A Sub-microwatt Long-term Monitoring Sensor

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SMART BUILDING

1. Sensors in a building monitor the building's movement in response to strong winds or earthquake tremors.
2. Shock absorbers (hydraulic dampers) can then be made to stiffen or relax and heavy weights (mass dampers) can be moved to reduce oscillations in strong winds, or minimise damage in the event of an earthquake.
3. Buildings that detect an earthquake tremor could even warn other buildings nearby of the approach of a shockwave, so they could sound an alarm and prepare themselves accordingly.

SMART BRIDGE

1. Wireless sensors mounted on the bridge monitor vibrations, displacement and temperature. This information then "hops" across the network of sensor nodes to a central computer for analysis.
2. If a problem is detected, such as a loose bolt or cable, or the beginning of a crack, a warning can be sent by SMS.

SMART TUNNEL

1. Wireless sensors mounted on the walls of a tunnel monitor displacement, temperature and humidity. This information then "hops" across the network of sensor nodes to a central computer for analysis.
2. If a problem with the tunnel lining is detected, appropriate maintenance can be carried out. In future, a smart tunnel could even use robots to perform some maintenance tasks automatically.

Basics of Usage Monitoring

Health monitoring:

The process of identifying the presence and quantifying the extent of damage in a system based on information extracted from the measured system response.

Usage monitoring:

The continuous process of acquiring operational loading data from a structure or system.

C R. FARRAR, N J. LIEVEN, "Damage prognosis: the future of structural health monitoring", Phil. Trans. R. Soc. A* **(2007)** *365*

***Los Alamos National Laboratory**

Damage Prognosis

Usage monitoring (UM)

+

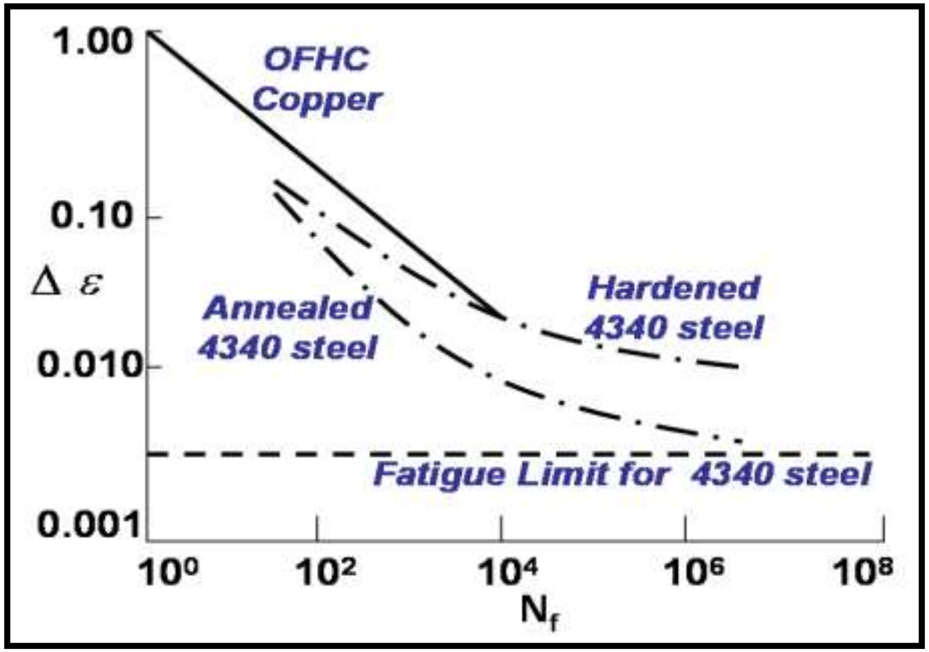
Health monitoring (SHM)

Damage prognosis attempts to forecast system performance by:

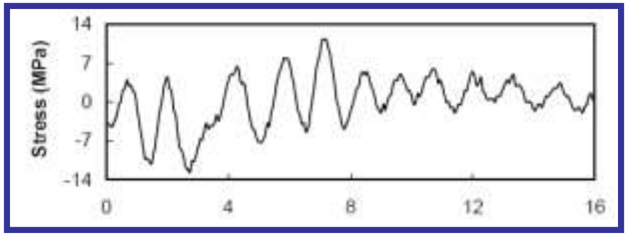
- **Measuring the current state of the system (SHM)**
- **Estimating the loading environments for that system (UM)**
- **Predicting the remaining useful life of the system.**

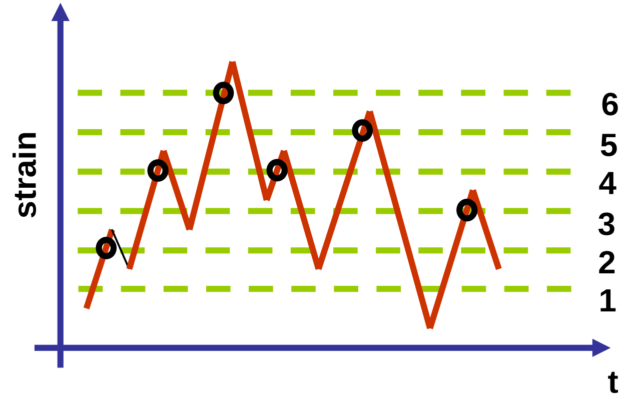
C R. FARRAR, N J. LIEVEN, "Damage prognosis: the future of structural health monitoring", Phil. Trans. R. Soc. A* ***(2007)*** *365*
****Los Alamos National Laboratory***

Fatigue prediction: Miner's Rule



S-N curve





n_i: Number of times the strain level exceeded level i

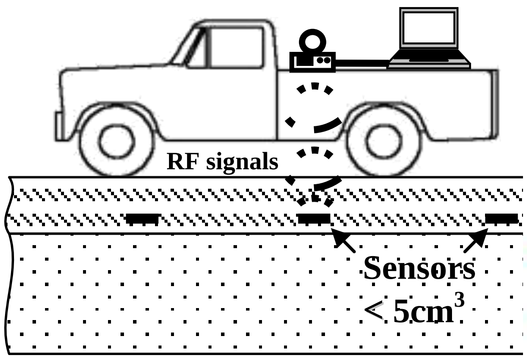
N_i : Number for strain level i obtained from S-N curve.

Miner's rule:

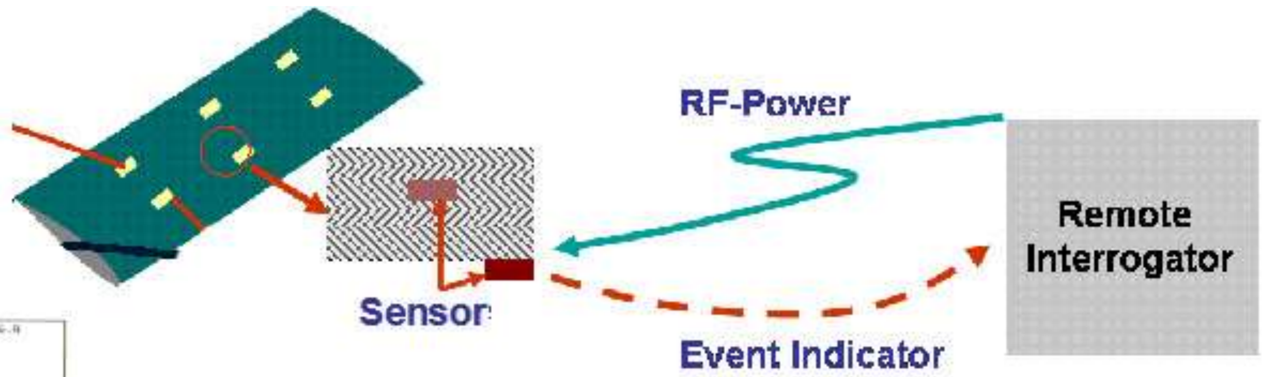
$$\boxed{\sum_{i=1}^{m} \frac{n_i}{N_i} = 1}$$

