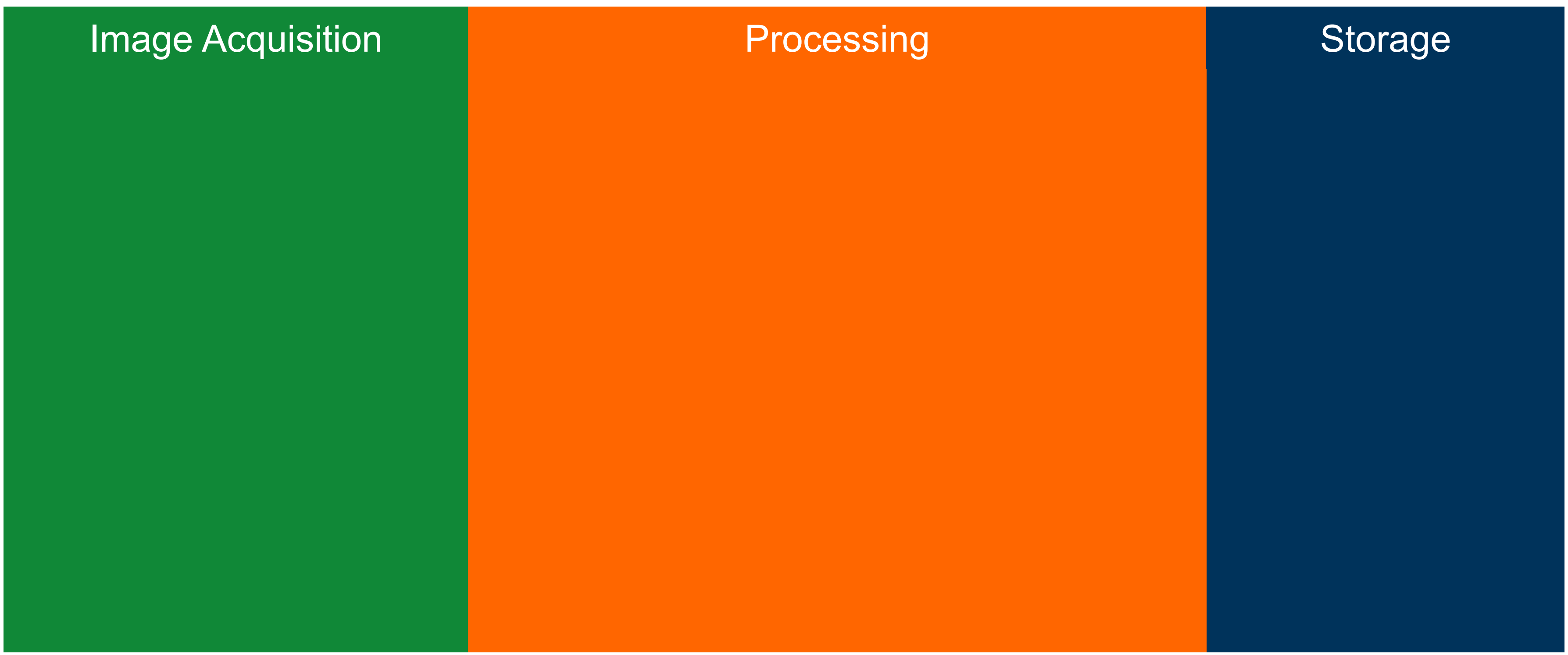
Burst 1: Sense

Burst 2: Store



System Design: Visual Velocity Estimation

- attach vision sensor to glasses
- camera is facing down



System Design: Image Acquisition

Image Acquisition	Processing	Storage

- acquire two images in the same burst

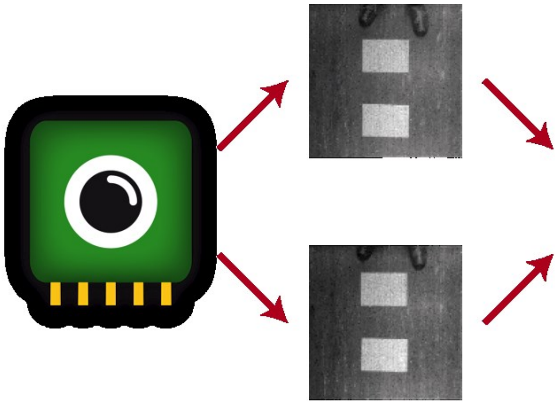


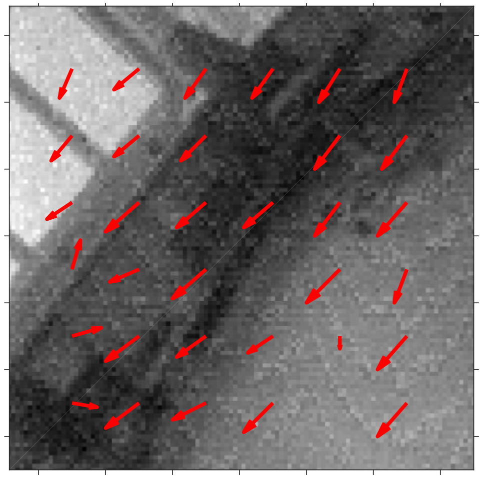
Image Acquisition

System Design: Velocity Estimation

Image Acquisition	Processing	Storage

- **Block-Matching Algorithm**
  - divide image into blocks
  - search position of block in next image for which a cost function is minimized

  ➔ optical flow field



- Displacement Estimation
  - average over all non-zero vectors of optical flow field
- Velocity Estimation
  - using distance to ground and time difference between images

System Design: Non-Volatile (Long-Term) Storage

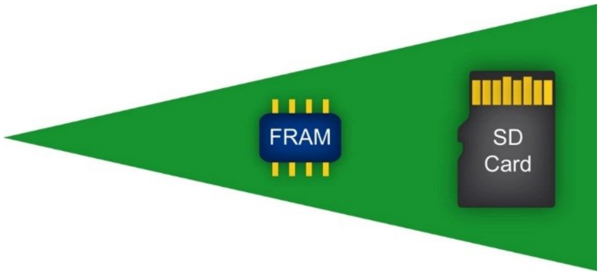
Image Acquisition | Processing | **Storage**

	SD Card (flash)	FRAM
density	high (~ GiB)	low (~ 256 KiB)
power consumption	high (~ 100mW)	low (~ 1mW)
initialization overhead	large & unpredictable	minimal

How can we store pictures efficiently?

