Pervasive Systems Centre

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Prospects for Energy Harvesting Devices

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Presentation Outline

- **Energy harvesting current progress and future challenges overview presented from three different prospective**
  - Devices: micro-generators
  - Computation: Ultra low power logic design
  - CAD tools: modelling, simulation and optimisation of energy harvesting systems

Devices: Micro-Generators

Energy Harvesting Background

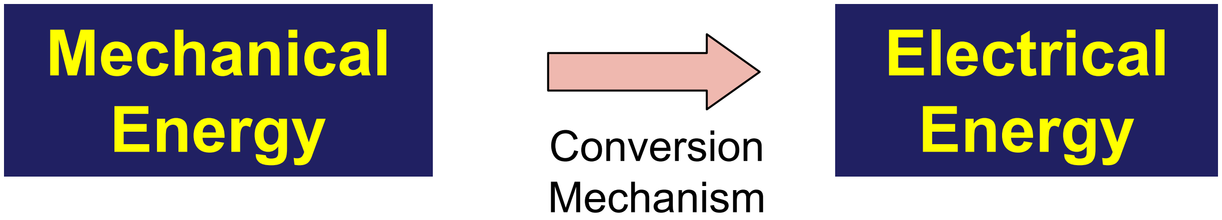
- **Energy harvesting: conversion of ambient energy present in the environment into electrical energy**
  - Dominant EH technologies: solar, vibration, thermoelectric

- **Our interest in energy harvesting applications**

  - Present: wireless remote sensors
    - Condition monitoring: building (structural health/energy management), industrial planets (machine health)
    - Batteries may not be viable for long-term "years" of monitoring; EH aim is to replace batteries

  - Future: Handheld/portable consumer electronics
    - phones, MP3 players, biomedical devices
    - EH aim is to increase capacity between battery re-charges

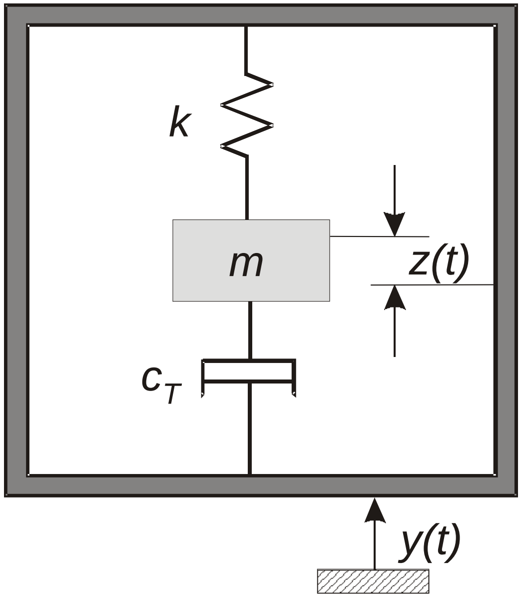
Vibration Based Micro-Generators



- **Why vibration? most widely available energy source for harvesting**
- **Micro-generates capture mechanical energy**

$$P_{av} = \frac{m\omega_n^3 Y z_{max}}{2}$$

ω and Y determined by application



2nd-order system
L = m, C = 1 / k,
mass m,
stiffness k

Vibration Based Micro-Generators (Contd.)

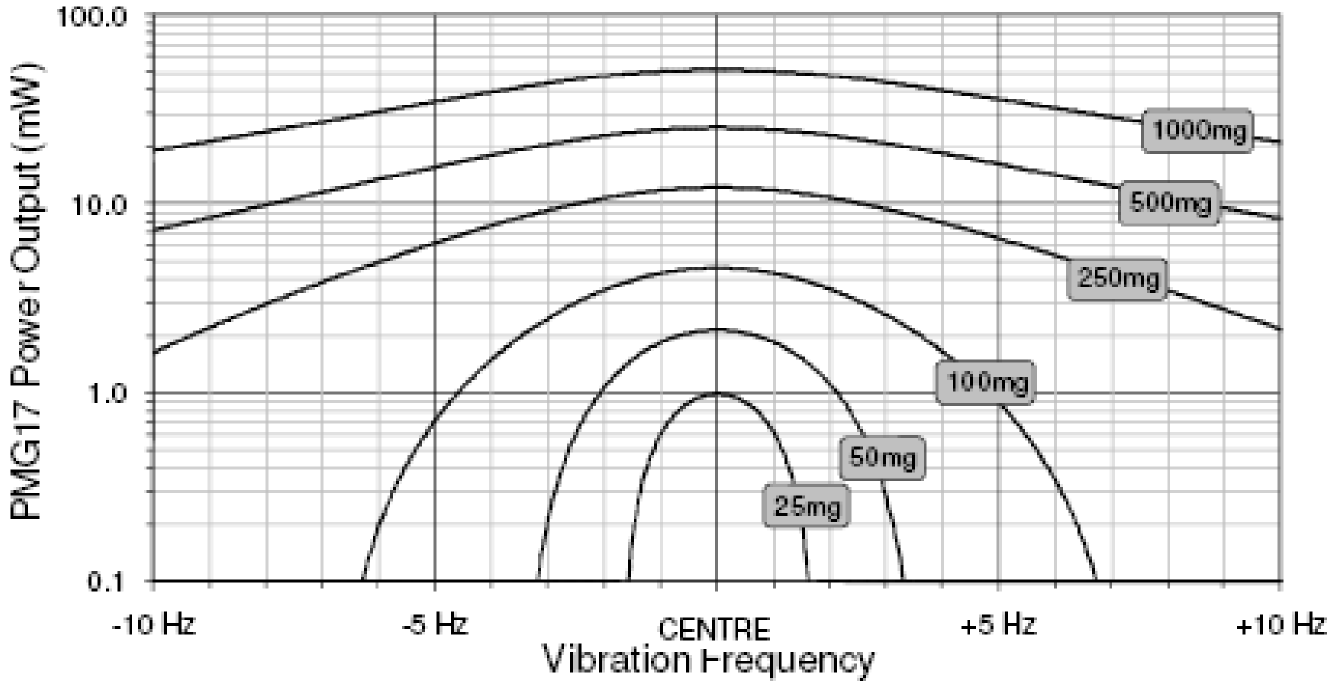
- **Amount of energy converted depend on conversion mechanism**
- **Three mechanisms commonly used [5]**
  - Piezoelectric generators (example: Southampton, Berkeley, IMEC)
    - Use materials (PZT) to generate charge when mechanically stressed
  - Electromagnetic generators (Southampton, Tyndall)
    - Use electromagnetic induction from motion between magnetic and coil
  - Electrostatic (Imperial, IMEC)
    - Use movement between charged capacitor plates to generate energy

- **State-of-the-art vibration micro-generator produce ~120µW/cm^3 for 100mg input; solar cells (outdoors at noon) ~ 15mW/cm^2**
  - Micro-devices: piezoelectric micro-generators produce highest power in theory, compared to electromagnetic/electrostatic

Perpetuum

- Founded in 2004. Developed vibration energy harvesters for condition monitoring
- PMG17 Micro-generator targeting oilfield applications
- Operates from the 100Hz/120Hz vibration bands found on electrical machines
- 10 years operational lifetime

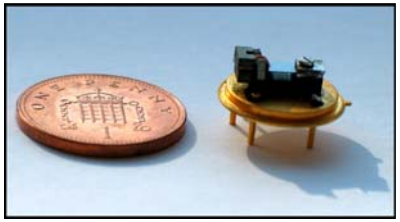
Perpetuum (Contd.)