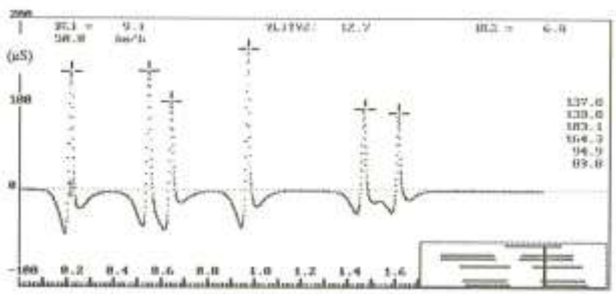
Level selection and Counting

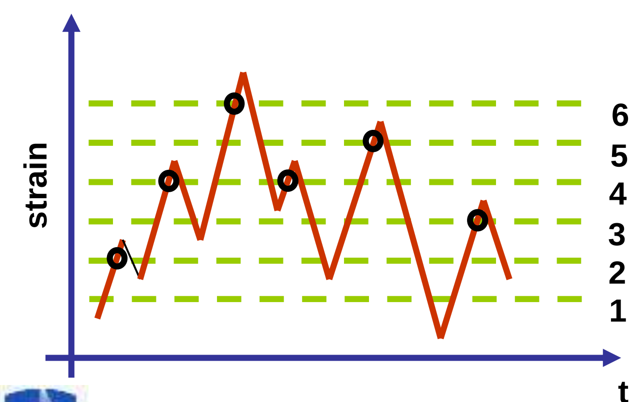
Envisioned monitoring system

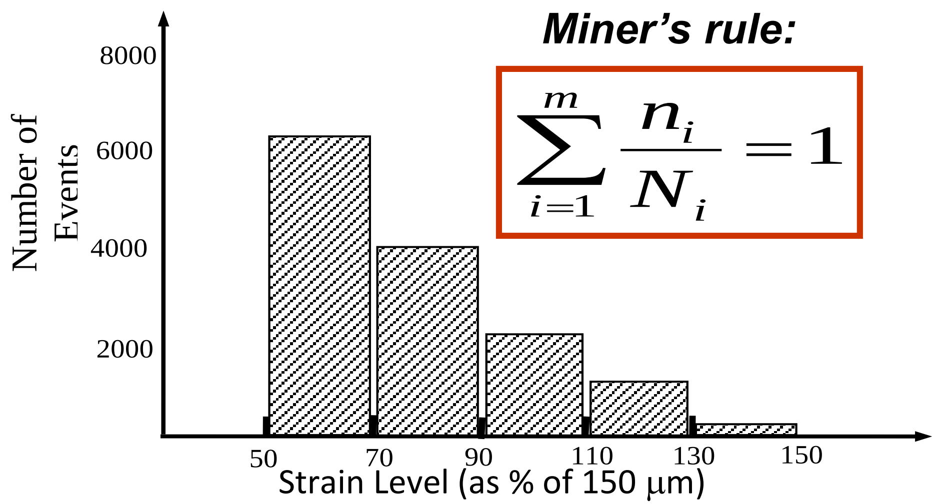


Pavement









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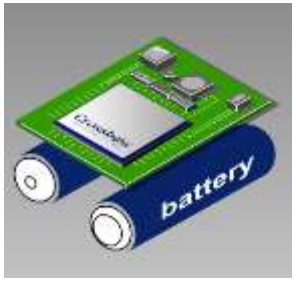
How to monitor events ?

Monitoring systems are expensive, bulky and require a continuous source of power.

www.hbm.com

Electronic powering is one of the major obstacle !

Yang Wang, Kenneth Loh, Jerome Lynch and Kincho Law, University of Michigan



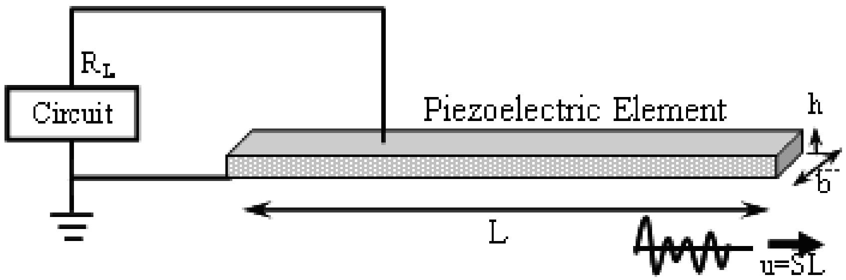
Strain-gauges with implanted batteries are impractical solution

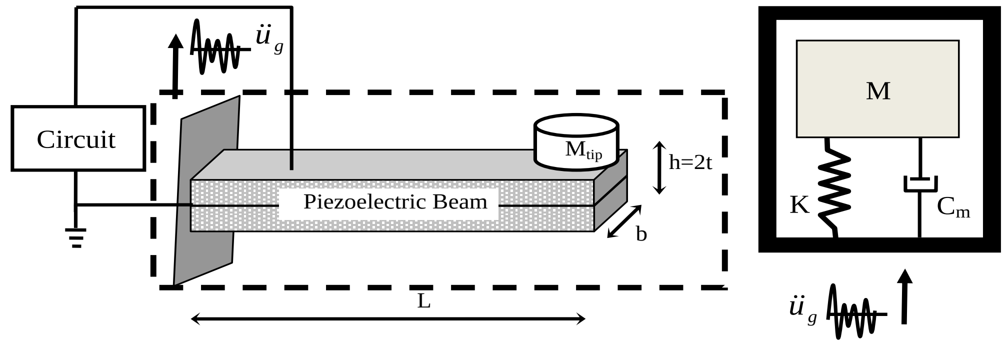
Solution: Self-powered sensing

Harvest computing power from the signal being sensed.

Piezoelectric sensors: Modeling

Two energy harvesting modalities





$$\begin{cases} Ku - \Theta v = F \\ \Theta \dot{u} + C\dot{v} = I \end{cases}$$

$$K = \frac{Y^E hb}{L}$$

$$\Theta = Y^E d_{31} b$$

$$C = \varepsilon \left(\frac{bL}{h} \right)$$

$$\begin{cases} M\ddot{u} + C_m \dot{u} + Ku - \Theta v = -M\ddot{u}_g \\ \Theta \dot{u} + C\dot{v} = I \end{cases}$$

