Micro Energy Harvesting

- from basic research to practical applications -

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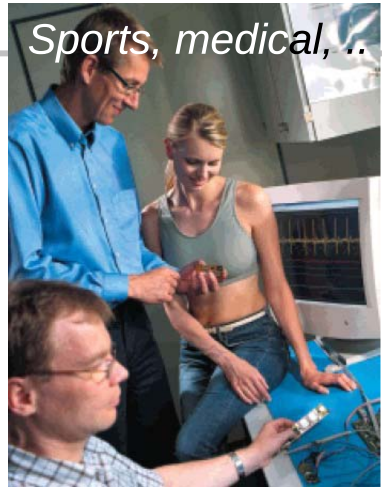
Distributed and embedded (Micro)systems


Building and Enviroment

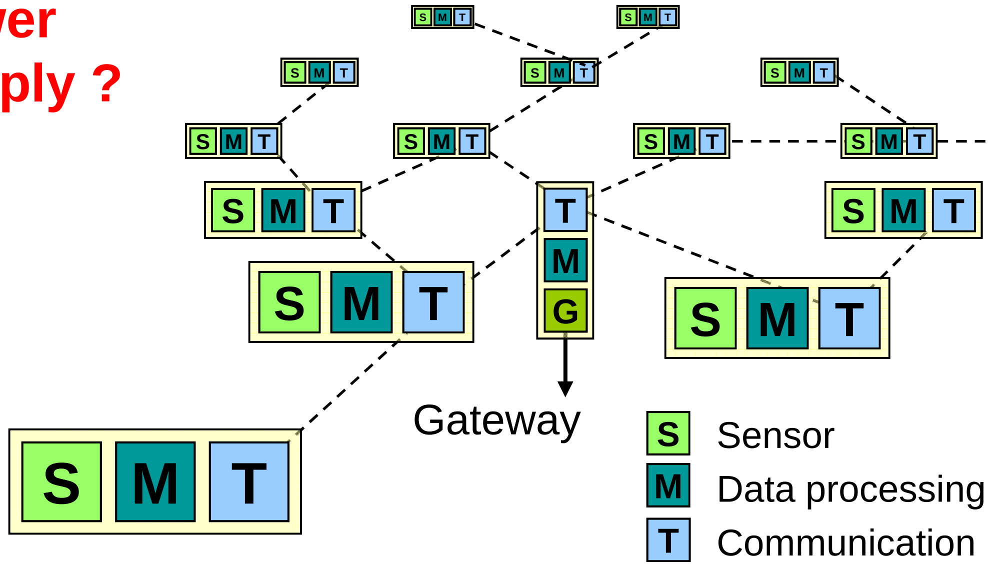

Sports, medical, ..

Space, ….

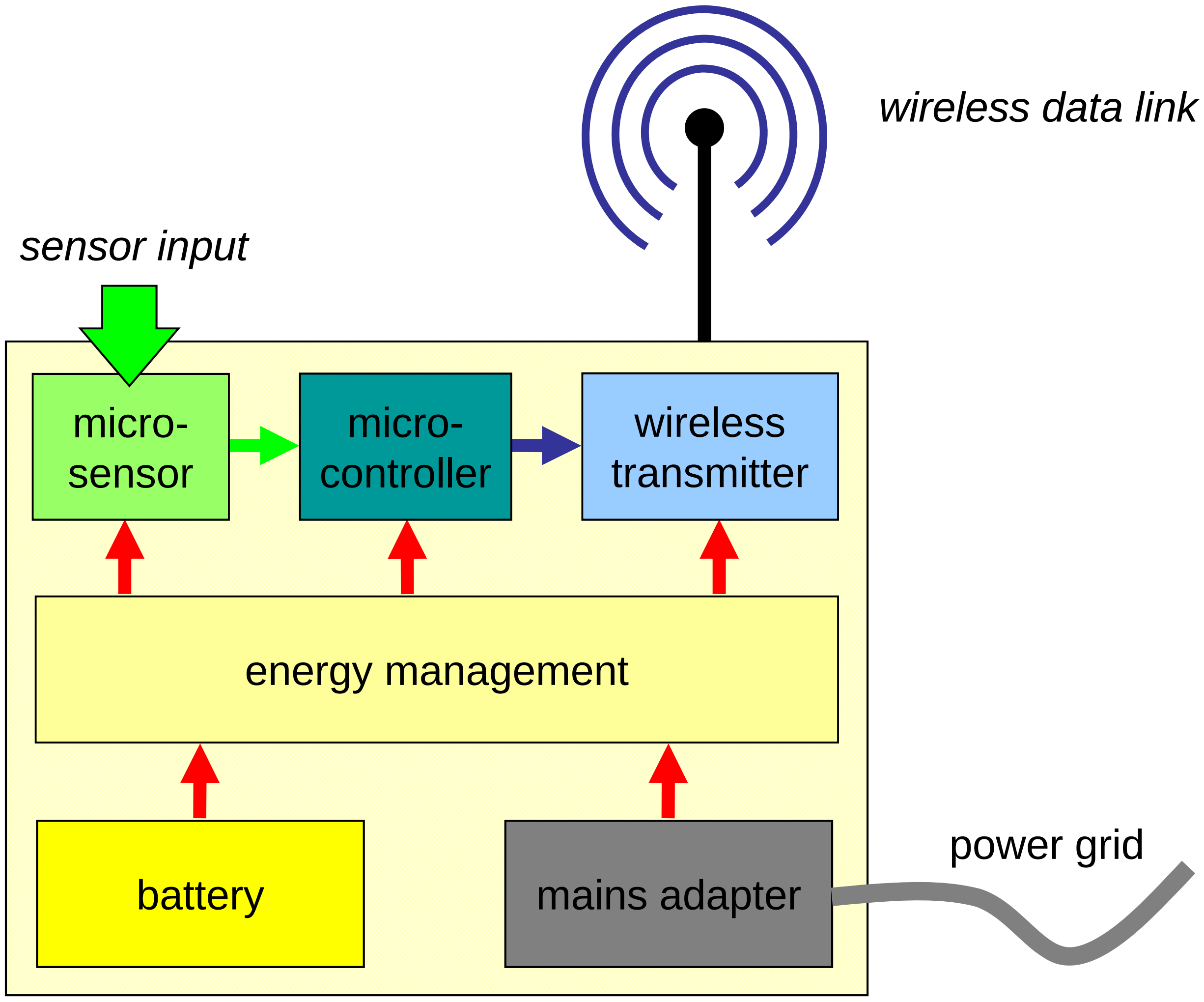

Fabrication and Transport


Automotive

… power supply ?



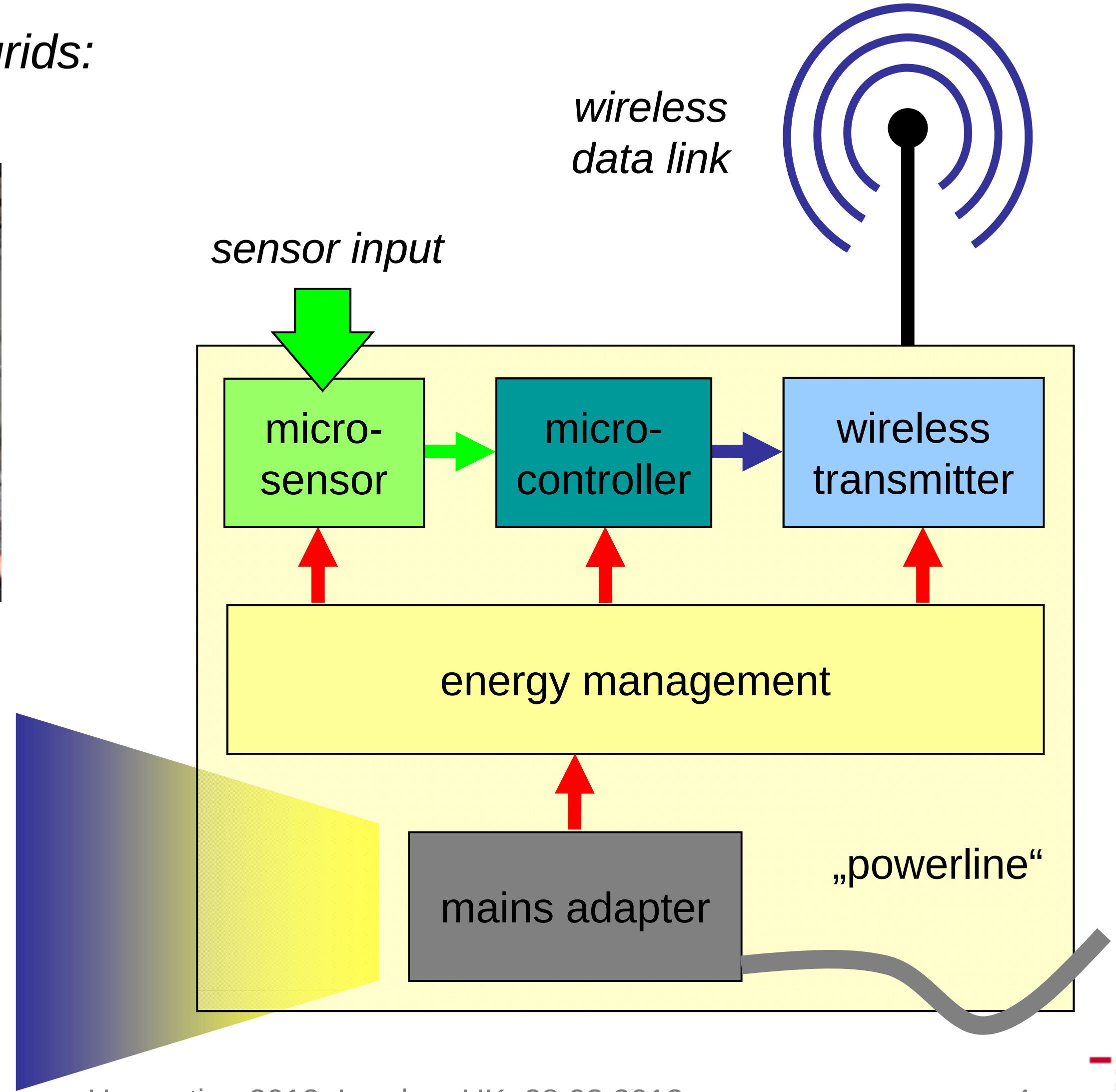
Power supply of distributed and embedded systems



Grid-based power supply

Wire length of mobile power grids:

Airbus A 380: ***530 km***

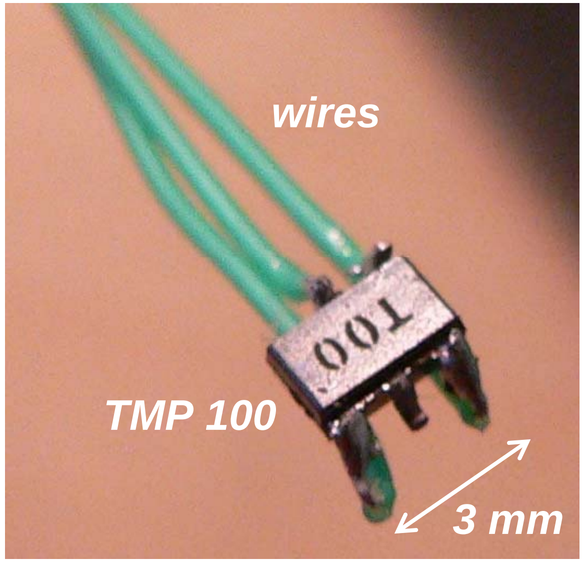


Problems

- grid deployment
- grid enlargement
- grid maintenance
- grid failure

„Grey energy“ of grid-based systems

Example : A low-power temperature sensor module,
connected through a thin power cord with **1 m wire length**



Questions

- How much “grey energy” is required to produce the connecting wires ?
- How long could we supply the sensor from this energy budget ?

