Theme C Technical Seminar
Accelerating EH simulation and design exploration

Holistic energy-harvesting project workshop and showcase
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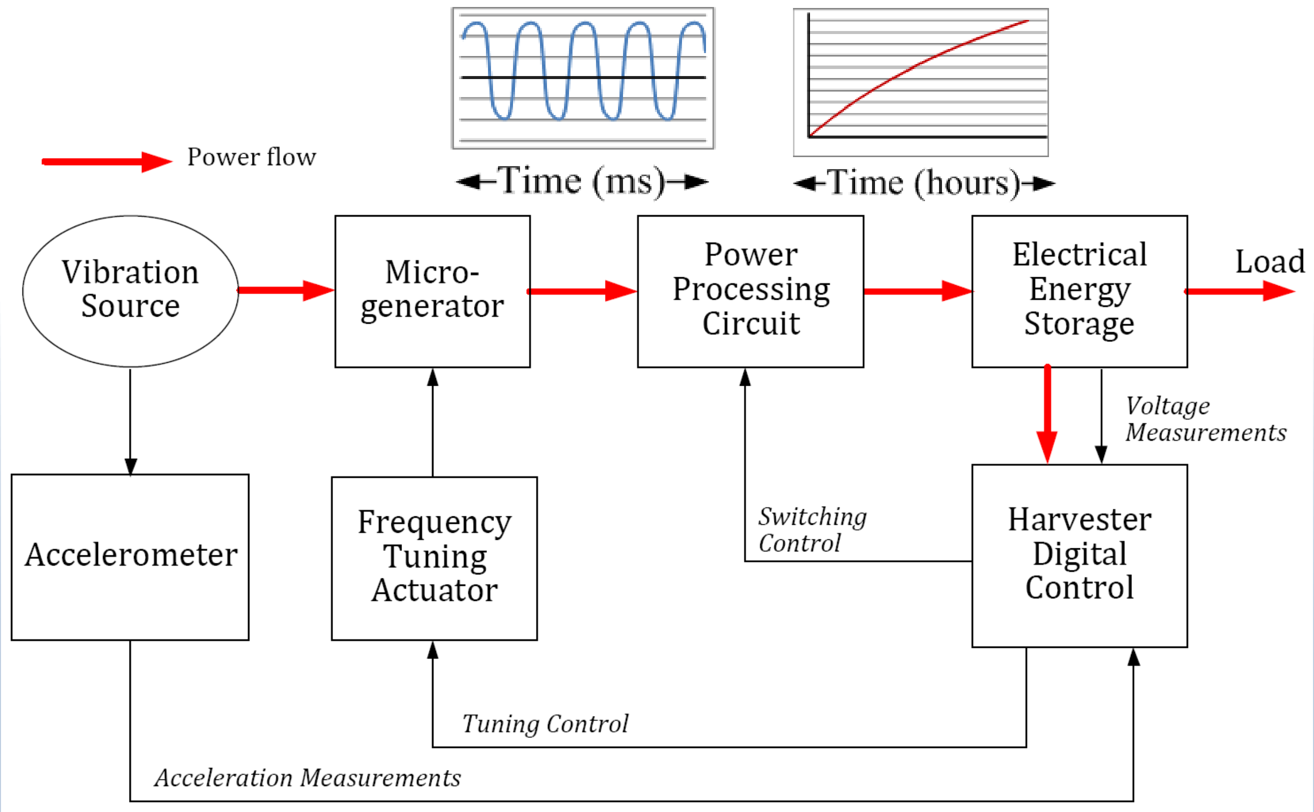
Outline

- Acceleration of EH Simulation
  - Challenge – classical simulation approaches too slow, must accelerate
  - Solution – linearised state-space technique
  - Simulation results
  - Compare CPU times on the same platform
    - Acceleration by two orders of magnitude
- Fast design exploration
  - Introduction and motivation
  - Response surface modelling technique
  - Modelling and simulation of a complete wireless sensor node powered by tunable energy harvester
    - Power consumption models of microcontroller and sensor node
    - Sensor node behaviour depends on available energy

Why EH simulations are CPU intensive

- Excessive CPU times due to disparate time scales
  - High-speed microgenerator: small simulation time step (0.1ms)
  - Low-speed storage: supercapacitor can take tens of hours to charge
- **Supercapacitor charging time is important**
  - It determines the system's duty cycle



Proposed linearised state-space technique

Existing state-of-the-art simulators use implicit equation formulation:

$$\boldsymbol{f}(\dot{\boldsymbol{x}}(t), \boldsymbol{x}(t), t); \qquad \boldsymbol{x}(0) = \boldsymbol{x}_0$$

State equations:

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), t); \quad \boldsymbol{x}(0) = \boldsymbol{x}_0$$

State equations can be solved very fast

- explicit march-in-time process
- no Newton-Raphson iterations.

However, explicit solution can be numerically unstable if step size is too large.

- State-of-the-art SPICE-like simulators do not use it.

Proposed linearised state-space technique

However, power conditioning analogue electronics in energy harvesters is **passive**.

This is how we propose to ensure stability of explicit integration with negligible computational expense:

- Linearise state equations at each time point $t_k, \; k = 0, 1, \ldots$

$$\dot{\boldsymbol{x}}_{k+1} = -\boldsymbol{J}_k(\boldsymbol{x}_k - \boldsymbol{x}_{k-1}) + \boldsymbol{f}(\boldsymbol{x}_k, t_{k+1})$$

$\boldsymbol{J}_k$ is the Jacobian of $\boldsymbol{f}$ at time point t_k

- The linearised state equation can be presented as:

$$\dot{\boldsymbol{x}}_{k+1} = -\boldsymbol{C}_k^{-1}\boldsymbol{G}_k(\boldsymbol{x}_k - \boldsymbol{x}_{k-1}) + \boldsymbol{e}_{k+1}$$

$\boldsymbol{C}_k$ - diagonal matrix representing energy storing components

$\boldsymbol{G}_k$ - diagonally dominant matrix representing resistive part of a passive electrical system, such as energy harvester electronics

Step size control

Linearised state equation:

$$\dot{\boldsymbol{x}}_{k+1} = -\boldsymbol{C}_k^{-1}\boldsymbol{G}_k(\boldsymbol{x}_k - \boldsymbol{x}_{k-1}) + \boldsymbol{e}_{k+1} \qquad (4)$$