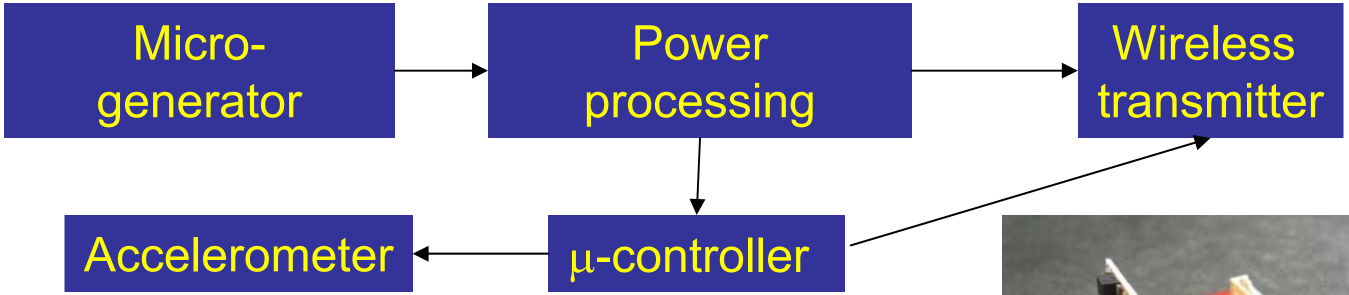


Energy Harvesting Electronics Applications

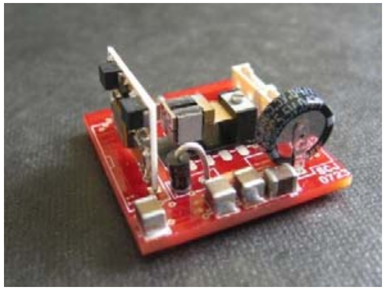
VIBES

- Self powered wireless sensor (accelerometer-based monitoring system) [3]



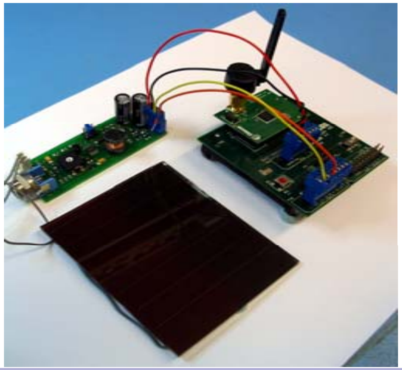


0.8cm^3, 58 μW, 60mg acceleration, 18 μW power/cycle

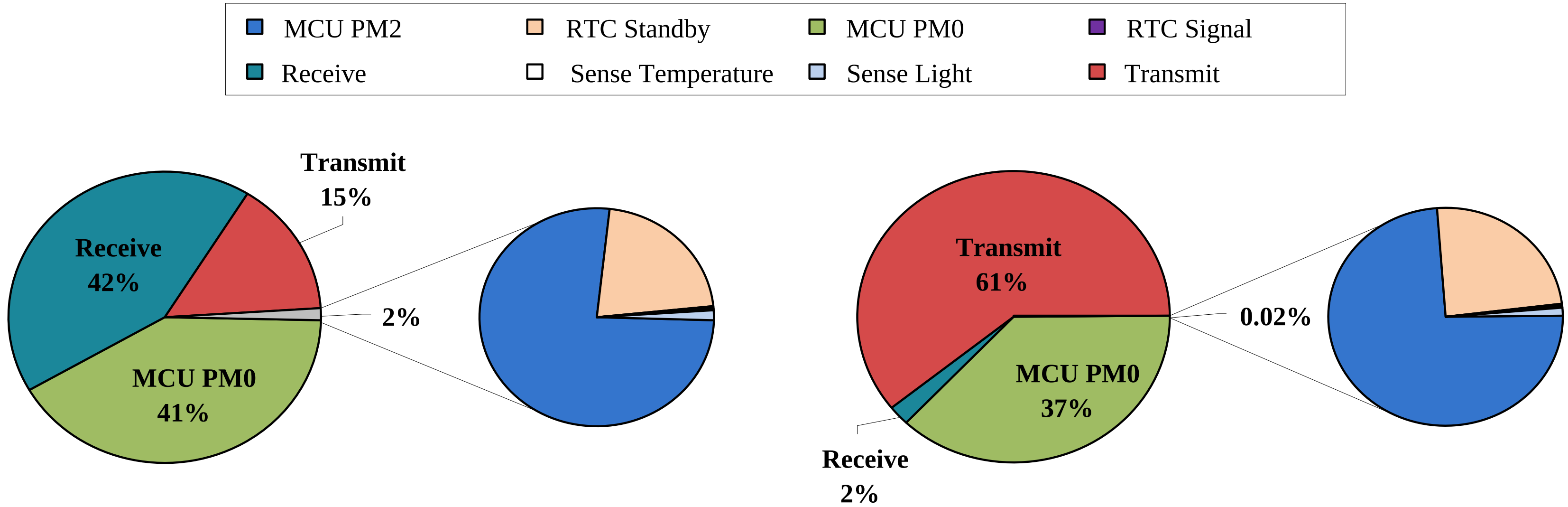


- Solar-powered u-controller 8051,~300 lines C-code [2]

500 Lux (runs in-doors), 500uW, 3V, solar panel size 90x72mm



Distribution of Energy Consumers [7]



a) two hour reporting frequency

b) thirty second reporting frequency

- Energy consumed highly dependent on the application and duty-cycle operation
- Identifying right balance between computation/communication need joint design

Computation: Ultra Low Logic Design

Ultra Low Power Design

- Energy harvesters can power ultra low power devices: examples CC2430, MSP430, ARM7TDMI

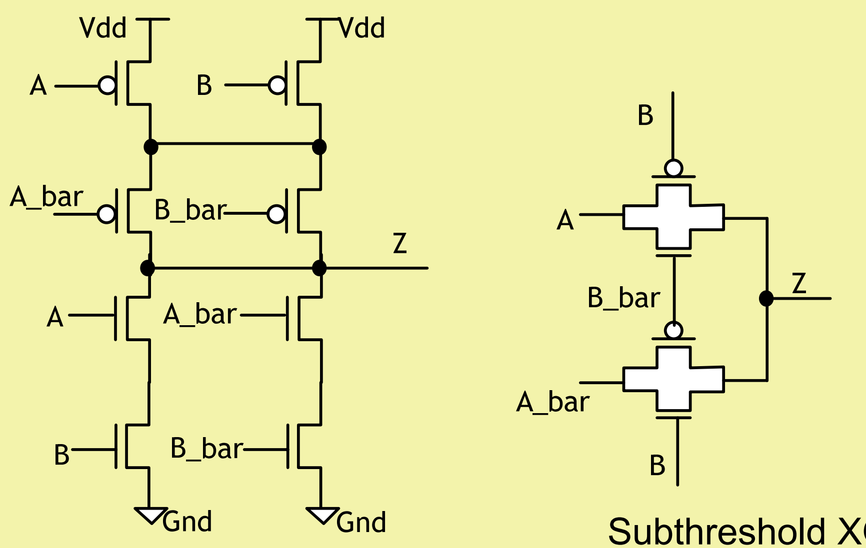
- **Our interest**
  - To develop circuit design technique with energy as key metric (not speed)
  - Aim to do more with less; need for min. energy consumption/computation

- **Sub-threshold logic [11]:** Vdd < V_T , Ion/Ioff~ 100
  standard logic super-threshold Ion/Ioff ~ 10,000

	Subthreshold	vs	Superthreshold
I_{on}	2uA	↔	1mA
Delay	$1/I_{on}$	↔	$1/I_{on}$
V_{dd}	0.2 - 0.5V	↔	0.8V-1.2V

Subthreshold Logic

- Static CMOS gates still work – 2input NAND, 2-input NOR
- Issues with 4-input NAND and XOR, stack devices – due to leakage current which degrades I_{on}/I_{off}



