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Next Generation Energy-Harvesting Electronics: A Holistic Approach

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holistic energy harvesting

EPSRC Project

Next Generation Energy-Harvesting Electronics: Holistic Approach

Consortium of 4 universities:

With an industrial advisory board:

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Overview

- Background
- Project aims and Objectives
- How bad is design in isolation?
- Holistic model of electrostatic harvester
- Adaptive harvester
- Holistic Modelling approaches/software
- Future work

Orders of Magnitude of Power

World electrical generation capacity	4 terawatts
Power station	1 gigawatt
House	10 kilowatts
Person, lightbulb	100 watts
Laptop, heart	10 watts
Cellphone power usage	1 watt
Wristwatch, sensor node	1 microwatt
Received Cellphone signal	1 nanowatt

Sensor nodes are receiving a lot of interest – but the constraints on volume and power are significant and we must push design to the limit

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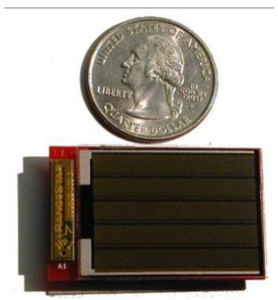
Energy Harvesting – quick overview

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



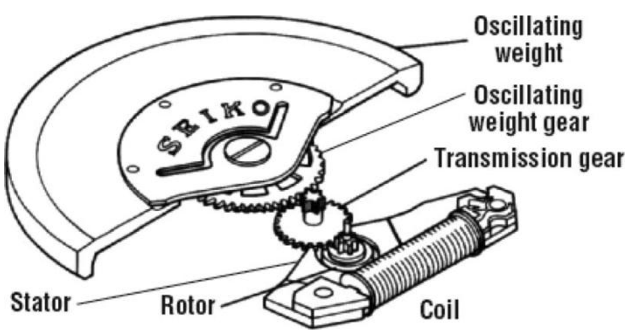
Pico Radio solar cell
[UC Berkeley]

•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



Seiko kinetic watch generator

So if you can buy commercial harvesters these days, what's the problem?

Past Work on EH powered systems

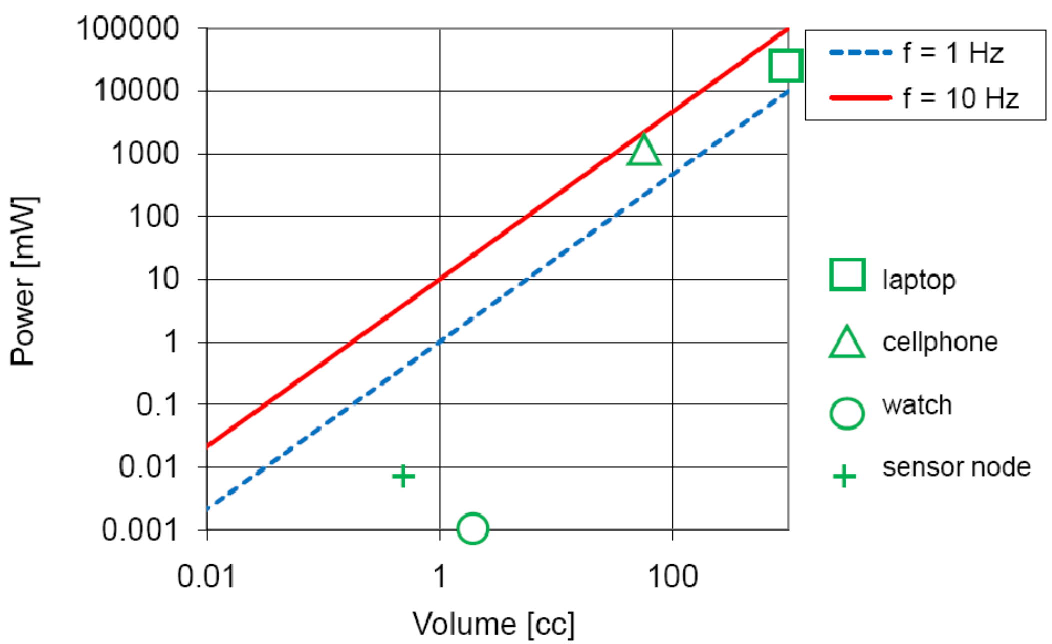
- Most past work energy harvester powered systems has not looked at the complete system
- Many people have designed and prototyped at the subsystem level
  - They define interfaces
  - Build the subsystems
  - Plug them together
  - And possibly produce a self powered system

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

Yes – but with energy harvesters powering WSNs we are very close to the limits and the global optimum become increasingly important

Why is it difficult to realise a self powered 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…*

We have to optimise the system globally to have a chance of making it functional

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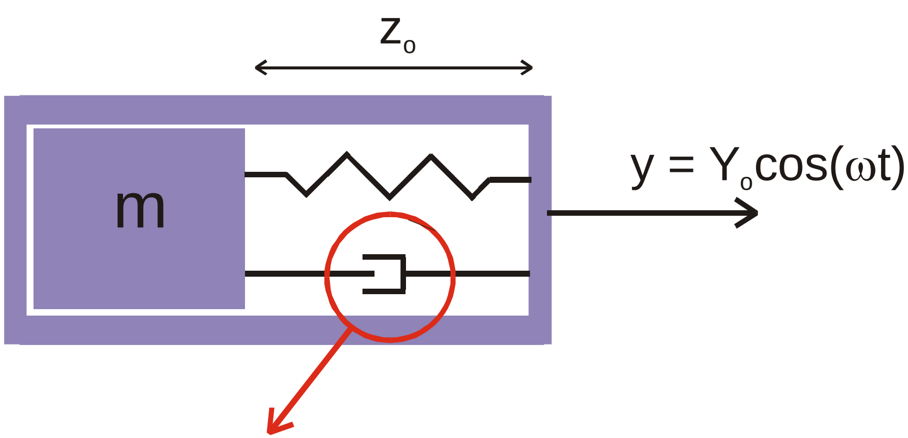
We are basing the work on inertial harvesters