Non-Volatile Memory Hierarchy (NVMH)

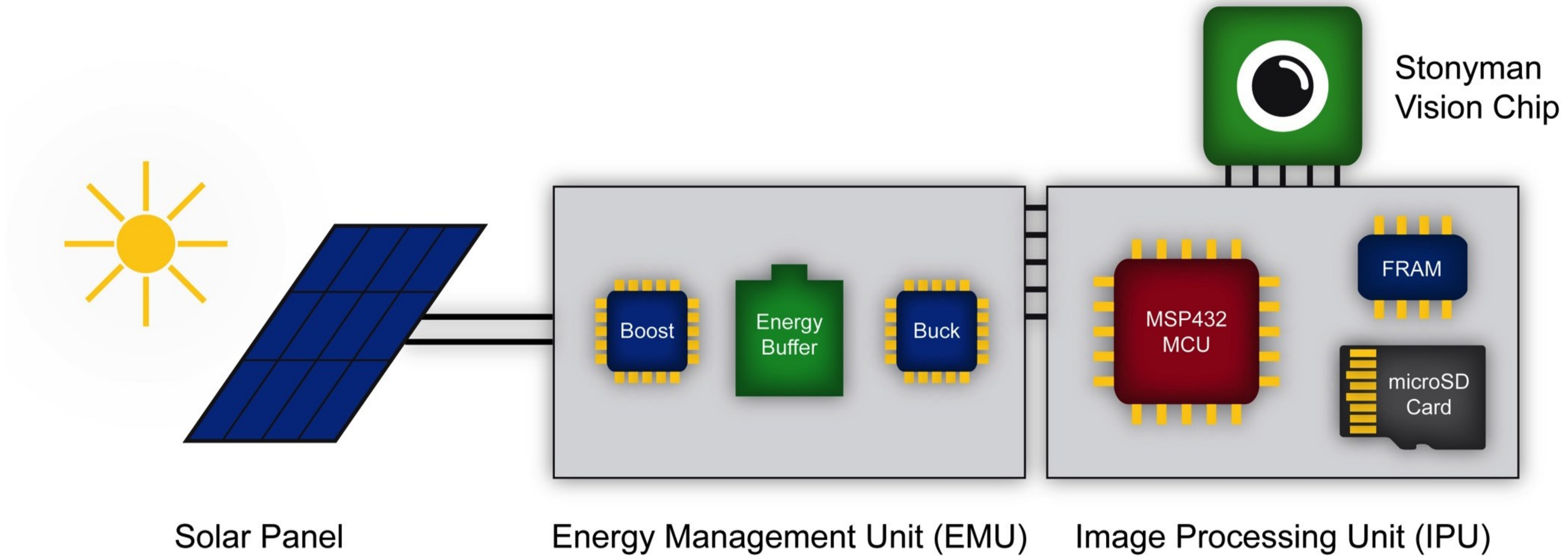
Recently published in TECS journal



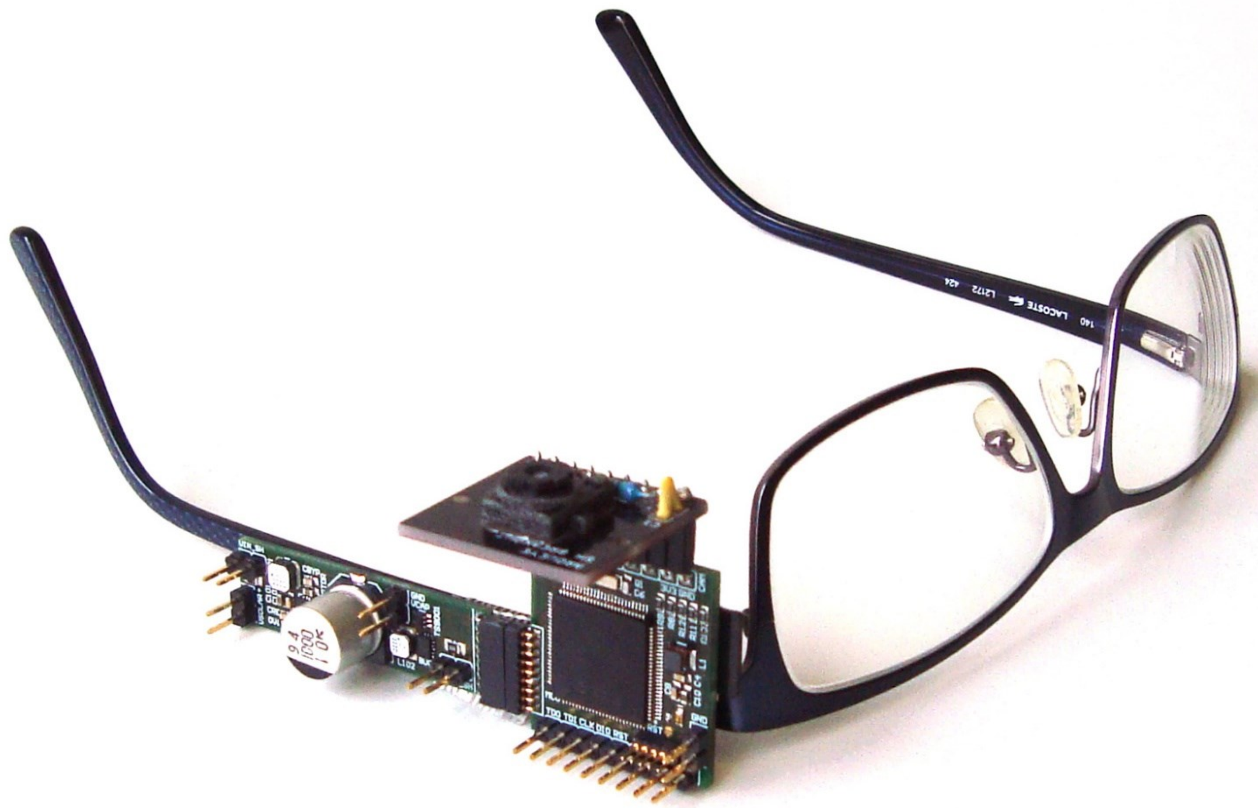
If we only save walking speed estimation (2 B):