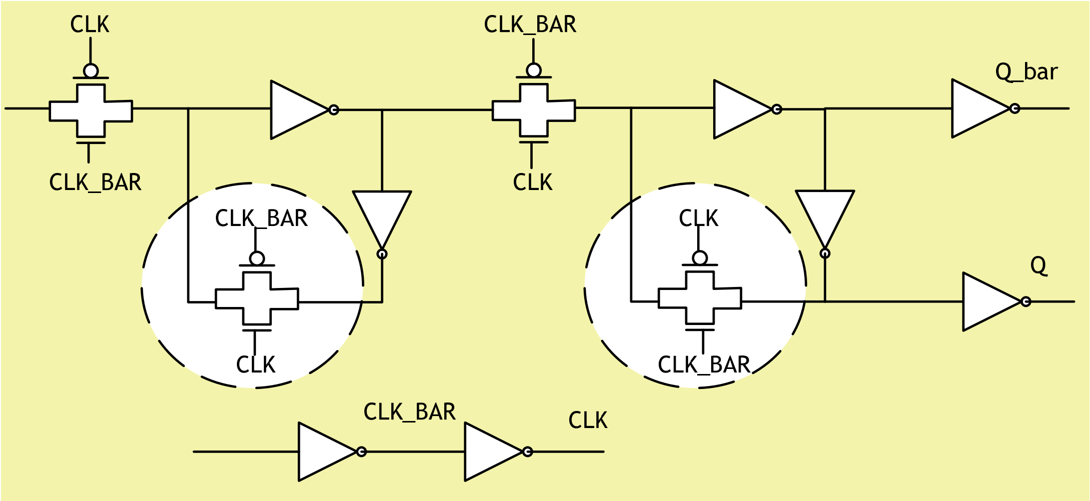
Standard XOR (stacked)
Poor I_{on}/I_{off}

Subthreshold XOR
Better I_{on}/I_{off}

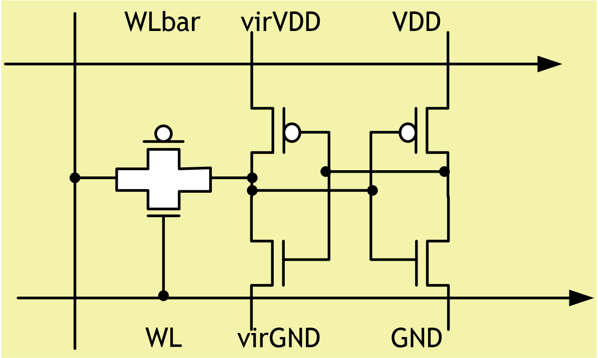
MUX-based XOR [11]

Flip Flop, SRAM

FF Cell [11]



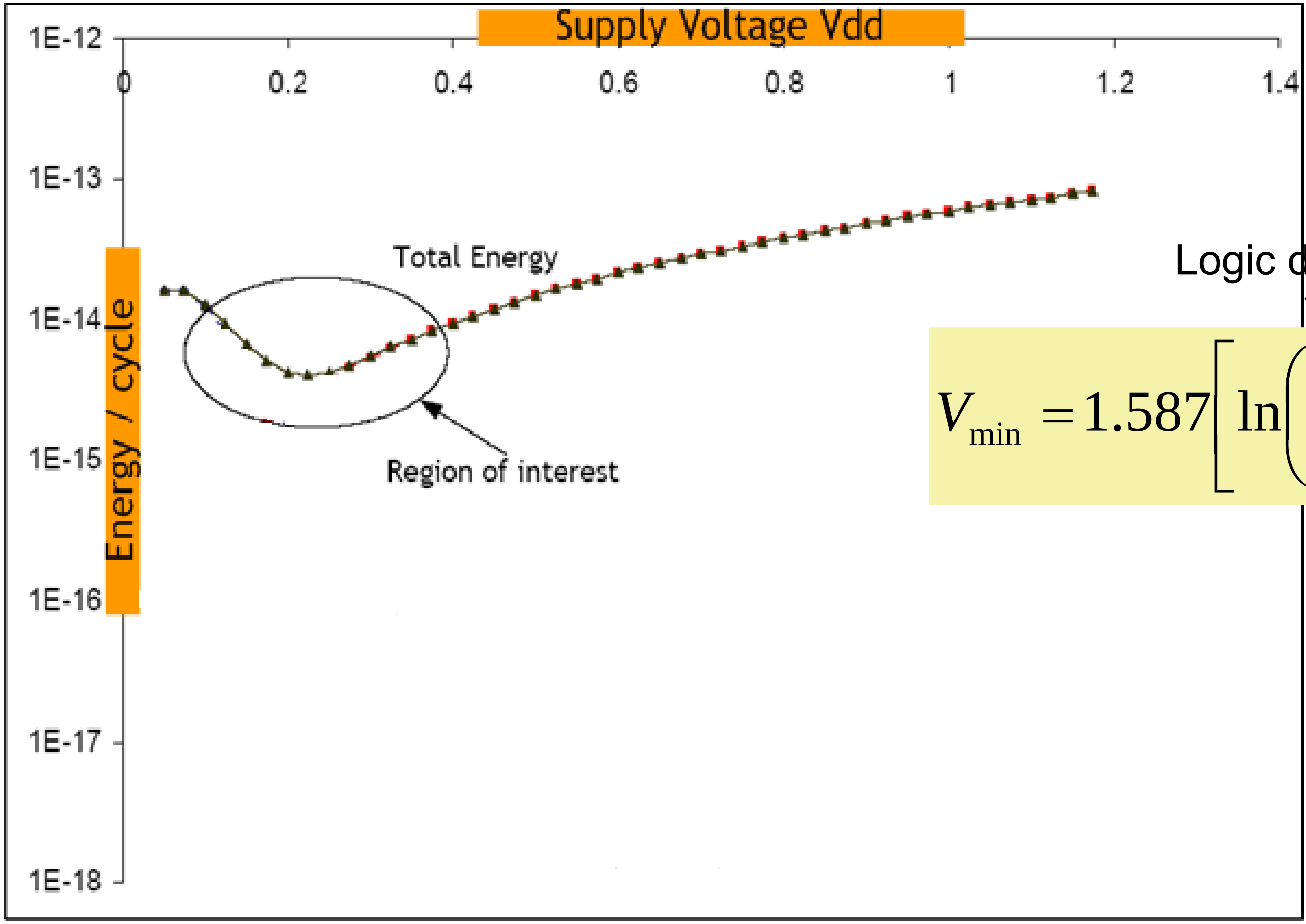
Additional MUX to increase master-slave drive



6T SRAM [13]

Sub-threshold 8T SRAM with full read/write operation at 400mV [15]

Key Metric – Minimum Energy Point



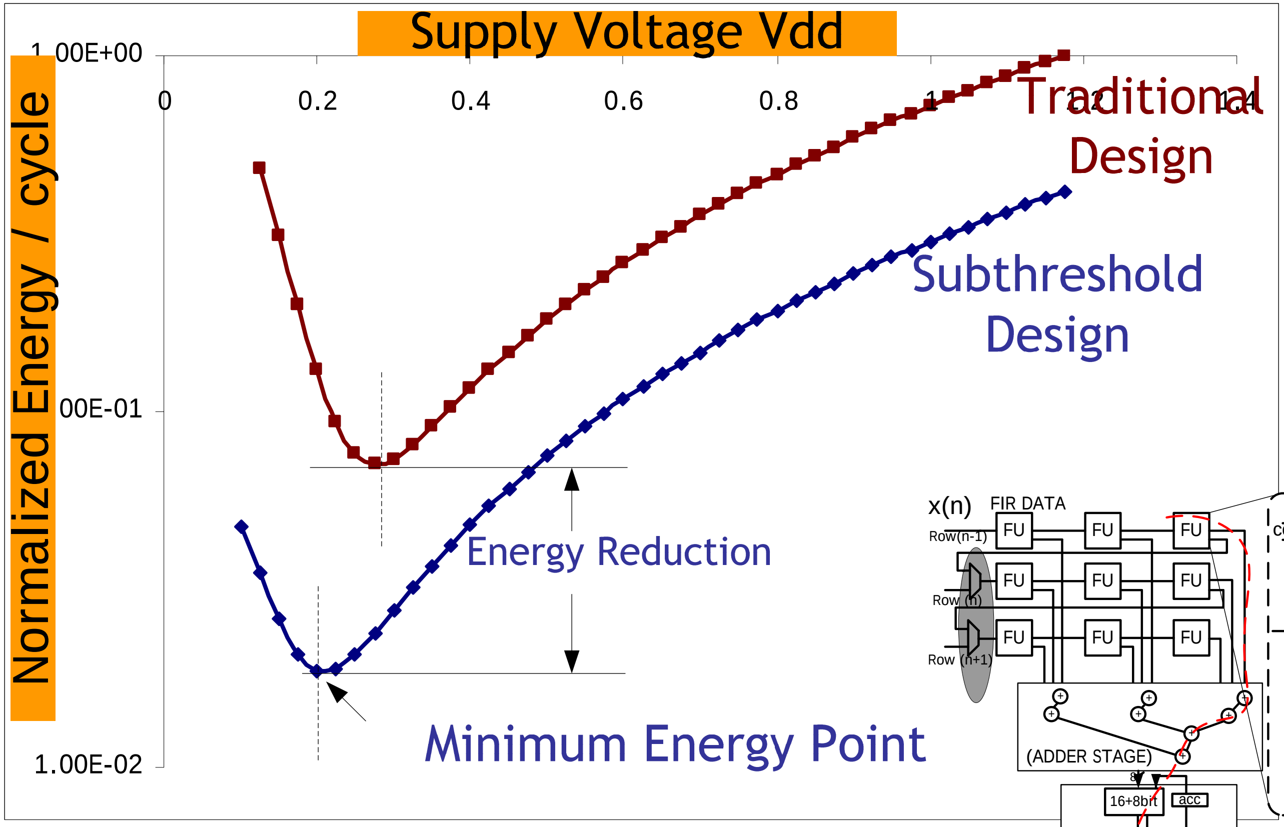
$$V_{min} = 1.587\left[\ln\left(\eta\frac{n}{\alpha}\right) - 2.355\right].mV_T$$