- Entire device is attached to moving “host” e.g. machine, person…
- Peak inertial force on proof mass: $F = ma = m\omega^2 Y_o$
  where a is the peak acceleration applied by the host
- Damper force < F or no internal movement

$\Rightarrow$ Maximum work per transit: $W = FZo = m\omega^2 Y_0 Z_0$

$\Rightarrow$ Maximum power: $P = 2W/T \quad = m\omega^3 Y_0 Z_0/\pi$



damper implements energy conversion

Maximum power only achieved when the damper is correctly set

$$\zeta_{opt} = \frac{1}{2\omega_c}\sqrt{\omega_c^{\,4}\left(\frac{Y_0}{Z_0}\right)^2 - (1-\omega_c^{\,2})^2}$$

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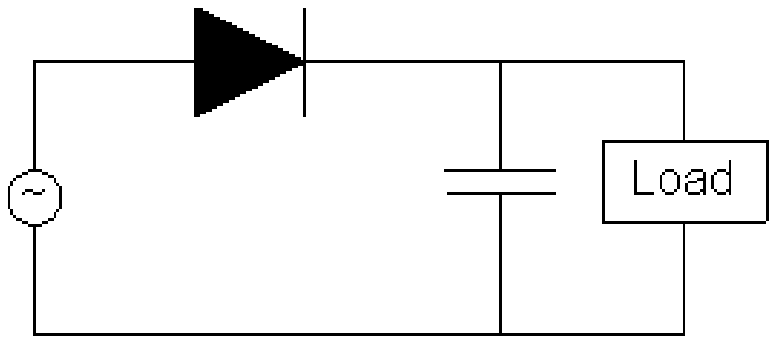
Naive Viewpoint

Harvester generally produces AC output, so why not use a rectifier and a capacitor?



- This may work to some extent – but no attempt has been made to set the optimal damping force.
- We also need to think about energy storage and regulation

Effectiveness of Previous Harvesters

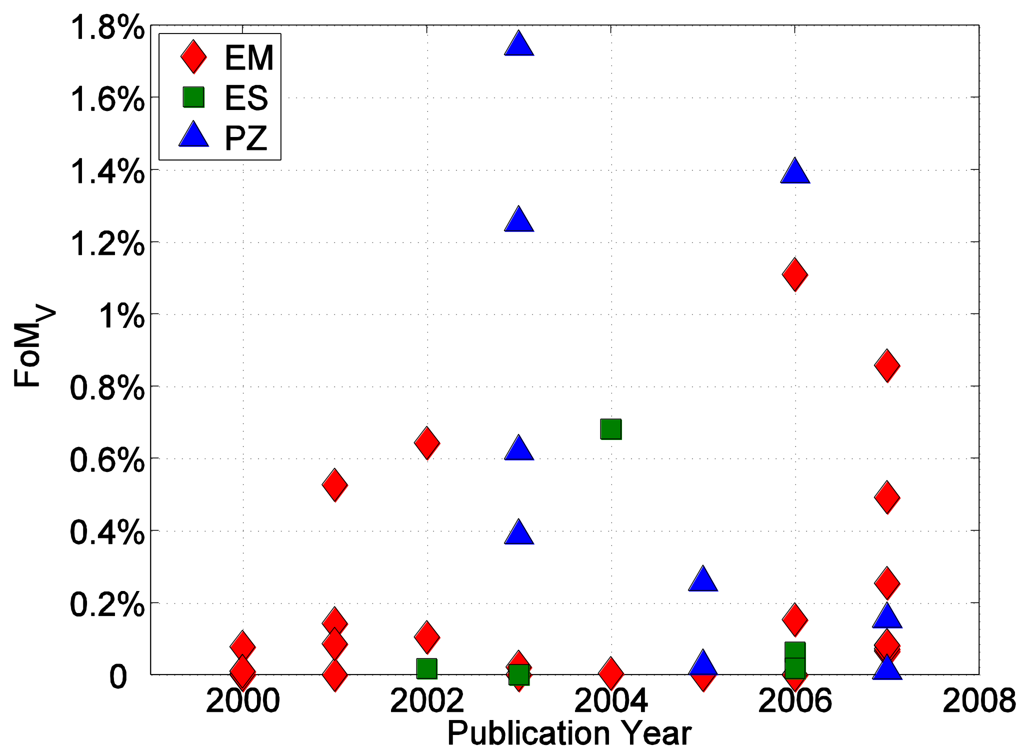
Volume Figure of Merit defined as:

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

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.

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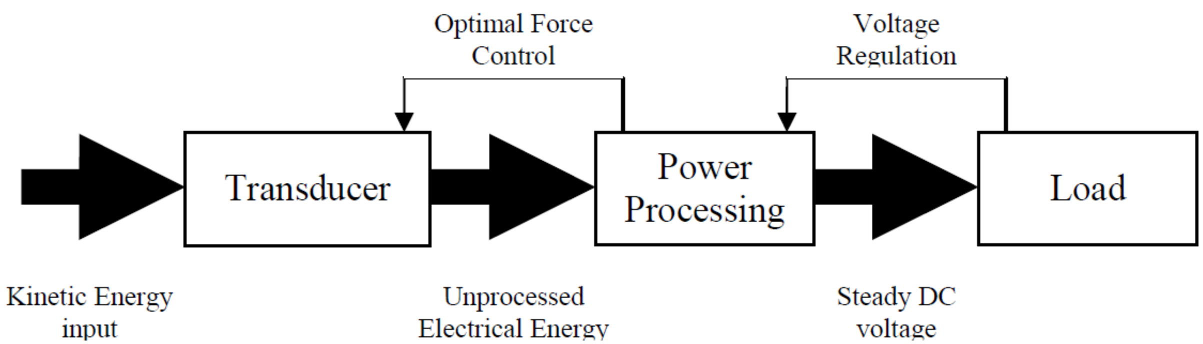
Holistic Project Aims