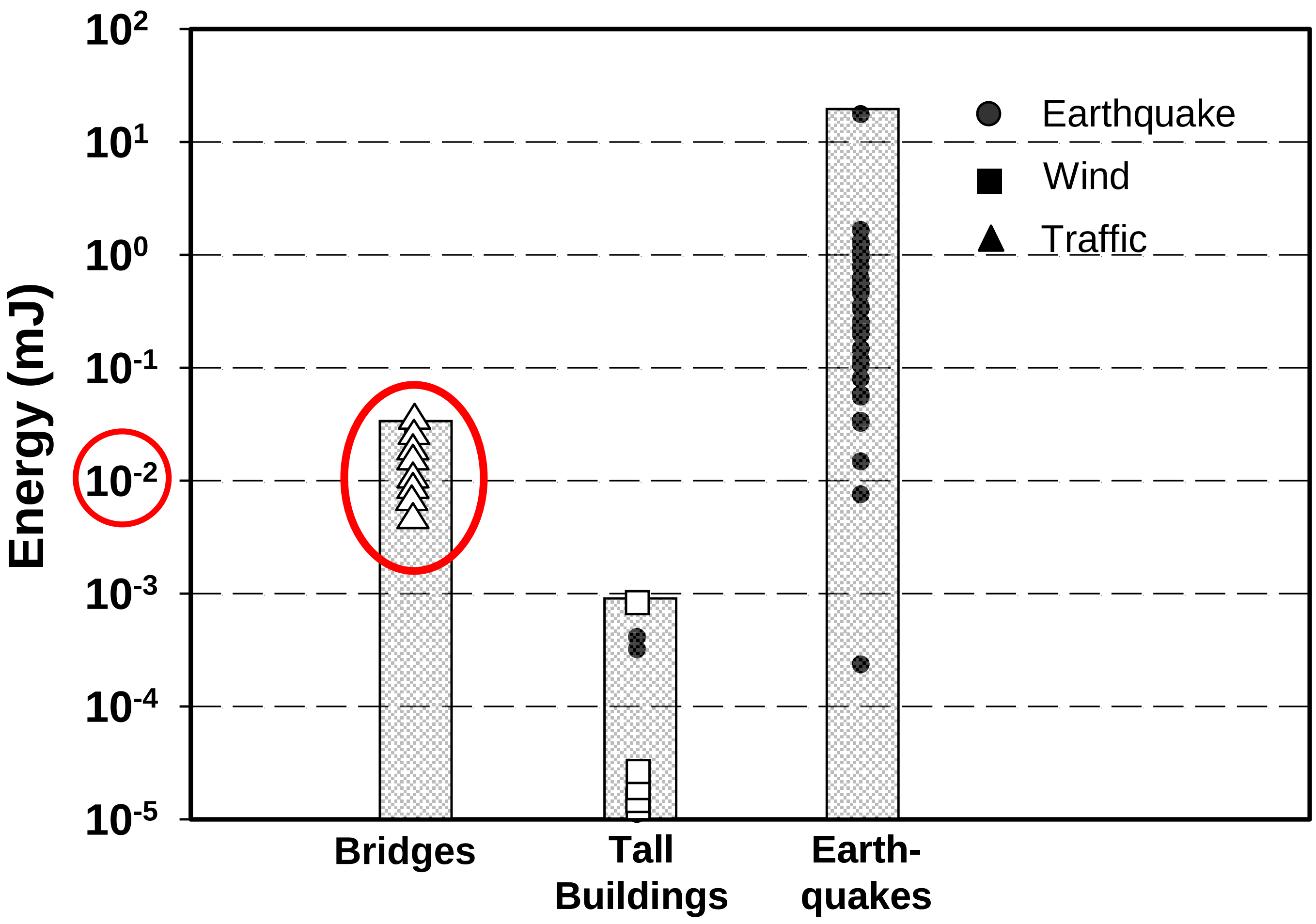
$$M = M_{tip} + \overline{m} L \left(\frac{3\pi - 8}{2\pi} \right)$$

$$K = \frac{Y^E I \pi^4}{32 L^3}$$

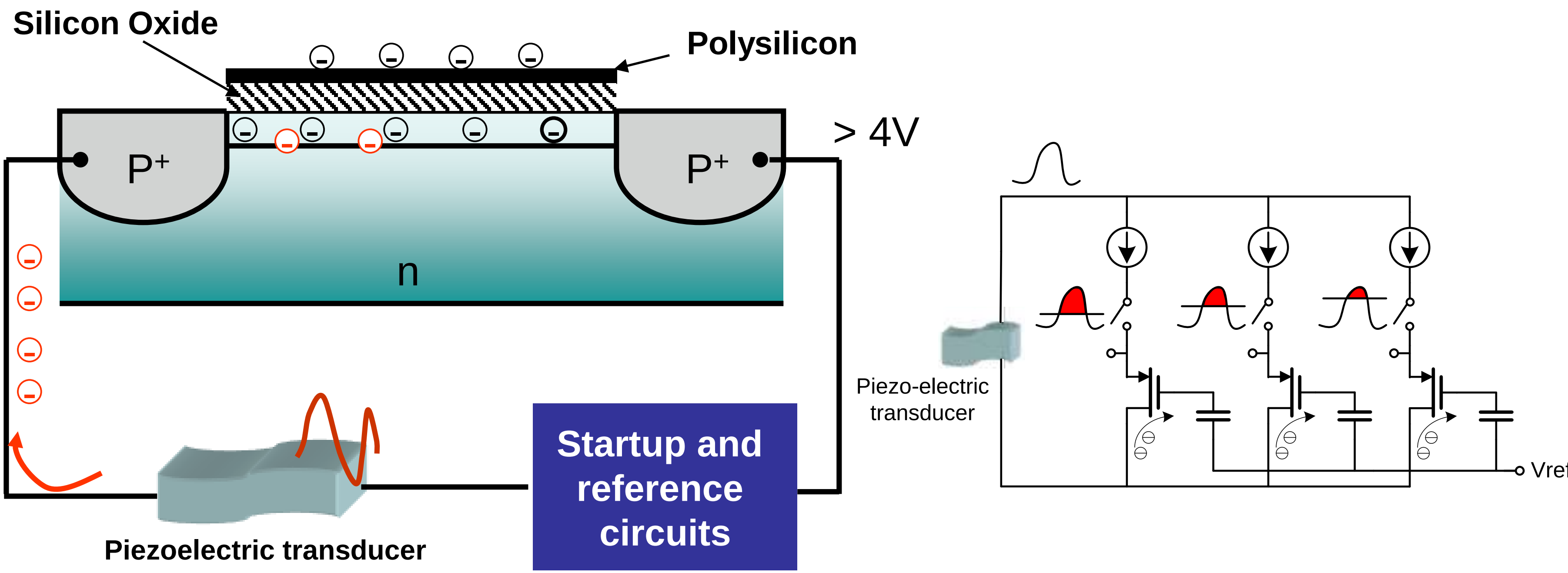
$$\Theta = \frac{Y^E d_{31} b t \pi}{2L}$$