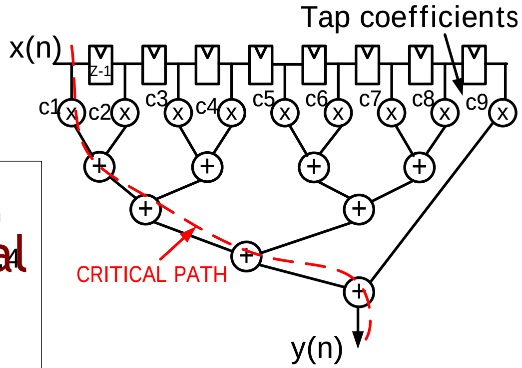
Logic depth

subthreshold Slope factor

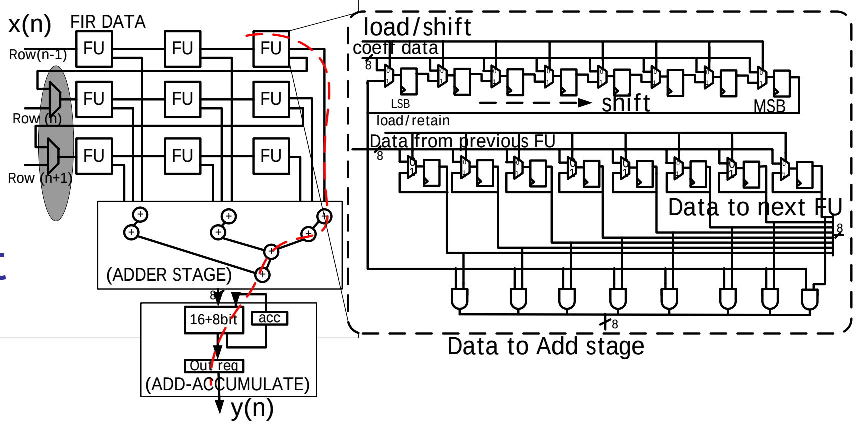
Activity factor

Digital Filtering [9]



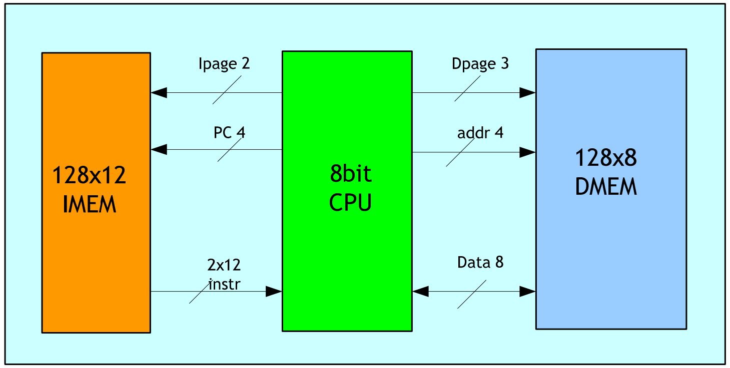


- Logic Depth ↓
- Transistor Utility ↑



9 tap filter, 1.3pJ/sample, carry save adder, 120kHz operational frequency

Processor Implementations

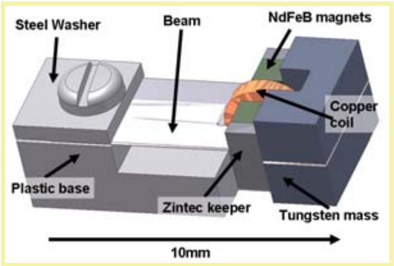


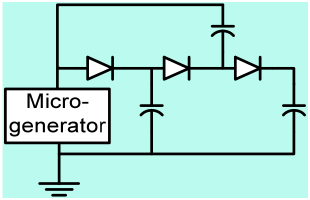
Processor	Type	V_{min}	Energy	Speed	Width
FFT	MIT (2005) [11]	350 mV	**155nJ/FFT**	10 kHz	8b-16b
Microprocessor	Michigan (2008) [12]	360 mV	**2.6pJ/instr**	833 kHz	8b
Microcontroller	MIT (2008) [14]	500 mV	**27.3pJ/instr**	434 kHz	16b

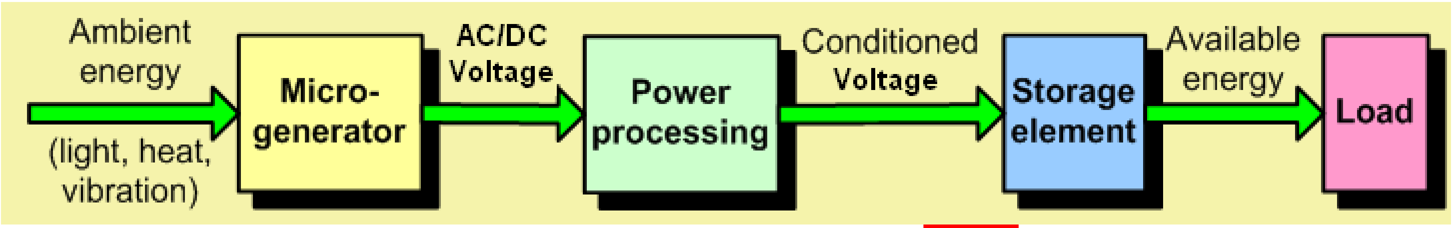
Innovation in cell library design

CAD Tools:
Modelling and Performance Optimisation of Energy Harvesting Systems

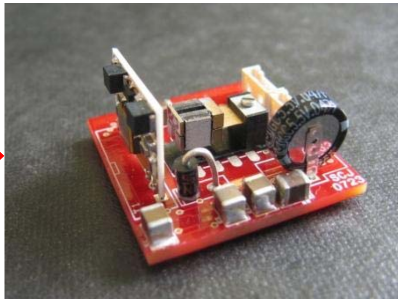
Energy harvesting system



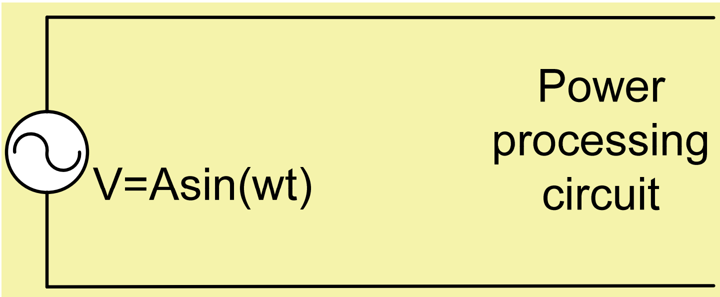




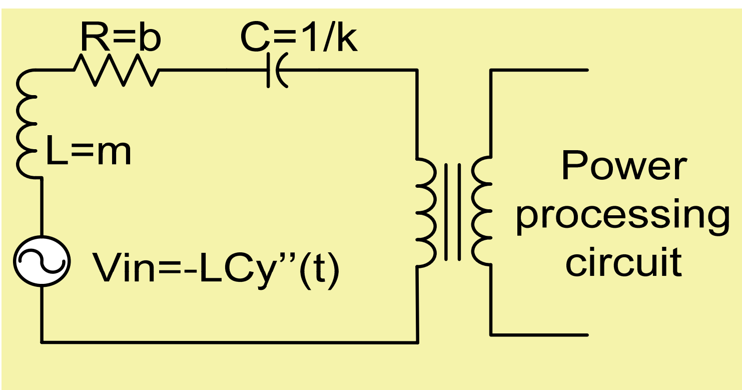
- Mixed-domain system (mechanical-electrical)
- Modelling/performance optimisation necessary to compensate for system performance loss due to mixed-domain interaction