We want to achieve the highest load functionality per unit volume of energy harvester, from a particular vibration source

- Fully consider the interactions between energy harvester, power processing and load



- Design and construct an adaptive harvester
- Investigate and prototype logic design for unpredictable energy sources (varying power and voltage)
- Develop a modelling and optimisation methodology and associated software
- Produce an energy harvesting system with a high effectiveness

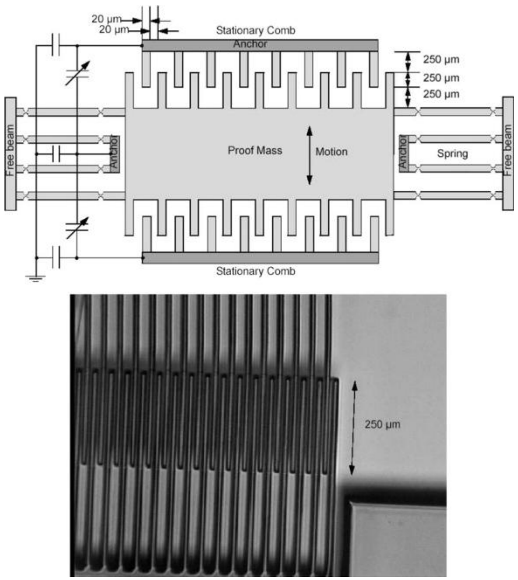
Why is the holistic optimisation important?

- There are two way interactions between each part of the system
- No individual subsystem can be assumed unaffected by other subsystems
- 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
- If the vibration input has a change in frequency, the resonance frequency of the generator should adapt – the actuation value must be computed
- If the load changes, the motion of the proof mass changes and so does the voltage output from the transducer
- How do we optimise and model a system containing mechanics, circuits, semiconductor devices, computation and algorithms?

Design in isolation - example

Design the electronics, then the transducer

MIT designed an electrostatic comb-drive generator to be compatible with low voltage CMOS power electronics



Chandrakasan et al, MIT

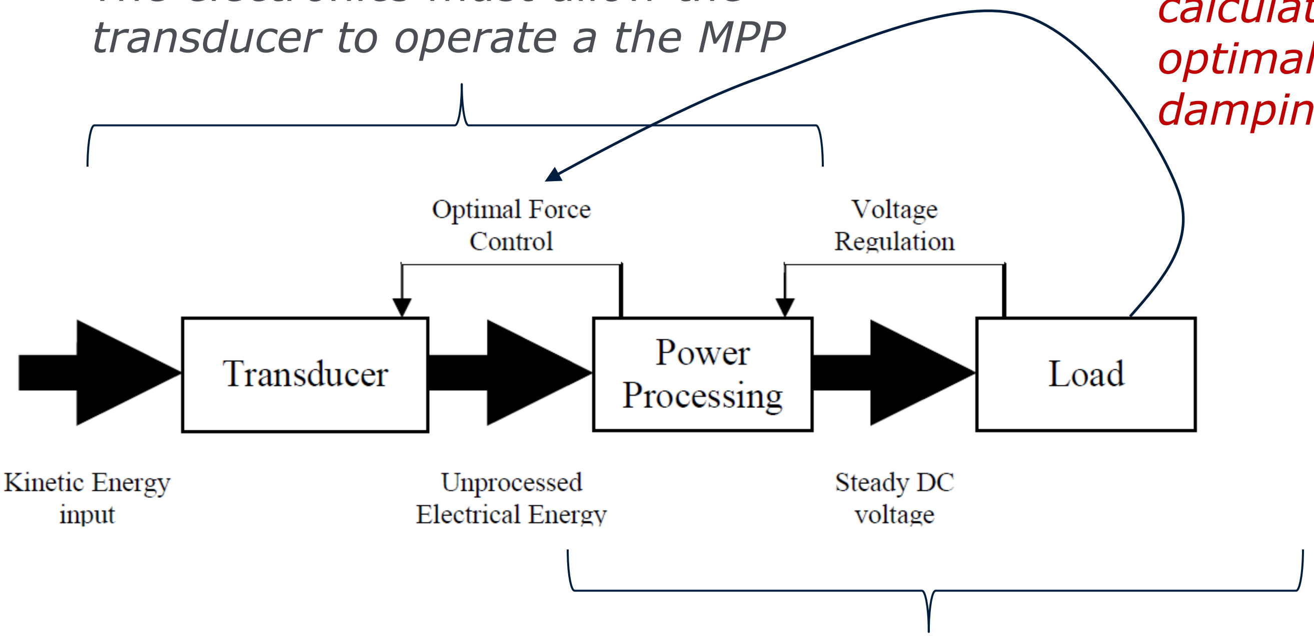
- *Even though the electronics can have high efficiency, the overall system effectiveness was < 0.1%*
- *Can't achieve high enough voltage on the transducer to maximise work done*

Can we do better with a 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



The load should operate efficiently off a poorly regulated supply

And one other interaction…

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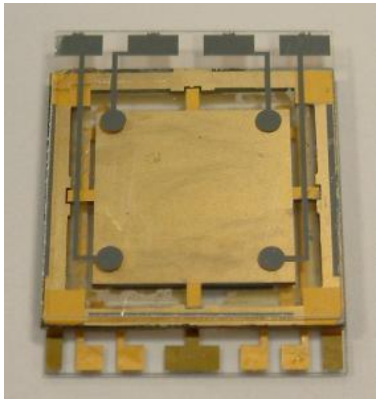
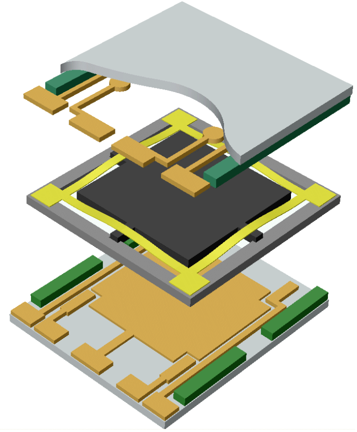
Holistic approach to electrostatic design

