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Next Generation Energy-Harvesting Electronics: A Holistic Approach

Paul D. Mitcheson

holistic energy harvesting

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EPSRC Project

Consortium of 4 universities:

University of Bristol · Imperial College London · Newcastle University · University of Southampton

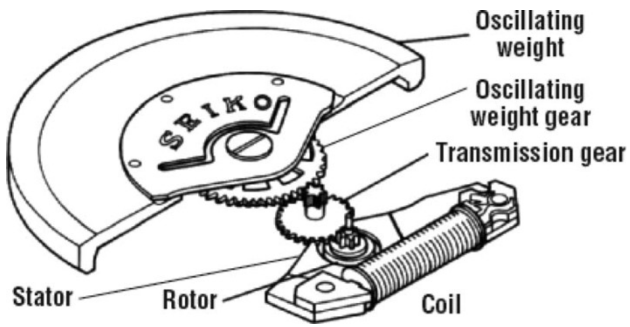
With an industrial advisory board:

ARM · Diodes Incorporated · Mentor Graphics · NXP · QinetiQ

How do we optimally design a self-powered adaptable system, from harvester to load functionality?

Energy Harvesting – quick overview

- Capture energy from the environment and convert to an electrical form



Seiko kinetic watch generator

- PMG17 from Perpetuum Ltd
- Resonant generator tuned to 100 or 120 Hz
- 55 mm diameter x 55 mm length
- 4.5 mW output power (rectified DC) at 0.1g acceleration

If commercial solutions exist, what are we doing in this project?

Past Work on EH powered systems

- Past work energy harvester powered systems has not looked at the complete system
- Many people have designed and prototyped at the subsystem level
  - They define interfaces
  - Build the subsystems
  - Plug them together
  - And *possibly* produce a self powered system

But isn't this how we tend to design many systems?

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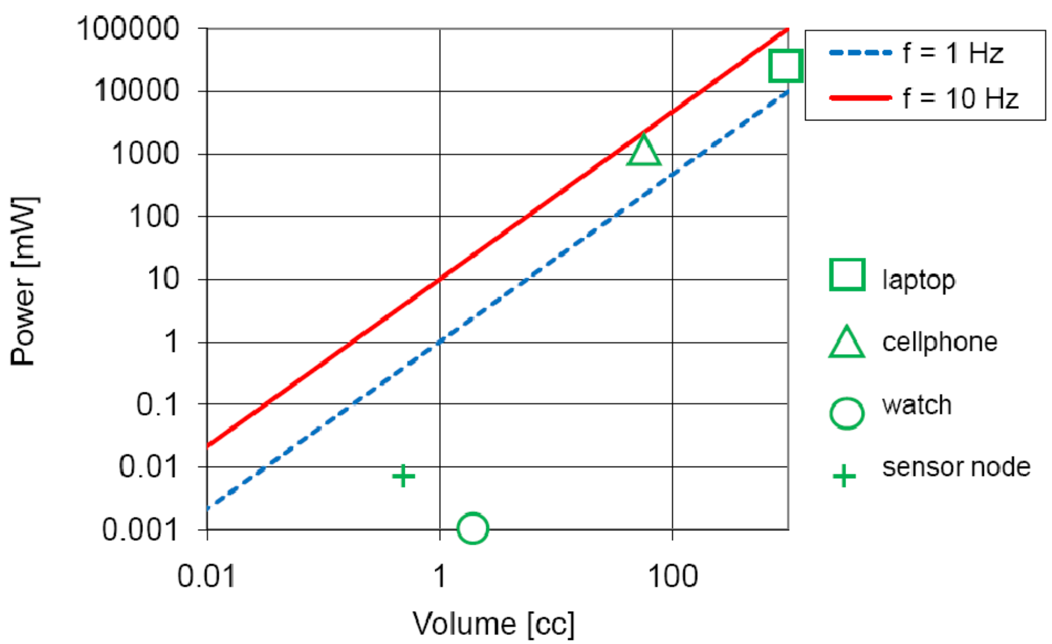
Holistic Design for the Miniature WSN

What can we power from low frequency vibrations?



- *1g acceleration*
- *Watch relatively easy to power*
- *Sensor node is around 2 orders of magnitude harder*
- *Forget the laptop and cell phone for several years… (forever?)*

Miniaturisation makes it more and more important to optimise

- ***Interfaces become less ideal***
- ***Interactions between subsystems start to dominate***