$$C = 2\varepsilon \left(\frac{bL}{t} \right)$$

Transferred energy - Conversion efficiency



Principle of operation

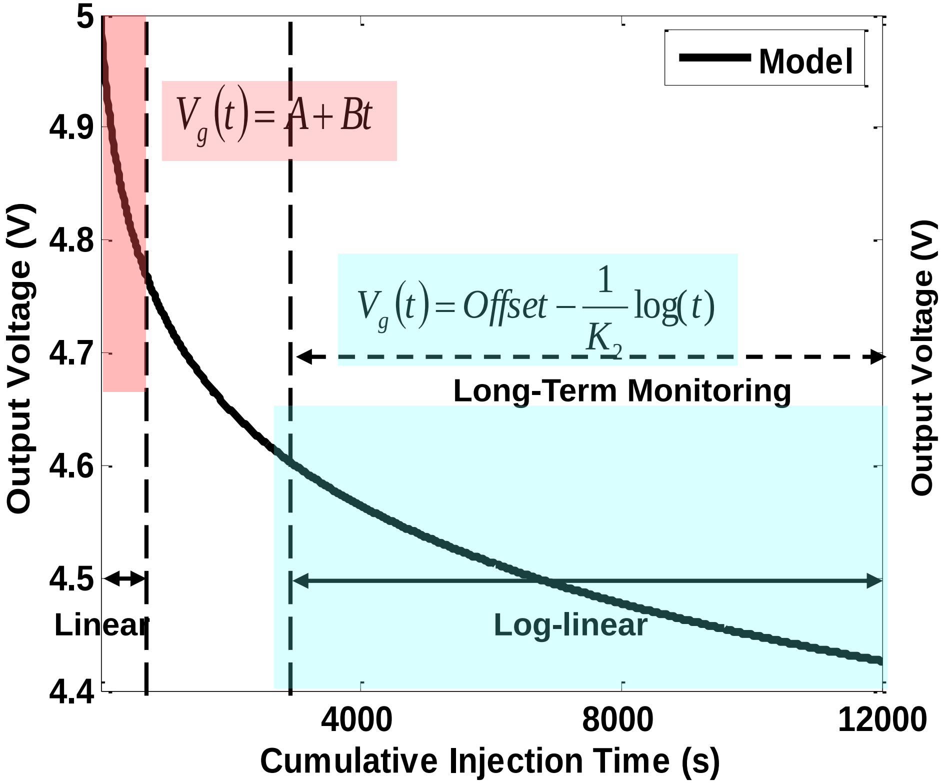


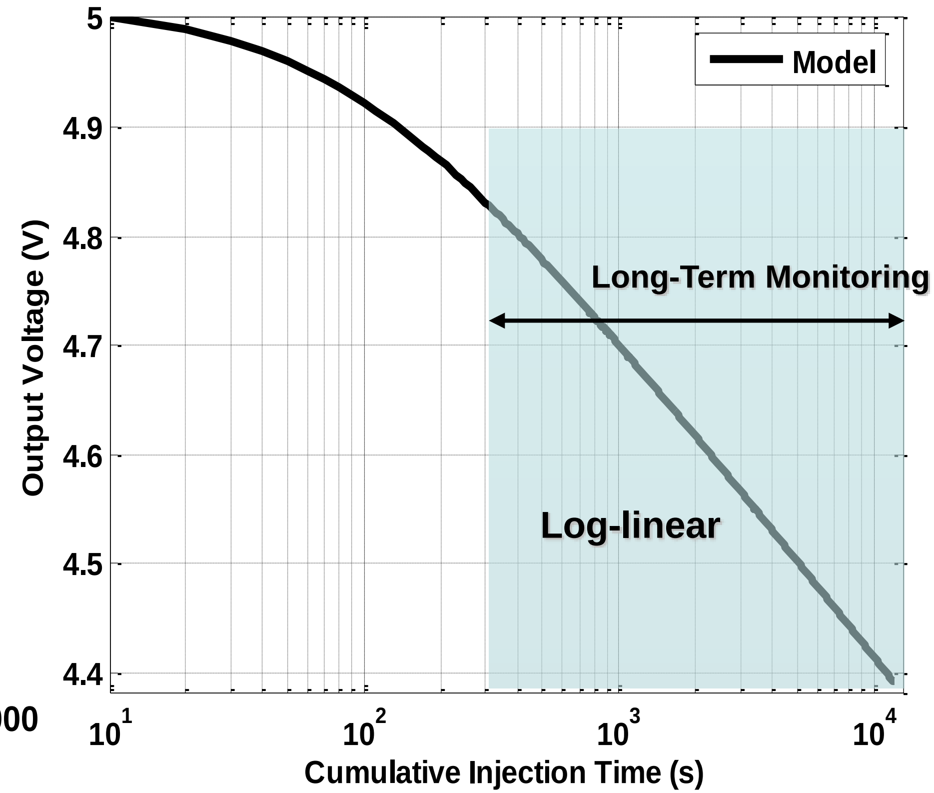
Piezoelectric can easily generate voltages >4V, but can only deliver a very low current

Self-powered, continuous and autonomous sensing

Autonomous computation and non-volatile storage of sensing variables

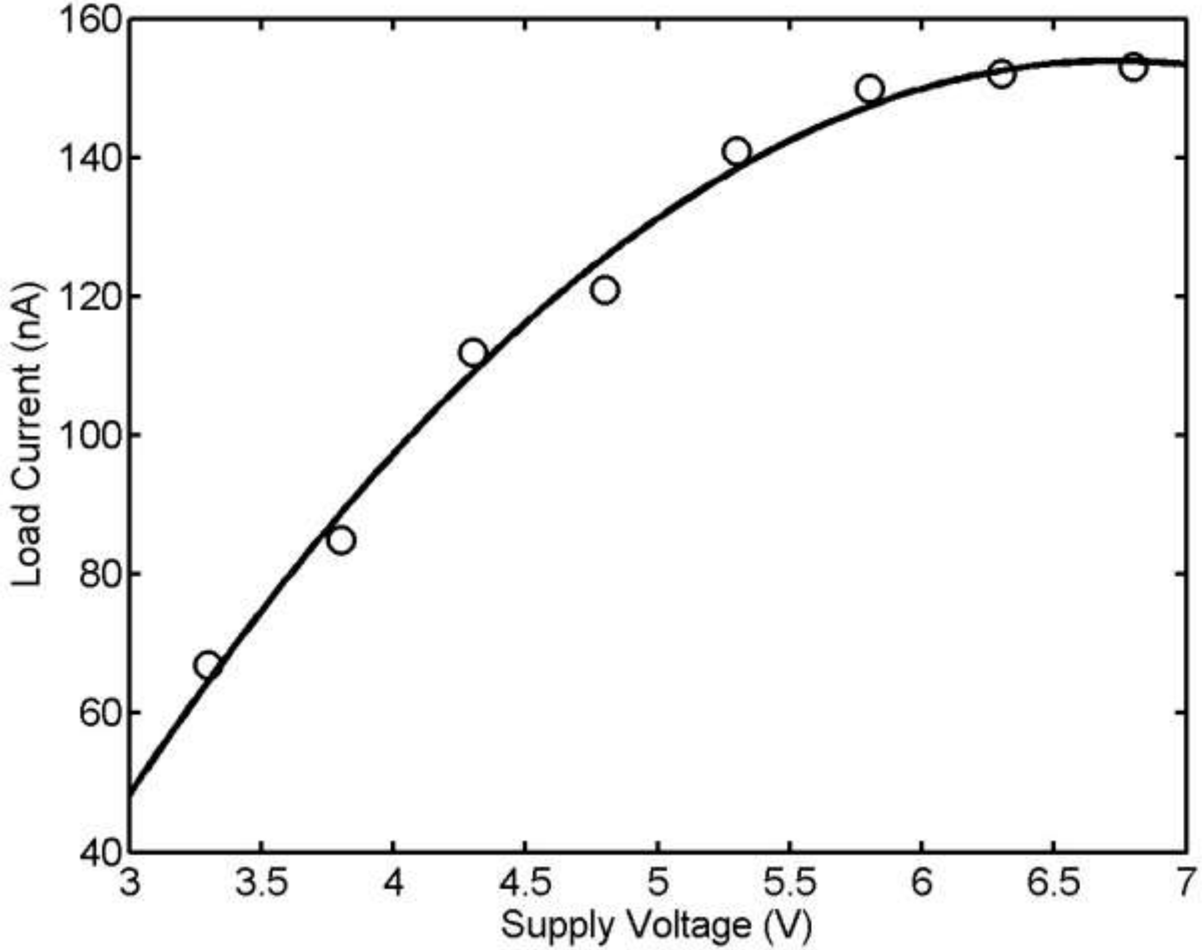
Electrical Modeling





$$\boxed{V_g(t) = -\frac{1}{K_2}\log\left(K_1K_2\int_{\tau\in t}\partial\tau + e^{-K_2V_{g0}}\right) + U_T\log\left(I_0/I_S\right)}$$