- FRAM alone can last for 128K samples

Hardware Design: Overview



Implementation: Wearable Prototype



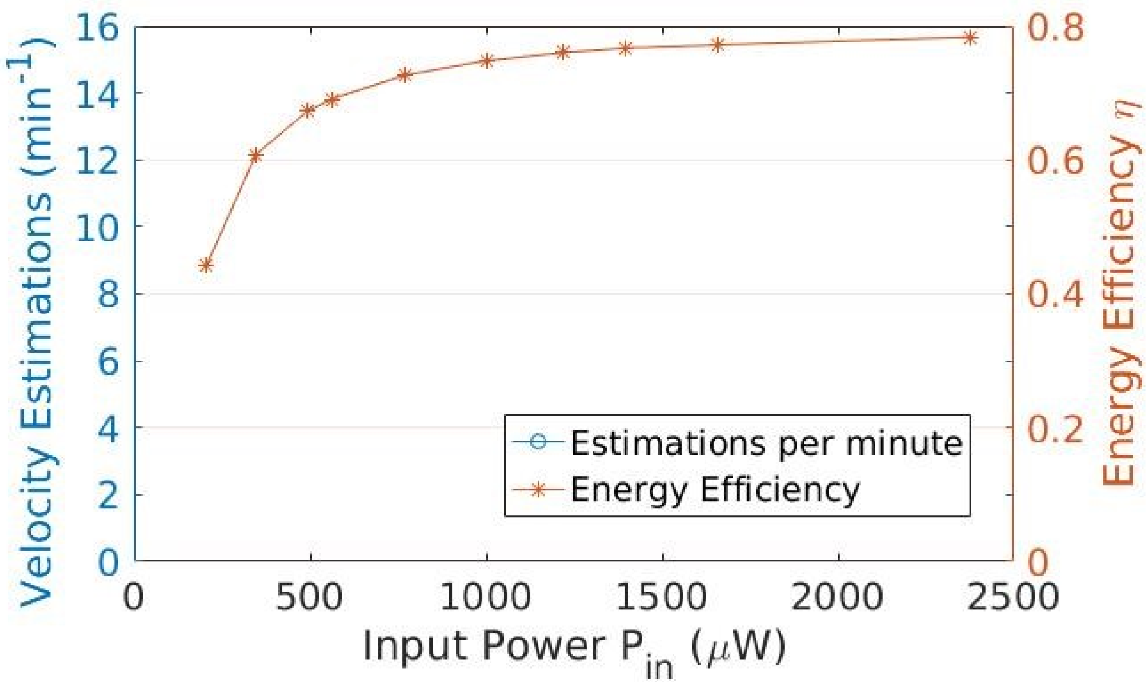
Transient System Evaluation

Experimental Set-up

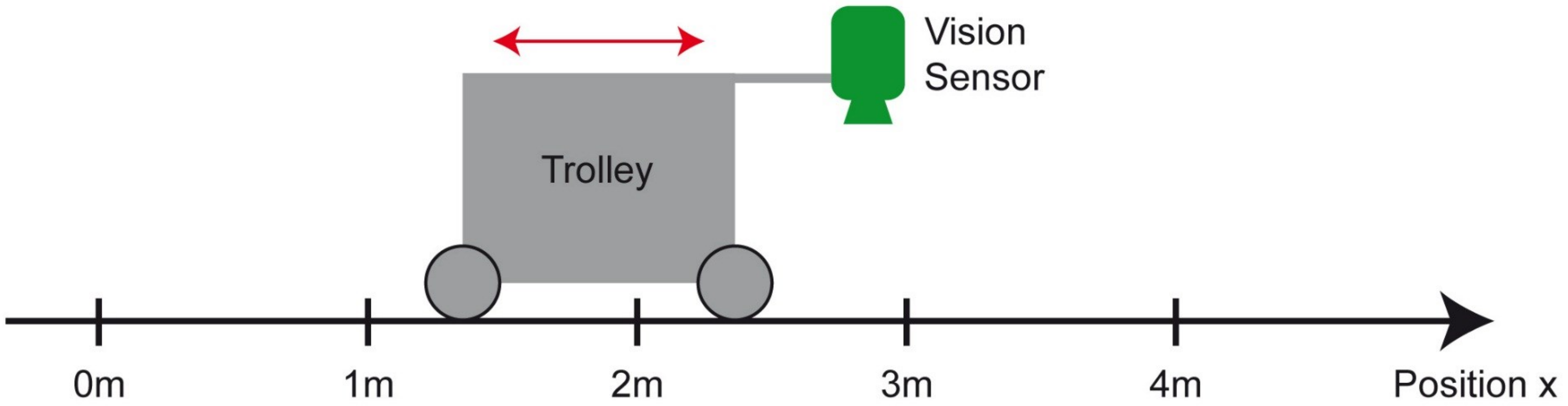
- Constant input power
- Low power ranges: **0 – 2500 µW**

Metrics:

- Energy harvested
- Energy consumed by load
- Execution Rate



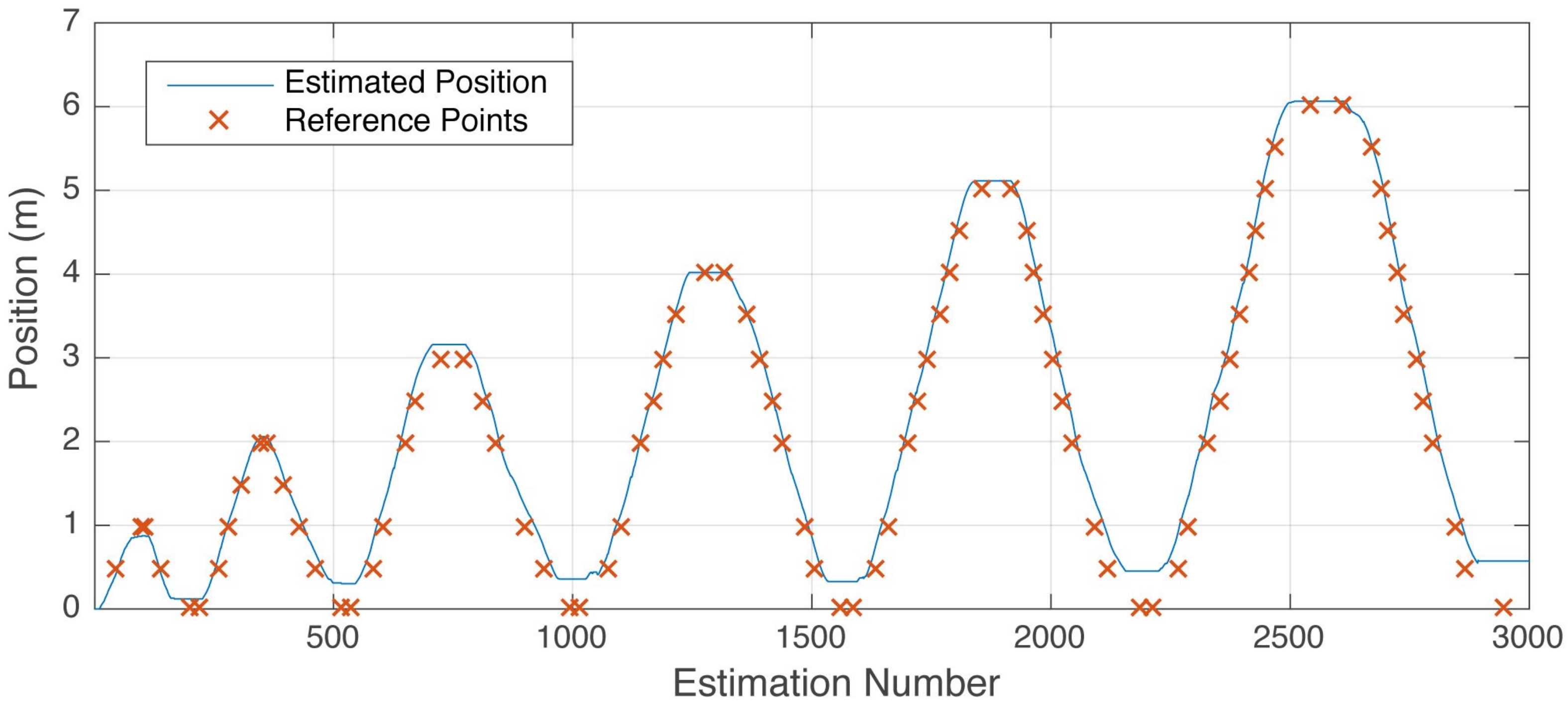
Evaluation: Velocity Estimation Algorithm