Effectiveness of Previous Harvesters

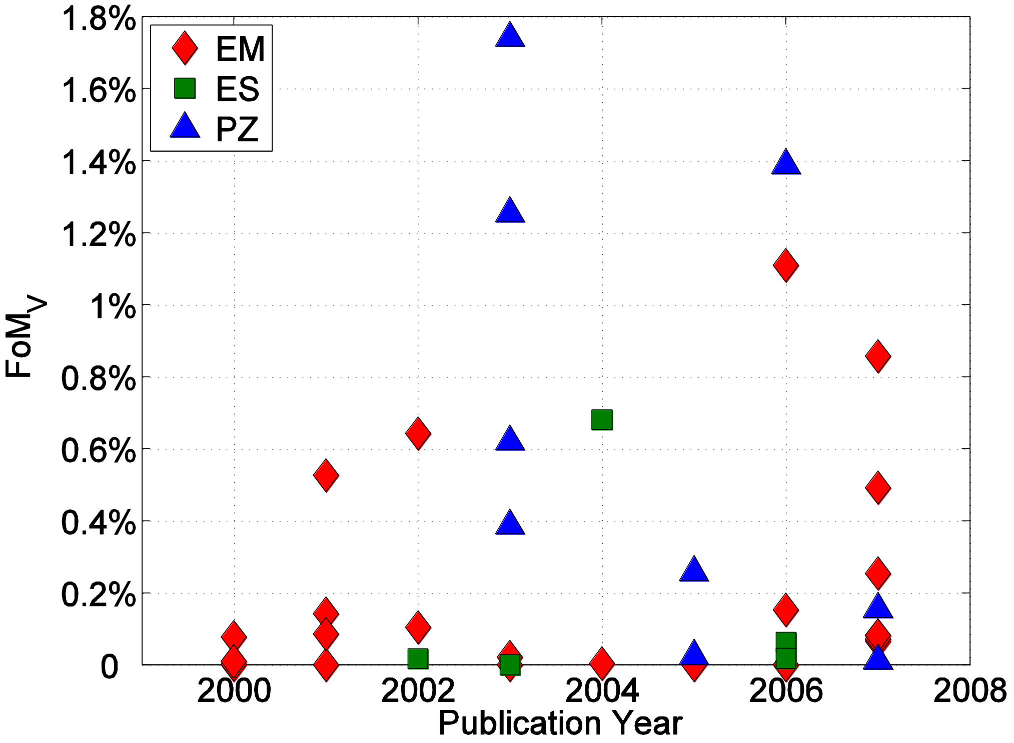
Volume Figure of Merit defined as:

$$FoM_V = \frac{\text{Useful Power Output}}{\frac{1}{16}\rho_{Au} Vol^{4/3} Y_0 \omega^3}$$

Represents ratio of output power to that of idealised generators on slide 7

Best devices to date achieve only about 2%

⇒ Can we improve with a holistic approach?



Mitcheson P.D., Yeatman E.M., Kondala Rao G., Holmes A.S., Green T.C., "Energy harvesting from human and machine motion for wireless electronic devices", Proc. IEEE 96(9), (2008), 1457-1486.

Why is the holistic optimisation important?

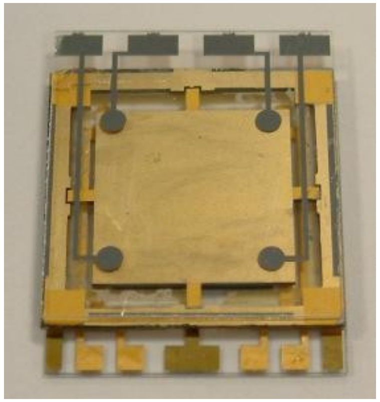
- Subsystem Interaction
  - No individual subsystem can be assumed unaffected by other subsystems
  - Improving one may degrade another

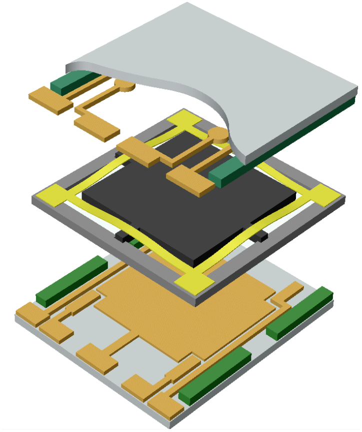
- Adaptability
  - If the energy input decreases, the load should know about it – and try to conserve power
  - If the vibration input changes amplitude, the transducer damping force must adapt. The new value needs to be calculated somewhere
  - The system resonant frequency must track the vibration frequency