Theorem. If $\boldsymbol{G}_k$ is diagonally dominant for all $k = 0, 1, \ldots$, the explicit Adams-Bashforth integration formulae of orders $p = 1, 2$ applied to the linearised state equation (4):

$$\boldsymbol{x}_{k+1} = \boldsymbol{x}_k + h_{k+1}\boldsymbol{C}_k^{-1}\boldsymbol{G}_k \sum_{i=1}^{p} \beta_i(\boldsymbol{x}_k - \boldsymbol{x}_{k-i}) + \boldsymbol{e}_k \qquad (5)$$

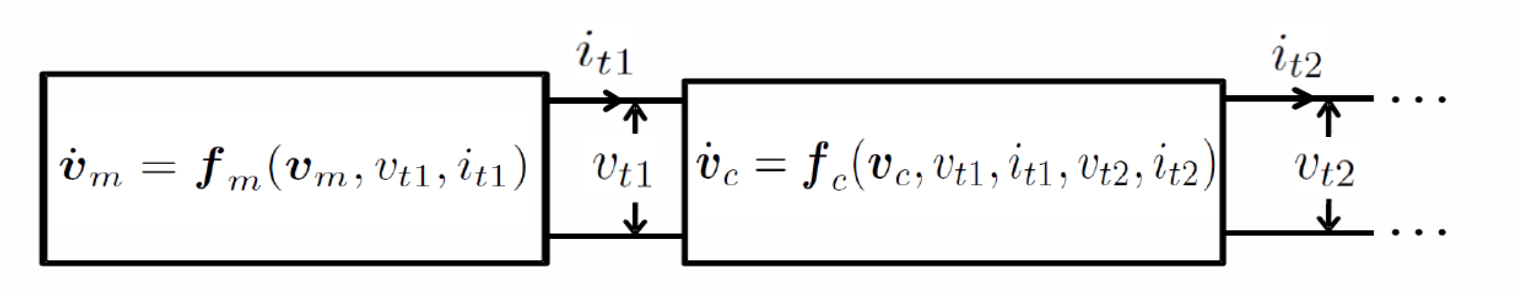
are stable, if the step-size $h < h_{max,p}$, where:

$$h_{max,1} = \frac{1}{\max\limits_{r=1,\ldots,N} |a_{r,r}|}; \quad p = 1 \qquad (6)$$

$$h_{max,2} = \frac{1}{2\max\limits_{r=1,\ldots,N} |a_{r,r}|}; \quad p = 2 \qquad (7)$$

Automatic elimination of terminal variables

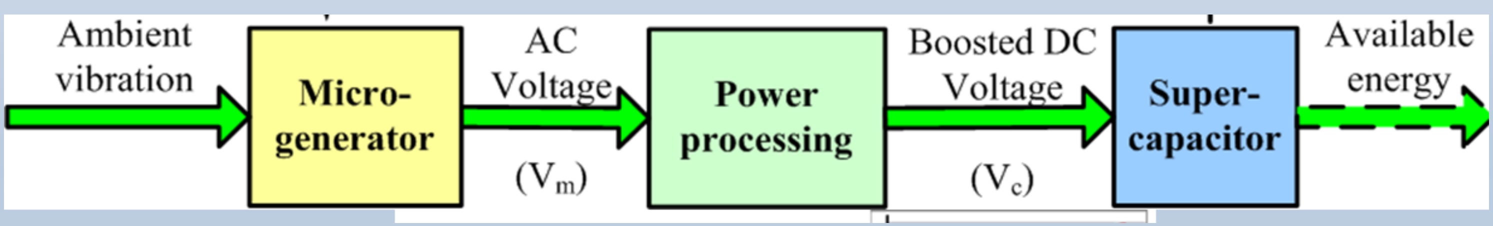
- A general, analogue part of an energy harvester system consists of interconnected blocks:



- Linearised model of a multiple block system contains non-state variables, e.g. terminal variables.

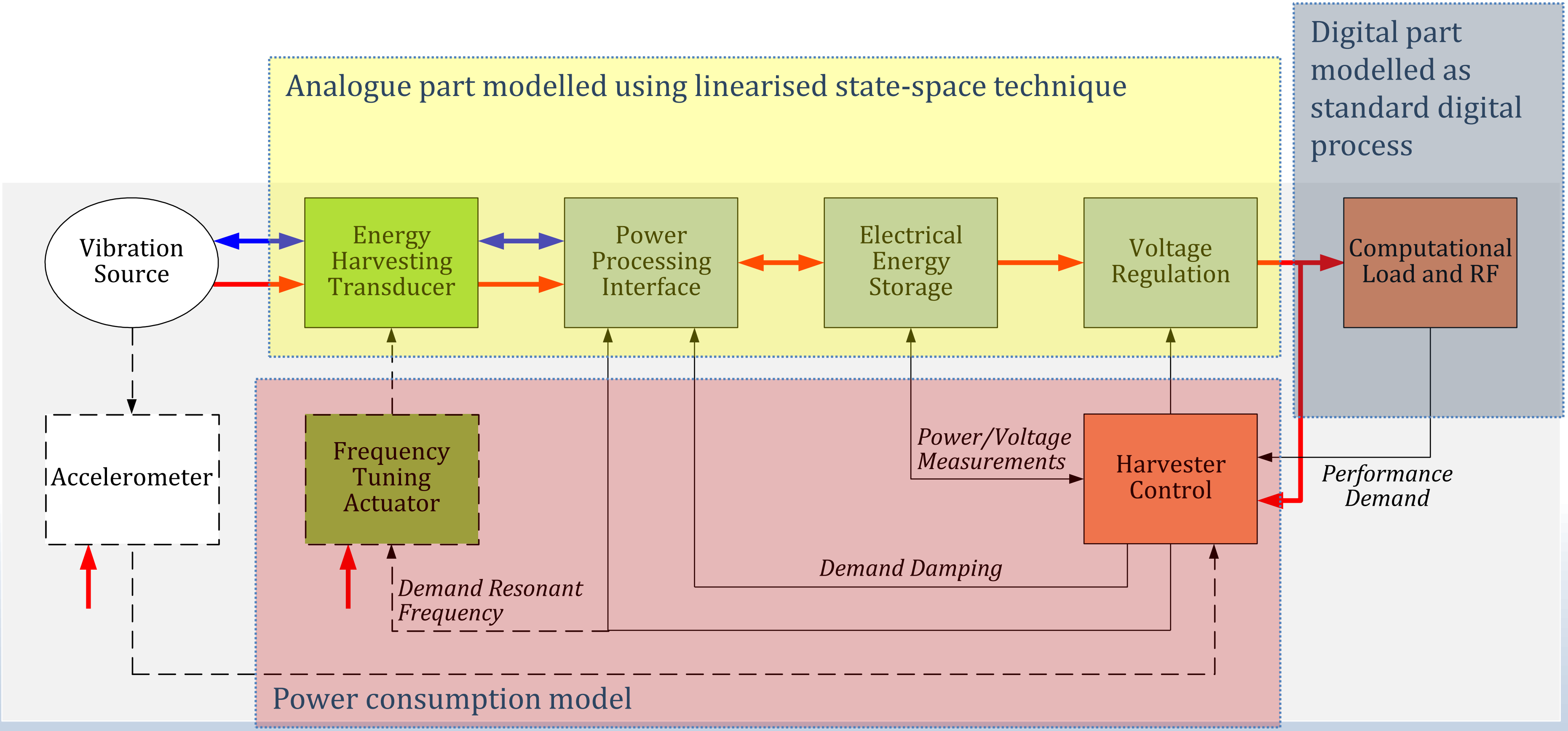
$$\begin{bmatrix} \dot{\boldsymbol{x}}_{(t_k)} \\ \boldsymbol{0} \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_{xx,k} & \boldsymbol{J}_{xy,k} \\ \boldsymbol{J}_{yx,k} & \boldsymbol{J}_{yy,k} \end{bmatrix} \begin{bmatrix} \boldsymbol{x}(t_k) \\ \boldsymbol{y}(t_k) \end{bmatrix} + \begin{bmatrix} \boldsymbol{e}_x(t_k) \\ \boldsymbol{0} \end{bmatrix}$$