Micro-Generator Models



- Ideal voltage source



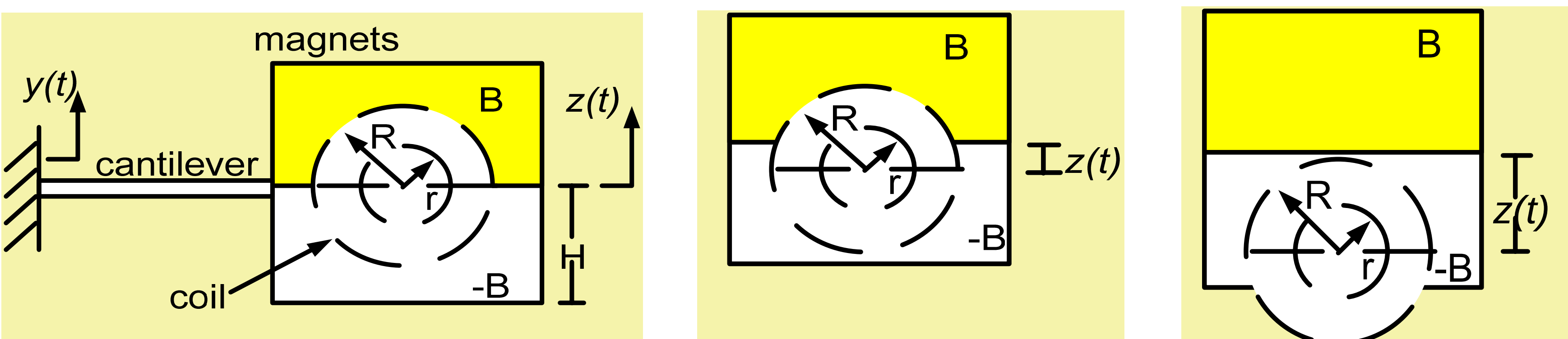
- Equivalent circuit

```
entity EH is
port(
terminal HOUSE:translational;
terminal LOAD:electrical
);
end entity EH;
architecture Behaviour of EH is
…
begin
mp*zt’DOT’DOT+Cp*zt’DOT+Ks*zt+Fem==-
mp*yt’DOT’DOT;
Phi*zt’DOT==emv;
emv==vt-Rc*it-Lc*it’DOT;
Fem==-Phi*it;
…
end architecture Behaviour;
```

- HDL model

Example: cantilever electromagnetic micro-generator [8]

- Describe micro generator as series of equations taking into account the relationship between coil-magnet displacement and magnetic flux



(a) Initial position $z(t)=0$

$$\Phi=(R+r)*2*B*N$$

(b) Small displacement $|z(t)|<r$

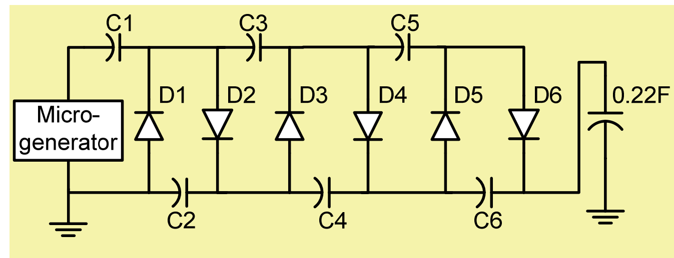
(c) Large displacement $H-r<|z(t)|<H$

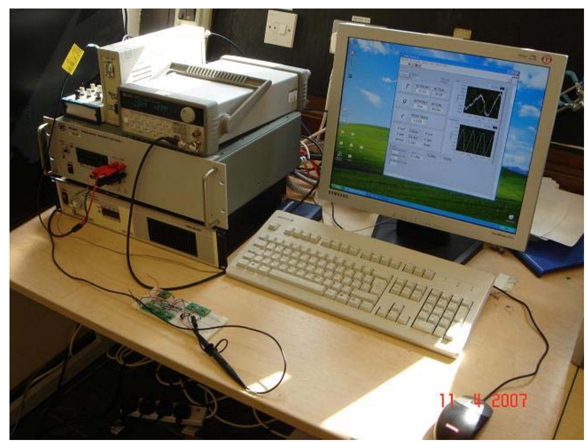
$$\Phi=(\sqrt{R^2-z^2(t)}+\sqrt{r^2-z^2(t)})*2*B*N$$

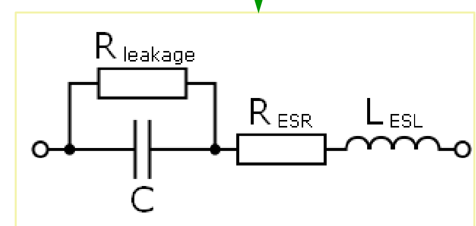
$$\Phi=-(\sqrt{R^2-(H-|z(t)|)^2}+\sqrt{r^2-(H-|z(t)|)^2})*B*N$$

Practical validation of micro-generator models

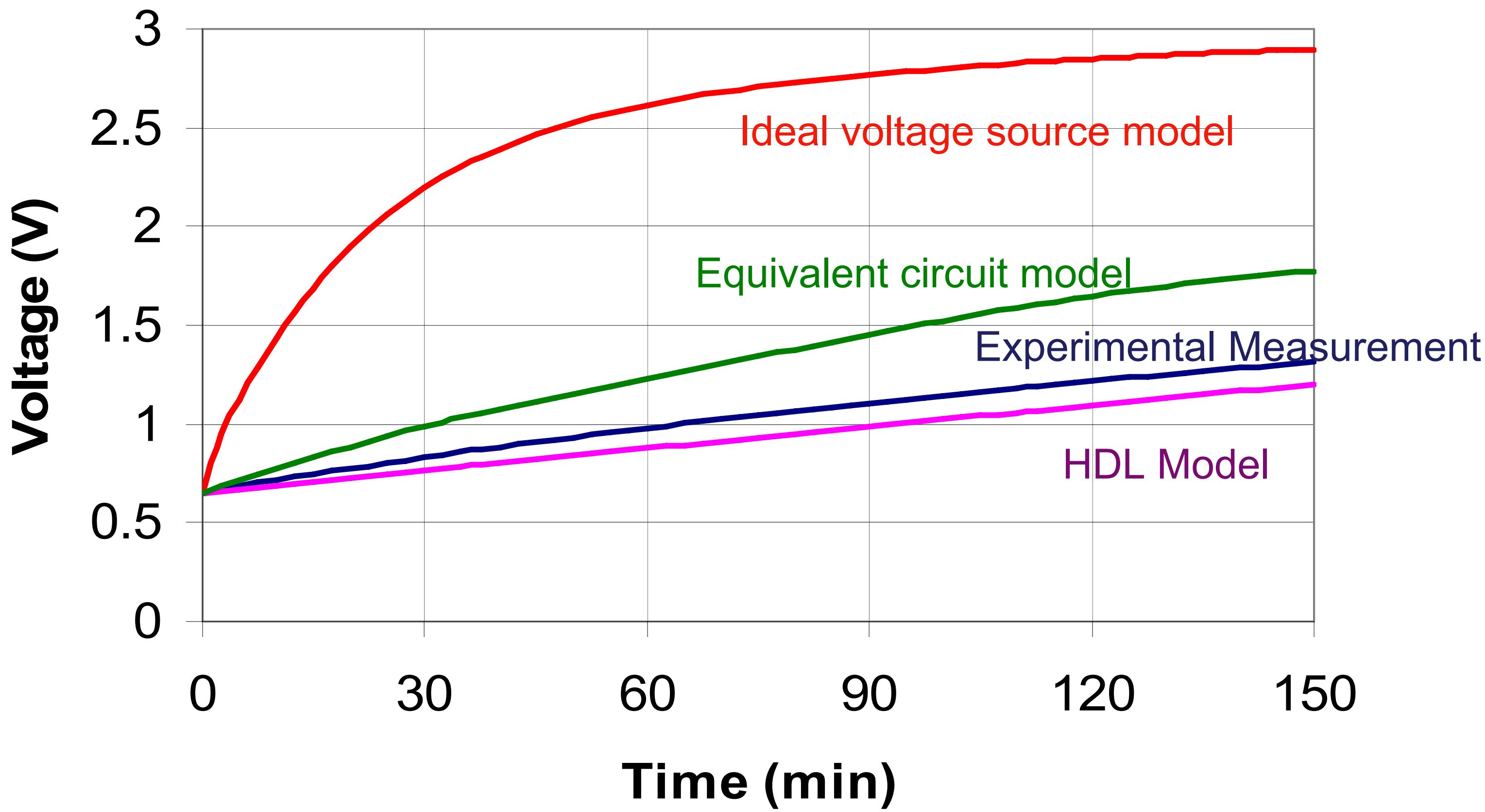
- Cantilever based micro-generator sitting on vibration generator
- Power processing (6-stage Villard voltage multiplier)
- Super capacitor modelled
- Output voltage measured using LabView