Materials

- 3 x 1 m of 26 AWG (7/34) copper wire
  with PVC insulation (wall thickness: 0,010“), e.g. from Alpha Wire
- 1 digital temperature sensor, e.g. Texas Instruments TMP 100
  power consumption: 100 µA @ 3 V = 300 µW

„Grey energy“ of grid-based systems

Example: Grey energy budget (lowest case) of the connecting wires

	specific fabrication energy [MWs/kg]	density [g/cm³]	amount [kg]	fabrication energy [Ws]	fabrication energy [Wh]
copper	55,7	8,96	0,00379	211.107,5	58,6
PVC	67,5	1,25	0,00131	88.166,4	24,5
				299.273,8	**83,1**

Theoretical operational lifetime of the temperature sensor, if supplied from this grey energy budget

$$\frac{299.273\,Ws}{300\,\mu W} \approx 1 \cdot 10^{9}\ s = 31.7\ years$$

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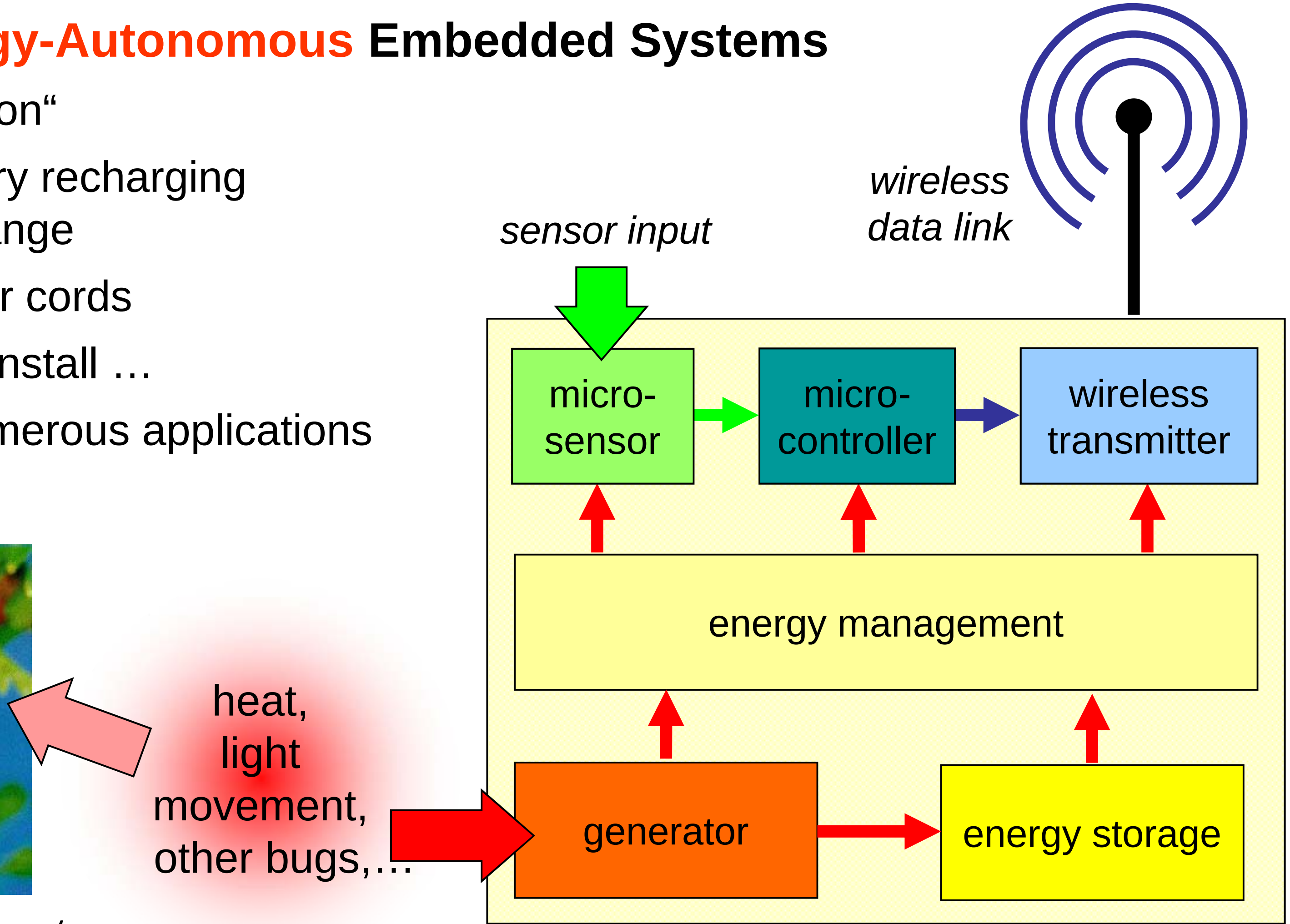
The Vision: Micro Energy Harvesting

… for Energy-Autonomous Embedded Systems

- „always on“
- no battery recharging or exchange
- no power cords
- easy to install …
- … in numerous applications

Graphosoma lineatum



Boundary conditions and requirements

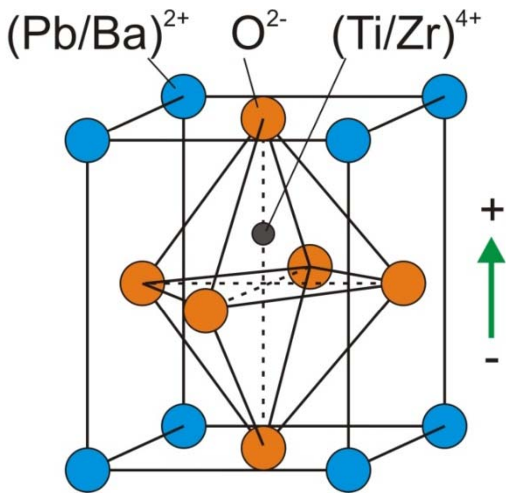
- highly variable ambient power
- low-energy and brown-out phases
- variable internal power consumption of the „system electronics" for sensing and wireless transmission

1. **Adaptation** …. to **variable** vibration frequencies, temperatures,…
2. **Appropriate energy storage concepts**
3. **How much „system electronics" do we need at all?**

(Adaptive) piezoelectric generators

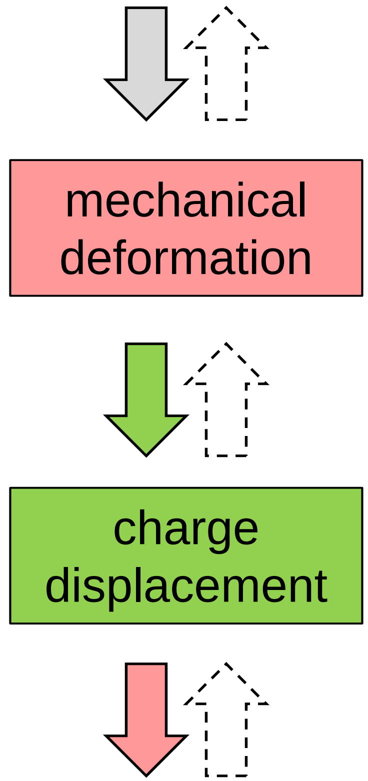
Principle: Direct piezoelectric effect

charge displacement in a nonsymmetric crystal lattice, obtained via a mechanical deformation of the piezoelectric material



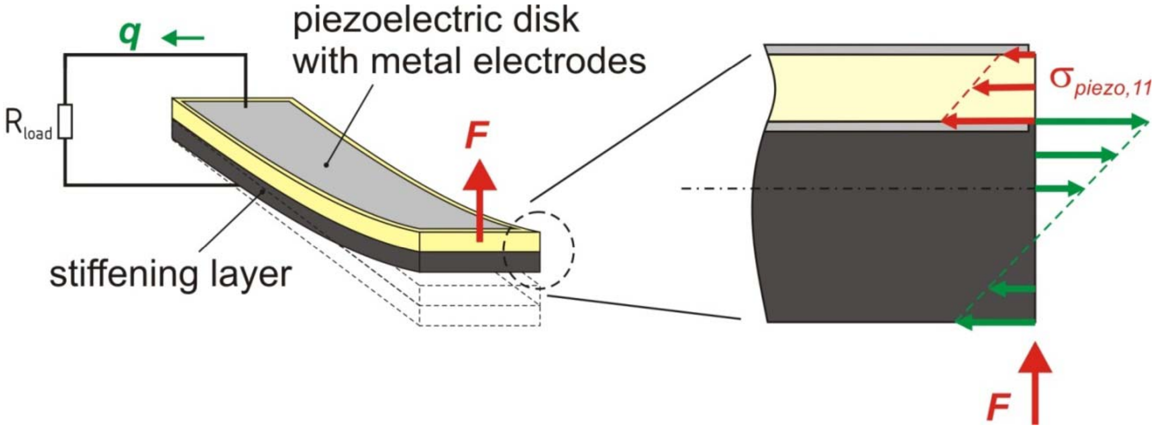
Perovskite crystal structure of standard piezoceramic material (here PbZrTi or PZT and BaZrTi)