- Non-state variables can be eliminated from the algebraic part of the equation set in an automated way, e.g. by Gauss elimination.

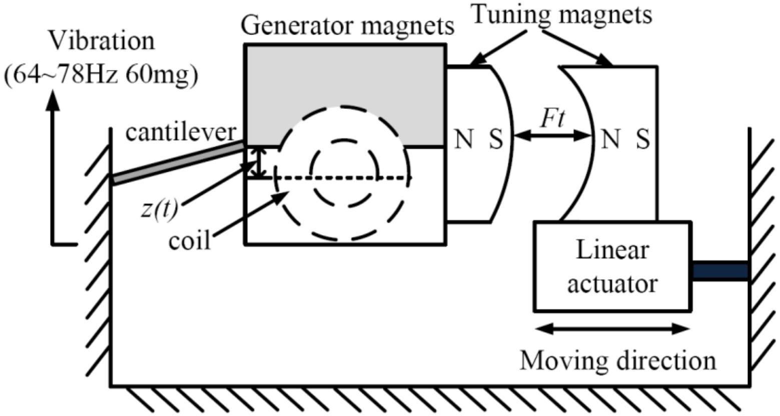


Case study – tunable energy harvester

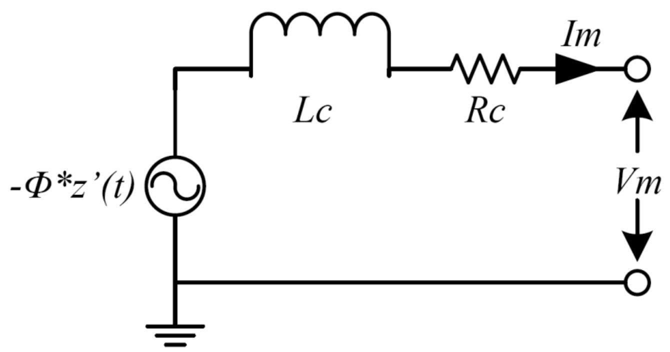
Mixed-signal and mixed-physical-domain model



Microgenerator



Mechanical part



Electrical part

– Implicit equations: $m\frac{d^2z(t)}{dt^2}+c_p\frac{dz(t)}{dt}+k_s z(t)+\Phi i_L(t)+F_{t\_z}-F_a=0$

$$\Phi\frac{dz(t)}{dt}+R_c i_L(t)+L_c\frac{di_L(t)}{dt}+V_m=0$$

– Explicit equations:

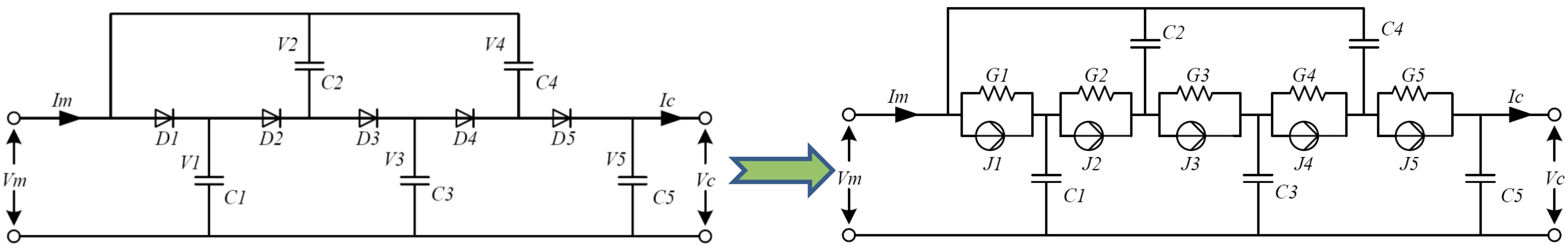
State variables

Terminal variables

$$\frac{d}{dt}\begin{bmatrix}\frac{dz(t)}{dt}\\ z(t)\\ i_L(t)\end{bmatrix}=\begin{bmatrix}\frac{-c_p}{m} & \frac{-k_s}{m} & \frac{-\Phi}{m}\\ 1 & 0 & 0\\ \frac{-\Phi}{L_c} & 0 & \frac{-R_c}{L_c}\end{bmatrix}\begin{bmatrix}\frac{dz(t)}{dt}\\ z(t)\\ i_L(t)\end{bmatrix}+\begin{bmatrix}0 & \frac{-\Phi}{m}\\ 0 & 0\\ \frac{-1}{L_c} & 0\end{bmatrix}\begin{bmatrix}V_m\\ I_m\end{bmatrix}+\begin{bmatrix}\frac{F_a-F_{t\_z}}{m}\\ 0\\ 0\end{bmatrix}$$