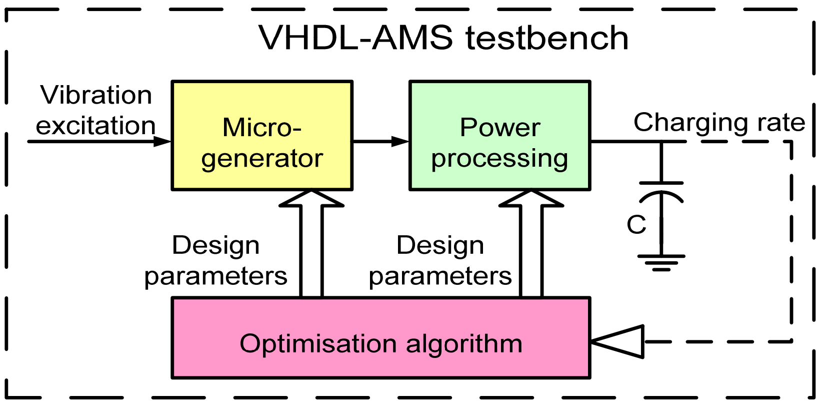


Practical validation of micro-generator models (Cont..)

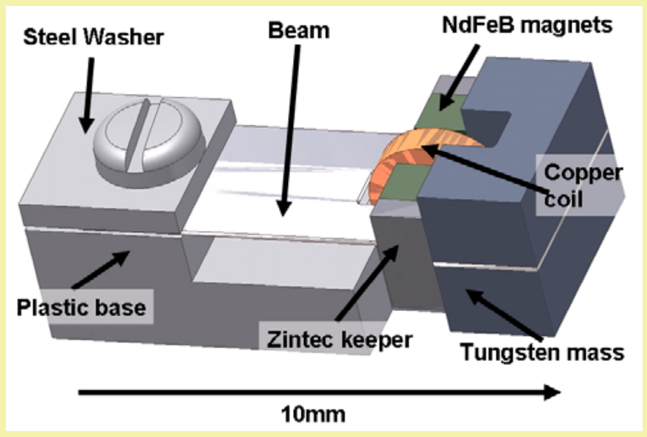


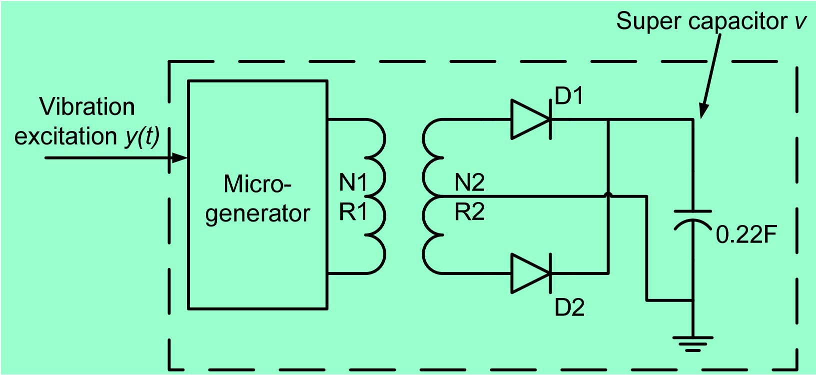
Performance optimisation

- Integrated modelling and performance optimisation




```
for i in 1 to 100
generate
entity EH
generic map(
generics => value(i)
..)
port map(
ports => port(i)
..);
end generate;
```





- Cantilever structure
- Power processing

Optimisation results

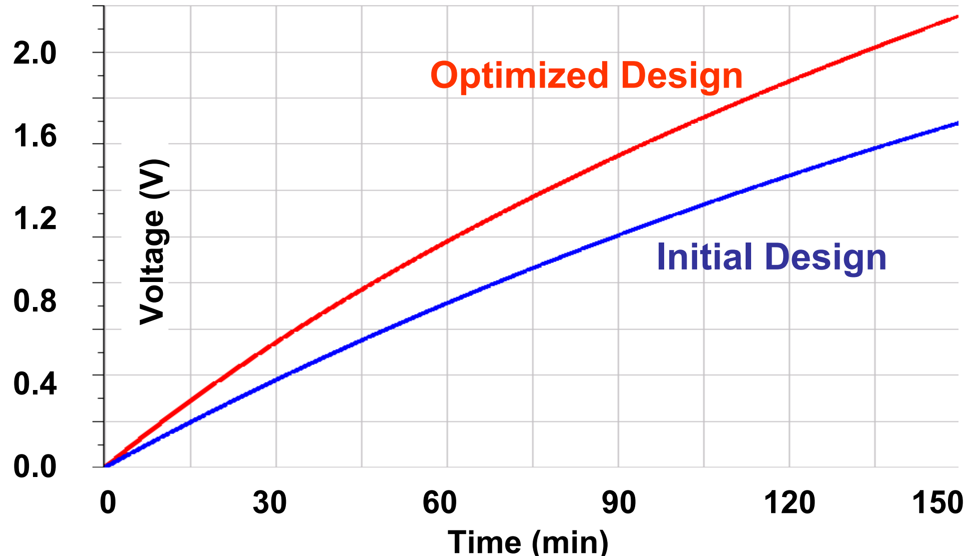
- Initial design

Micro-generator		
Coil radius		1.2mm
Coil turns		2300
Voltage transformer		
	Resistance	Winding
Primary	400 Ω	2000
Secondary	1000 Ω	5000

- Optimized design

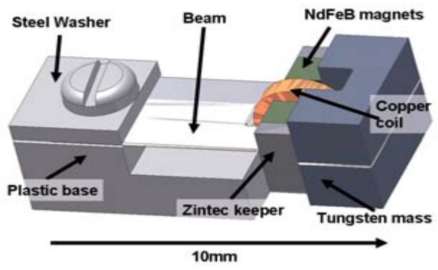
Micro-generator		
Coil radius		1.1mm
Coil turns		2100
Voltage transformer		
	Resistance	Winding
Primary	340 Ω	1900
Secondary	690 Ω	3800

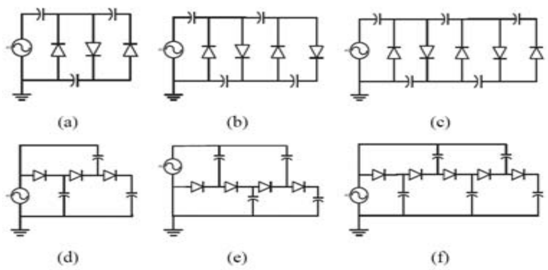
- **Optimisation objective: increase charging rate of the storage element**