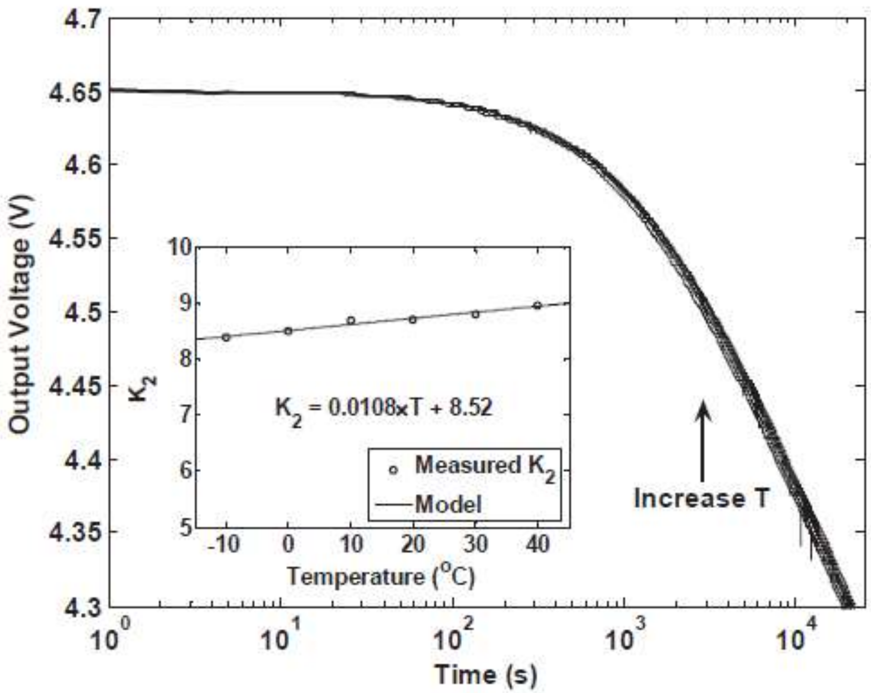
Energy efficiency



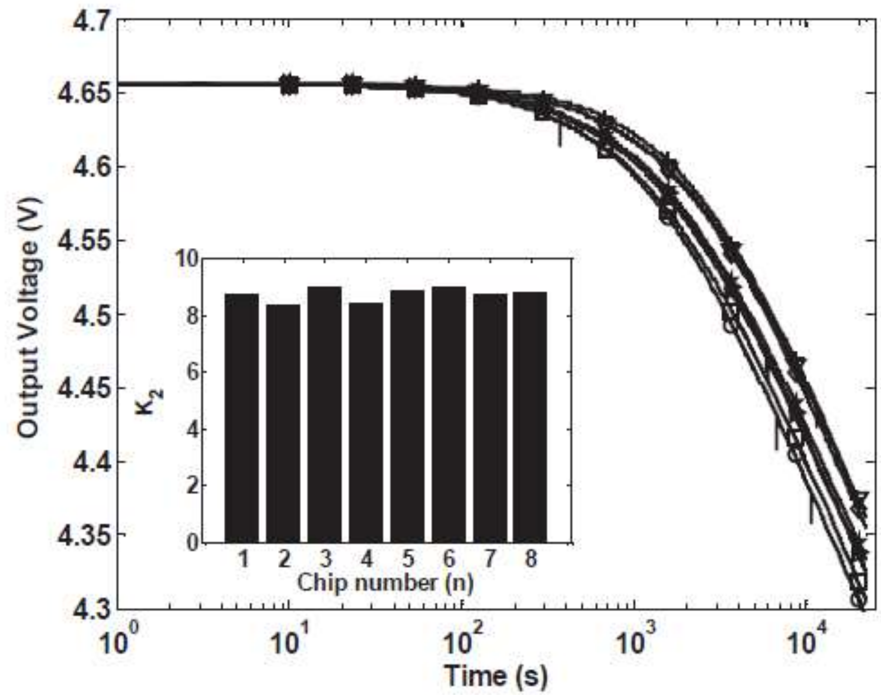
Power required for sensor operation: ~~800nW~~