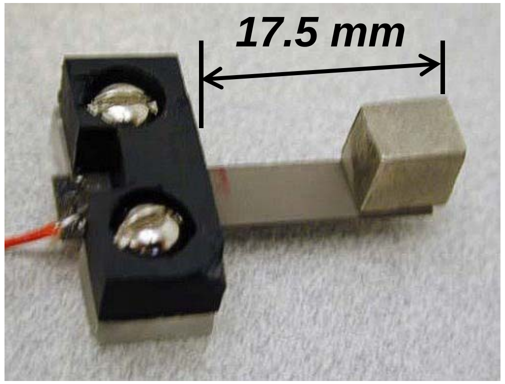
mechanical energy

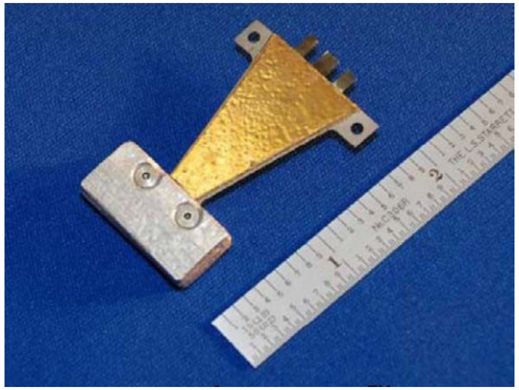


electrical energy

Examples of beam-type piezo generators







P_{max} = 0.08 mW @ 0.23 g and 120 Hz

S. Roundy et al.,
UC Berkeley, ***2004***

P = 0.45 mW @ 1g and 60 Hz

„Joule Thief" © AdaptivEnergy, before ***2009***

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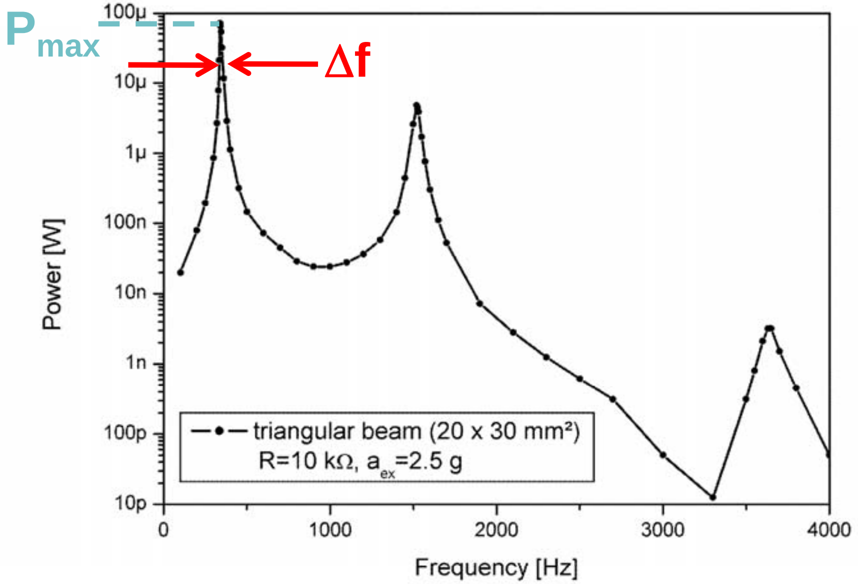
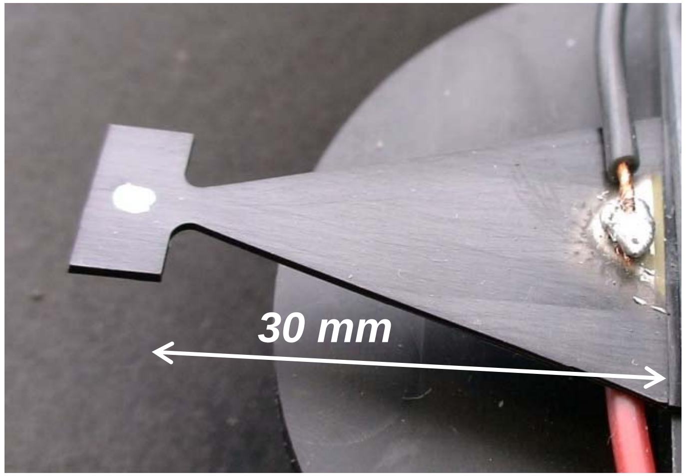
Typical (non-adaptive) power output

spectral power output (no tip mass)





F. Goldschmidtböing, P. Woias, *JMM* 18, **2008**, 104013

Characteristics of resonant operation

- highest output power P_{max} at resonance only
- small power bandwidth Δf at high conversion efficiency
- **not adapted to variable input frequencies**

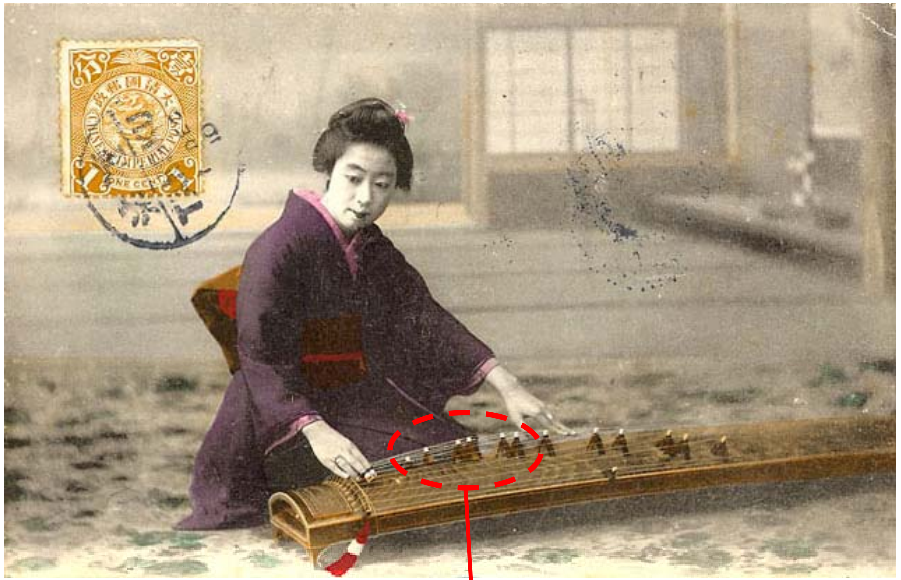
Frequency-tunable piezo generators ?

Principle and inspiration

- **continuous re-tuning** of a mechanical oscillator
- similar to the tuning of a musical string instrument

robot violinist *© Toyota, 2010*

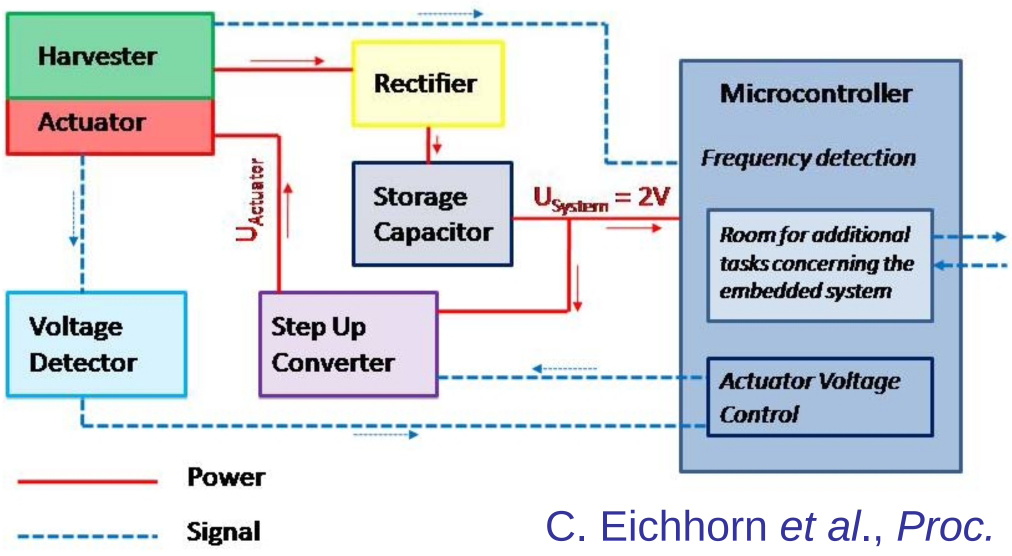
koto player, (postcard, around 1900)



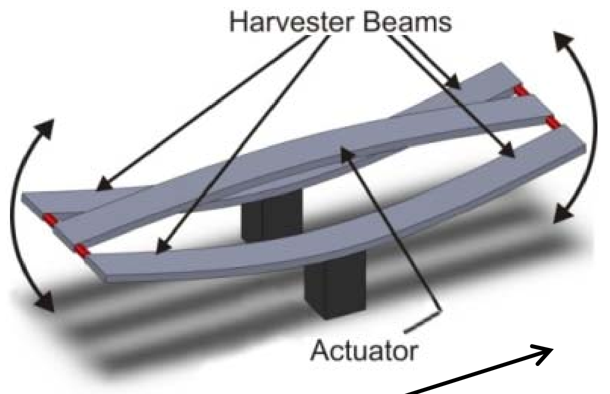
Frequency tuning via change of …

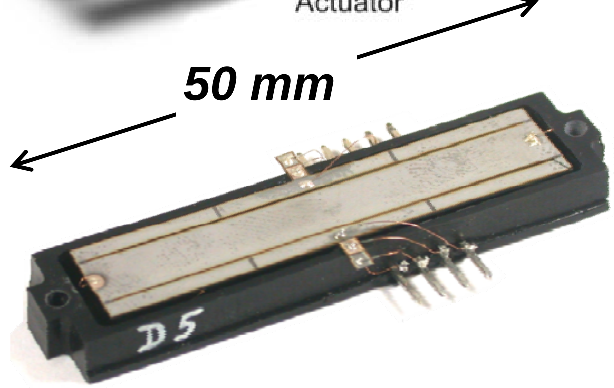
- mechanical stress
- size (length)
- seismic mass

Frequency-tunable generator system



C. Eichhorn *et al*., *Proc. PowerMEMS* ***2010***, Leuven, Belgium



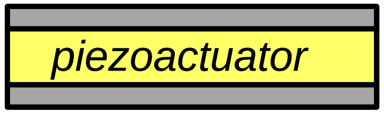


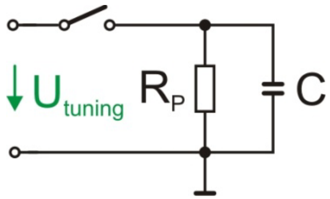
Fundamental questions

- How often will a „re-tuning“ be required ?
- Will the tuning operation itself use up all the harvested power ?
- If so, how to avoid this ?