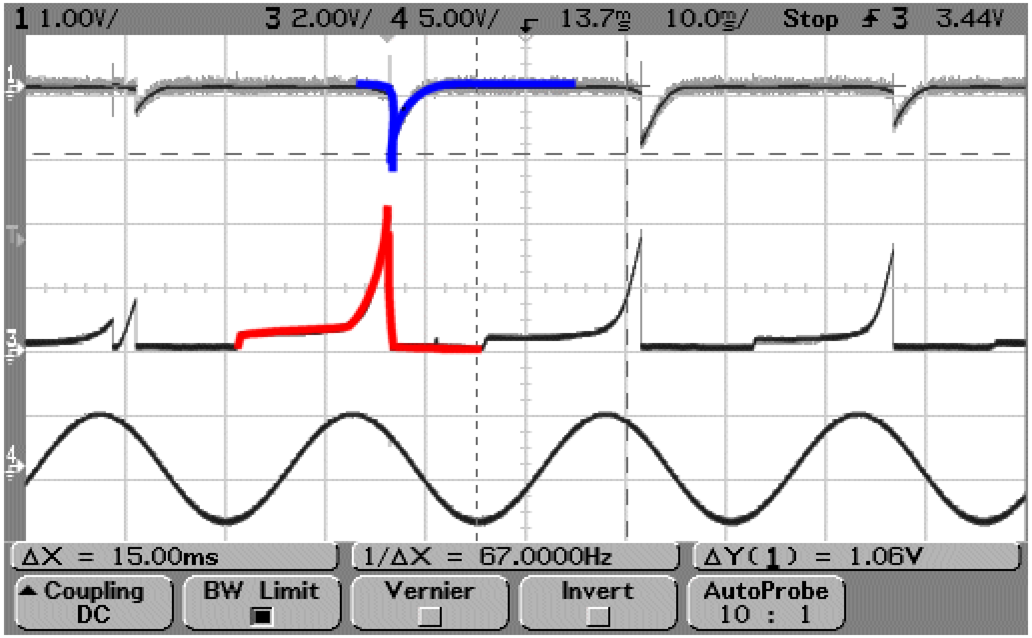
Electrostatic Harvester Interactions

Design electronics in conjunction with transducer

Electrostatic generator - Imperial College, 2004



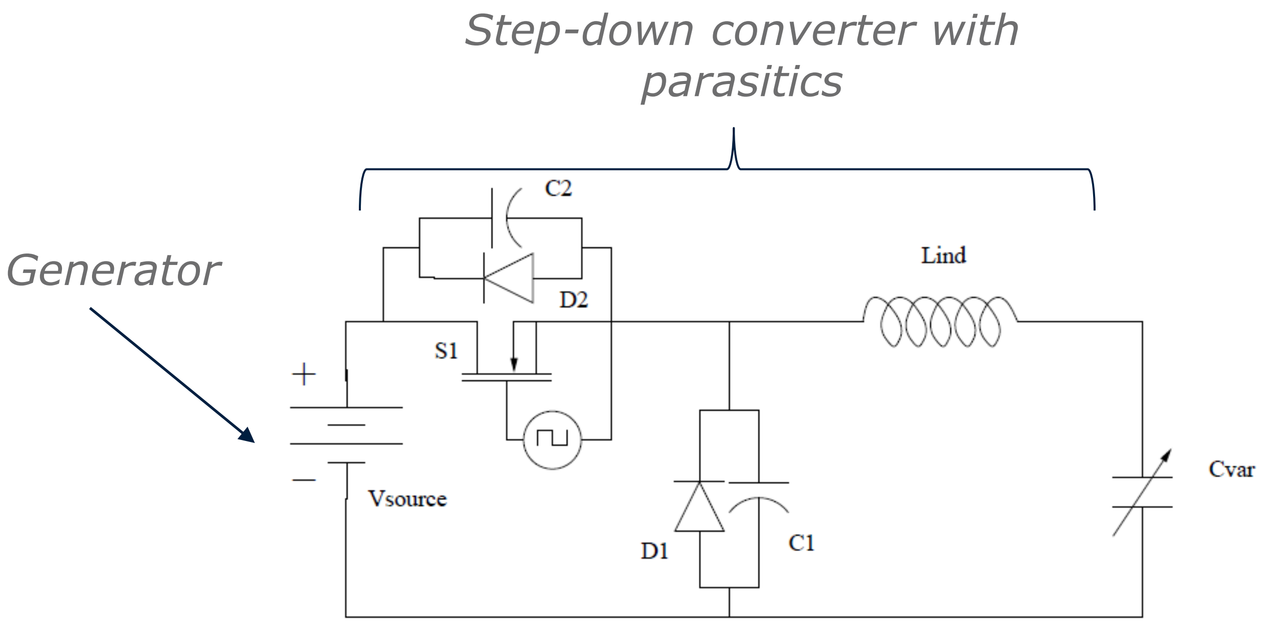




What is the final combination of voltage and charge on the generator?

Holistic approach to transducer and power electronics

Now we need to do co-design and optimisation of the transducer, circuit, semiconductor devices and mechanical interactions…



We must write equations which allow us to optimise the whole system

Trade off: Large area semiconductor devices mean low conduction loss but high charge sharing. What is the optimal design?