Power processing

5-stage Dickson voltage multiplier



– Linearised diode model :

$$I_d = I_s(e^{V_d/V_t} - 1) \Rightarrow I_d = GV_d + J$$

G(Vd) and *J(Vd)* are fetched from a look-up table at each time point

Linearised State Equations

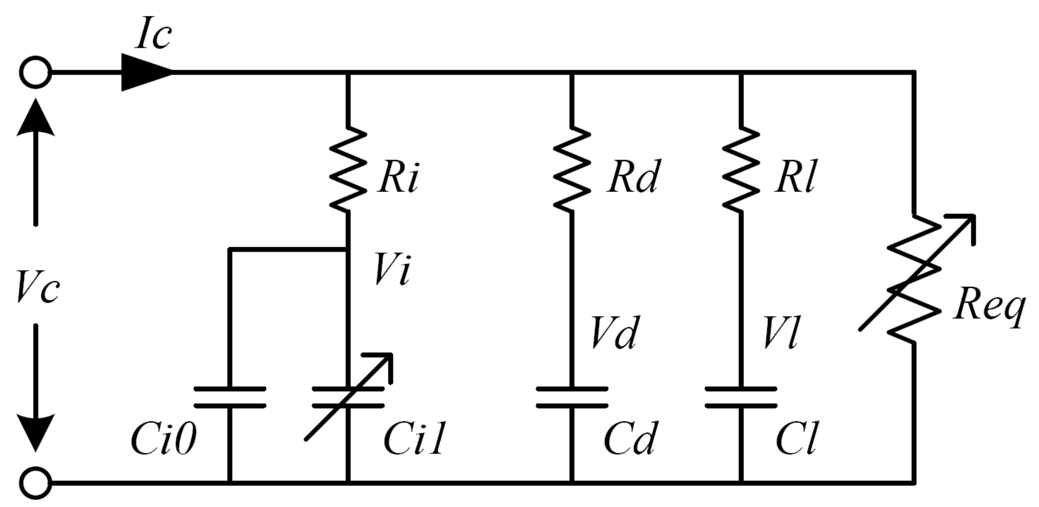
State variables

Terminal variables

$$\frac{d}{dt}\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \end{bmatrix} = \begin{bmatrix} \frac{-G_1-G_2}{C_1} & \frac{-G_2}{C_1} & 0 & 0 & 0 \\ \frac{-G_2}{C_2} & \frac{-G_2-G_3}{C_2} & \frac{-G_3}{C_2} & 0 & 0 \\ 0 & \frac{-G_3}{C_3} & \frac{-G_3-G_4}{C_3} & \frac{-G_4}{C_3} & 0 \\ 0 & 0 & \frac{-G_4}{C_4} & \frac{-G_4-G_5}{C_4} & \frac{-G_5}{C_4} \\ 0 & 0 & 0 & \frac{-G_5}{C_5} & \frac{-G_5}{C_5} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \end{bmatrix} + \begin{bmatrix} \frac{G_1+G_2}{C_1} & 0 & 0 & 0 \\ \frac{G_2+G_3}{C_2} & 0 & 0 & 0 \\ \frac{G_3+G_4}{C_3} & 0 & 0 & 0 \\ \frac{G_4+G_5}{C_4} & 0 & 0 & 0 \\ \frac{G_5}{C_5} & 0 & 0 & \frac{-1}{C_5} \end{bmatrix} \begin{bmatrix} V_m \\ I_m \\ V_c \\ I_c \end{bmatrix} + \begin{bmatrix} \frac{J_1-J_2}{C_1} \\ \frac{J_3-J_2}{C_2} \\ \frac{J_3-J_4}{C_3} \\ \frac{J_5-J_4}{C_4} \\ \frac{J_5}{C_5} \end{bmatrix}$$

Supercapacitor

Three-branch model by Zubieta and Bonert (2000)



State equations:

State variables

Terminal variables

$$\frac{d}{dt}\begin{bmatrix} V_i \\ V_d \\ V_l \end{bmatrix} = \begin{bmatrix} \frac{-1}{R_i*(C_{i0}+C_{i1})} & 0 & 0 \\ 0 & \frac{-1}{R_d*C_d} & 0 \\ 0 & 0 & \frac{-1}{R_l*C_l} \end{bmatrix} \begin{bmatrix} V_i \\ V_d \\ V_l \end{bmatrix} + \begin{bmatrix} \frac{1}{R_i*(C_{i0}+C_{i1})} & 0 \\ \frac{1}{R_d*C_d} & 0 \\ \frac{1}{R_l*C_l} & 0 \end{bmatrix} \begin{bmatrix} V_c \\ I_c \end{bmatrix}$$

Complete model of analogue part

Terminal variables are eliminated

$$V_m = ((G_1 + G_2)V_1 + (G_2 + G_3)V_2 + (G_3 + G_4)V_3 + (G_4 + G_5)V_4 + G_5V_5$$
$$- J_1 - J_3 - J_5 + J_2 + J_4 - I_L(t))/(G_1 + \ldots + G_3 + G_4 + G_5)$$

$$I_m = I_L(\ldots$$

$$V_c = V_5 \ldots$$

$$I_c = (\frac{1}{R_i} + \frac{1}{R_d} + \frac{1}{R_l} + \frac{1}{R_{eq}}) \ldots - \frac{V_i}{R_i} - \frac{V_d}{R_d} - \frac{V_l}{R_l}$$

$$\boldsymbol{v}_t = \boldsymbol{A} \begin{bmatrix} \boldsymbol{v}_m \\ \boldsymbol{v}_c \\ \boldsymbol{v}_s \end{bmatrix} + \boldsymbol{e}_t$$