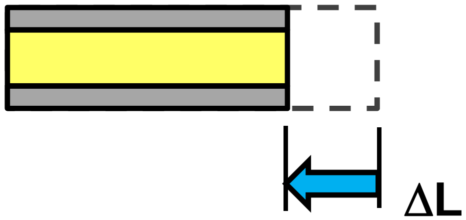
Quasi-static tuning of piezoactuators

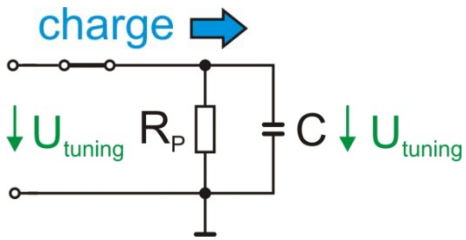
1. untuned





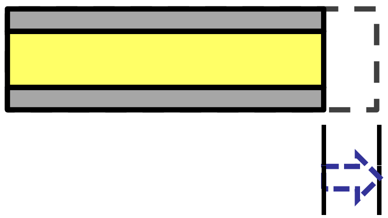
2. fast tuning

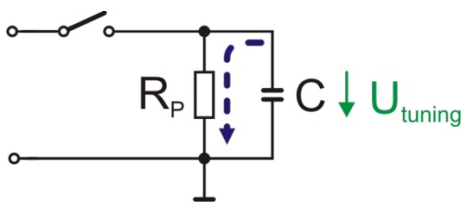




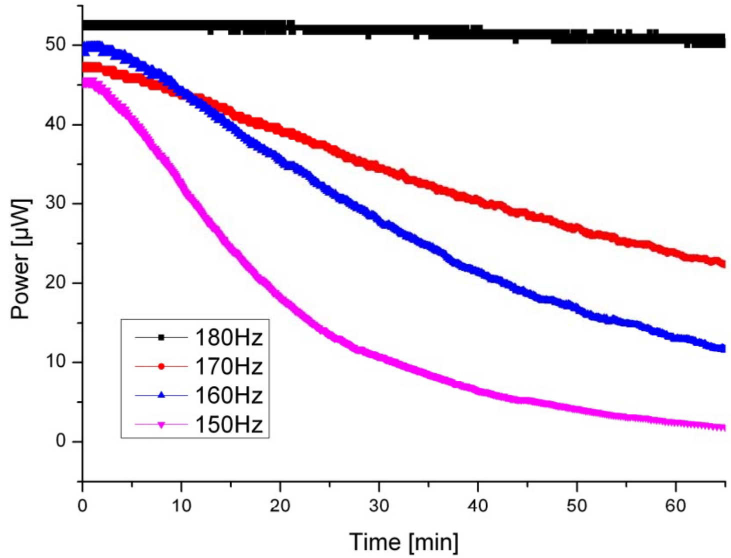
3. **slow relaxation**

slow discharge





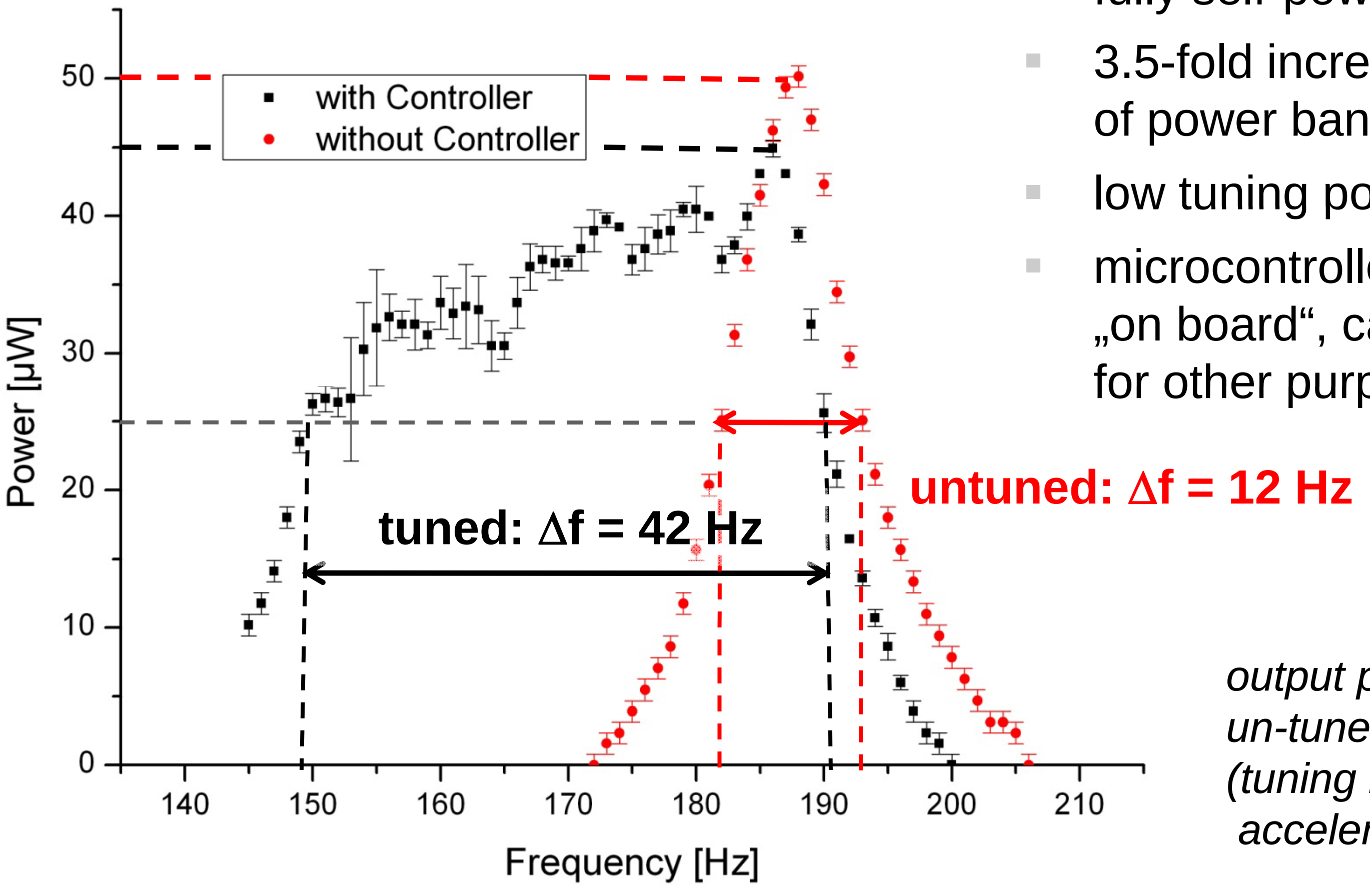
effect of relaxation on the harvested power vs. time



Advantages

- piezoactuator stores charge and position
- only slow relaxation due to leakage currents

System characteristics

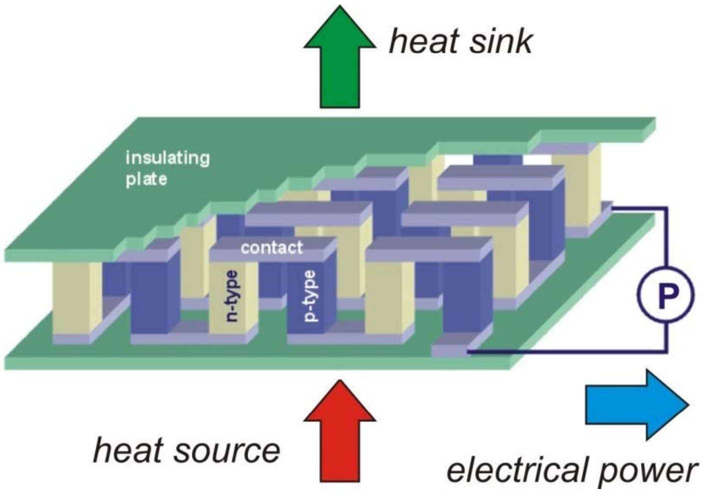


- fully self-powered system
- 3.5-fold increase of power bandwidth Δf
- low tuning power (5…25 µW)
- microcontroller already „on board“, can be used for other purposes as well

output power in tuned and un-tuned operation (tuning intervals: 20 s, acceleration: 0.6 G)

C. Eichhorn *et al.*, *Proc. PowerMEMS **2010***, Leuven, Belgium

Thermoelectric generators (TEGs)



Seebeck voltage

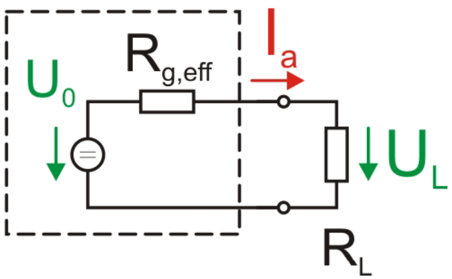
$$\Delta U = n \cdot \alpha \cdot \Delta T$$

electric output power

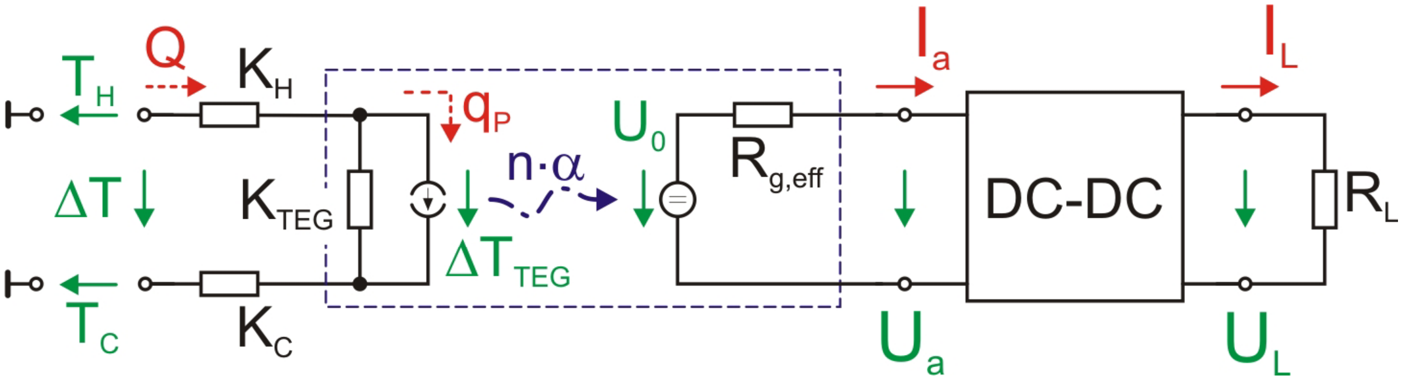
$$P_{el} = \frac{n^2 \cdot \alpha^2 \cdot R_L}{\left(R_{g,eff} + R_L\right)^2} \cdot \Delta T^2$$

Properties

- no moving parts
- DC-like currents, however…
- **polarity changes** with
  the direction of the temperature field
- low to fair output voltages (100 mV … V)



Thermal and electrical interfaces



thermal interface — *TEG* — *electrical interface*

$$P_{el} = \left(\frac{K_{TEG}}{K_{TEG} + K_H + K_C} \right)^2 \cdot (n \cdot \alpha \cdot \Delta T)^2 \cdot \frac{R_L}{(R_{g,eff} + R_L)^2} \cdot \eta_{DC-DC} = E \cdot \Delta T^2$$

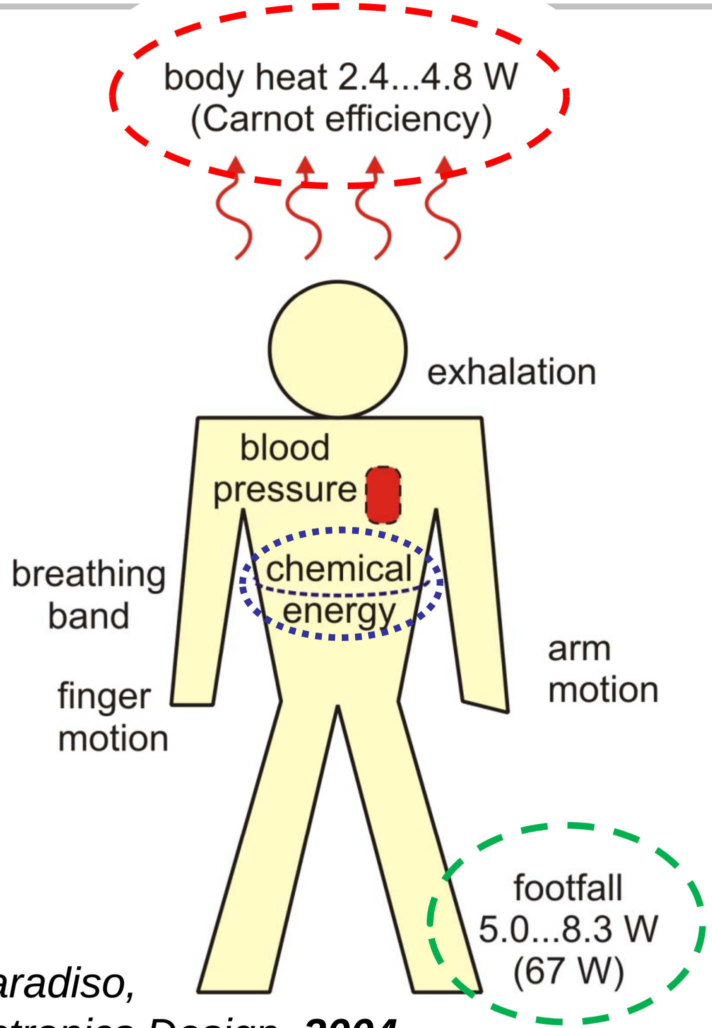
peltier heat flow q_P neglected

DC-DC-converter efficiency

Medical and sports

force, movement, flow, chemical energy, heat

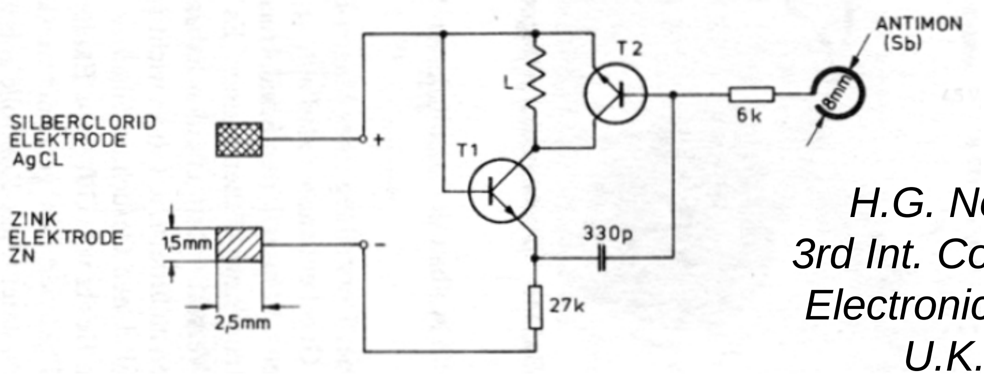
- stress-controlled prostheses
- condition monitoring (downfall, faint,…)
- **autonomous sensors and implants**
- **autonomous sports equipment**
- …