Circuits equations in terms of acceleration and length

Develop equations for the circuit in terms of the mechanical system:

$$V_{plate-opt} = 2.07 \times 10^{7} \sqrt{L^{3} A_{cc}}$$

$$I_{leakage} = 1.78 A_{semi} \sqrt{(V_0 - V_{operation})} \left[L_c{}^{3} A_{cc} \right]^{1/4}$$

$$C_j = \frac{2.337 \times 107\, A_{semi}}{\left[L_c{}^{3} A_{cc} \right]^{1/4} \sqrt{V_0 - V_{operation}}}$$

There are two stages to the optimisation:

- *Calculate how much energy is actually generated on the capacitor*
- *Calculate how much of this is available from the output of the converter*

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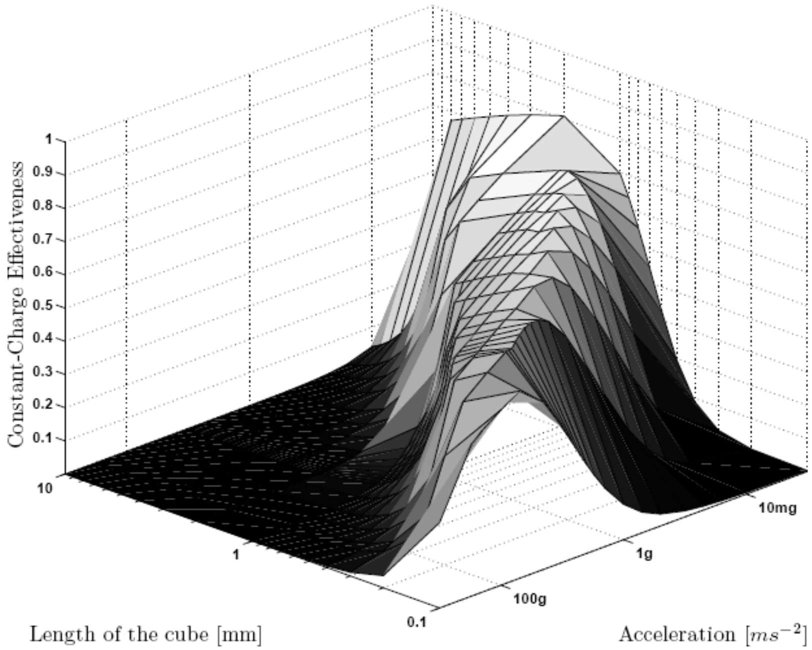
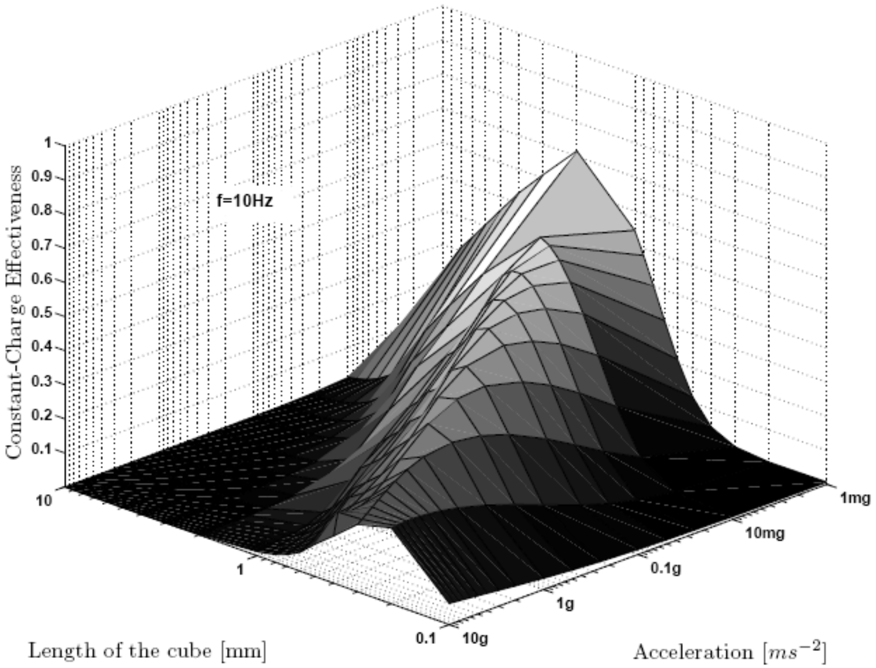
Results of global optimisation



Effectiveness at high frequency



Effectiveness at 10 Hz

- Electrostatic transducers are very poor at low frequency and at large sizes and low acceleration
- Very hard to make one work well at a few Hz or greater than 10mm in length and
- ***Limits only become apparent when considering whole system***