Design electronics in conjunction with transducer





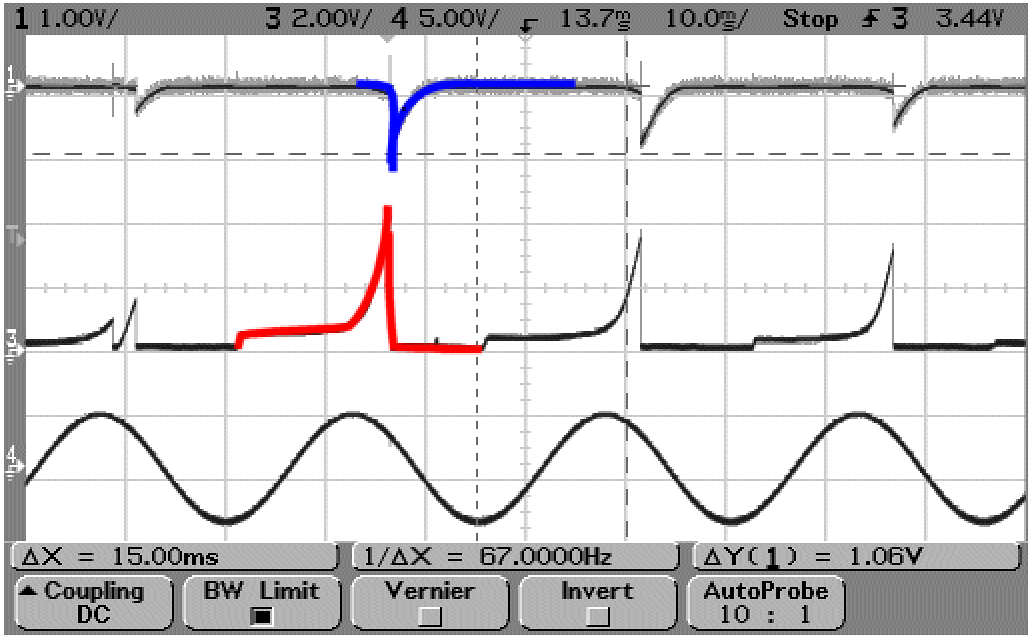
Electrostatic generator - Imperial College, 2004

- *Capacitor charged at high capacitance*
- *Inertia and motion causes plates to move apart*
- *Voltage on plates rises*
- *Electrical energy generated*
- *Pre-charge the capacitor to get just the right force to maximise force times distance*

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

Output of device

- *Depends on the vibration source but can easily be hundreds or thousands of volts and only a few nC of charge*
- *Very Difficult to design the power electronics*



Off the shelf devices are not available – must design custom devices

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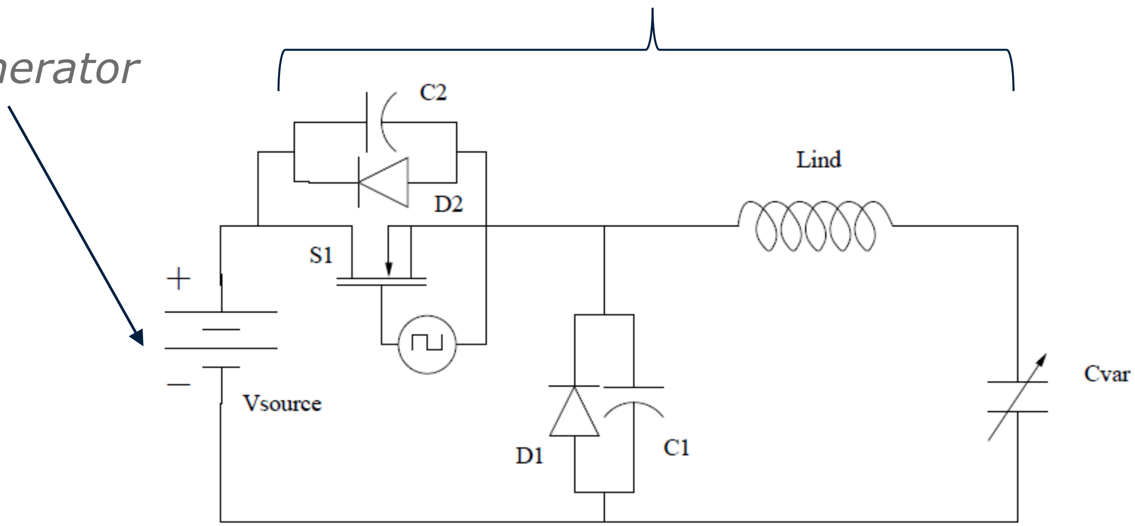
Holistic approach to transducer and power electronics

