Minimizing Energy Storage in Cyber-Physical Systems

08.04.2018

Did you ever own one of these?

Source: GSM arena

Nokia 1110 (2004)

Average use: several days

Battery: **800 mAh**

Do you own one of these?

Source: GSM arena

Nokia 1110 (2004)

Average use: several days

Battery: **800 mAh**

Source: GSM arena

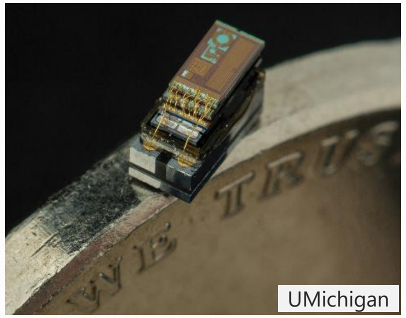
iPhone X (2018)

Internet use: ~12 h

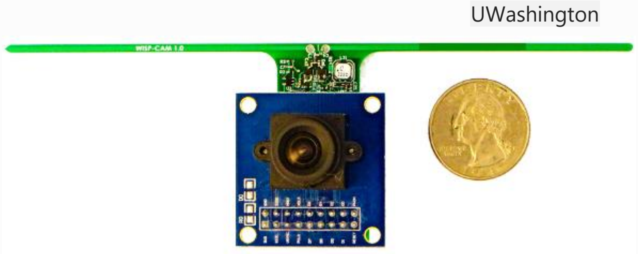
Battery: **2716 mAh**

Trend: as **functionality** increases so does the **battery size**
cost
env. impact

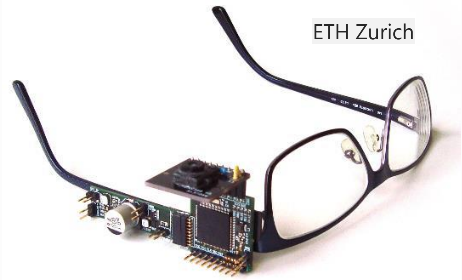
Batteryless systems



Miniaturized

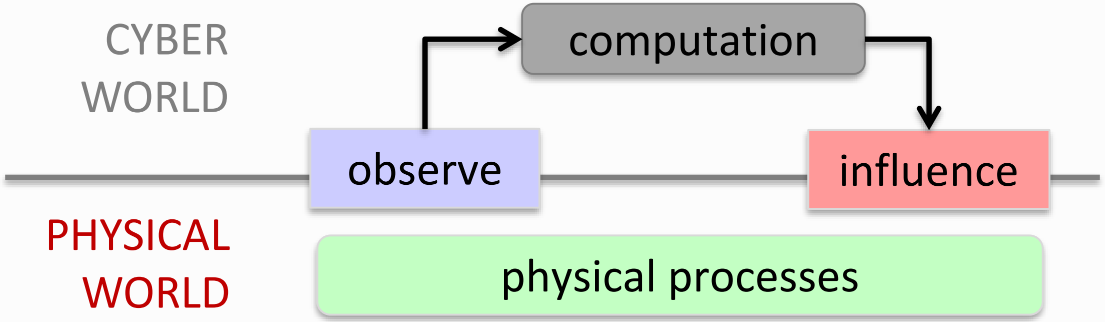


Distributed



Wearable

Cyber-physical systems



<u>Main goal:</u>

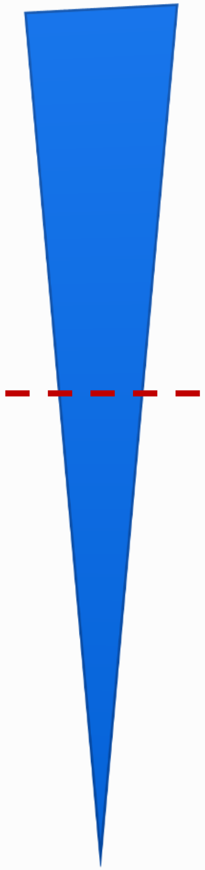
powering loads
from transducer
not storage*

Electrical vs electronic systems

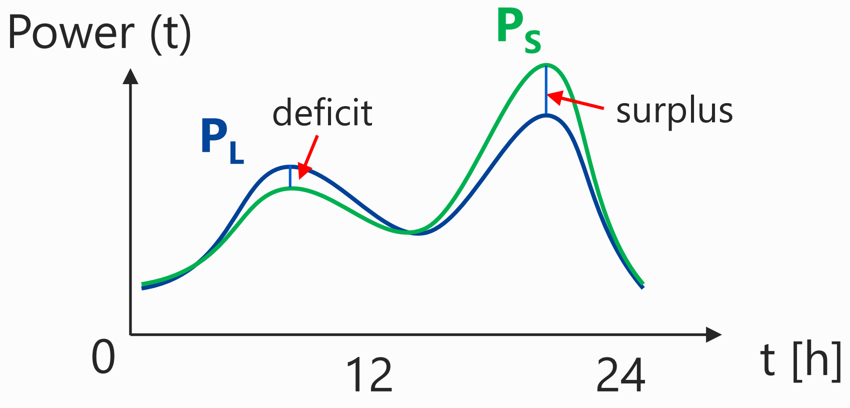
P_L (Load Power) [W]

Water Boiler: 10^4

Washing machine: 10^3



Grid-powered

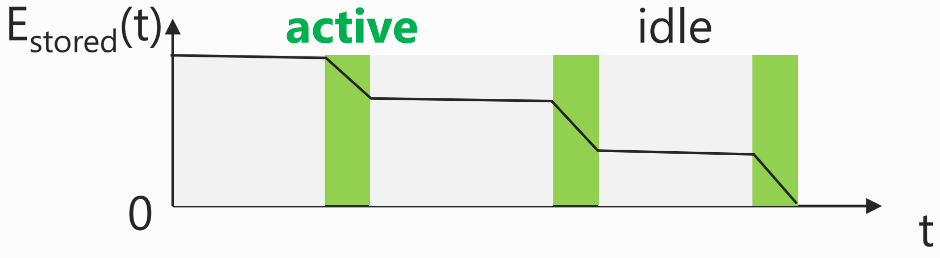


Goal: **adjust P_S** as $f(\mathbf{P_L})$

Cell phone: 10^0

Wearables: 10^{-3}

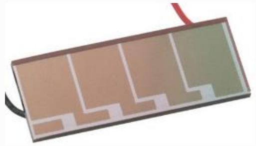
“Battery-powered”



Goal: **maximize lifetime** (minimize P_L)

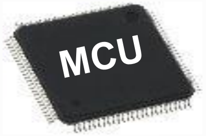
Low power embedded systems

Common DC **Transducers**



	Solar	**TEG**
power density	< 10 mW / cm^2	< 5 mW / cm^2
voltage range	< 5 Volts	< 0.5 Volts
dynamics	fast (indoor) slow (outdoor)	Slow-changing