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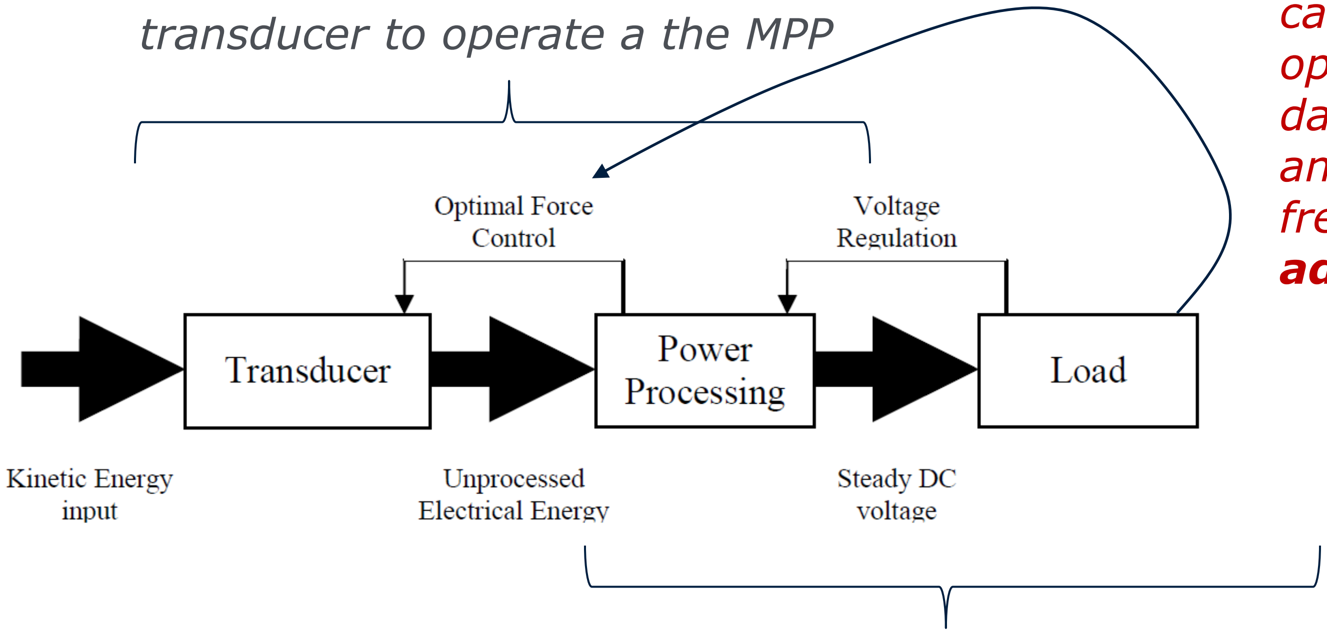
Holistic approach

There are two direct interactions to take account of:

The electronics must allow the transducer to operate a the MPP

*Load must calculate optimal damping force and resonant frequency - **adaptability***