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

Step-down converter with parasitics

Generator



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

Trade off: Large area devices mean low conduction loss but high charge sharing

Circuits equations in terms of acceleration and length

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

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

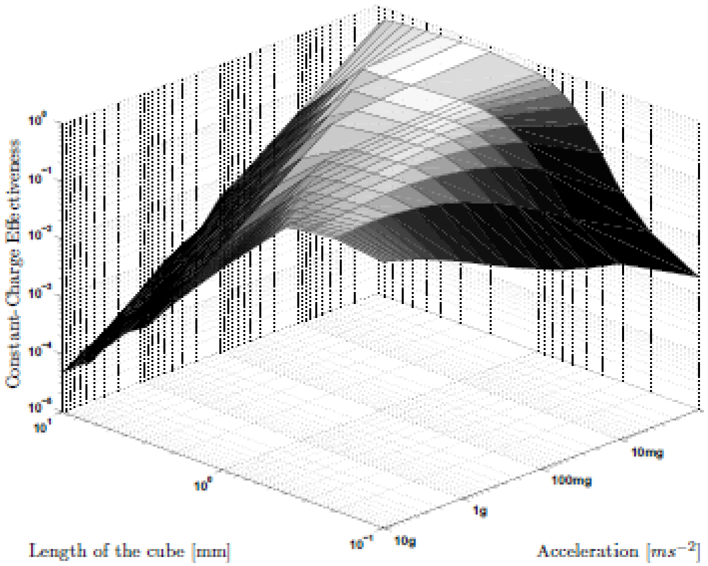
$$I_{leakage} = 1.78 A_{semi} \sqrt{(V_0 - V_{operation})} \left[L_c{}^{3} A_{cc} \right]^{1/4}$$

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

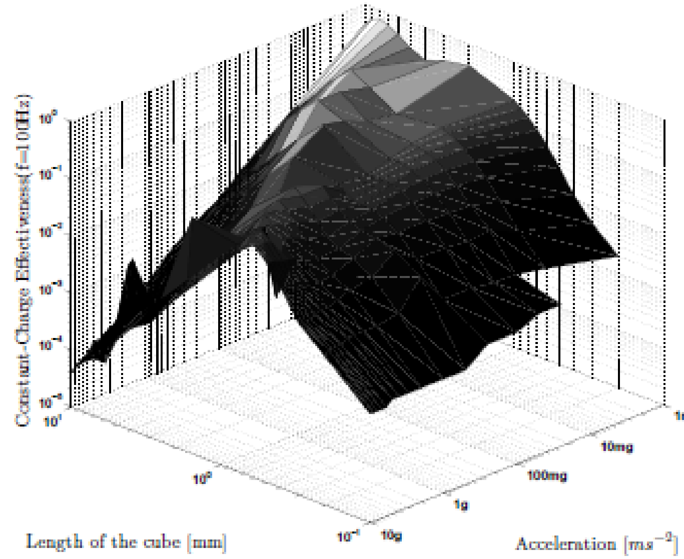
There are two stages to the optimisation:

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

Results of global optimisation



Effectiveness at high frequency

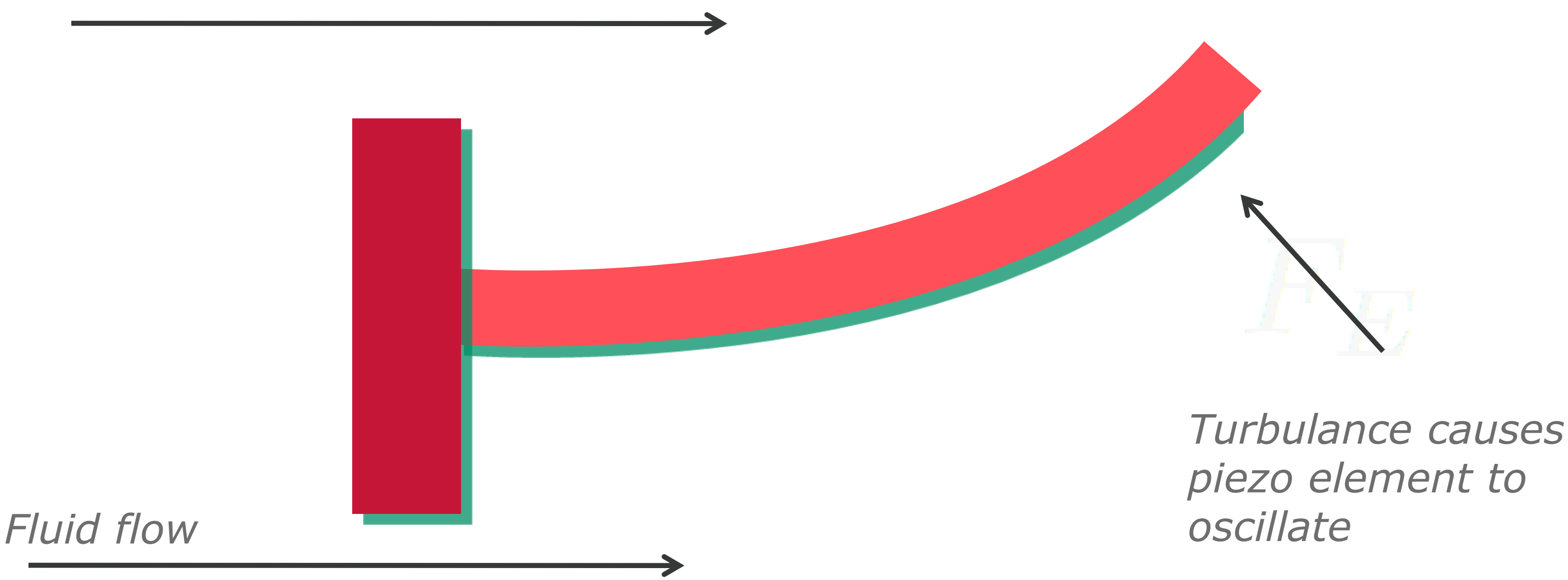


Effectiveness at 1 Hz

- Electrostatic transducers are very poor at low frequency and at large sizes
- Very hard to make one work well at a few Hz or greater than 10mm in length
- **We should be able to do much better than the previous attempts because we looked at co-design of transducer, devices and circuits… effectiveness of over 70% possible…**

Design in isolatio – piezoelectric devices

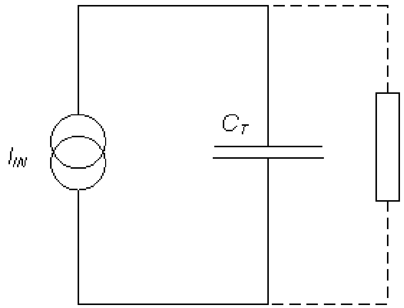
- Cantilever beam in a fluid flow
- Vortex street developed by bluff body
- Effectively infinite force on cantilever
- What is the optimal resistive load impedance for maximum power?