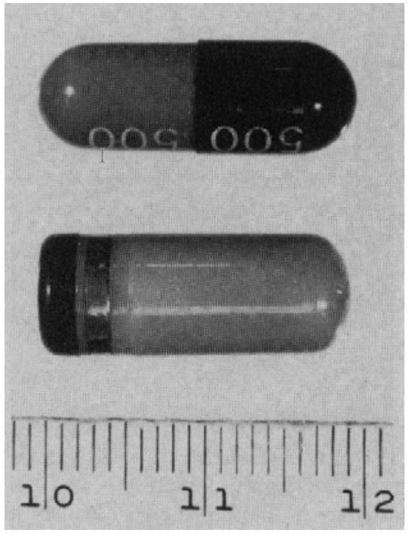
T. Starner, J. Paradiso,
Low Power Electronics Design, ***2004***

Biomedical embedded systems

An early example from 1961:
The „Heidelberg Capsule"



*H.G. Noeller, Proc. 3rd Int. Conf. on Med. Electronics, **London**, U.K., **1961**, 111.*



an energy-autonomous embedded system with „almost zero" electronics

- continuous wireless pH measurement in the patient's stomach
- energy harvesting via a Zn-AgCl battery driven by the stomach's acid
- two-transistor radio
- frequency modulation (1.8 … 2 MHz) via the voltage of an Sb pH probe
- power consumption: **appr. 15 µW at 1.5 V (still low power today)**

Autonomous sensors in tunnel buildings

IMTEK

- environmental monitoring
  (temperatur, humidity, ventilation, …)
- detection of fire, explosions, earthquake, …
- monitoring of the building‘s structural health

AISIS
Automatisierte Informationsgewinnung und Schutz kritischer Infrastruktur im Katastrophenfall

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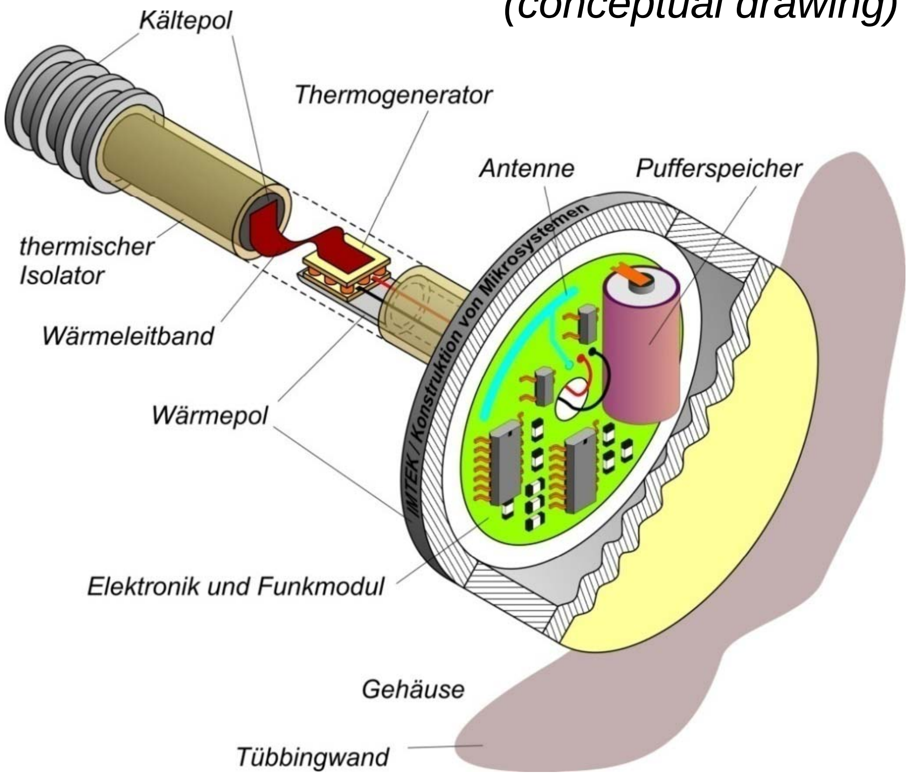
Geothermal energy harvesting ?

Concept

- thermal probe embedded in the tunnel wall
- thermoelectric energy harvesting between the (cold ?) tunnel bed and the (warmer ?) wall surface

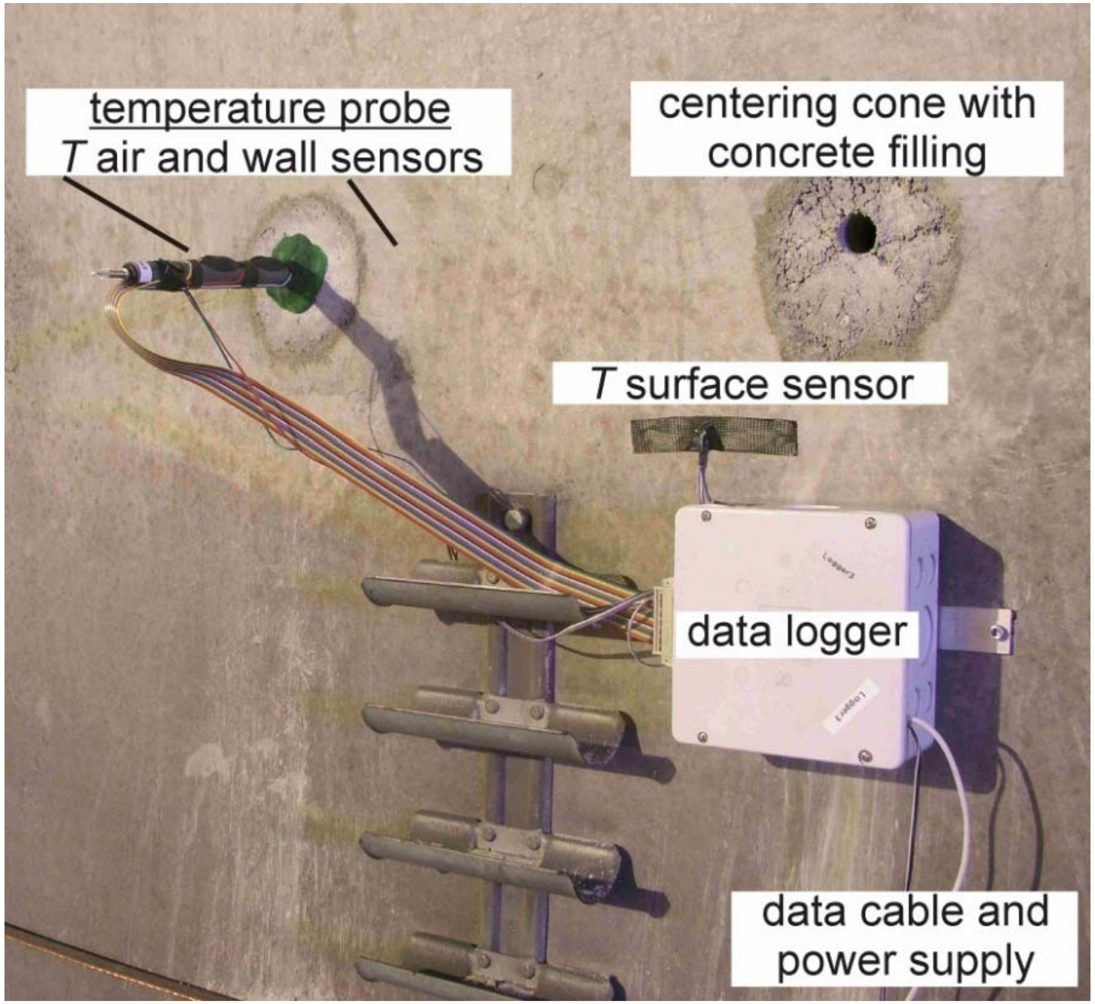
Thermal probe with integrated thermogenerator (conceptual drawing)