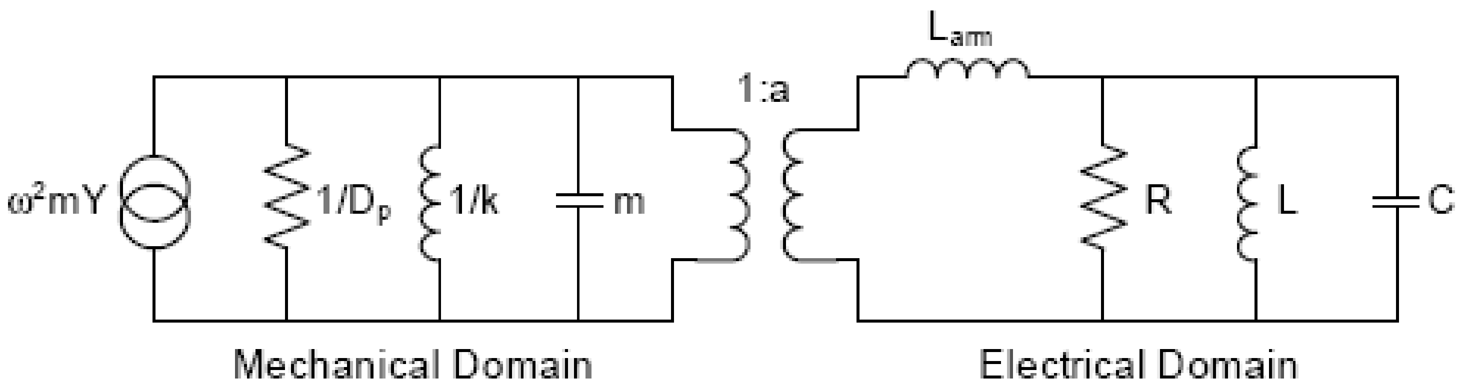


The load should operate efficiently off a poorly regulated supply

And one other interaction…

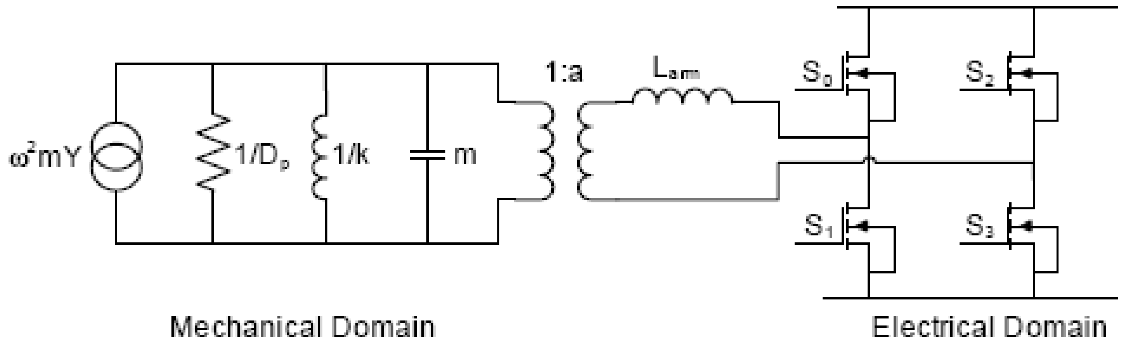
Adaptability of Harvester

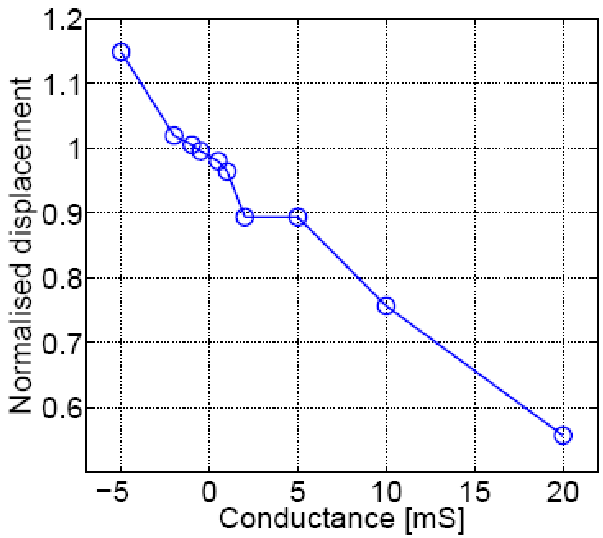
How do we make a device tune resonant frequency and damping?

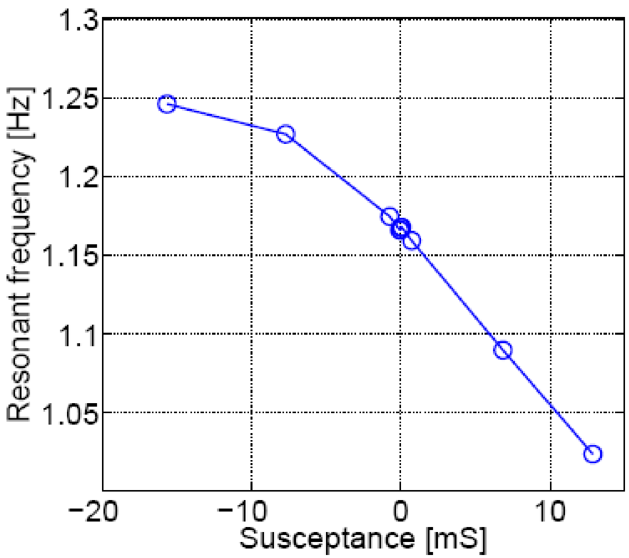


- *We can modify the mechanical system (primary side)*
- *We could modify the electrical side*
- *Can we do that in a continuous way?*
- *Not clear which approach is best*

Power Electronics for adaptability







Tuning the Resonant Frequency and Damping of an Energy Harvester Using Power Electronics, submitted IET Electronics Letters, Jan 2011

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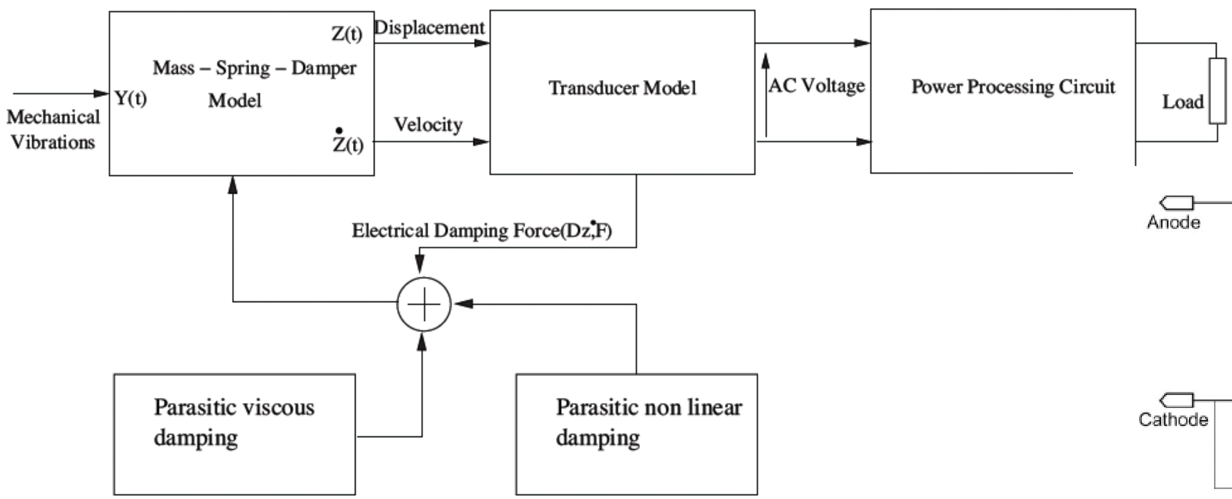
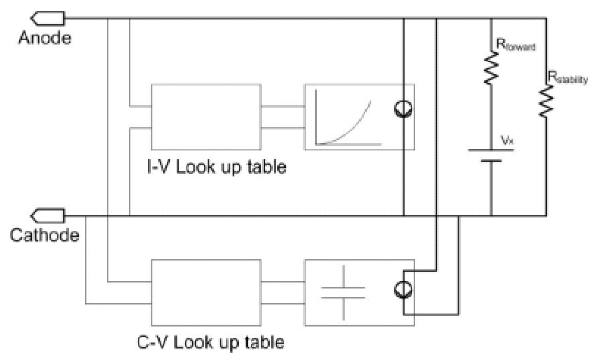
Holistic System Modelling