Combination of blocks

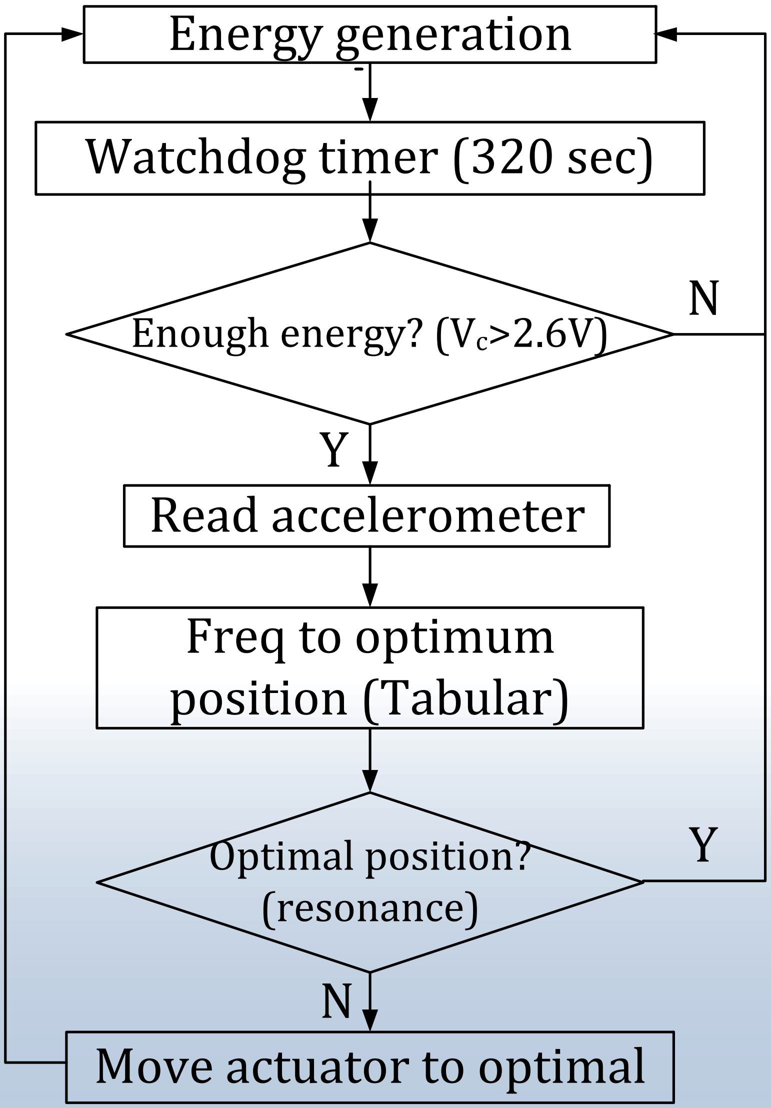
$$\begin{aligned} \dot{\boldsymbol{v}}_m &= \boldsymbol{J}_1\boldsymbol{v}_m + \boldsymbol{B}_1\boldsymbol{v}_t + \boldsymbol{e}_1 \\ \dot{\boldsymbol{v}}_c &= \boldsymbol{J}_2\boldsymbol{v}_c + \boldsymbol{B}_2\boldsymbol{v}_t + \boldsymbol{e}_2 \\ \dot{\boldsymbol{v}}_s &= \boldsymbol{J}_3\boldsymbol{v}_s + \boldsymbol{B}_3\boldsymbol{v}_t + \boldsymbol{e}_3 \end{aligned}$$

- Microgenerator
- Voltage booster
- Supercapacitor

Complete linearised state-space equations

$$\frac{d}{dt}\begin{bmatrix} v_m \\ v_c \\ v_s \end{bmatrix} = \left(\begin{bmatrix} J_1 & 0 & 0 \\ 0 & J_2 & 0 \\ 0 & 0 & J_3 \end{bmatrix} + \begin{bmatrix} B_1A \\ B_2A \\ B_3A \end{bmatrix} \right) \begin{bmatrix} v_m \\ v_c \\ v_s \end{bmatrix} + \begin{bmatrix} e_1 + B_1e_t \\ e_2 + B_2e_t \\ e_3 + B_3e_t \end{bmatrix}$$

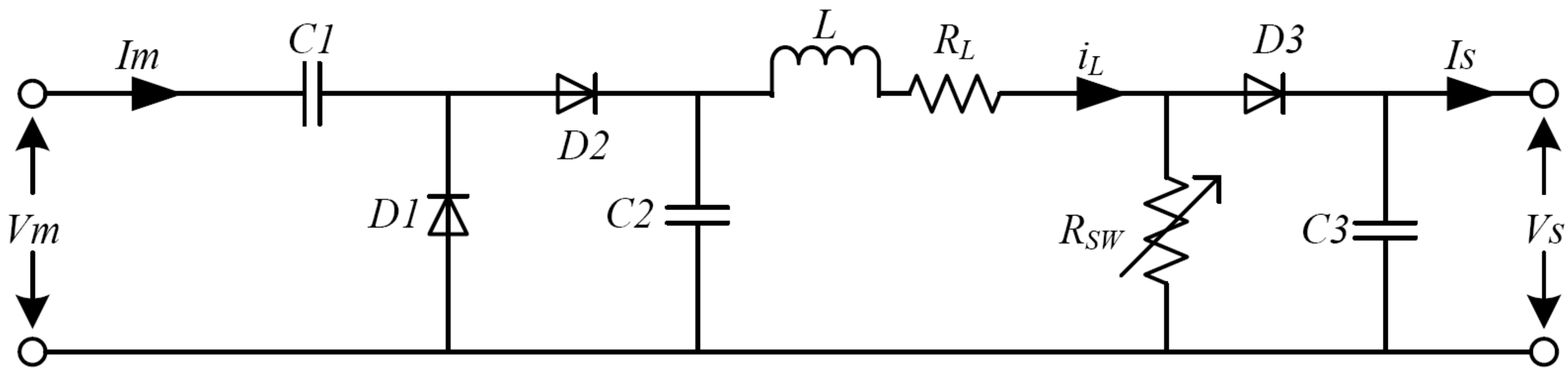
Microcontroller



$$R_{eq} = \begin{cases} 1.0e9\Omega & \text{when microcontroller is in sleep mode} \\ 33\Omega & \text{when microcontroller wakes up} \\ 16.7\Omega & \text{when actuator performs tuning} \end{cases}$$

- Microcontroller
  - Monitors input frequency and controls actuator
- Equivalent load resistor R_{eq} to model power consumption
- Modelled as a digital process
- Power consumption models are required for both the actuator and microcontroller

State-space modelling of boost converter



– Switch is modelled as

$$R_{SW} = \begin{cases} 1.0e9\Omega & \text{when the switch is off} \\ 4\Omega & \text{when the switch is on} \end{cases}$$

– State-space matrix

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ i_L \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{-G_2}{C_2} & \frac{-G_2}{C_2} & 0 & \frac{-1}{C_2} \\ 0 & 0 & \frac{-G_3}{C_3 X} & \frac{G_3 R_{SW}}{C_3 X} \\ 0 & \frac{1}{L} & \frac{-G_3 R_{SW}}{LX} & \frac{-R_L X - R_{SW}}{LX} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ i_L \end{bmatrix}$$

$$+ \begin{bmatrix} 0 & \frac{1}{C_1} & 0 & 0 \\ \frac{G_2}{C_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{C_3} \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_m \\ I_m \\ V_s \\ I_s \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{J_2}{C_2} \\ \frac{J_3(X+G_3 R_{SW})}{C_3 X} \\ \frac{J_3 R_{SW}}{LX} \end{bmatrix}$$