Challenge is to get a high force to harvest as much energy as possible

Optimum load for this case

Simple mechanical model predicts:



$$R_{opt} = \frac{1}{C_T}$$

But, if you go back and model the complete system with this load, then you find the damping this gives is small – you could increase the damping

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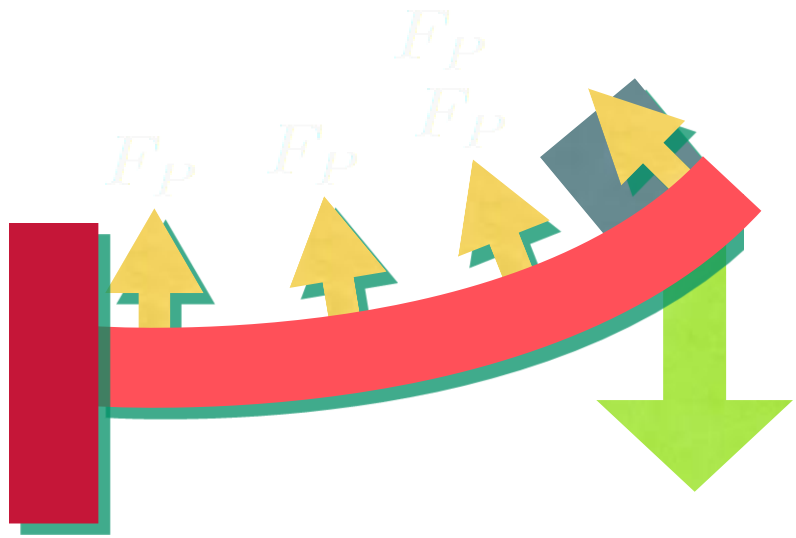
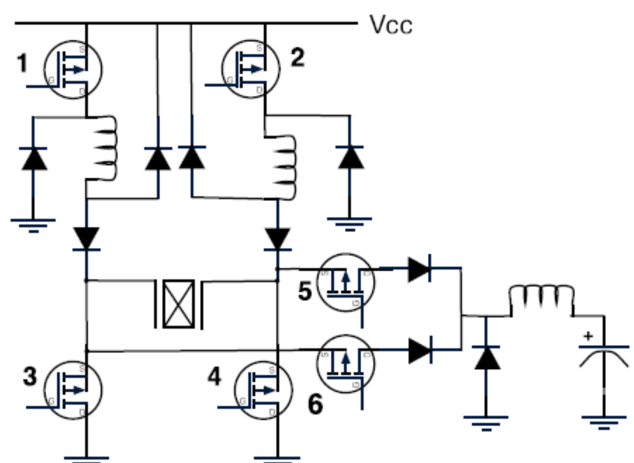
Holistic approach – Piezoelectric Pre-biasing

- Put a bias charge on piezo before it moves
- Thus more work can be done against it when it does move
- Technique demonstrated giving power output increase of 20 times over resistive load



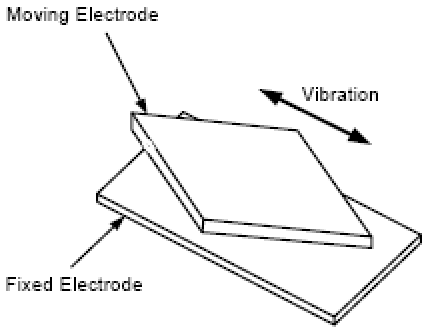


Dicken J, Mitcheson PD, Stoianov I, et al, Increased Power Output from Piezoelectric Energy Harvesters by Pre-Biasing, PowerMEMS 2009, Pages:75-78,

An Adaptive Harvester

One aims of this project is to make an adaptive harvester (variable frequency and damping)

We can make an electrostatic spring (electrically tuneable) with a diamond shuttle on a fixed rectangular electrode



Required stiffness:

- Target frequency 100 Hz, est. mass 0.1 g (integrated solution)
- Requires suspension stiffness 40 N/m
- To get reasonable tuning range need electrostatic spring > 1 N/m
- If 1 mm motion this suggests Fmax ≈ 1 mN
- For 100 V, d = 1 μm: very challenging

Still looking for a good solution…

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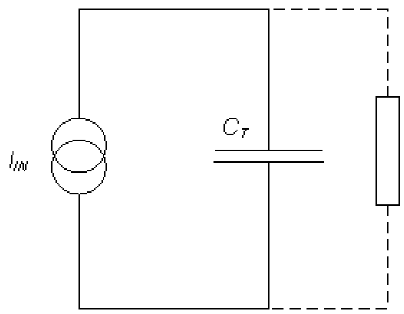
System Modelling - 1

- A major stumbling block to the optimisation of these systems is software availability
- Need to model:
  - mechanics,
  - analogue/power circuits at device level
  - digital circuits (not just functionally – but also under varying voltage rails)