Active power needs

10's mW 

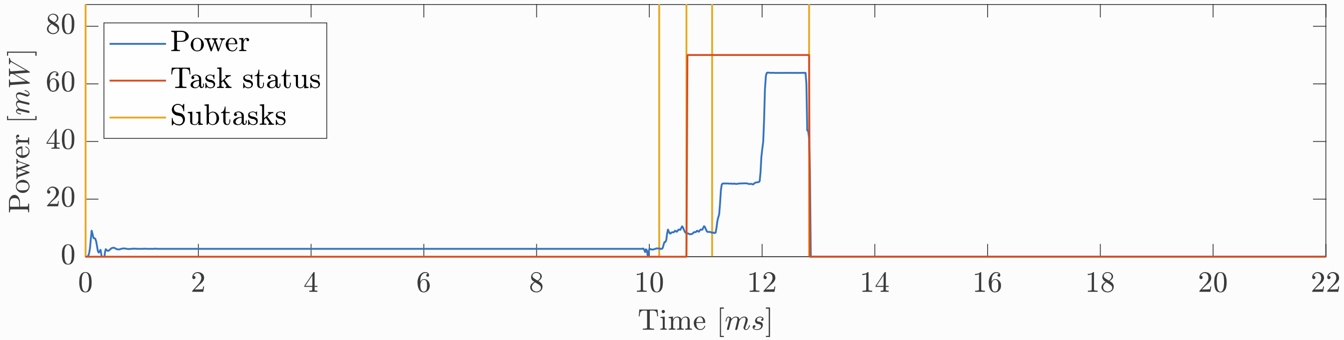
1-10's mW 

10-100's mW 

Idle power: 10 nW

Reliable execution in batteryless systems

CC430 single wireless transmission

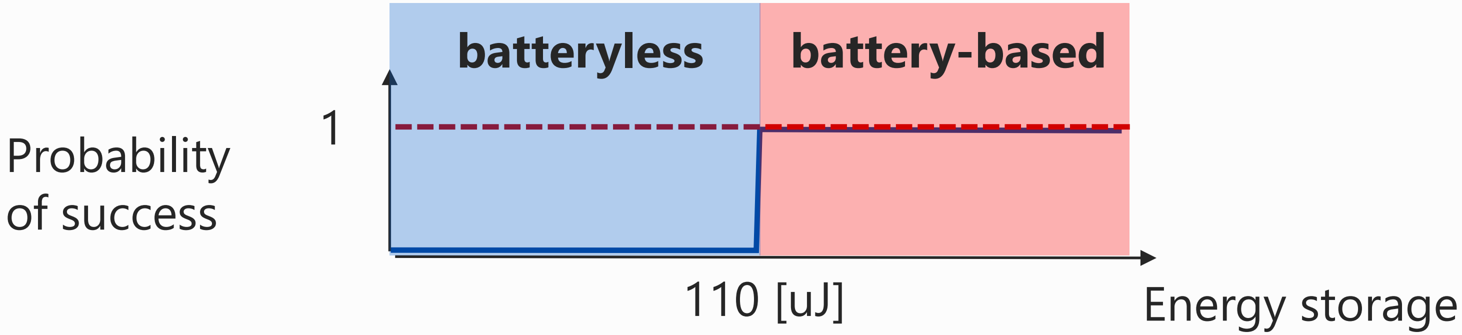


Duration: 12.8 ± 0.03 [ms]

Energy: 108.2 ± 0.32 [uJ]

Successful transmission depends on supplied energy (transducer + storage)

Assuming an adversarial source:



About myself

Andrés Gómez

Masters in Embedded System Design at ALaRI, USI (Lugano)

Currently 4th year PhD student at D-ITET

IIS: (75%) Prof. Luca Benini

VLSI design, HW accelerators, heterogeneous computing platforms

TIK: (75%) Prof. Lothar Thiele

Real-time scheduling, modular performance analysis, wireless network protocols

under the supervision of

Prof. Lothar Thiele

Prof. Luca Benini

in collaboration with

Lukas Sigrist

Andreas Tretter

Rehan Ahmed

Pascal Hager

Michele Magno

and many (many) master students...

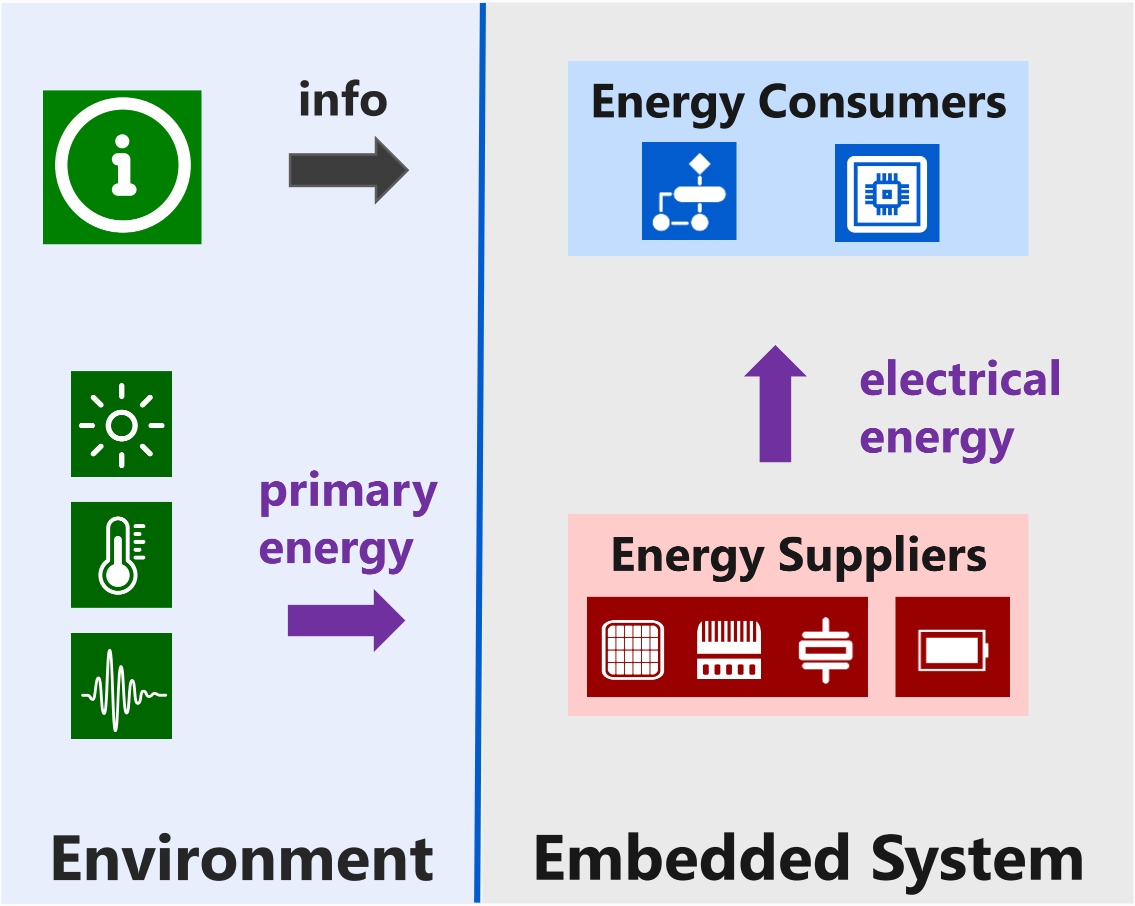
with the support of

FNSNF

Swiss National Science Foundation

Design Aspects

Harvesting-based systems



Advantages:

<u>Potentially</u> **large** energy flow

Challenges:

Keeping modular design

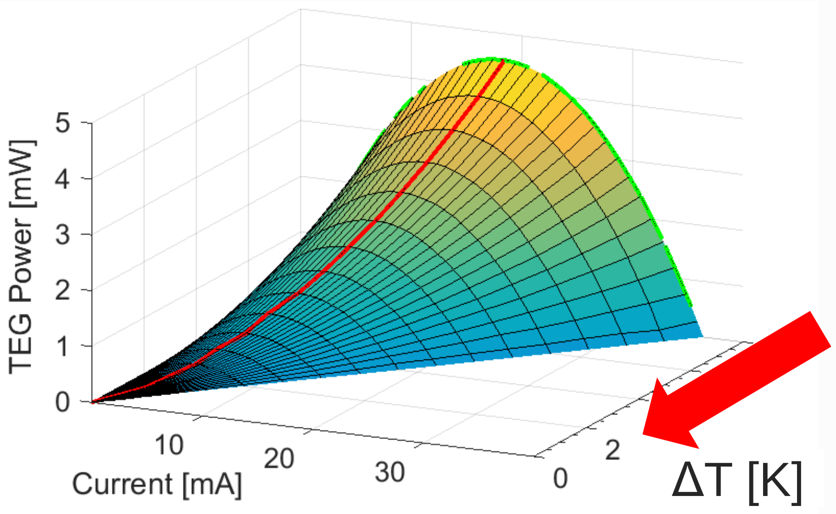
Cost/space constraints

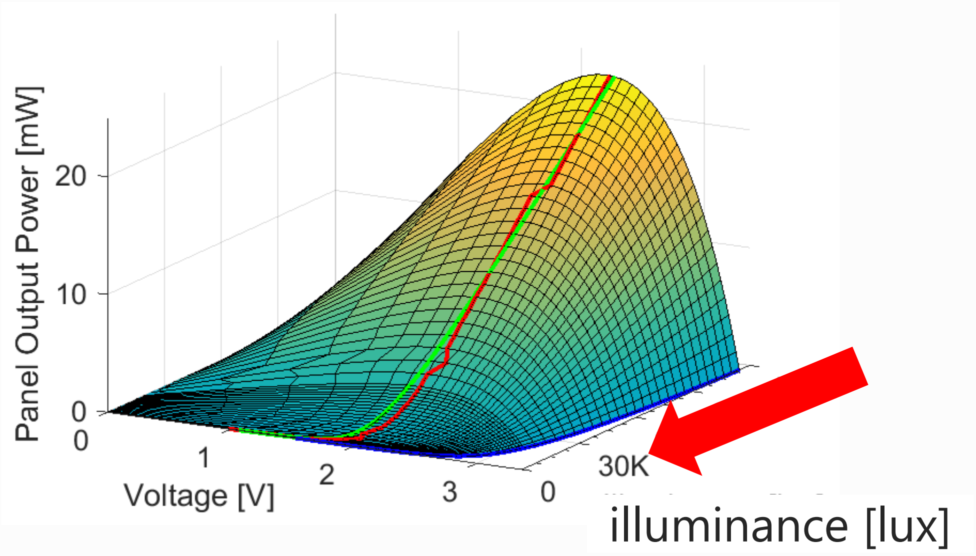
Making guarantees

Is harvesting a safe bet?

absolute guarantees — **predict** the future

conditional guarantees — **correlate** primary/electrical energy



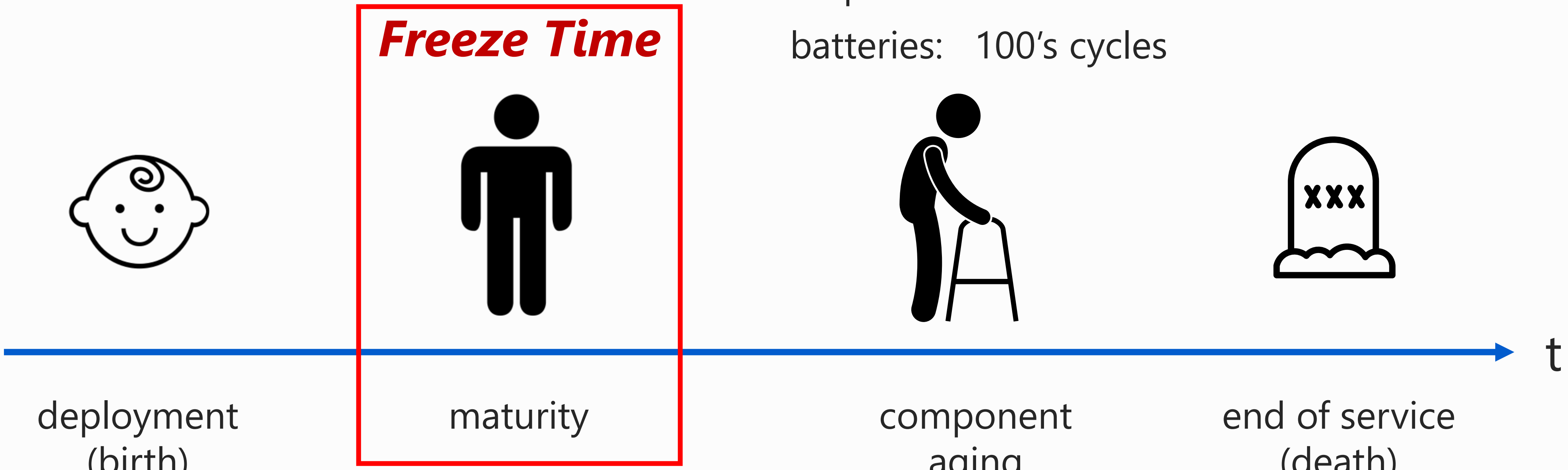


As a system designer, I want to **minimize** assumptions/requirements

But I also want immortal systems!

Desired lifecycle:

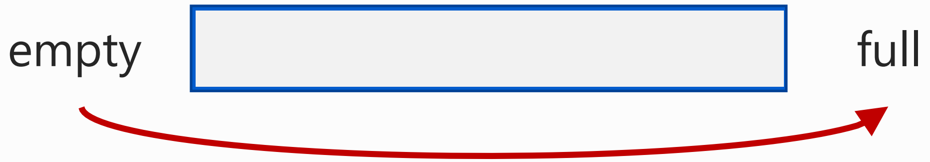
silicon:	millennia*
solar panel:	decades*
batteries:	100’s cycles



Are long lifetimes the only reasonable design goal?