200nW

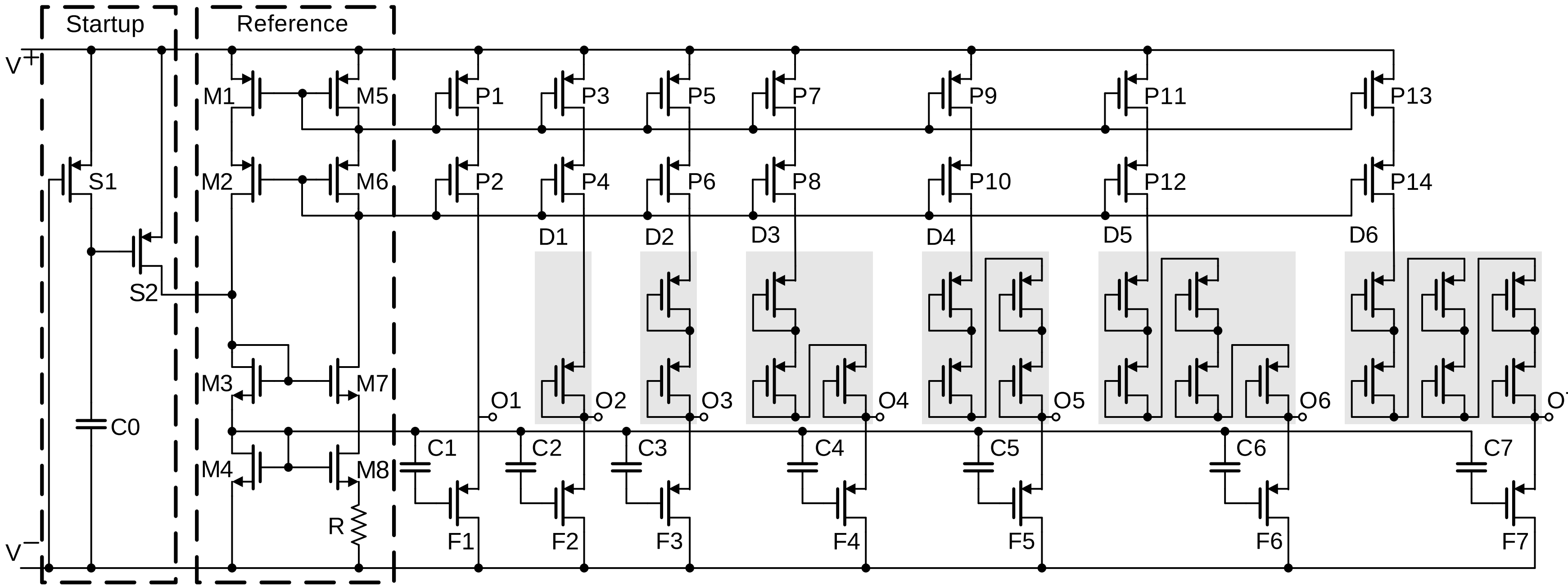
System robustness

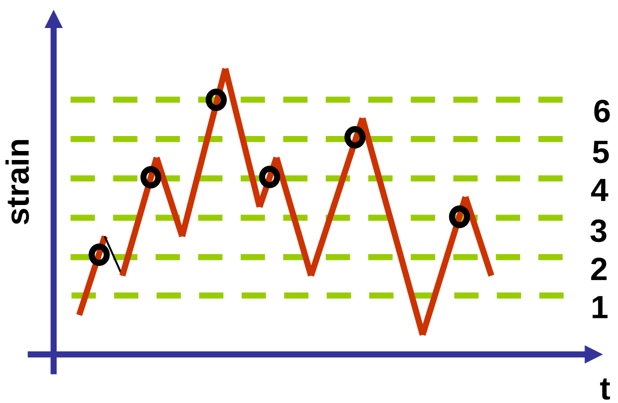


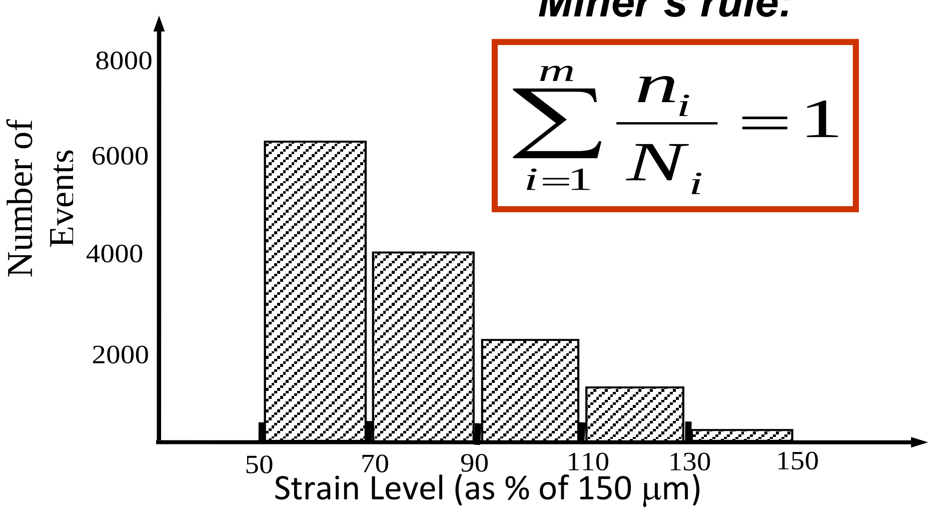
Injector response measured under different temperature conditions



Injector response measured using 8 prototypes fabricated in the same and different runs