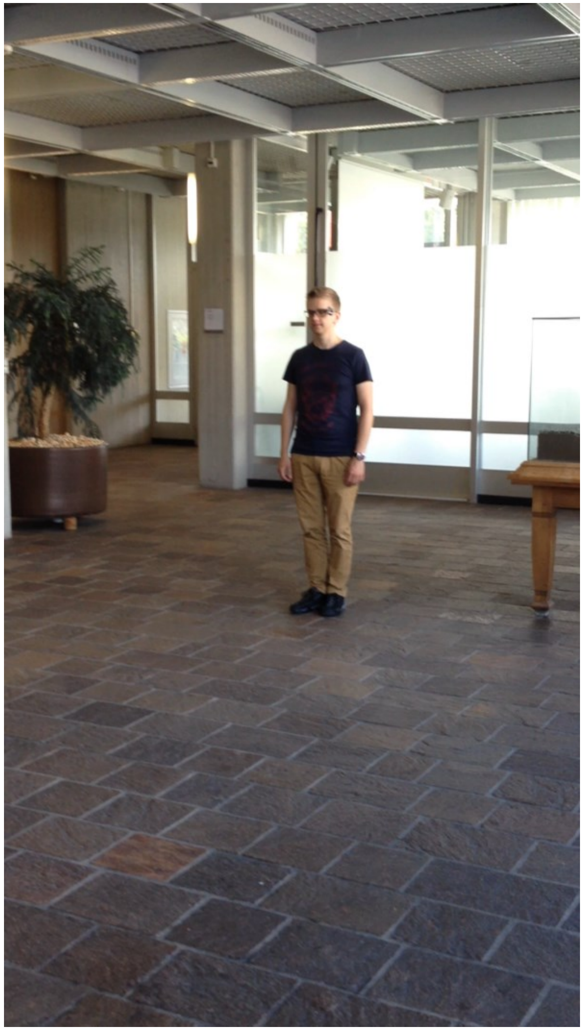
- continuously powered vision sensor

- **Visual Odometry**
  - track position of the moving sensor
  - integrate velocity estimations

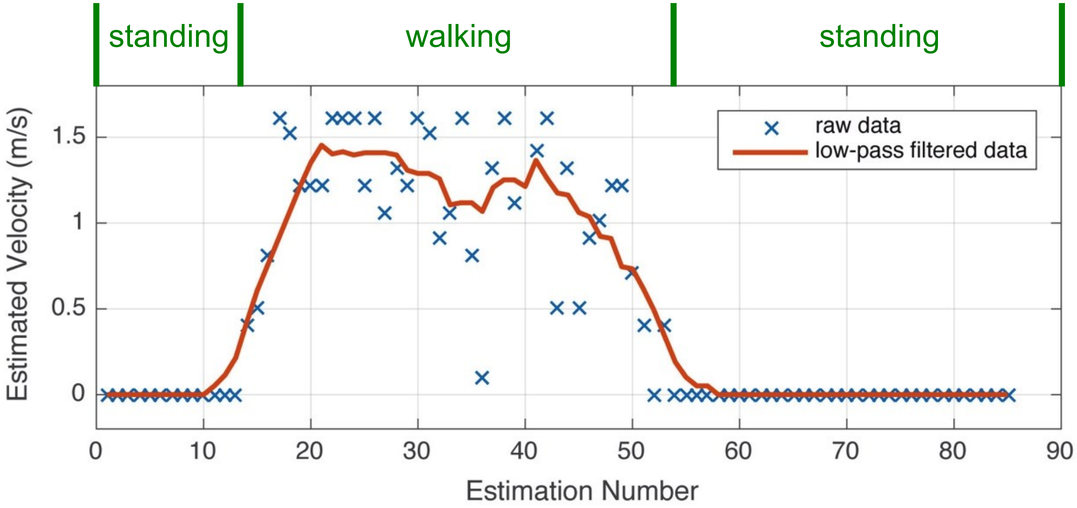
Evaluation: Velocity Estimation Algorithm