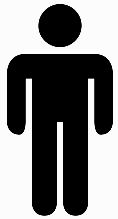
Predictability vs resilience

System should "live" as **long** as possible —— **large** energy cycle Q

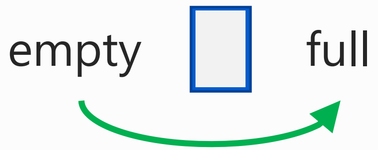


charging is **expensive**

Predictable
Life



System should "revive" as **quickly** as possible —— **small** energy cycle Q



charging is **cheap**

Resilient
"Life"

A few words about energy storage

I'm not a battery expert!

Main tradeoffs:

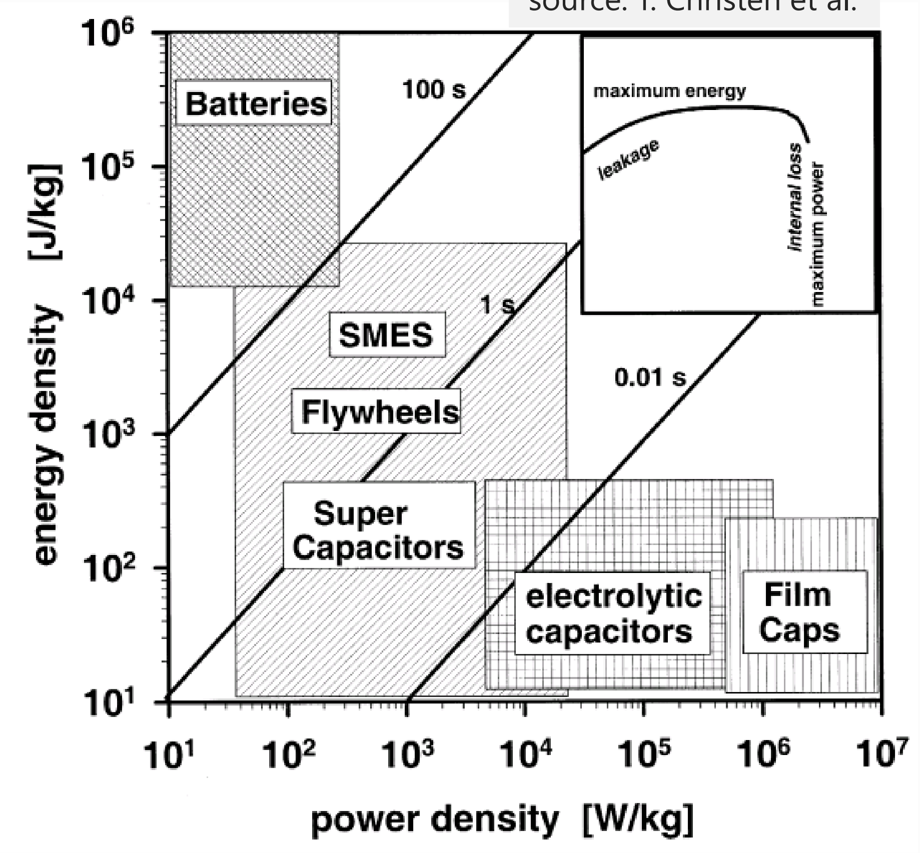
- recharge cycles
- power density
- energy density
- leakage