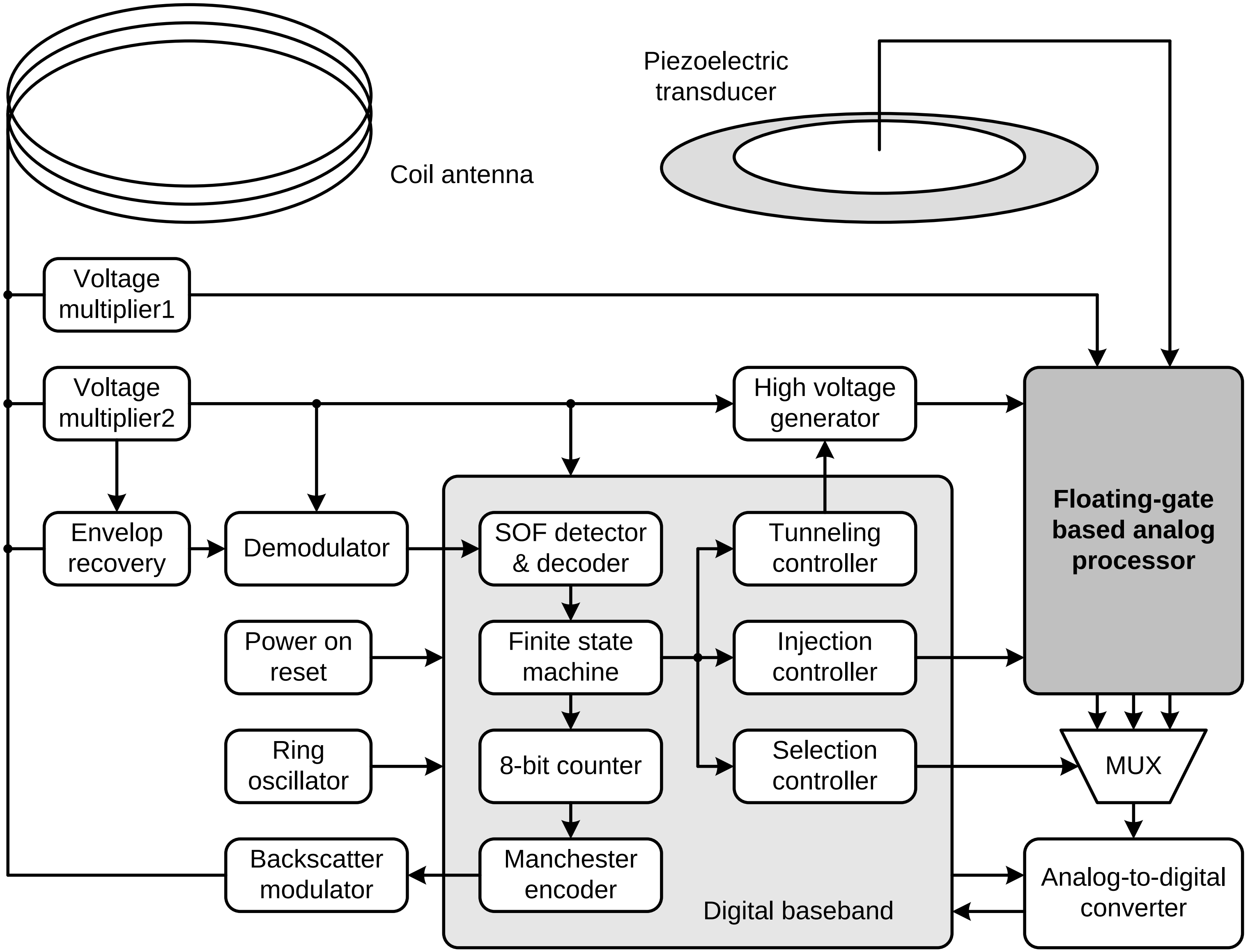


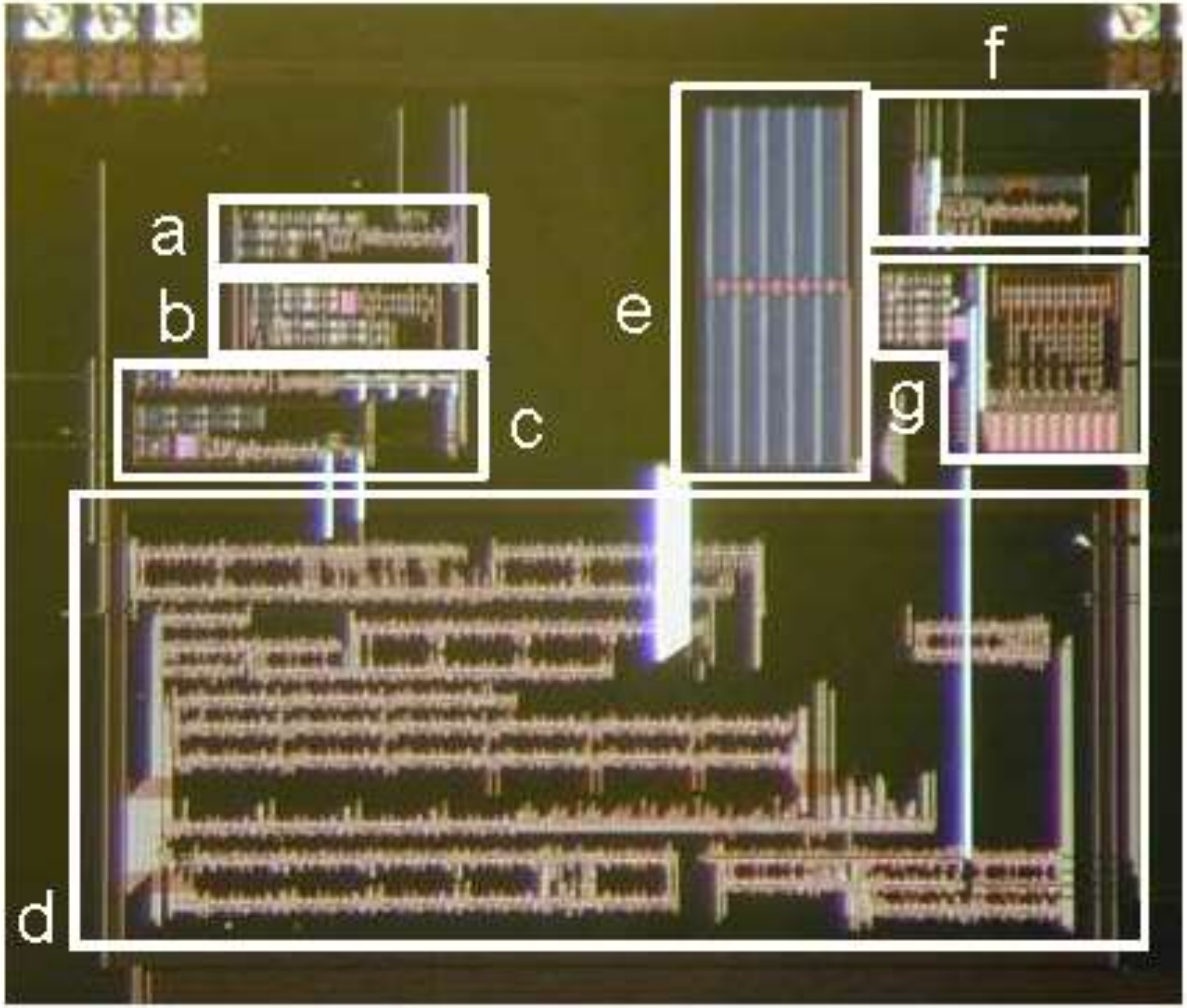


Miner's rule:

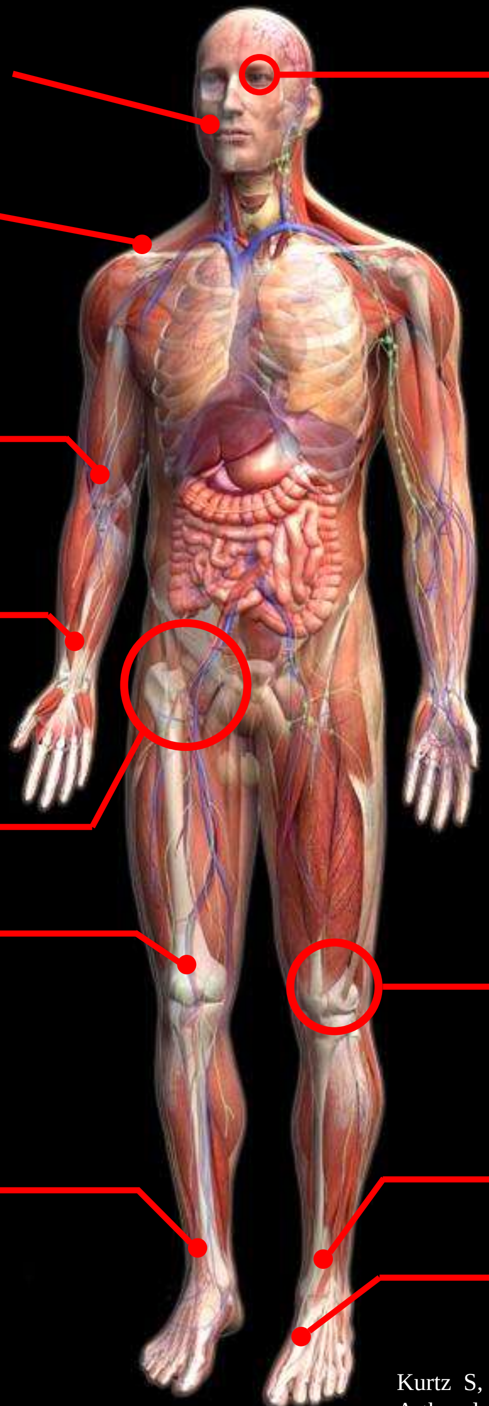
$$\boxed{\sum_{i=1}^{m} \frac{n_i}{N_i} = 1}$$

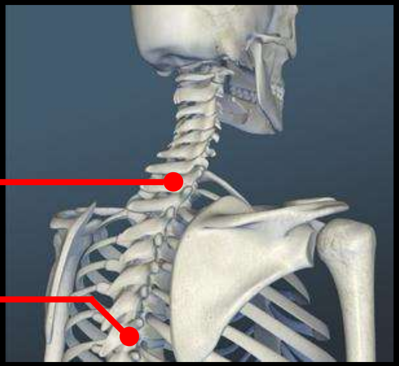
Wireless communication and data upload protocol