Automatic energy harvesting system design flow

- Previous slide only varied micro-generator coil values and given power processing circuit (primary and secondary winding)
- **Automated design flow**
  - **Input**
    - User specified micro-generator type (piezoelectric, electromagnetic, electrostatic)
    - Frequency/amplitude of excitation
  - **Output**
    - dimension of micro-generator (e.g. cantilever: magnet size, cantilever length, coil turns,...)
    - suitable power processing circuits

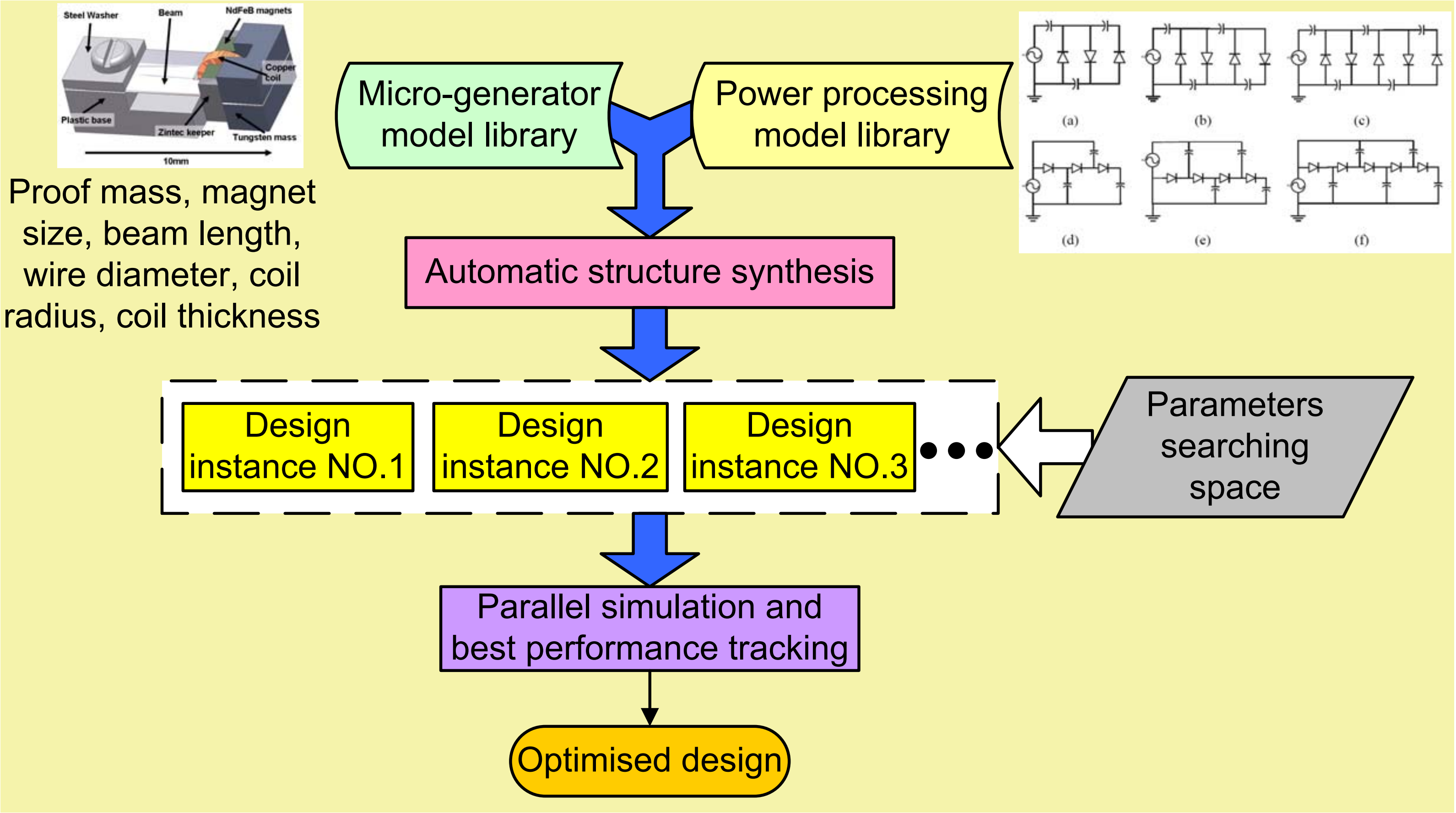




- Aim: achieve the best possible power density (resonance operation) for specified micro-generator type and application spectra, under specific design constraint (e.g. generator size)

Automatic EH system design flow (contd.)

- Specified micro-generator type find suitable dimensions
- Identify suitable power processing configuration(s)

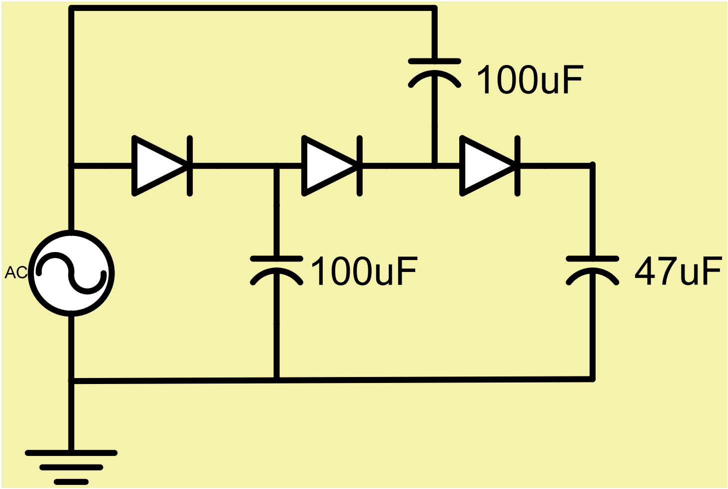


Case study: Electromagnetic Energy Harvester

- Aim: produce micro-generator dimension with appropriate power processing circuit to charge the super capacitor to certain voltage in shortest time

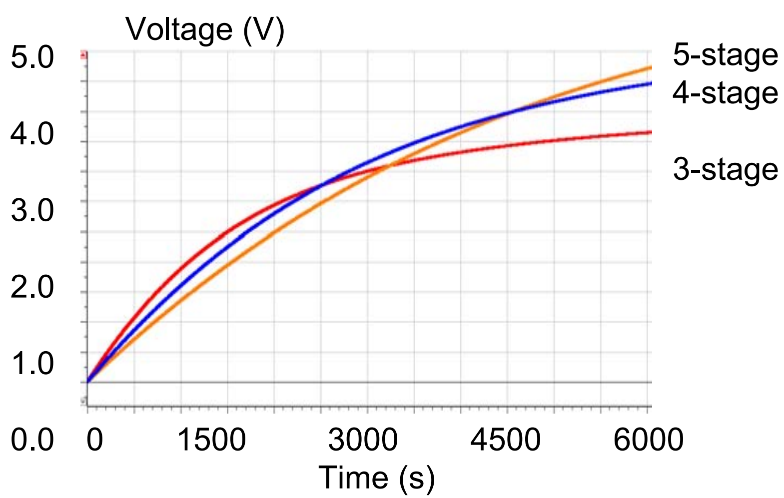
Proof mass (g)	2.4
Magnet size H (mm)	3.0
Beam length (mm)	13.7
Wire diameter (um)	16
Coil radius (mm)	2.0
Coil thickness (mm)	1.3