My objectives: high power density
high recharge cycles

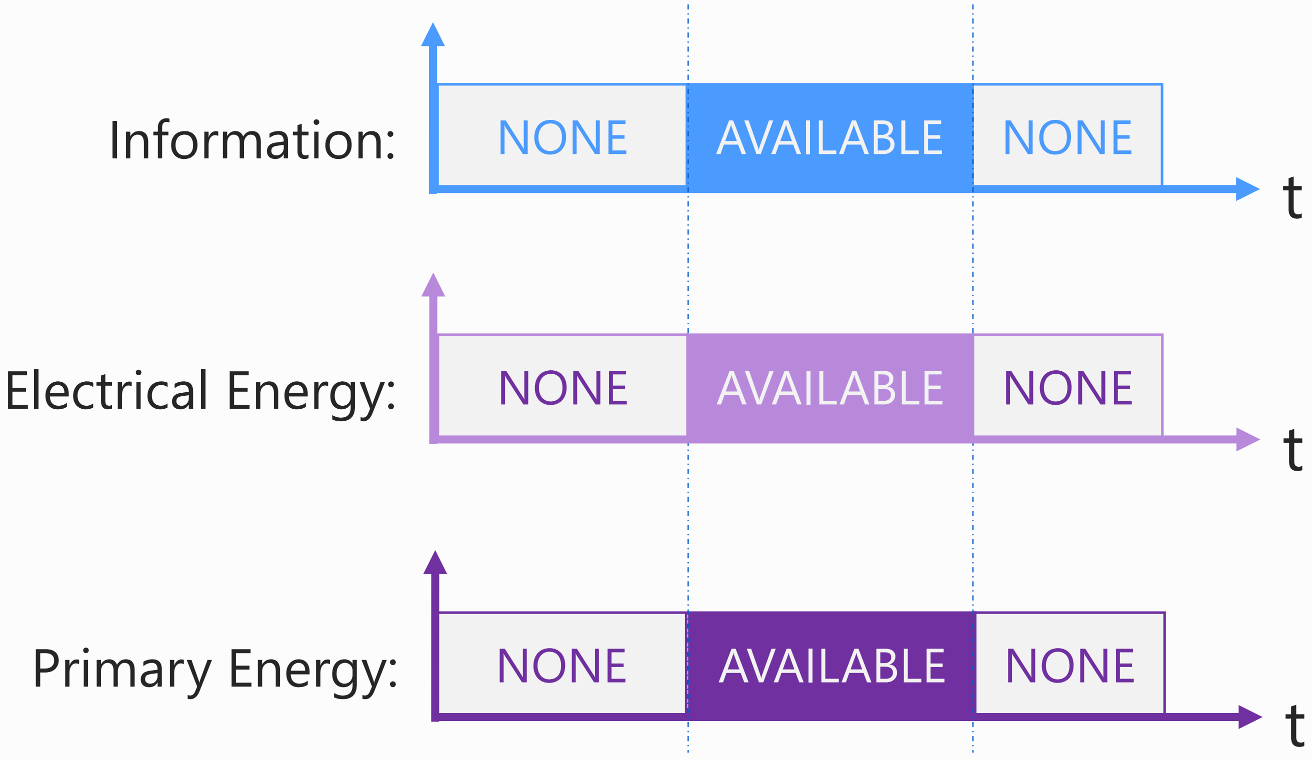
I use ceramic/electrolytic capacitors

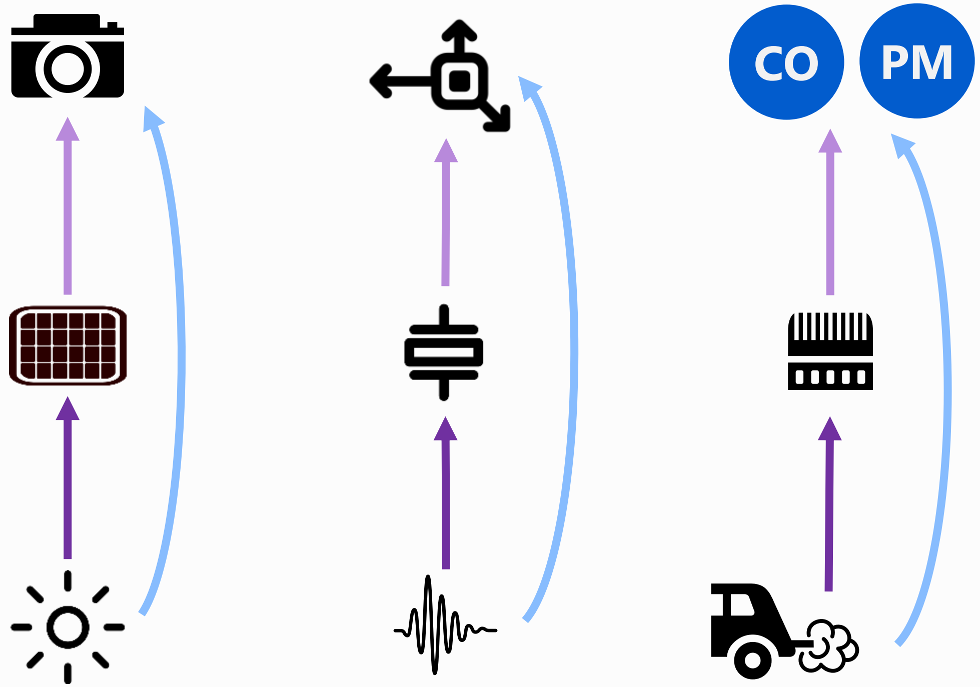
Ragone Plot

source: T. Christen et al.



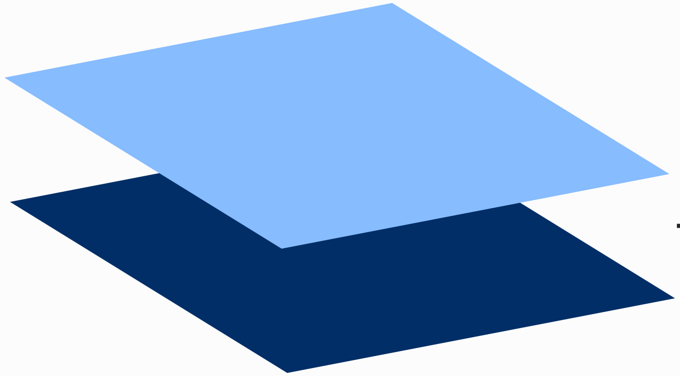
When are batteryless systems most useful?





System requirements

Application



Environment

We need: control voltage
retain data

We want: **minimize** energy (Q)
- low power techniques
- divide-and-conquer

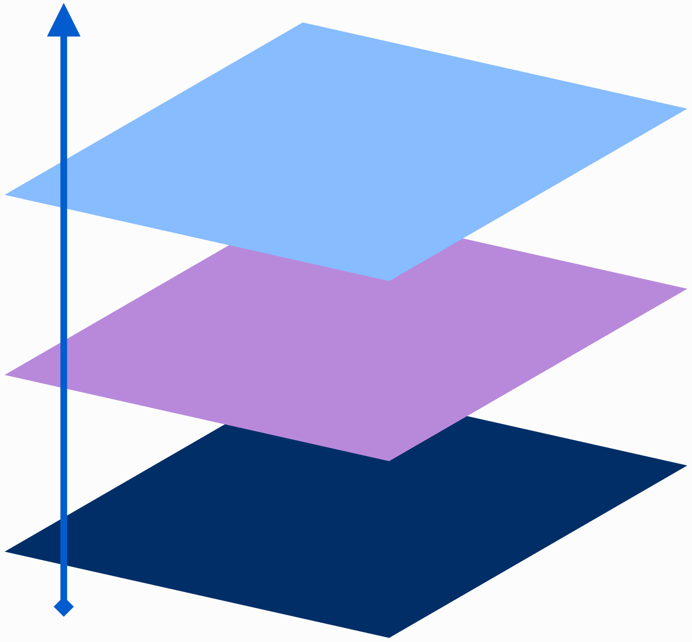
We **do not** assume: **regular** availability
specific transducers

We assume: primary energy > 0

Decoupled design

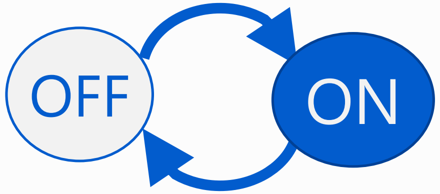
Figures of Merit:

$$\theta_{app}(P_{source})$$



$$\eta_{sys} = \frac{E_{app}}{E_{input}}$$

Specification: if(Q=$\mathbf{E_{min}}$)