Evaluation: Real-World Experiment

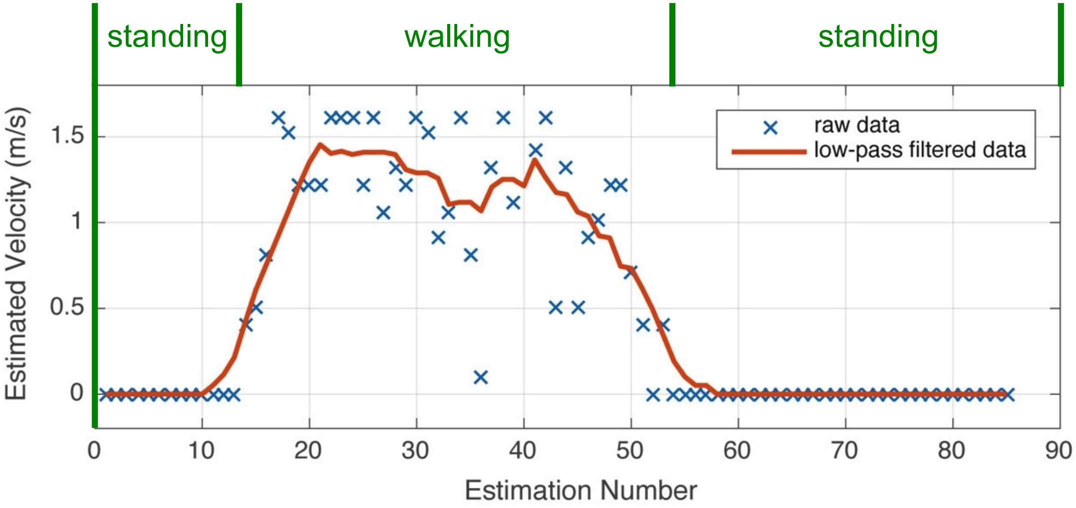


- continuously powered vision sensor

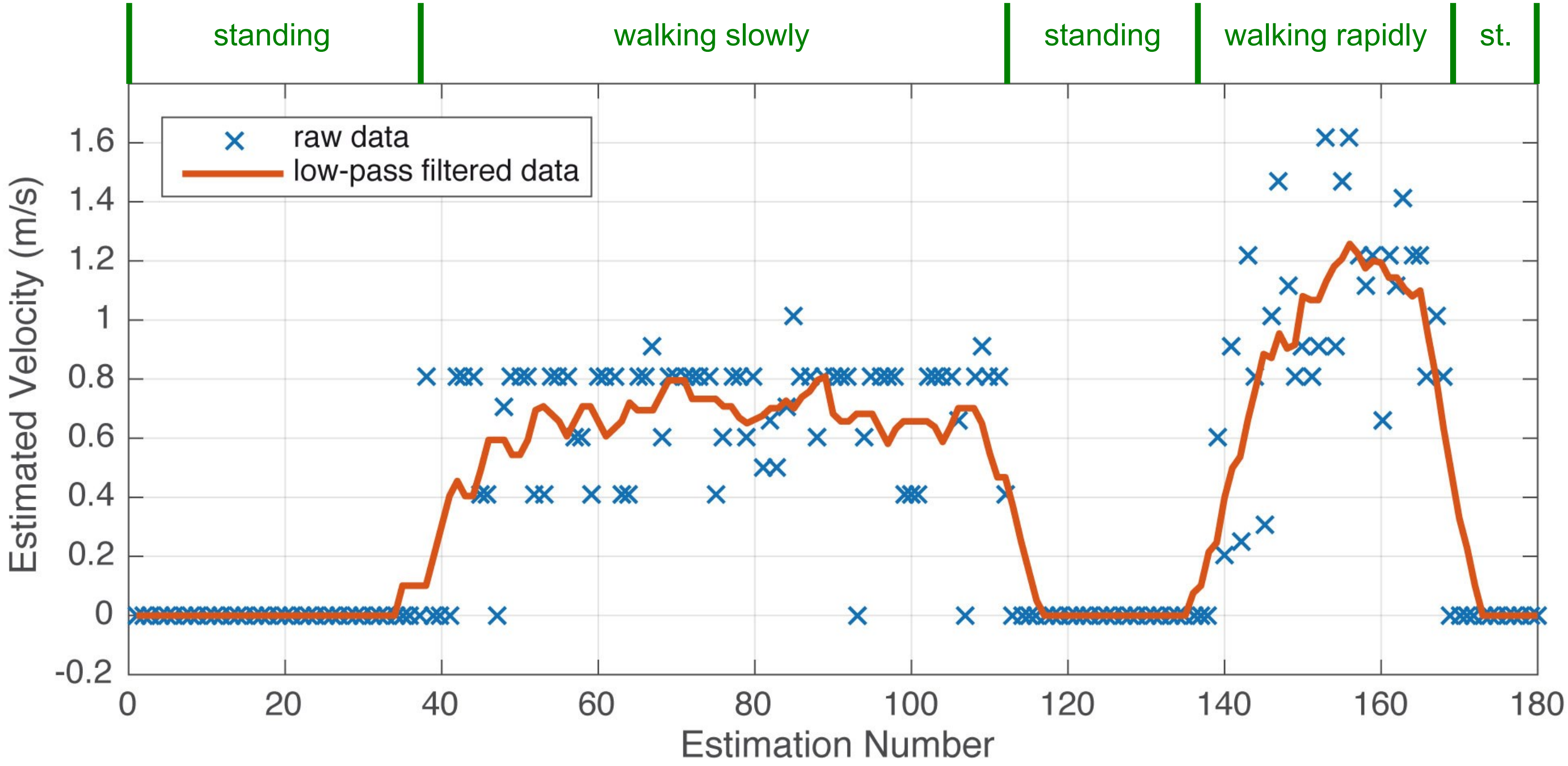


→ context recognition

Evaluation: Real-World Experiment



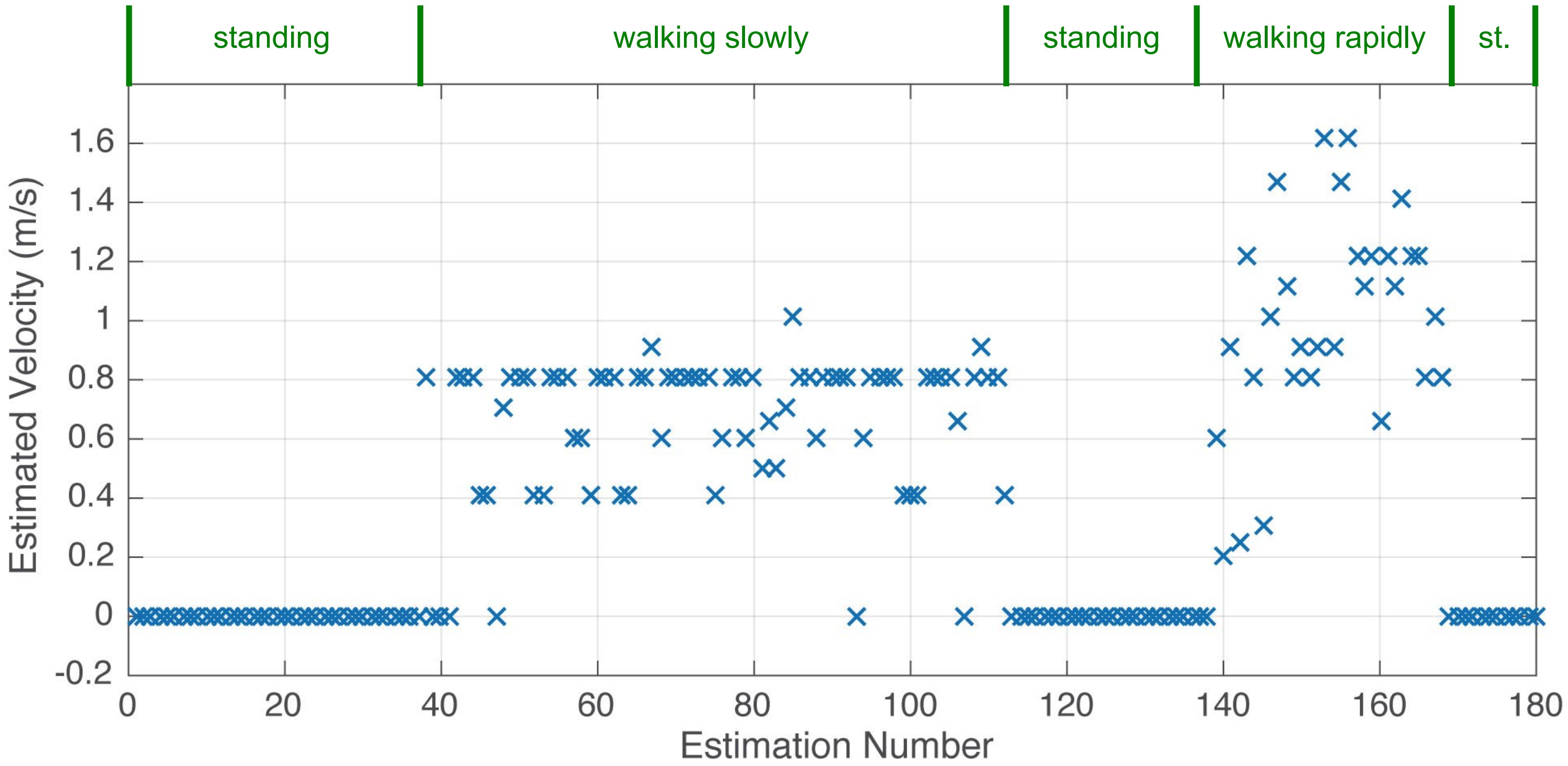
Evaluation: Real-World Experiment



➔ distinguish between different walking speeds

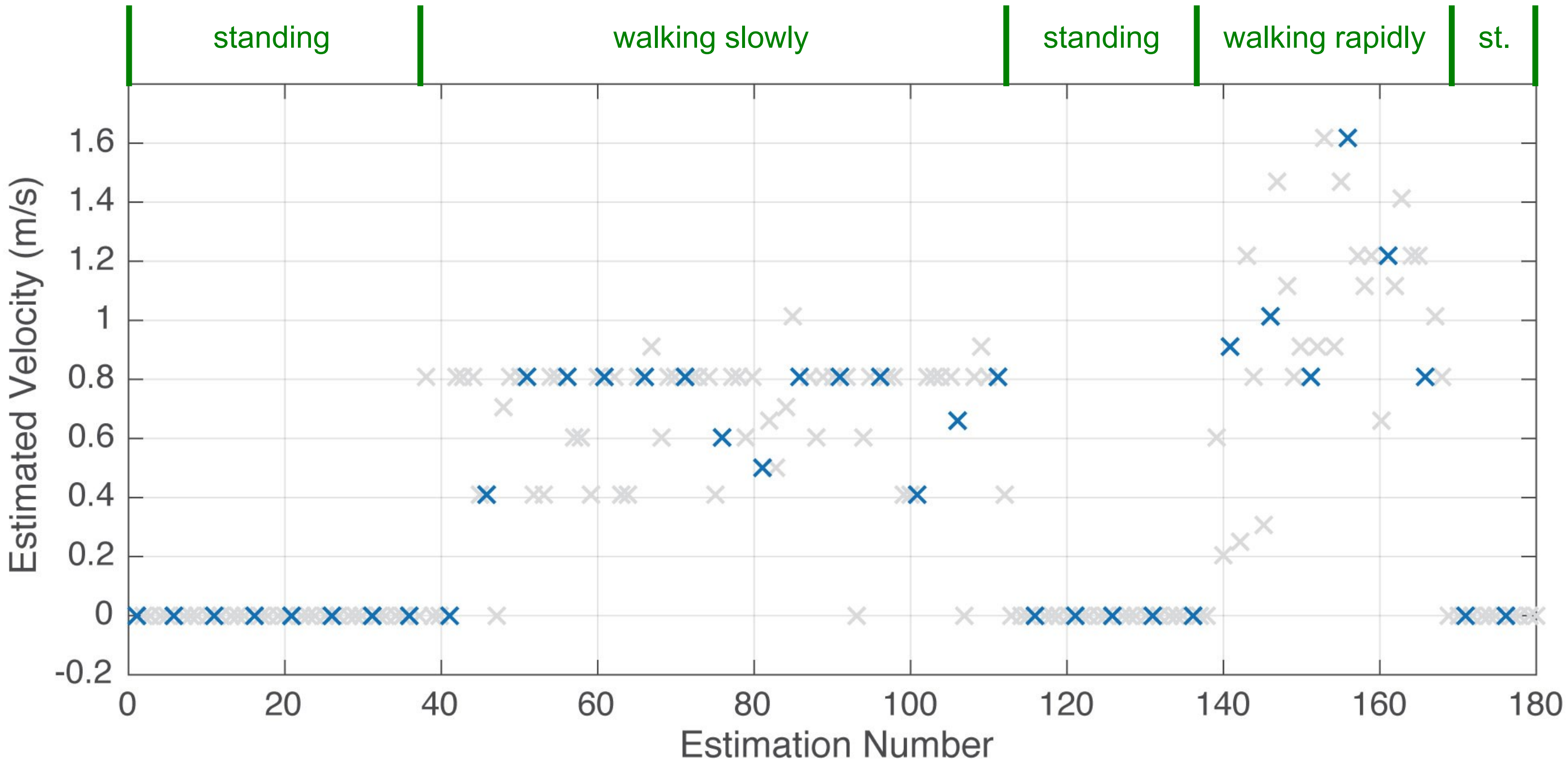
Evaluation: Real-World Experiment

- $P_{in} = P_{load} = 40$ mW ➔ ~ 480 estimations per minute



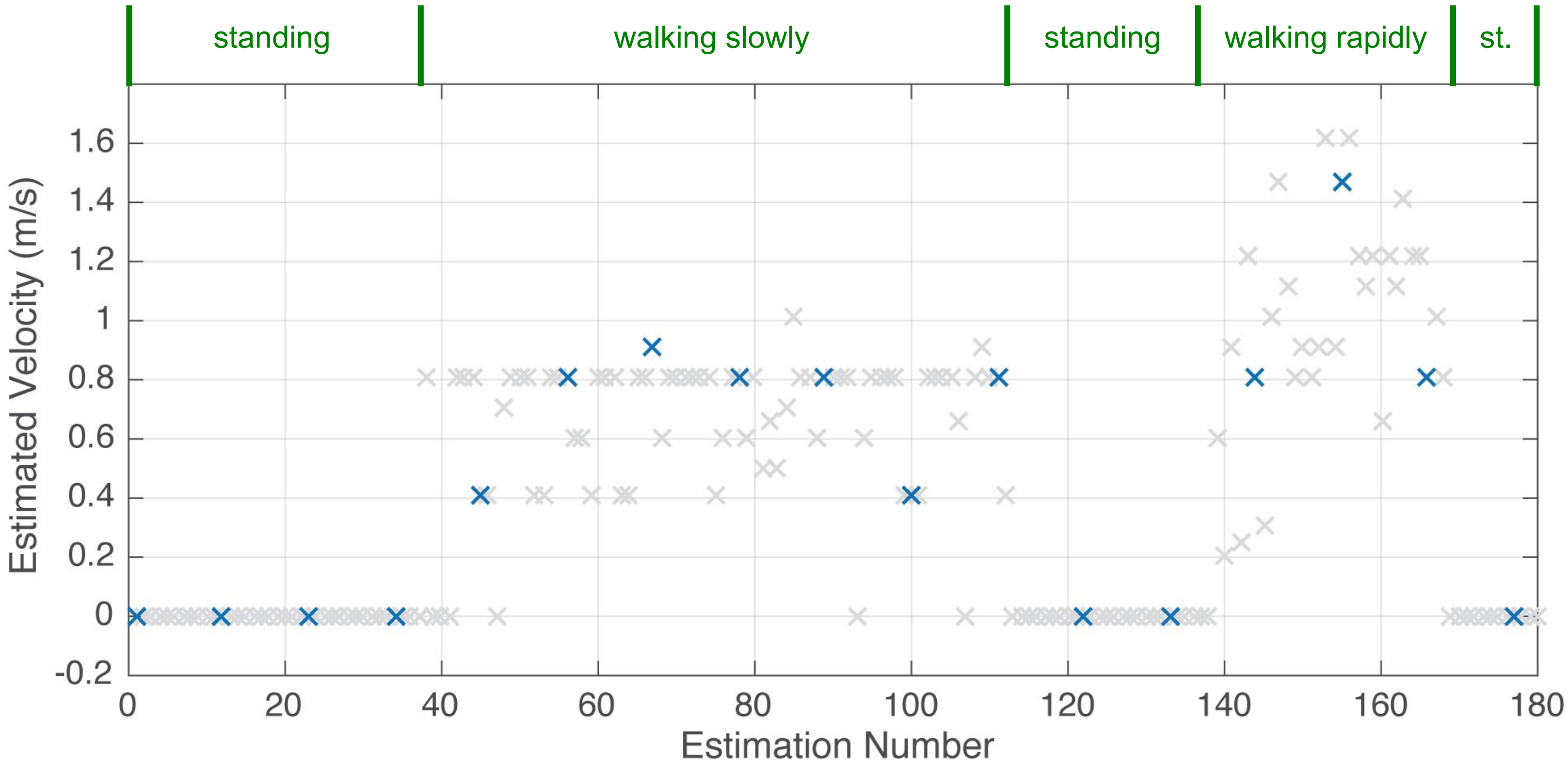