State-space modelling of boost converter

- Direct application of Adams-Bashforth method is difficult
  - Small inductance – unstable or small time step
  - Fast switching behaviour – inaccurate solution around switching
- Solve the inductor current analytically to avoid reducing simulation time step
  - The differential equation of inductor current

$$\frac{\mathrm{d}i_L(t)}{\mathrm{d}t} + \frac{i_L(t)}{\tau} = I_0$$

  - General solution to a first-order linear equation

$$i_L(t) = I_0\tau + Ce^{-t/\tau}$$

  - Initial condition (present time-point value)

$$t = 0, i_L(0) = i_n \Rightarrow C = i_n - I_0\tau$$

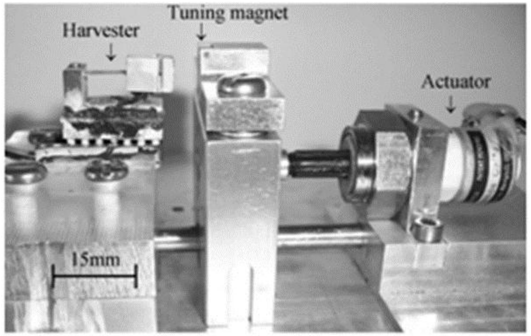
  - Solution (next time-point value)

$$i_{n+1} = i_n + (I_0\tau - i_n)(1 - e^{-h/\tau})$$

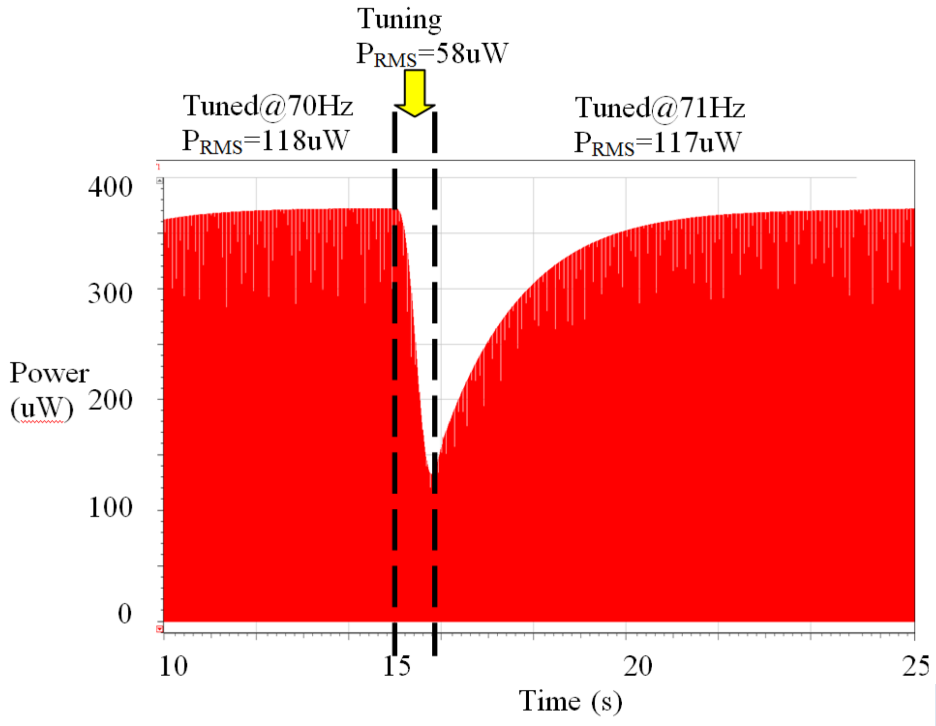
Simulation results and validation

Scenario 1: tuning by 1Hz

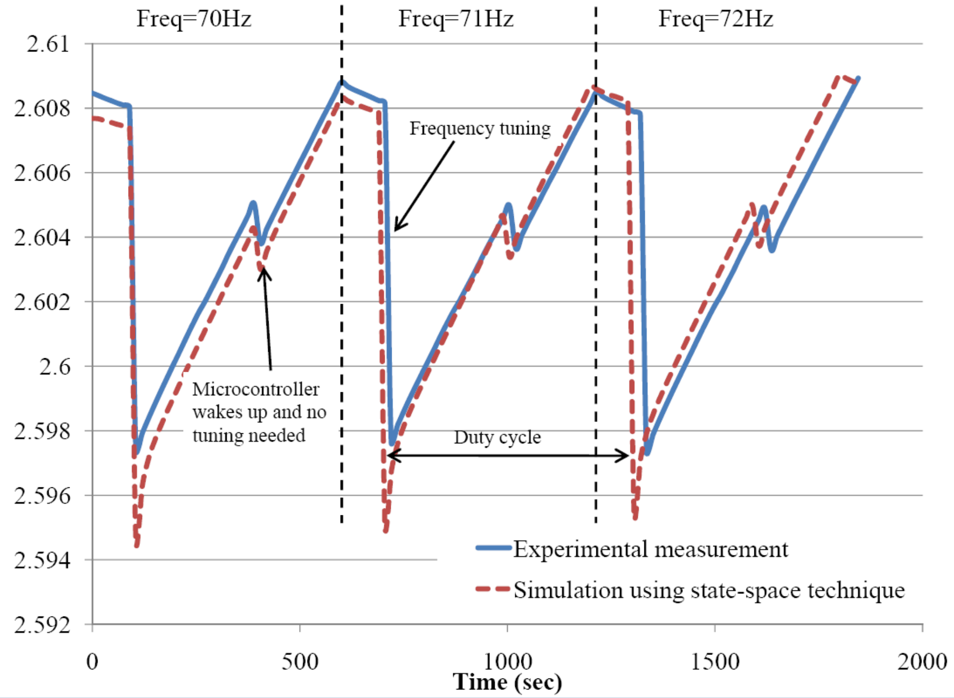
Recovery time/duty cycle - 600 seconds



Output power from microgenerator:



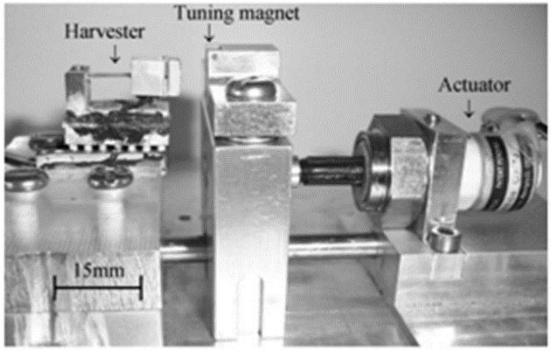
Supercapacitor voltage:



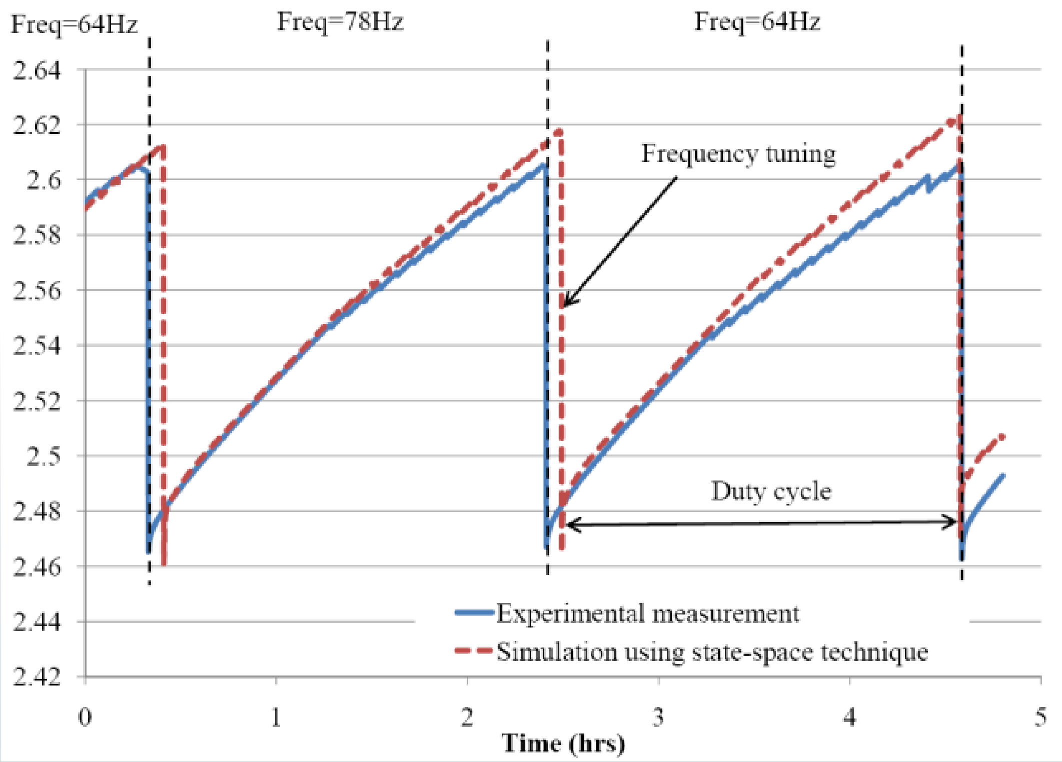
Simulation results and validation

Scenario 2: tuning by 14Hz

- Maximum tuning range (64~78Hz)
- Recovery time/duty cycle - approx. 2 hours



Supercapacitor voltage:



Simulation results and validation

Comparison of CPU times

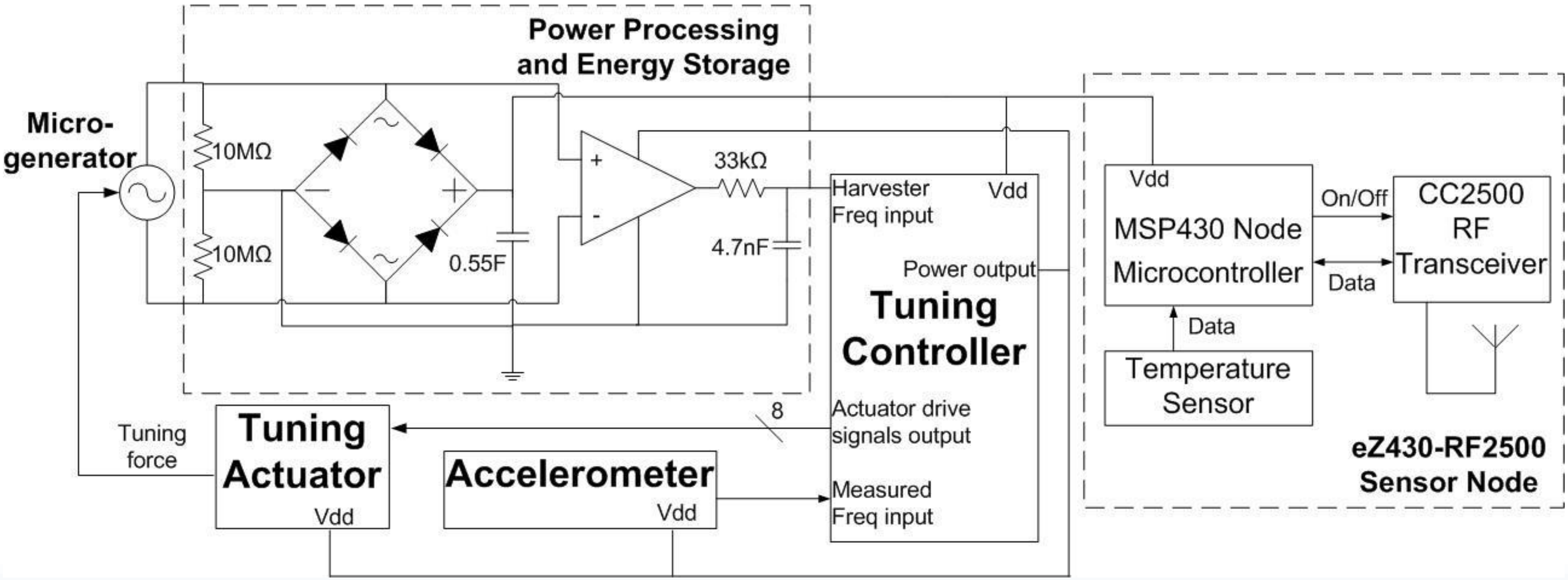
Two order of magnitude acceleration

	Existing technique		Proposed technique
HDL	VHDL-AMS	SystemC-A	SystemC-A
Integration method	Newton-Raphson based	Newton-Raphson based	Linearised state-space
CPU time for Scenario 1	2185 sec	2386	**20.3 sec**
CPU time for Scenario 2	7 hours	8 hours	**228 sec**

Why fast design space exploration?