But first: measurement of the available ΔT

- temperature profile in the wall
- surface and air temperature
- wind speed

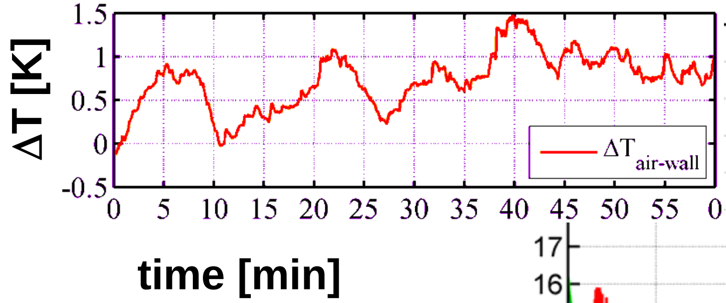
Measurement site in a road tunnel

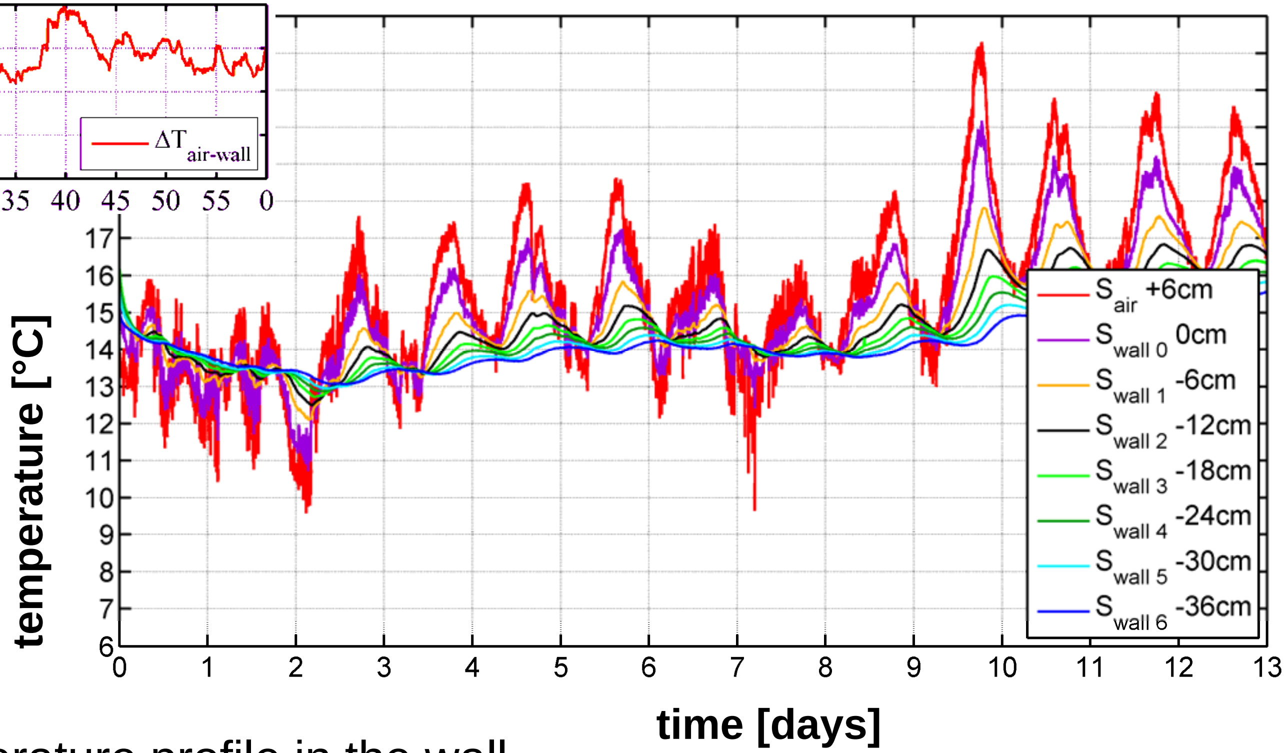


temperature measurement set-up with bore-hole probe, surface and air probe and data logger,

Hugenwald tunnel, Freiburg, Germany

Road tunnel: field measurements



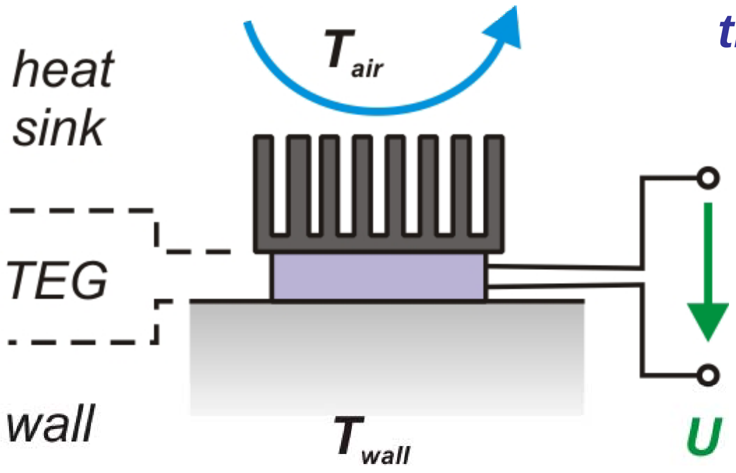


Results

- predictible temperature profile in the wall
- highy dynamic air temperature
- influence of weather and traffic density
- **small temperature gradients (1…2 K)**

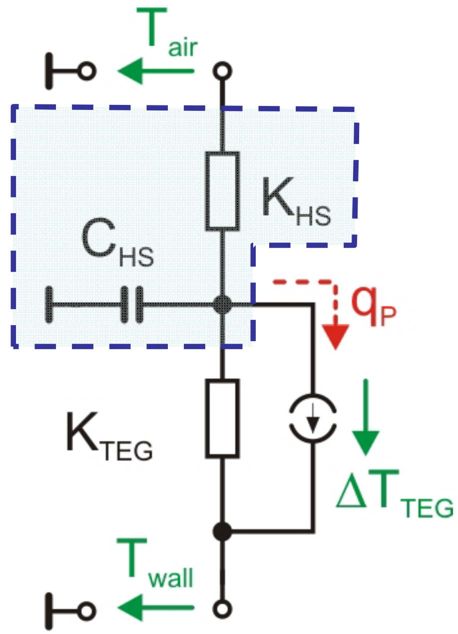
Hugenwald tunnel, Freiburg, Gemany

Thermal time constants



thermal time constant τ:

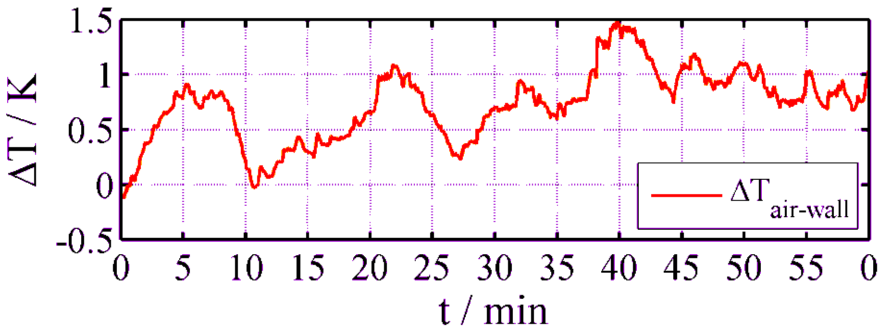
$$\tau = K_{HS} \cdot C_{HS}$$

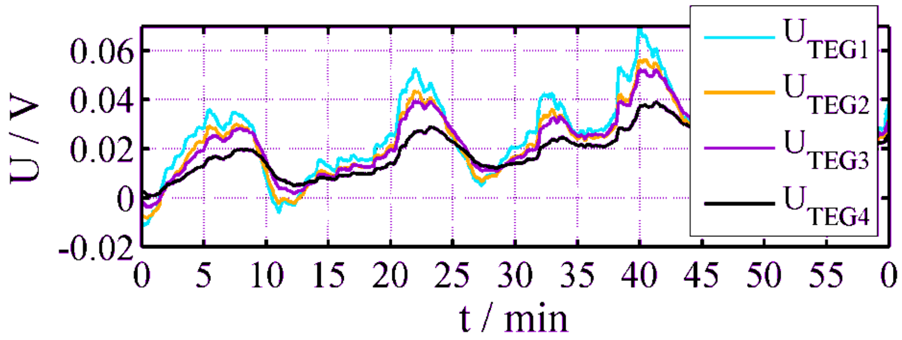


$$P_{el} = P_{el}(t) = E \cdot [\Delta T(t)]^2$$

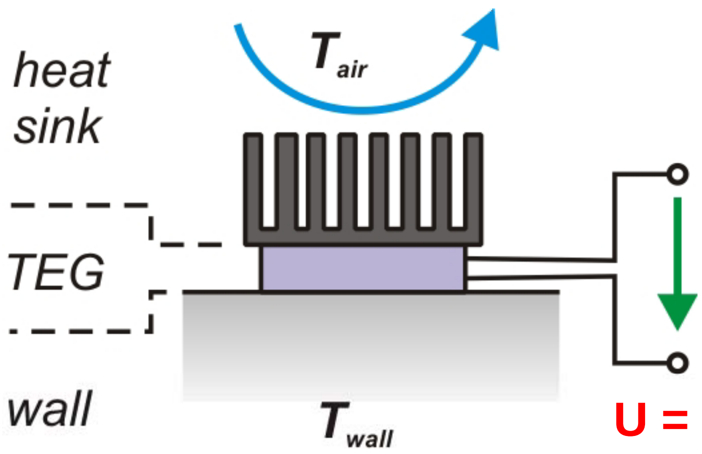
temporal behaviour *of ΔT² defines the output power*