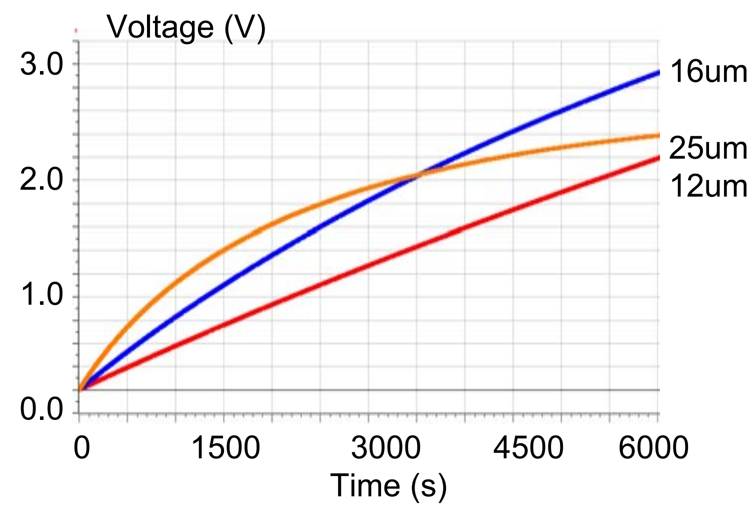
Micro-generator



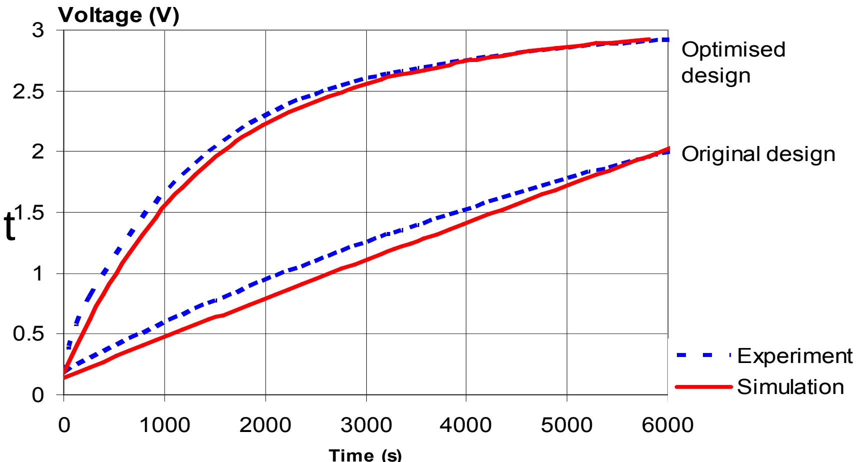
Voltage booster

Case study: Simulation / Experimental Results





- Same micro-generator with different voltage multipliers
- Same micro-generator with different wire diameters
- Optimisation result



Some Open Problems

- **Micro-generators devices**
  - Adaptive energy harvester capable of modifying its resonant frequency/damping depending on excitation source to achieve resonance
  - Energy harvesting system with different micro-generators (vibration and solar) combined to maximise energy available including MEMS-based energy harvesters enabling complete electronic systems integration
- **Ultra low power circuit design**
  - Variation resilient sub-threshold circuits to improve robustness [10] including AC powered and asynchronous approaches
  - Power management-awareness of energy availability varies with time in nondeterministic manner [6]
- **Design automation of energy-harvesting electronics**
  - CAD tool for Integrated modelling/performance optimisation and synthesis of mixed-technology EH systems including wide range of micro-generator models/computational load

Conclusions

- Overview of advances in EH devices, computation/CAD tools
- Industrial monitoring/autonomous sensor nodes where EH (vibrations and solar) are already employed successfully [8]
- Numerous technical challenges exist and need innovative research/development before energy harvesting can become main stream technology in electronics design
- EH may not universal solution to all applications requesting free energy, it is likely in the near future that consumer electronics will benefit from energy harvesting [4]

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  - Dr. John Tudor

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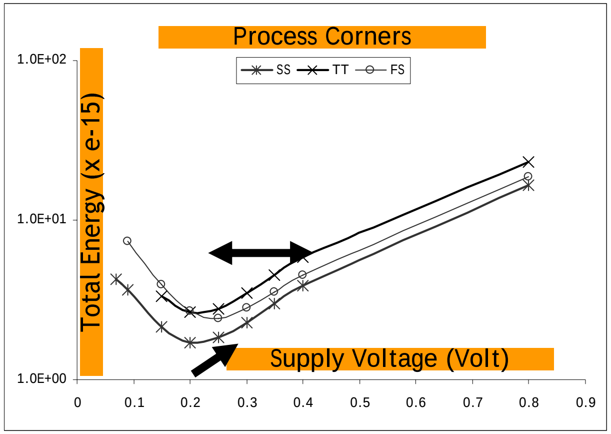
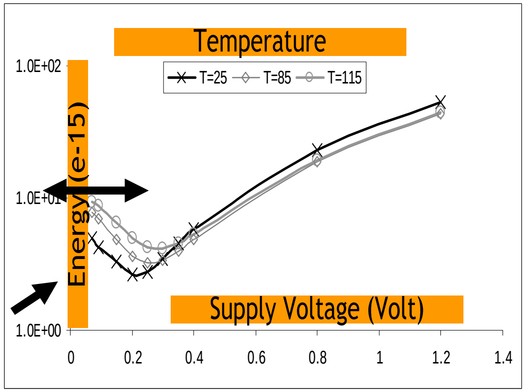
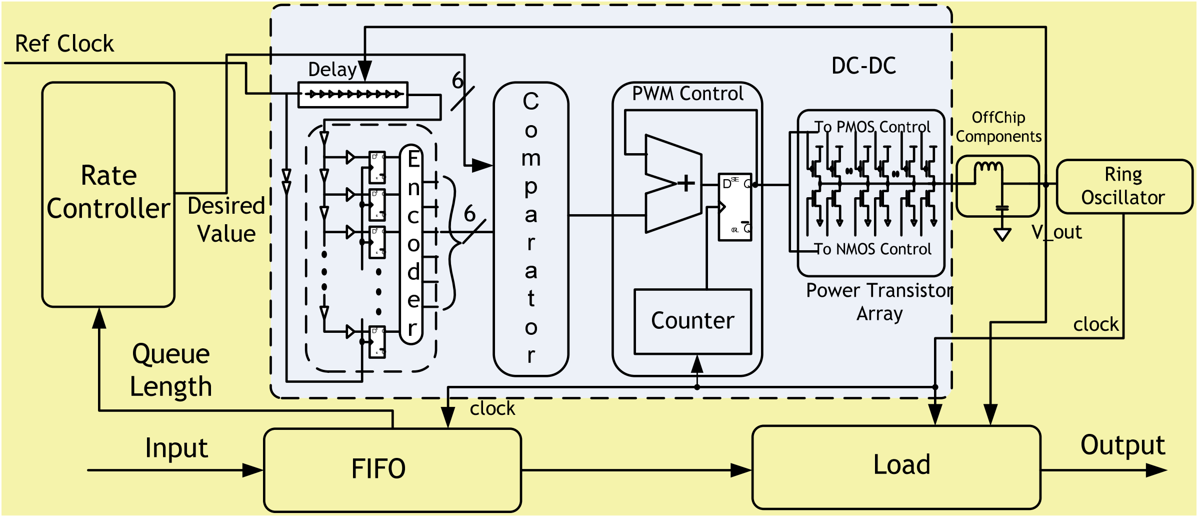
Challenges: Process and Temperature Variations [10]



- MEP shifted due to P & T variations
- 10% shift in V_T –> V_{min} shifted by ~50mV



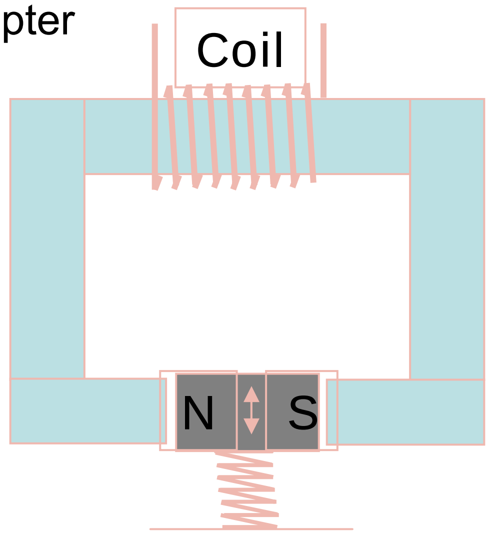


Controllers can help bring the minimum energy point adaptively [10]

Electromagnetic Based Micro-Generators

- Electromagnetic induction: movement between coil and magnetic field, will produce an electrical current

Flux interrupter



$$P_{L\max} = \frac{m\omega_n^3 Y^2}{16\xi_P}\left(\frac{R_{load}}{R_{load} + R_{coil}}\right)$$

Power in the load limited by coil resistance