- Include the non-linear mechanical components (mass limited travel, spring hardening)
- Include custom semiconductor device models
- All done in SPICE – Imperial College Energy Harvesting Toolkit (ICES)





Kondala Rao G, Mitcheson PD, Green TC, Mixed Electromechanical Simulation of Electrostatic Microgenerator Using Custom-Semiconductor Device Models, PowerMEMS 2009, Pages:356-359

Detailed Mechanics

Custom device model

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New Modelling Approaches

- The previous full SPICE model is accurate but slow
- We are now working on various other modelling approaches

Simulation of 1 hour with 0.1ms time step			
Simulator	SystemVision (VHDL-AMS)	OrCAD (PSPICE)	Visual C++ (SystemC-A)
CPU time (P4, 2G RAM)	4h 24min	9h 48min	6h 40min
DATA file size	1099MB	777MB	Controllable

- These are faster for simulation without modification – although they can be modified further
- They are more easily ported into the complete design flow (this is harder with SPICE)

L. Wang, T. J. Kazmierski, B. M. Al-Hashimi, A. S. Weddell, G. V. Merrett, and I. N. Ayala Garcia, "Accelerated simulation of tunable vibration energy harvesting systems using a linearised state-space technique", Design, Automation and Test in Europe 2011 (DATE 2011), Grenoble, France, 14-18 March 2011 [in press]

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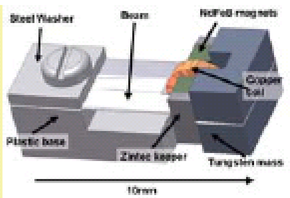
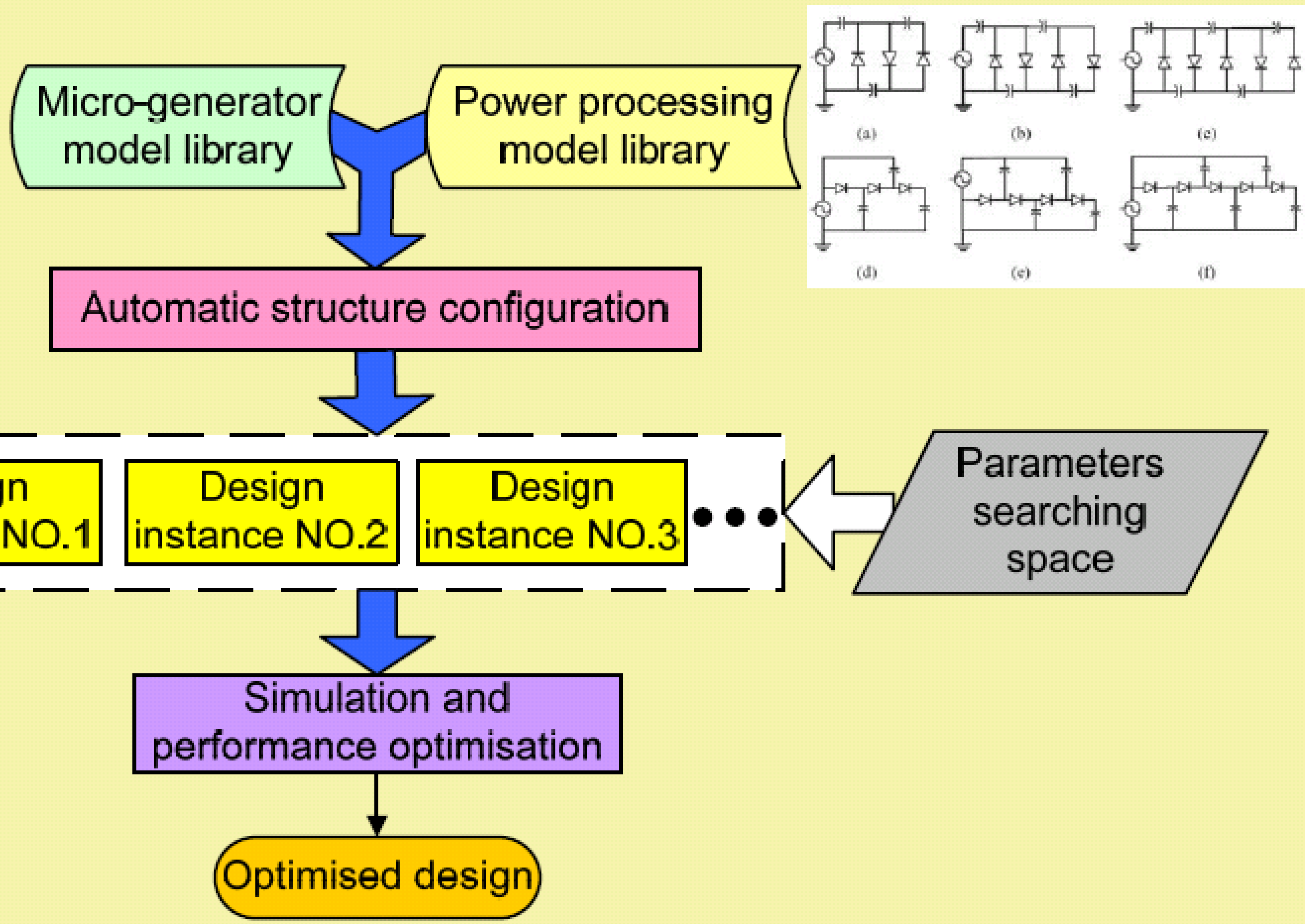
Proposed Design Flow