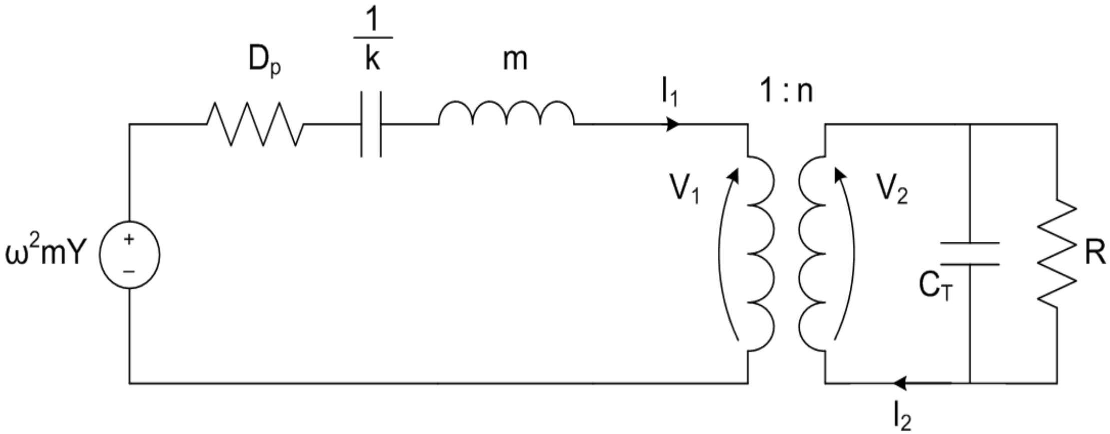
- There have been several approaches:
  - Assume the harvester generates a perfect AC voltage of fixed amplitude and frequency



Simplified model of piezo harvester

Holistic System Modelling - 2

- More sophisticated to model the interaction between the load and the generator
- Here, a short circuited load will increase the mass motion



- This can be modelled in SPICE and can allow the load circuit to be modelled with good device models

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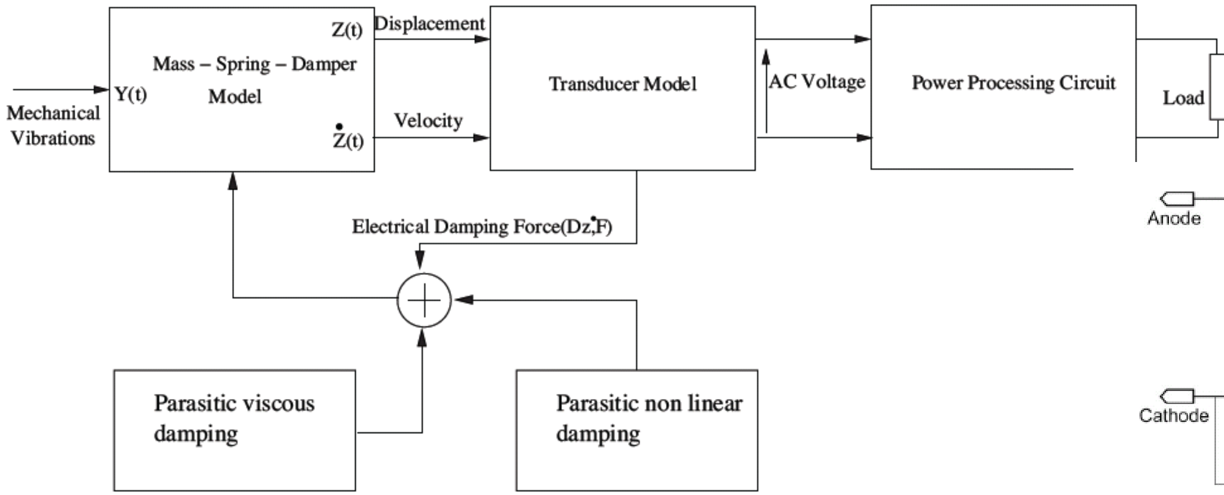
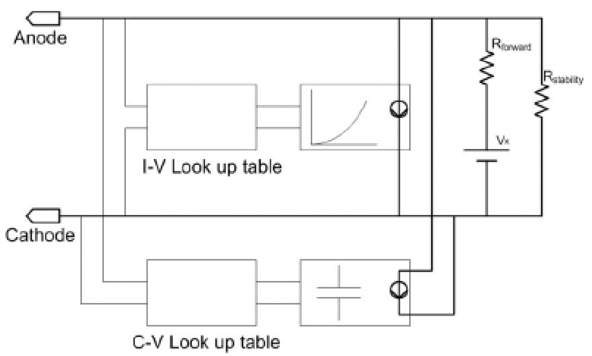
Holistic System Modelling - 3

- 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

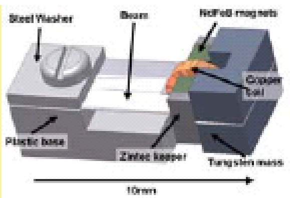
Simulation of 1 hour with 0.1ms time step			
Simulator	SystemVision (VHDL-AMS)	OrCAD (PSPICE)	Visual C++ (SystemC-A)
CPU time (P4, 2G RAM)	4h 24min	9h 48min	6h 40min
DATA file size	1099MB	777MB	Controllable

- 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)