Energy harvesting from low ΔT in a tunnel





$$\tau = K_{HS} \cdot C_{HS}$$

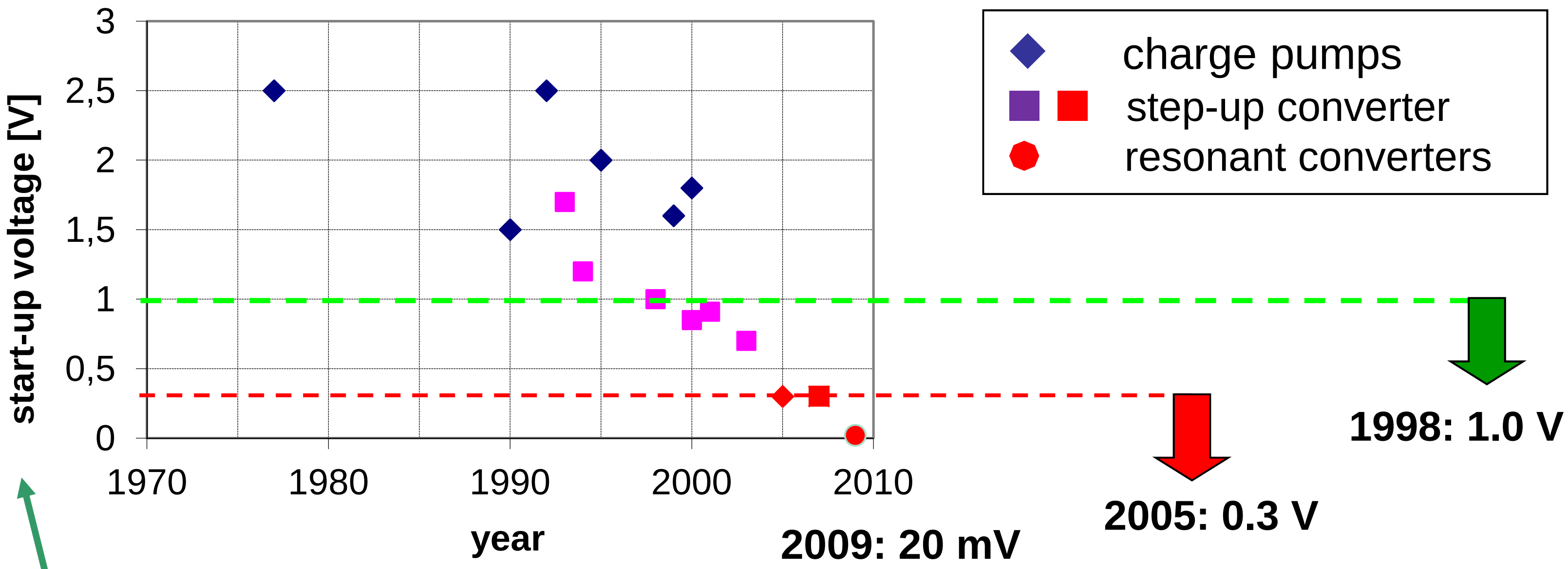


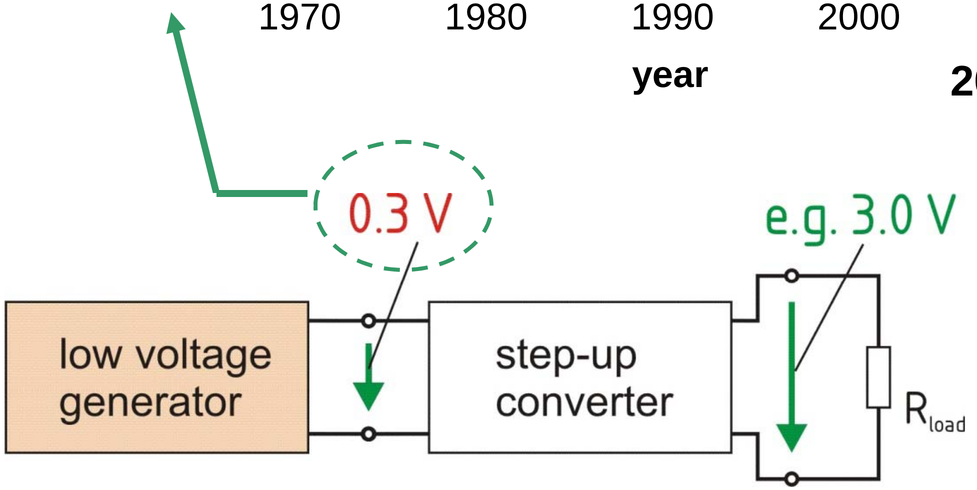
U = 20…60 mV

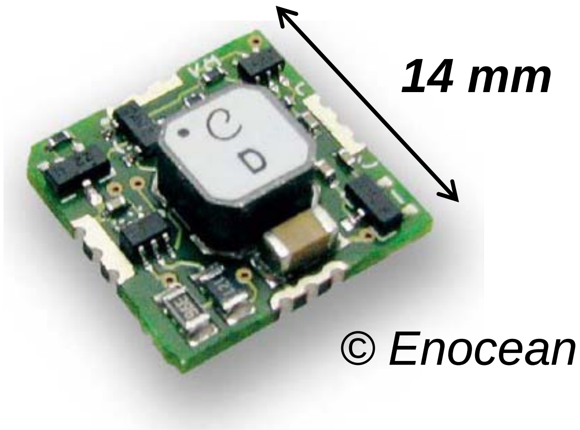
TEG	K_{HS} [K/W]	τ [s]	E [J/day]
1	8.3	239	1.74
2	8.5	374	1.32
3	2.8	402	0.87
4	4.9	416	0.68

A. Moser et al., *Proc. PowerMEMS **2010***, Leuven, Belgium, 431-434.

Commercial low voltage (LV) step-up converter ICs







© Enocean

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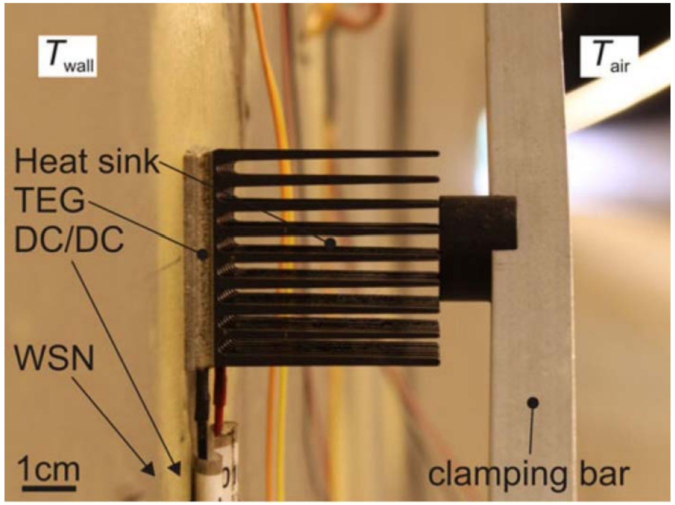
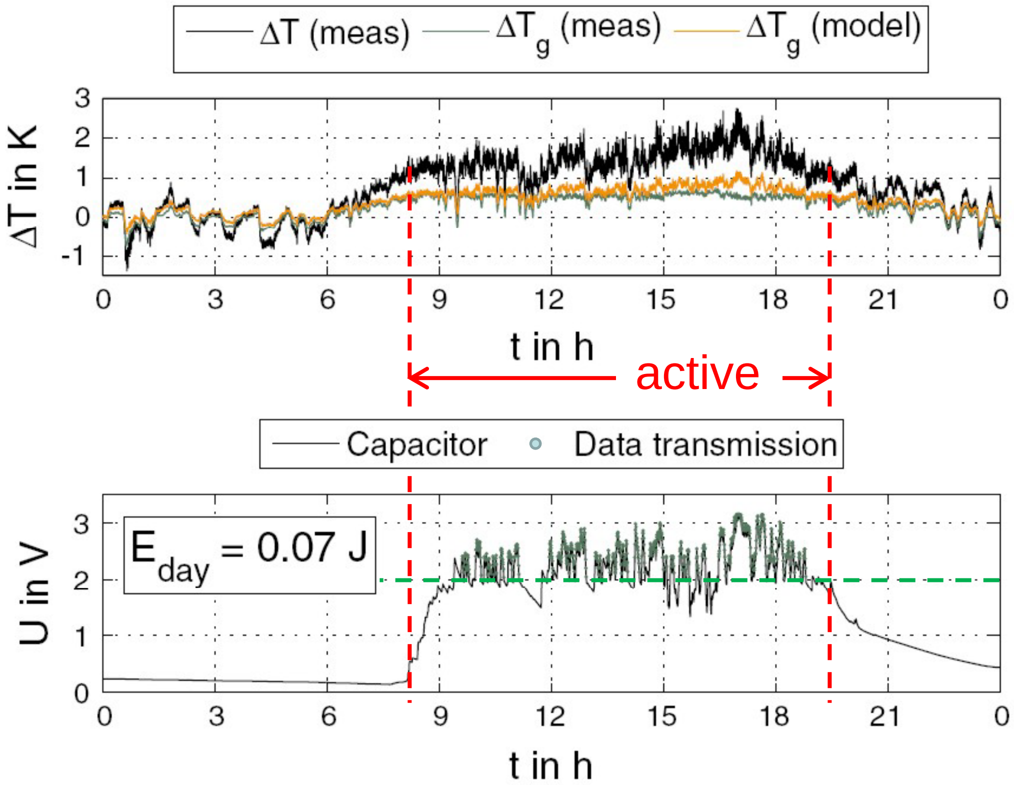
Energy harvesting from low ΔT in a tunnel



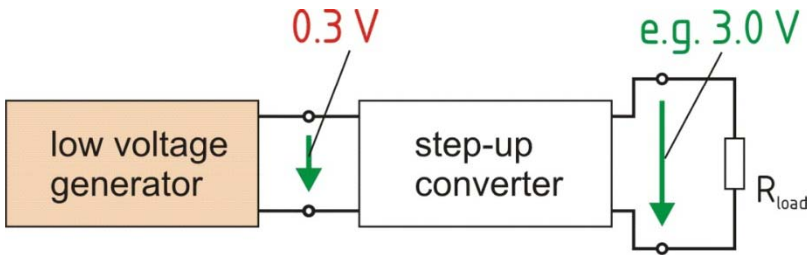


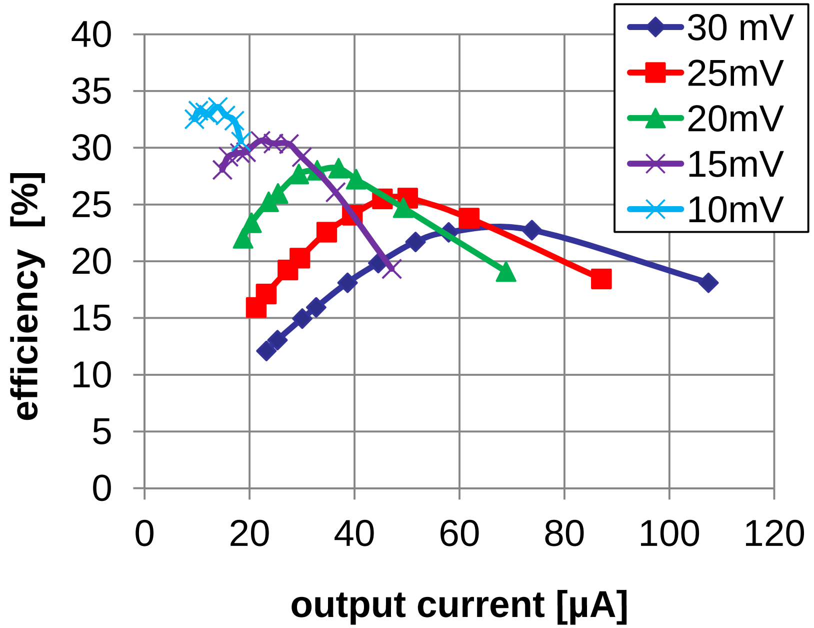
Results

- harvesting of 0.07 J/day,
  from ΔT ≥1.2 K at the TEG over appr. 20 hrs
- 415 energy-autonomous radio telegrams per day
  (200 µJ per telegram, average interval: 3.5 min)

A. Moser et al., *Journal of Electronic Materials* ***2012***, in print.

Our own LV step-up converter (pat. pending)





- start-up voltage: 10 mV
- power-down voltage: 6 mV
- efficiency: 22…33 %
- transistor count: <10

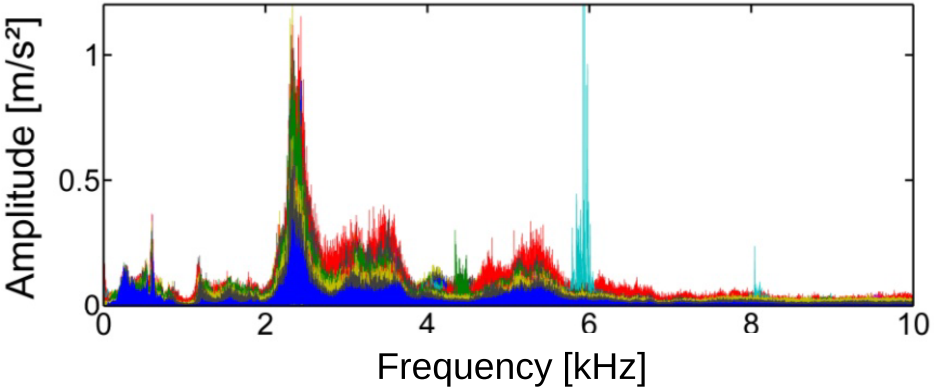
Harvesting from vibrations at the rail

Application: train monitoring

- detection of train passage
- measurement of train velocity
- detection of train stops

But first: measurement of the available vibrations

- wide frequency spectrum
- different levels at different locations
- severe influence of train (passenger train, cargo train)

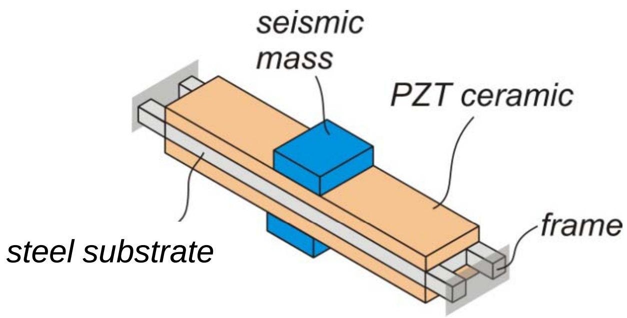


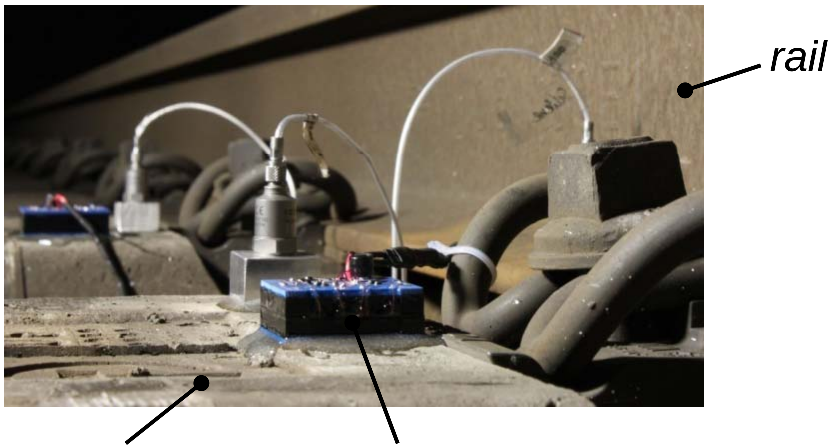
vertical acceleration spectrum from 57 trains at a modern concret rail sleeper, measured in the Arlberg tunnel, Austria