Simulation: Reduced Input Power

- $P_{in} = P_{load} / 5 = 8$ mW ➔ ~ 94 estimations per minute



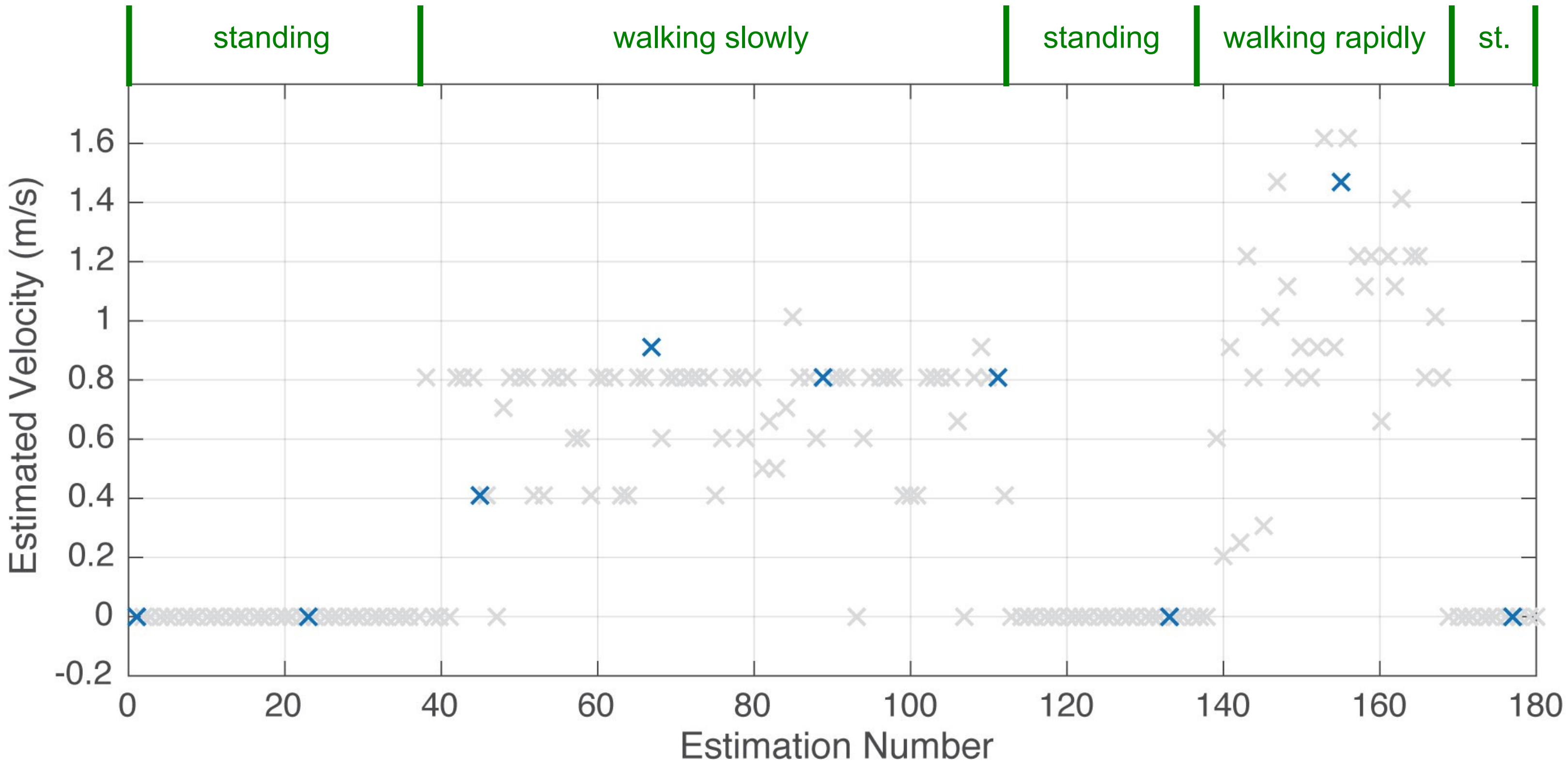
Simulation: Reduced Input Power

- $P_{in} = P_{load} / 10 = 4$ mW ➔ ~ 46 estimations per minute



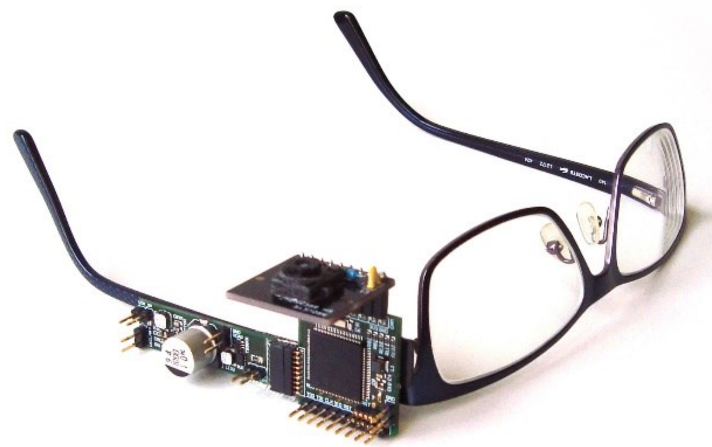
Simulation: Reduced Input Power

- $P_{in} = P_{load} / 20 =$ 2 mW ➔ ~ 22 estimations per minute



Summary

- **Transiently Powered Vision Sensing**
  - Reliable application execution
  - Energy efficient design
  - Accurate walking speed estimation

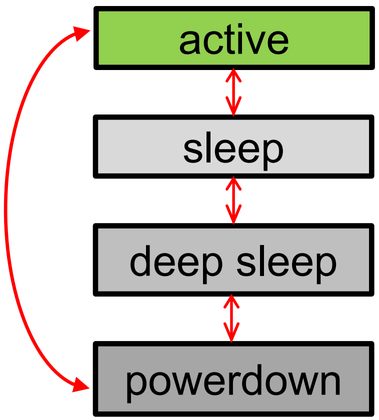