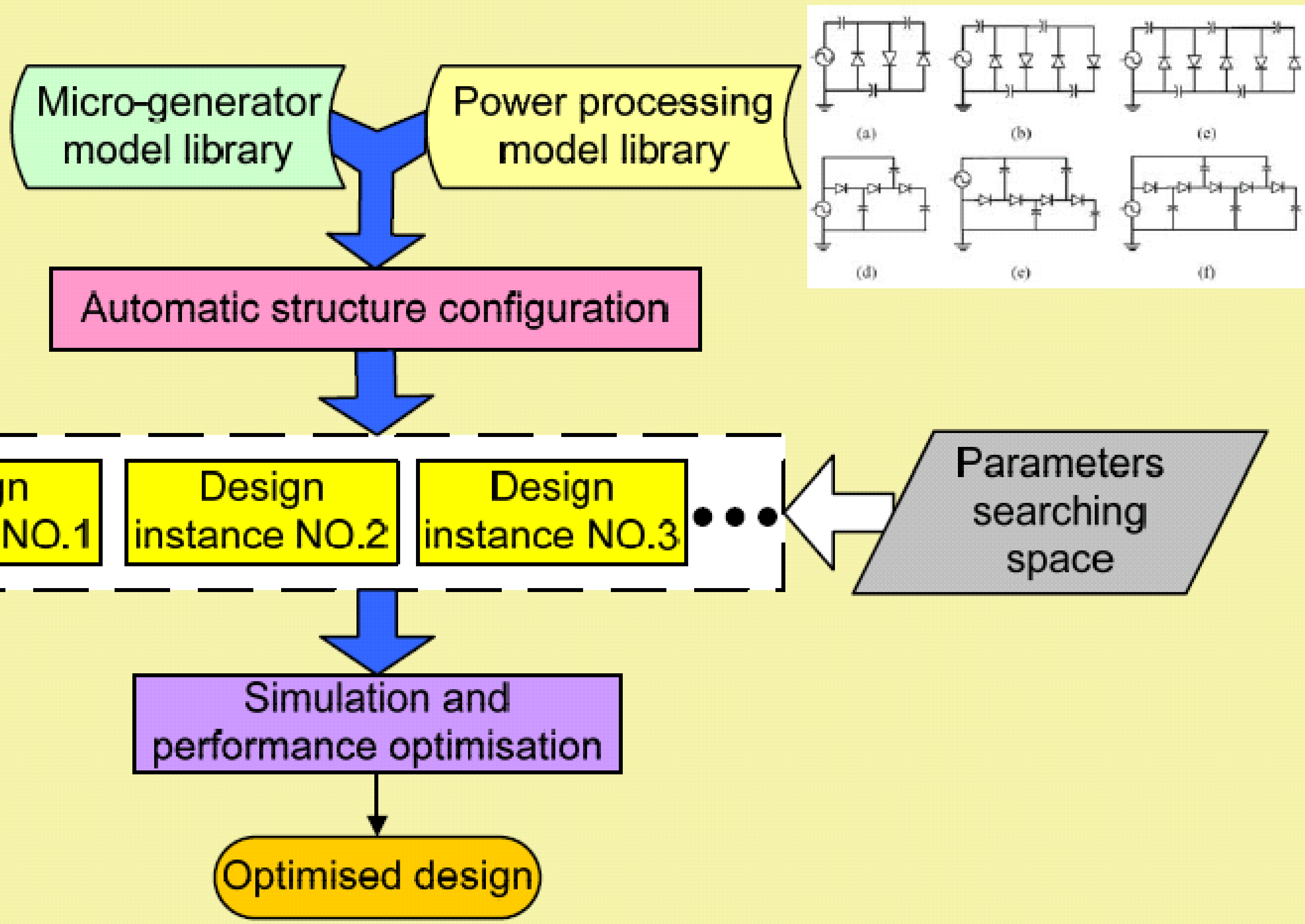
Dr Tom Kazmierski
Prof Bashir Al-Hashimi
Dr Leran Wang
Dr Geoff Merrett

Alex Weddell

Proposed Design Flow



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



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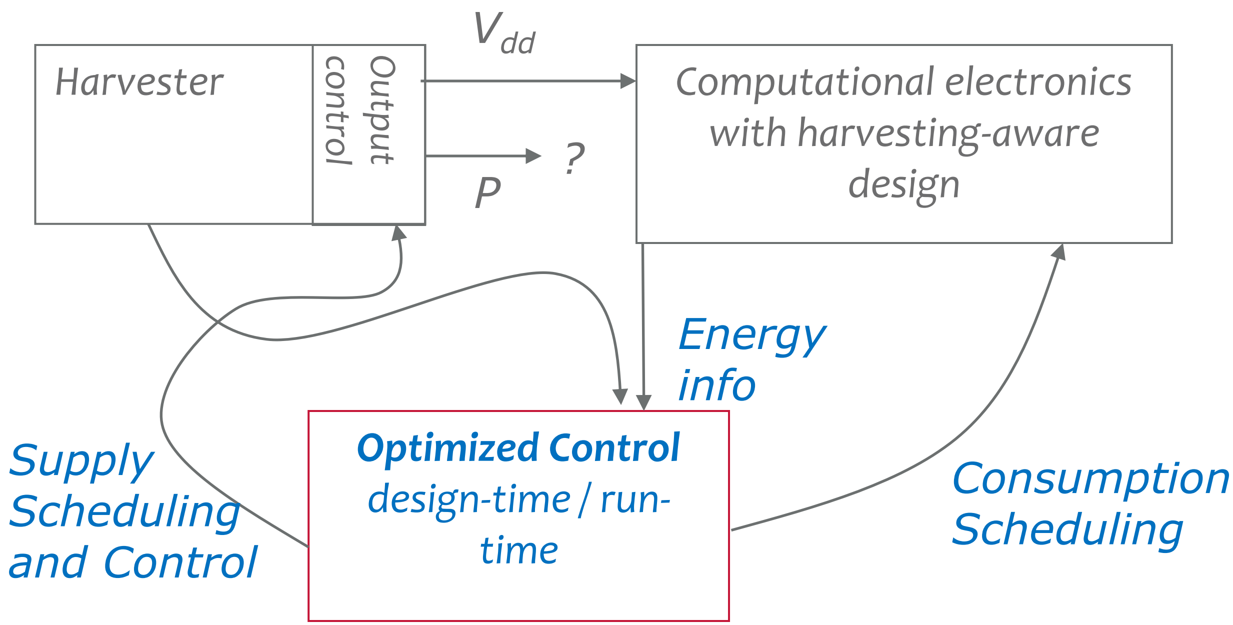
Complete System Overview

Prof Yakovlev earlier talked about the digital electronics:



- *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*

Conclusions

- Multi-disciplinary topic – mechanics, circuits, devices, algorithms
- Adaptive devices are necessary if harvesters are to be less bespoke in design
- Power is very limited and we always wanting more functionality – so we need to optimise the whole system
- Existing microgenerators are not adaptive and have poor effectiveness
- Holistic system modelling is a difficult talk – different parts of the system operate with different time constants
- Holistic approach is necessary to allow us to achieve the highest functionality per unit volume of sensor node

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