Micrograph of the sensor prototyped in a 0.5 micron CMOS process





Joint Replacements Expected to Soar

By CLAUDIA WALLIS — Thursday, Mar. 06, 2008

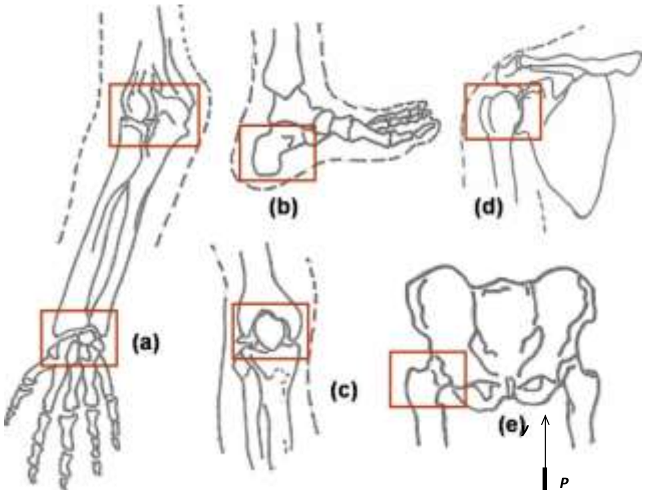
An X-ray of a hip replacement

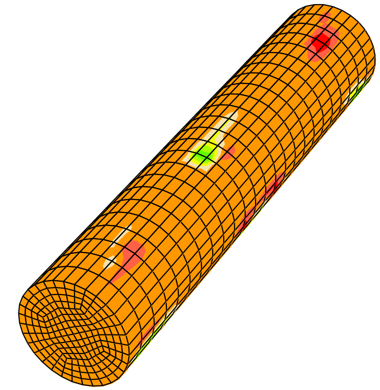
PHOTOMORGANA / CORBIS

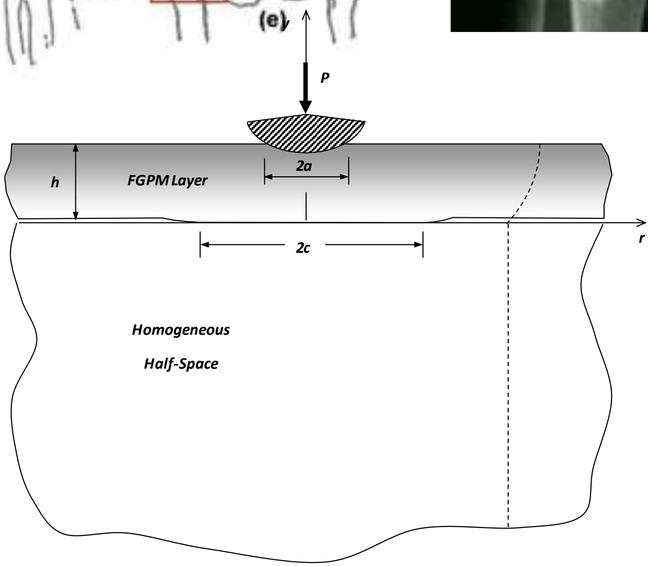
Source: Time Magazine

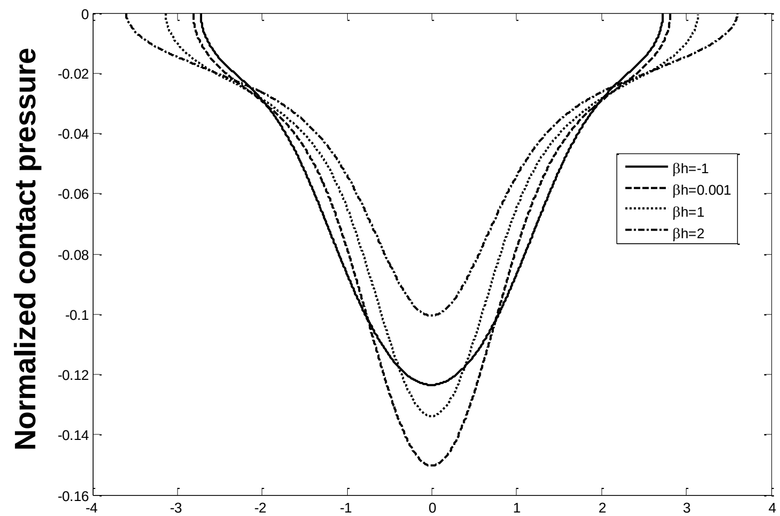
By 2030, cases of primary hip arhtroplasty in U.S. is expected to double to 0.5 million and cases of knee arthroplasty will grow by 7 fold to 3.5 million.

Kurtz S, Ong K, Lau E, Mowat F, Halpern M. "Projections of Primary and Revision Hip and Knee Arthroplasty in the United States from 2005 to 2030" J. of Bone and Joint Surgery, 2007; 89(4):780-785









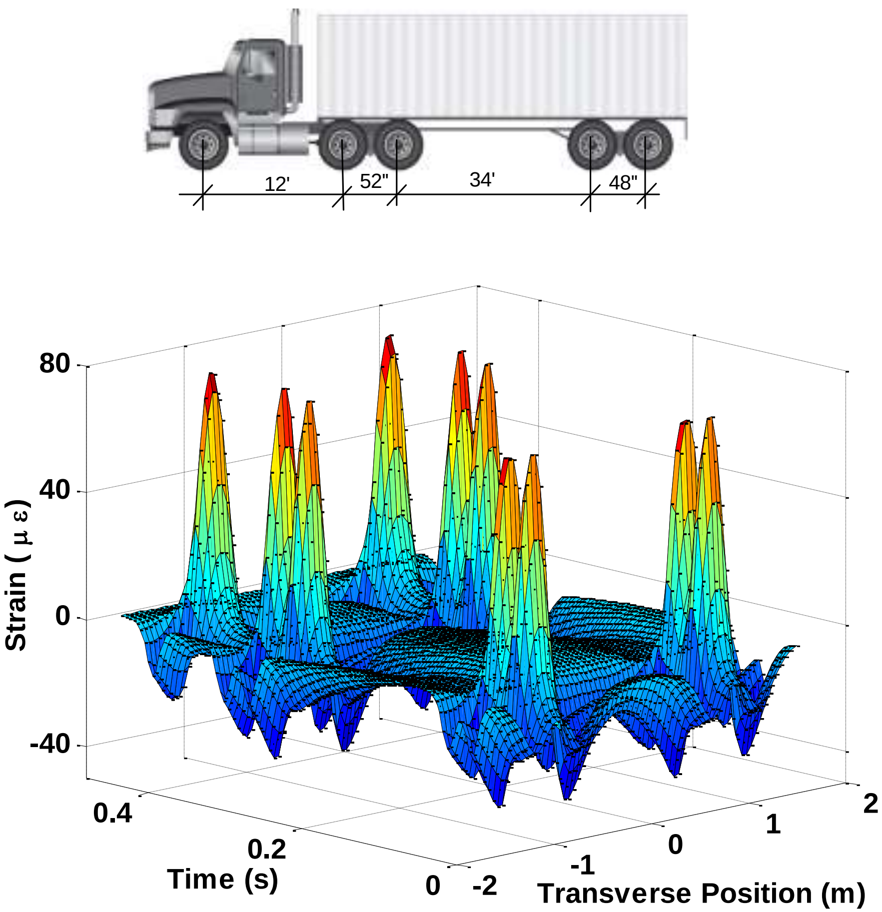
$$\partial\sigma_{rr}/\partial r + \partial\sigma_{rz}/\partial z + 1/r\,(\sigma_{rr} - \sigma_{\theta\theta}) = 0$$

$$\partial\sigma_{rz}/\partial r + \partial\sigma_{zz}/\partial z + 1/r\,\sigma_{rz} = 0$$

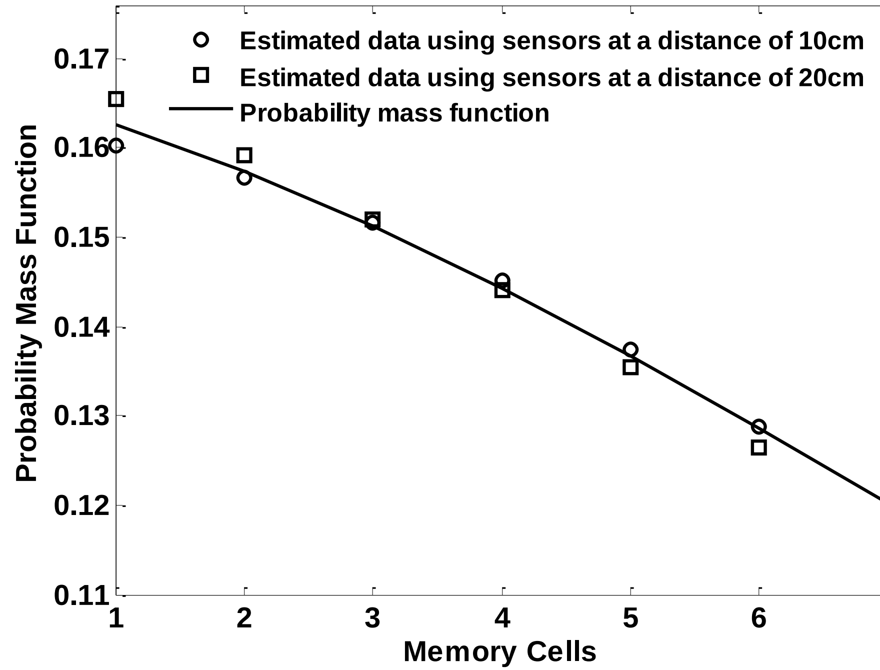
$$\partial D_r/\partial r + \partial D_z/\partial z + 1/r\,D_r = 0$$

$$\Gamma(r) = \int_0^{+\infty} [B_1(\rho)p(\rho) + B_2(\rho)R(\rho) + B_3(\rho)q(\rho) + B_4(\rho)S(\rho)]\rho J_1(r\rho)\partial\rho = 0$$

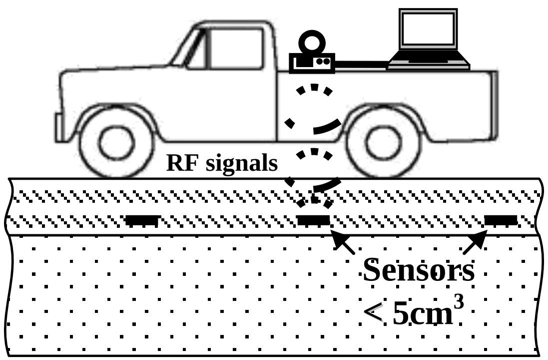
Randomly Distributed Sensors – Generation of full field data in missing points



Example of longitudinal strain profile evaluated at the bottom of the HMA layer for a moving load induced by a class 9 truck



Theoretical and estimated strain probability distributions at a selected transverse location (23cm away from the center of the wheel path) using data from groups of two sensors at different spacing distances



Pavement

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