consume $\mathbf{E_{min}}$

Application

power/control: $\sum P\Delta t$

Energy Conditioning

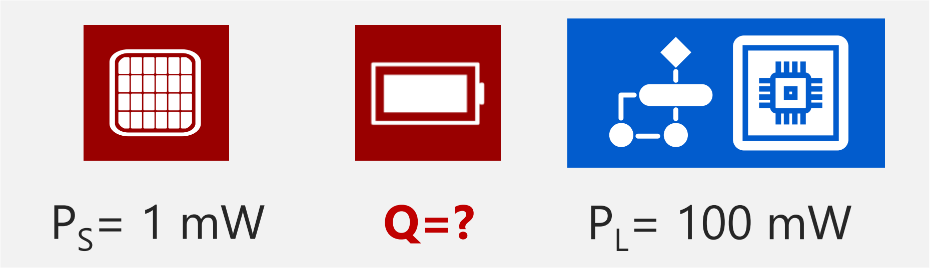
charge

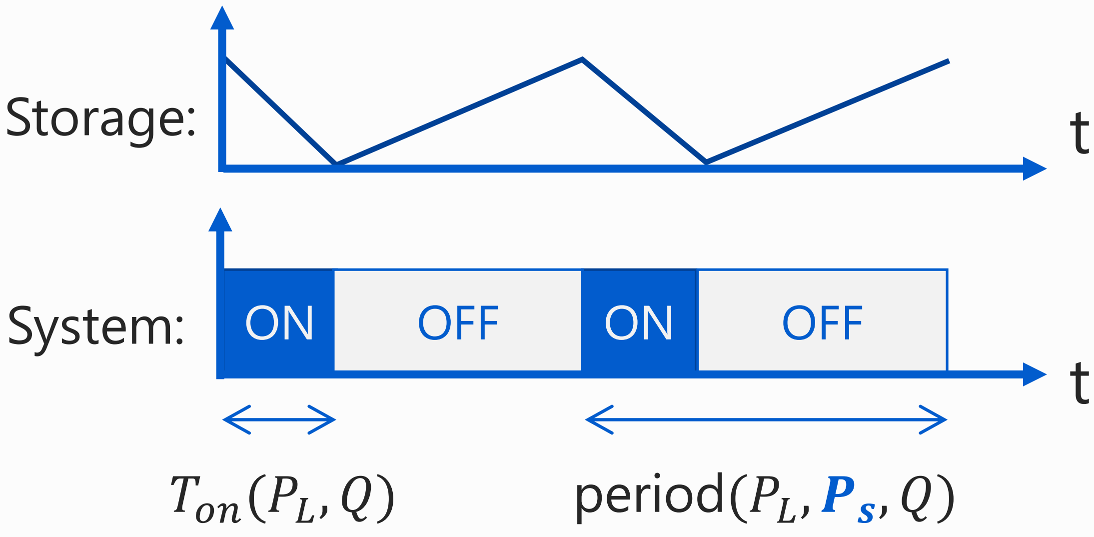
harvester: $\int P\,\mathrm{dt}$

Environment

primary energy

System Dynamics





If I want **T_{on} ≈ 24 hours**

Q ≈ 10 kJoules (AA batt.)

T_{off} ≈ 2400 hours

If I want **T_{on} ≈ 10 ms**

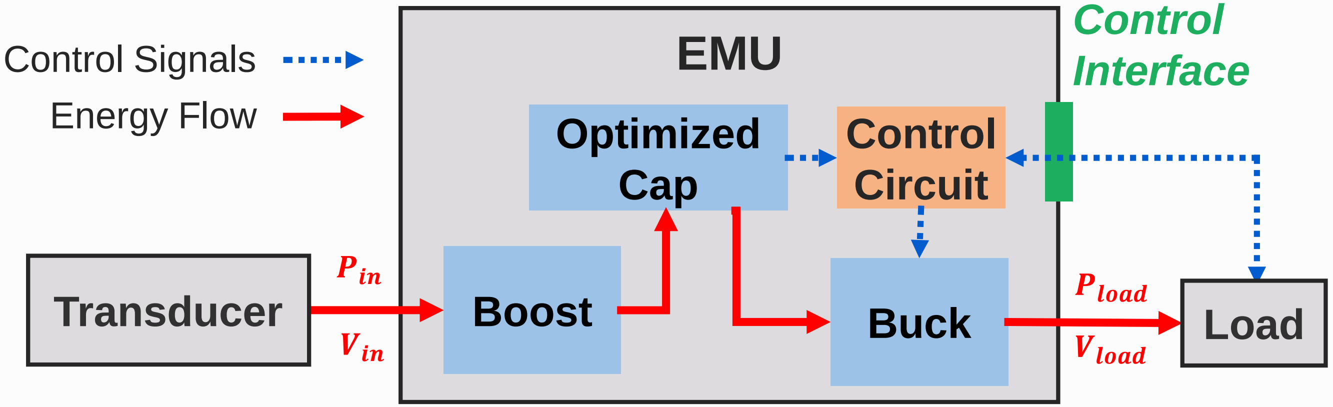
Q ≈ 1 mJoule (100 µF @ 5V)

T_{off} ≈ 1 s

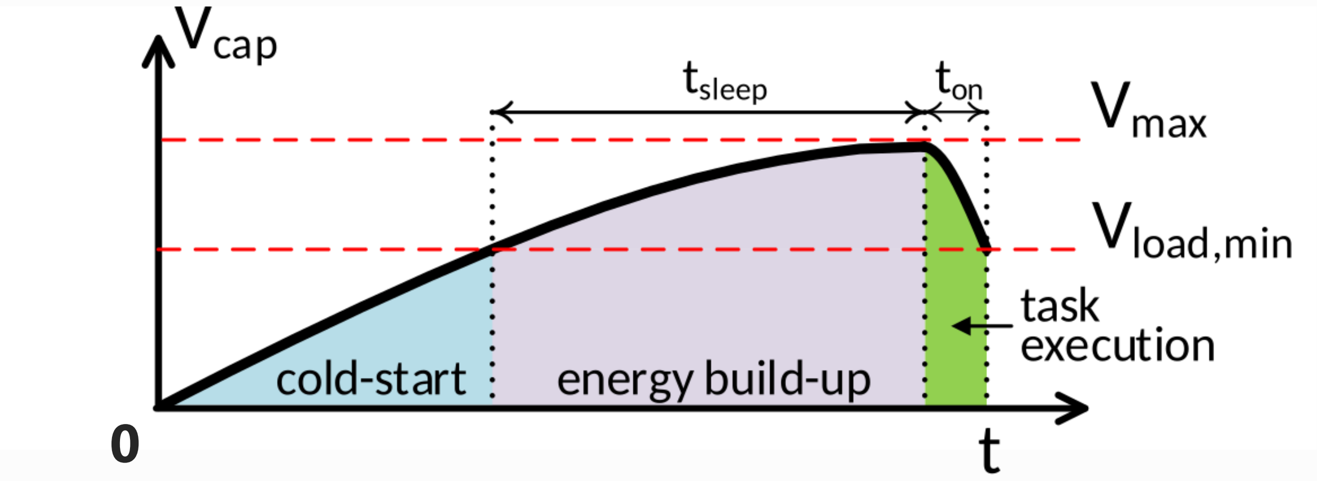
Implementation

Energy Management Unit

Architecture:



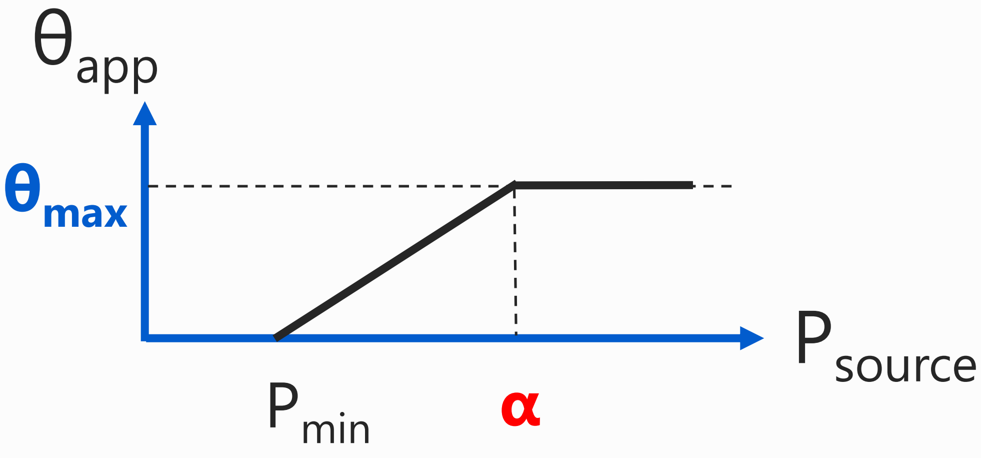
Behavior:

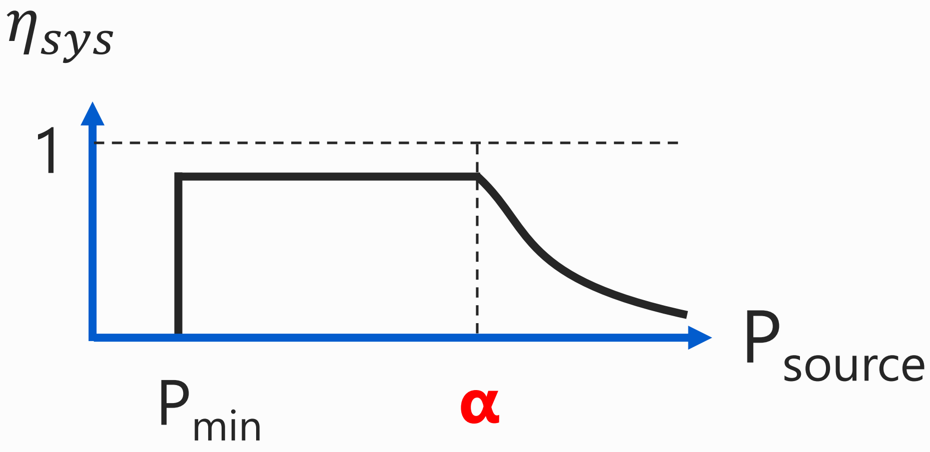


1) $$\int_0^t P_{in} \times \eta = \int_{t_{on}} P_{active}$$

2) $$\frac{\widetilde{\boldsymbol{P}}_{\boldsymbol{in}}}{\widetilde{P}_{active}} \propto \frac{t_{on}}{\boldsymbol{t}_{\boldsymbol{sleep}}}$$

Performance evaluation

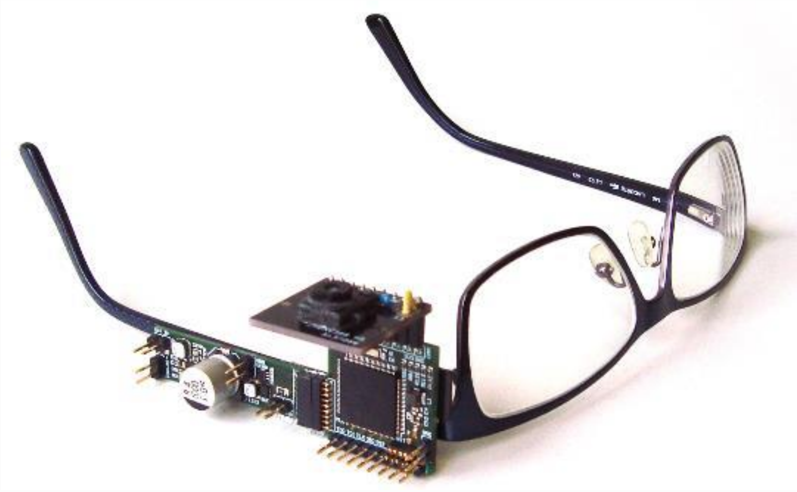




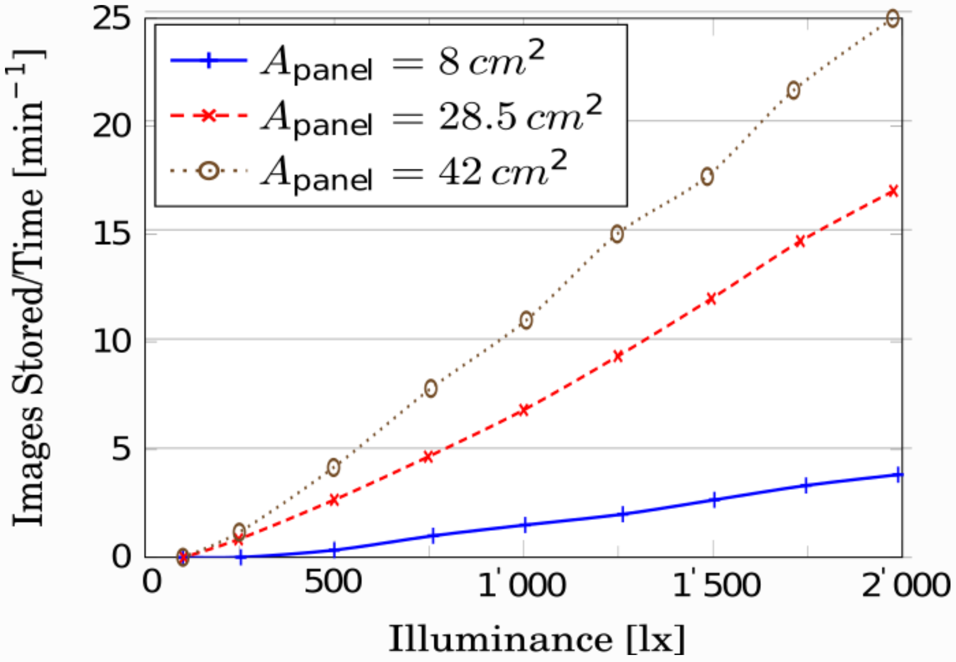
Border values:

Converter-dependent: P_{min} ≈ **20 µW** and η_{sys} ≤ **0.8**

Sample Applications



Application: storing Images in SD Card



Batteryless Camera:

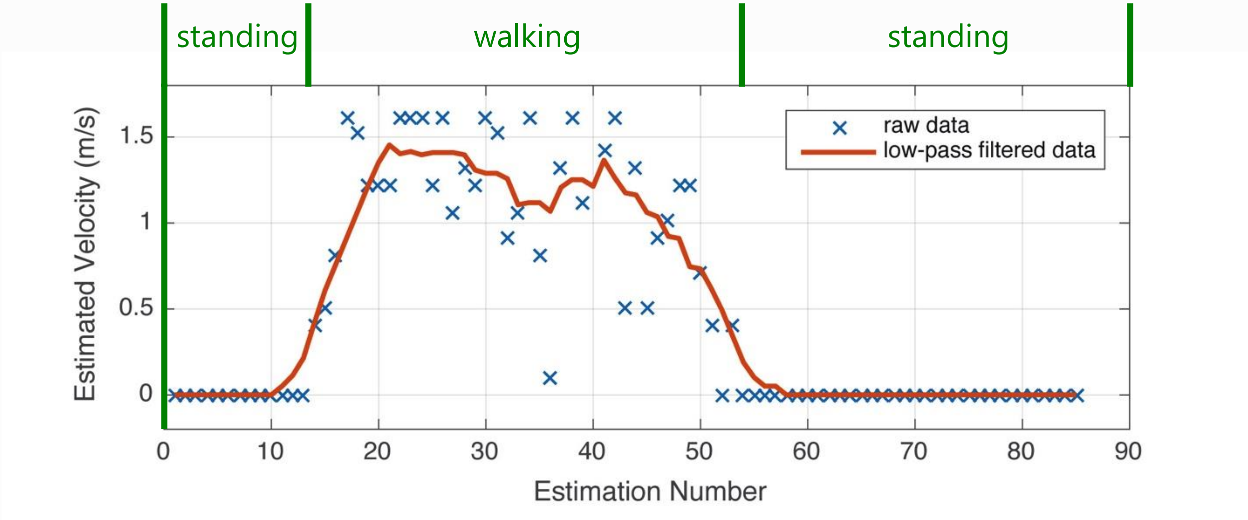
Low power grayscale camera

Cortex M4

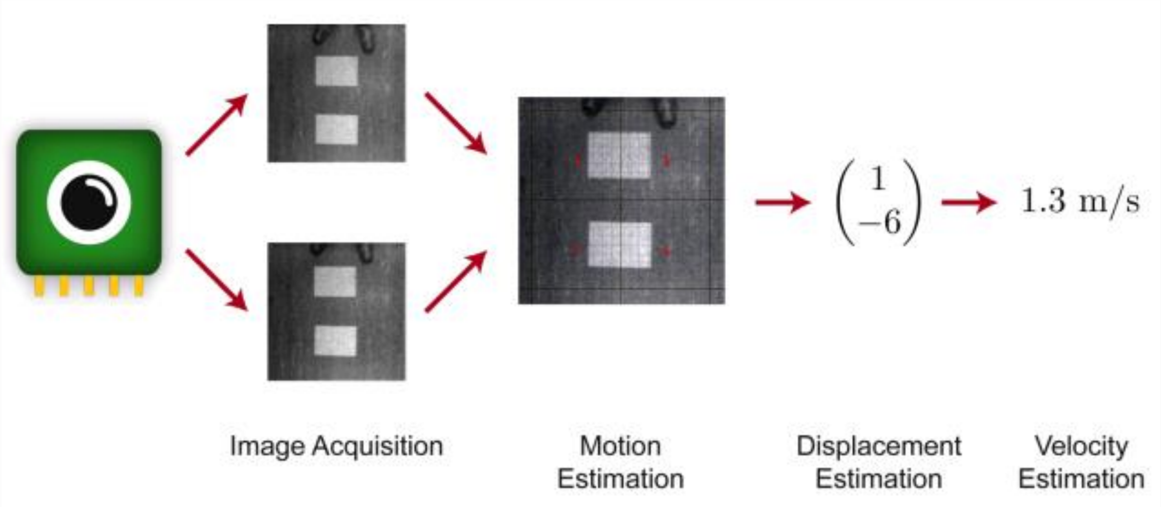
SD card

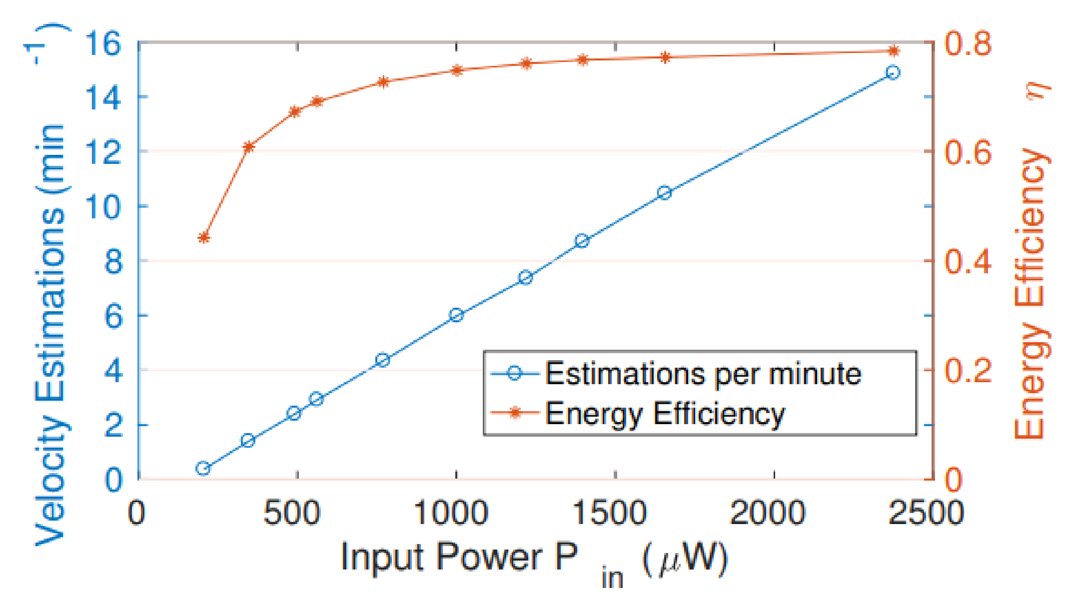
Sample Applications

Application: Estimating walking speed



Sample Applications

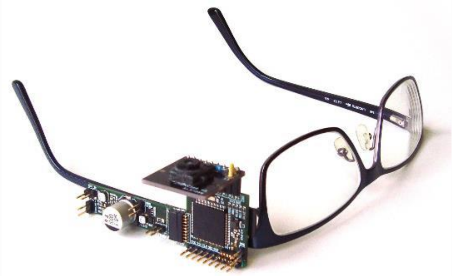




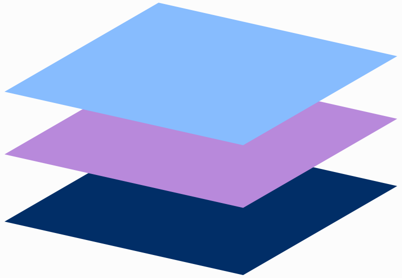
Note: Entire estimation cycle is executed atomically

Summary

Design methodology for batteryless systems



Decoupling for modular and scalable design



Selected Publications

- **Gomez A**, Sigrist L, Schalch T, Benini L, Thiele L.
  "Efficient, Long-Term Logging of Rich Data Sensors using Transient Sensor Nodes."
  Transactions on Embedded Computing Systems. 2017. ACM.

- Sigrist L, **Gomez A**, Lim R, Lippuner S, Leubin M, Thiele L.
  "Measurement and validation of Energy Harvesting IoT Devices."
  In Proceedings of Conference on Design, Automation & Test in Europe (DATE). 2017. EDA Consortium.

- **Gomez A**, Sigrist L, Schalch T, Benini L, Thiele L.
  "Wearable, Energy-Opportunistic Vision Sensing for Walking Speed Estimation."
  In Proceedings of Sensors Applications Symposium (SAS). 2017. IEEE.

- **Gomez A**, Sigrist L, Magno M, Benini L, Thiele L.
  "Dynamic Energy Burst Scaling for Transiently Powered Systems."
  In Proceedings of Conference on Design, Automation & Test in Europe (DATE). 2016. EDA Consortium.