Open Hardware/Software:

To be released in March 2017

Advanced Power Management

Transient Node



1-100's mW

100's uW

1's μW

10-100's nW

- Digital Core: scales with V_{dd} and F
- Peripherals: do not scale

How can we supply power to a transient node?

- Direct Coupling – minimize error between I_{in} - I_{load}
- Energy Bursts – minimize energy requirement per task

Evaluation: Task Characterization

Image acquisition:

FPN compensation	CPU Freq.	Executions	$E_{task,avg}$	$t_{task,avg}$
on-line	48 MHz	1152	930 μJ	**53 ms**
sequential	24 MHz	1829	**537 μJ**	61 ms

Image processing:

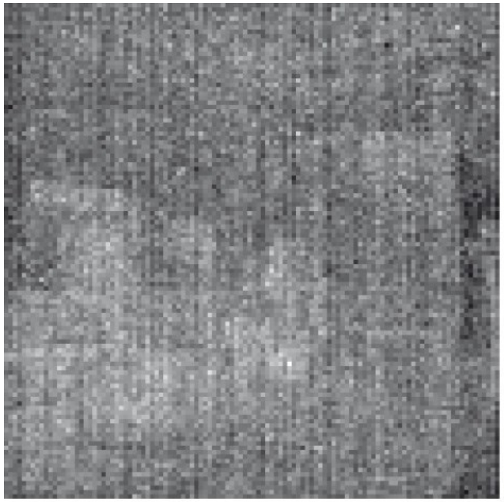
CPU Freq.	Executions	E_{task} (mean)	t_{task} (mean)	P_{task} (mean)
48 MHz	1079	757 μJ	**56 ms**	13.5 mW
24 MHz	1254	**635 μJ**	110 ms	5.8 mW
12 MHz	770	1371 μJ	388 ms	3.5 mW

Storing walking speed estimation:

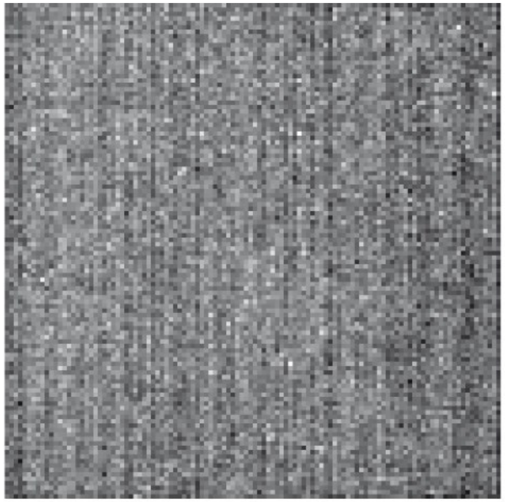
2 Bytes per estimation requires 16 µs and 96 nJ

Stonyman Vision Chip: Fixed Pattern Noise

- $I_{compensated} = I_{mask} - I_{raw}$



Raw Image



Mask

FPN compensated Image