Harvesting from vibrations at the rail

Generator and power management

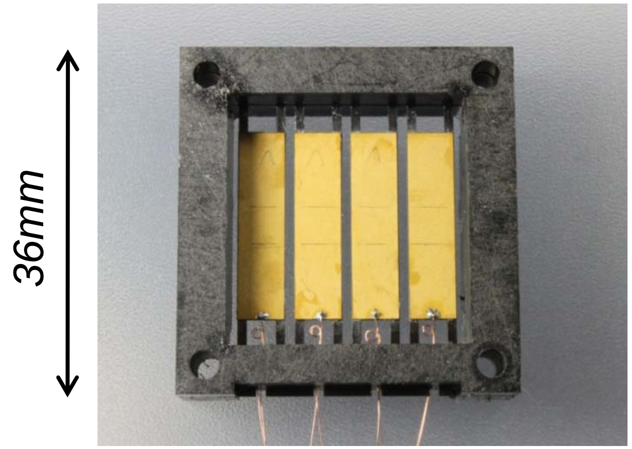
- array of four piezogenerators with different resonance frequencies
- low power start-up electronics
- 2010: on-site test under real conditions (Loetschberg basis tunnel, Switzerland)





rail sleeper

piezogenerator array with power electronics



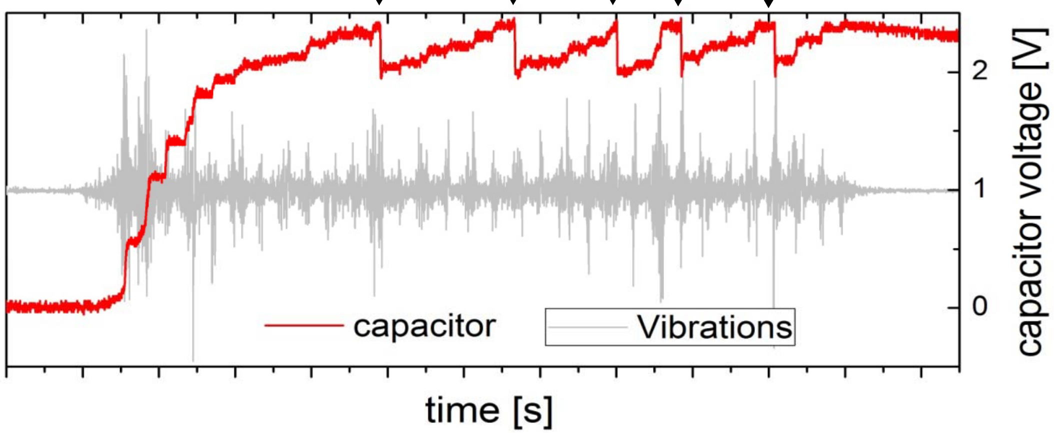
piezogenerator array (without seismic masses)

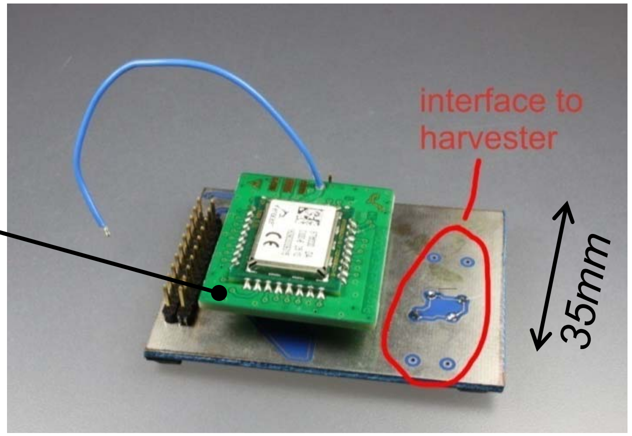
Harvesting from vibrations at the rail

System integration and test

- integration of harvester, storage capacitor, power management and wireless module (Enocean STM 300)
- test on a shaker with real-life vibration pattern

transmission of radio telegrams

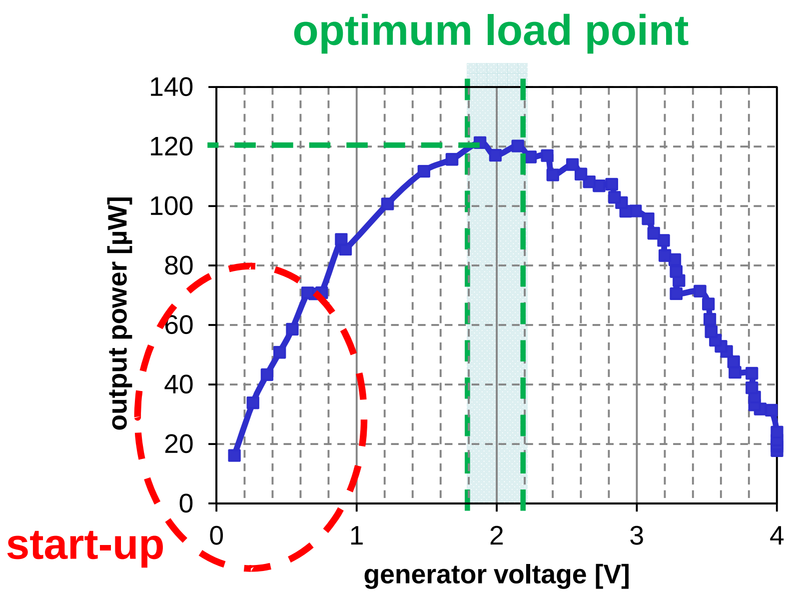


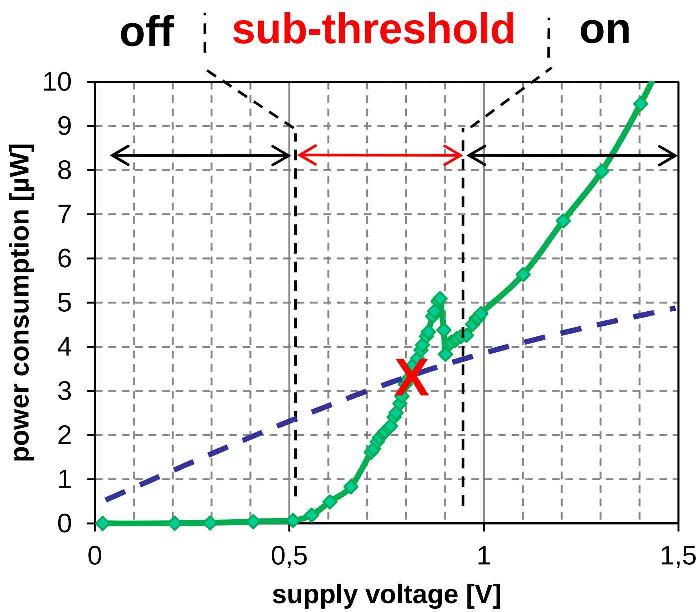


energy-autonomous train passage detector

system operation during the simulated passage of a cargo train in the Loetschberg basis tunnel, Switzerland

Problems with wake-up from zero-power



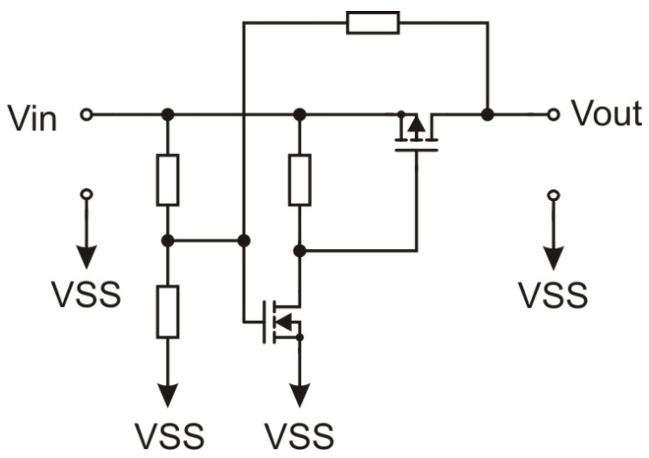


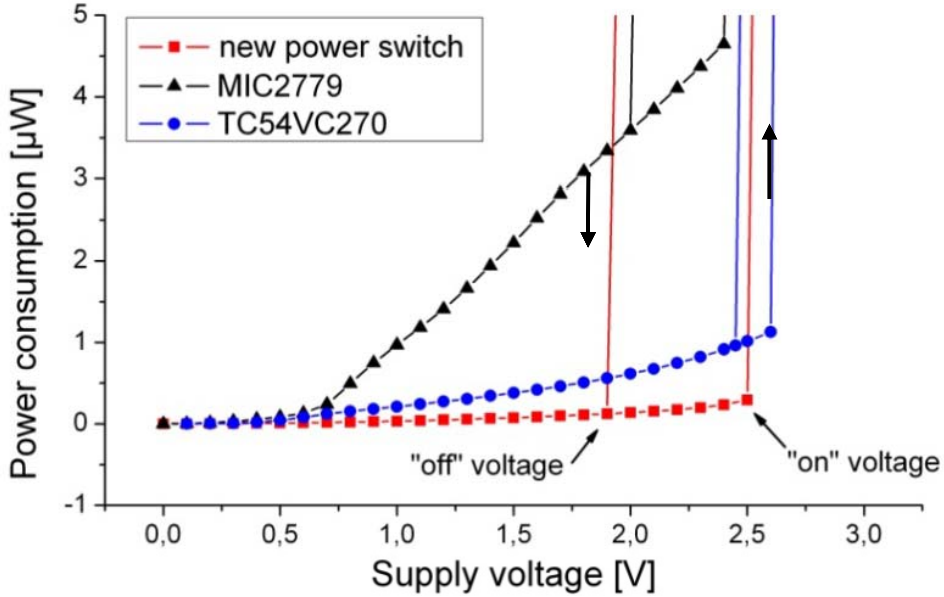
Result

- Most CMOS electronics draws sub-threshold power during start-up
- Empty storage capacitors draw large charge and leakage currents
- Generator delivers only small power during start-up

  ➡ **Danger of deadlock situations or heavily delayed start-up**
- **solution:** controlled wake-up and power-down

Low-voltage power switch (pat. pending)





Characteristics

- simple design: 2 transistors
- low voltage operation: from 0 V
- ultra low power consumption: 300 nW

Summary and conclusions

Micro Energy Harvesting ist a key enabling technology for the realization of **energy-autonomous embedded systems**. (mothing more, but also nothing less)

Striking advantages of this new technology are:

- a simple installation of the system nodes
- no maintenance at all
- operation at remote and hardly accessible locations, and
- an extremely broad application spectrum

Thank you very much for your attention !

… with a large acknowledgement to my co-workers:

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