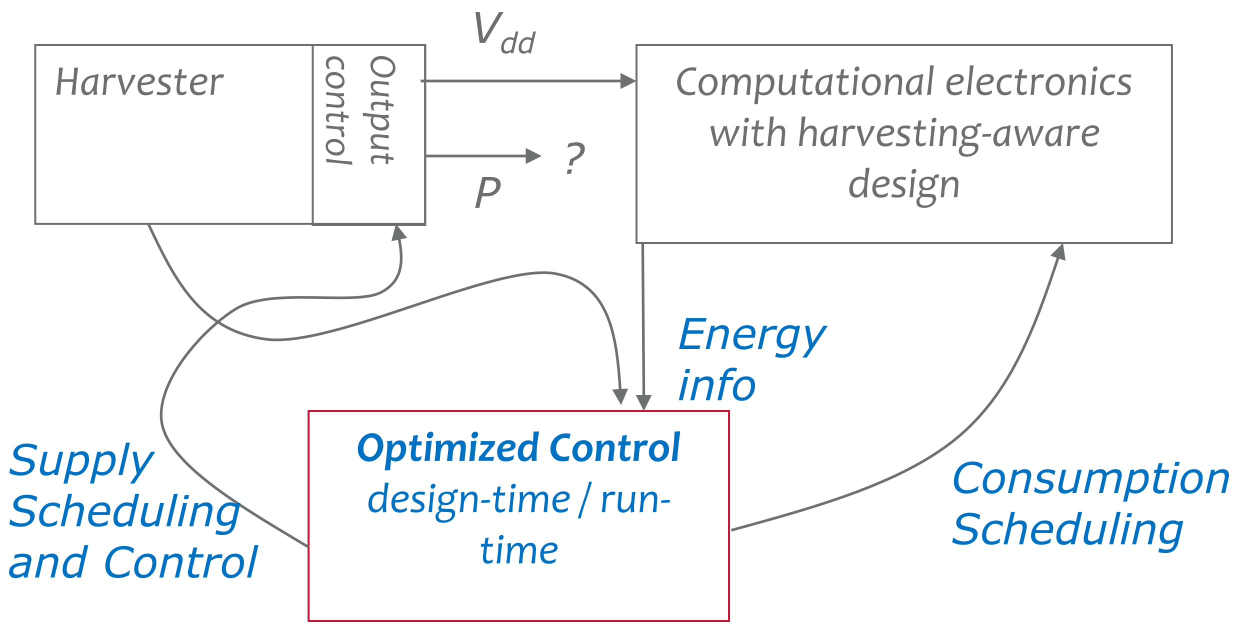
Proof mass, magnet size, beam length, wire diameter, coil radius, coil thickness



Dr Tom Kazmierski
Prof Bashir Al-Hashimi
Dr Leran Wang
Dr Geoff Merrett
Alex Weddell

Complete System Overview

Work by Newcastle on low power harvester-aware loads::



- *Harvester and power electronics must be co-designed*
- *Computational load must calculate parameters to allow harvester to track MPP*
- *Load must be aware of rate of energy generation and reserve*

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Conclusions

- Whilst commercial harvester are available, and systems are deployed, further miniaturisation requires a holistic approach
  - System interfaces become less well defined and less ideal
- Adaptive devices are necessary if harvesters are to be less bespoke in design
- This can be done using electronics or through mechanical means
- Holistic system modelling is a difficult talk – different parts of the system operate with different time constants

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