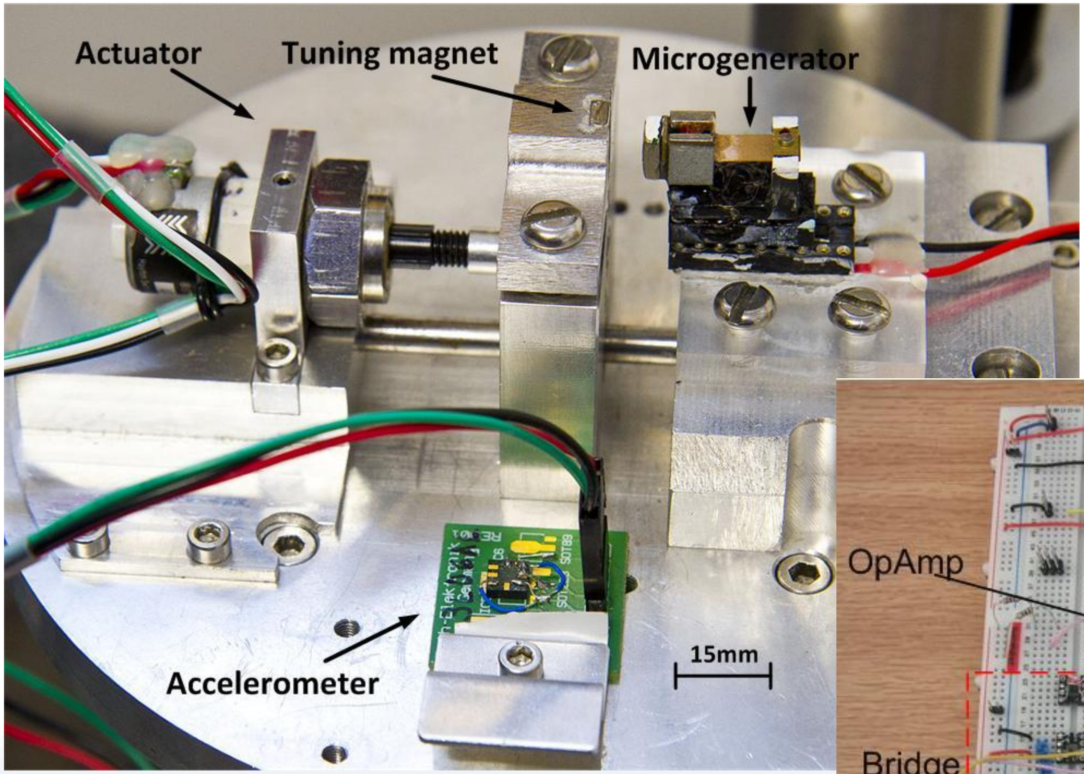
- Even with accelerated simulation – it still takes to long to optimise an EH system by multiple simulations
  - A complicated system which has many parameters that can affect the system performance
  - There are trade-offs between increasing and decreasing each of the parameters, energy generation vs. energy consumption
- Optimisation of the complete system
  - Most reported work only optimise the analogue part of an energy harvester
  - The digital control algorithms also affect the system performance
- Proposed technique
  - RSM model for fast design space exploration
  - Optimisation of the RSM model using MATLAB
  - Combination of the power of HDL in modelling multi-domain systems and the power of MATLAB in computation

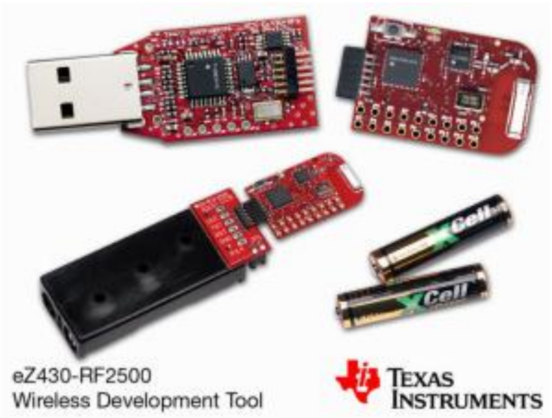
System diagram of an EH-powered sensor

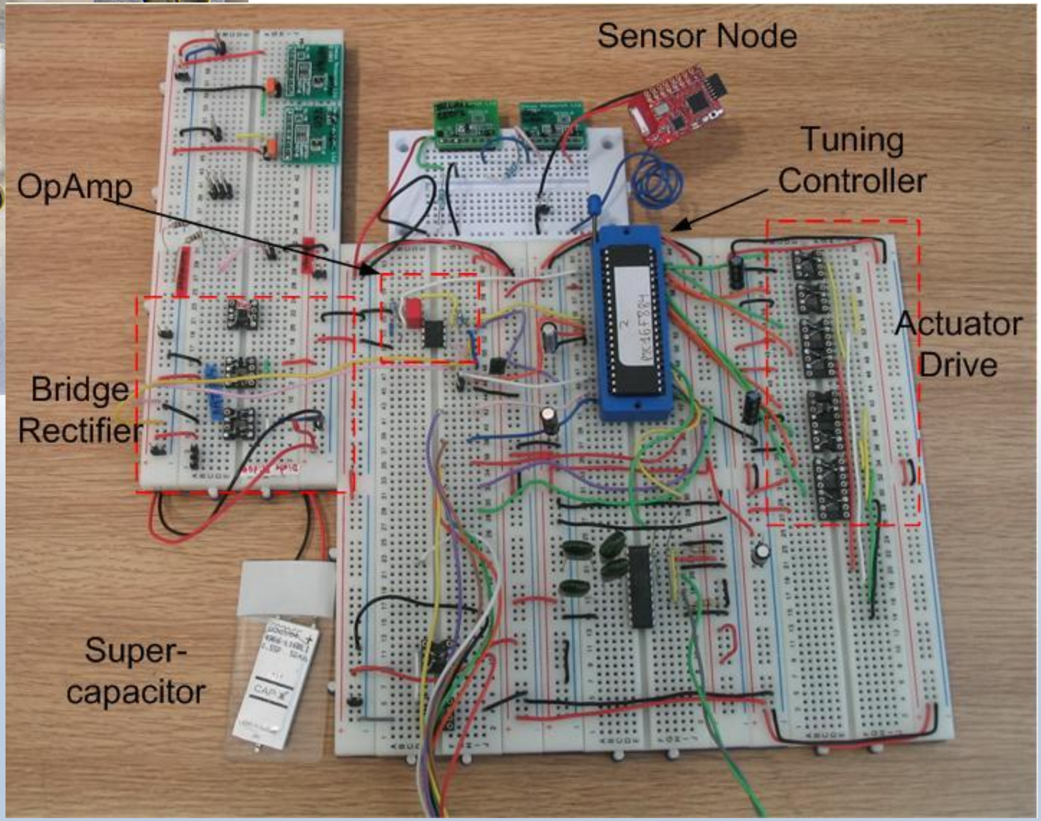


Component	Type	Make
Microcontroller	PIC16F884	Microchip
Accelerometer	LIS3L06AL	STMicroelectronics
Linear actuator	21000 Series Size 8 stepper motor	Haydon
Radio transceiver	eZ430-RF2500	Texas Instruments

System photos



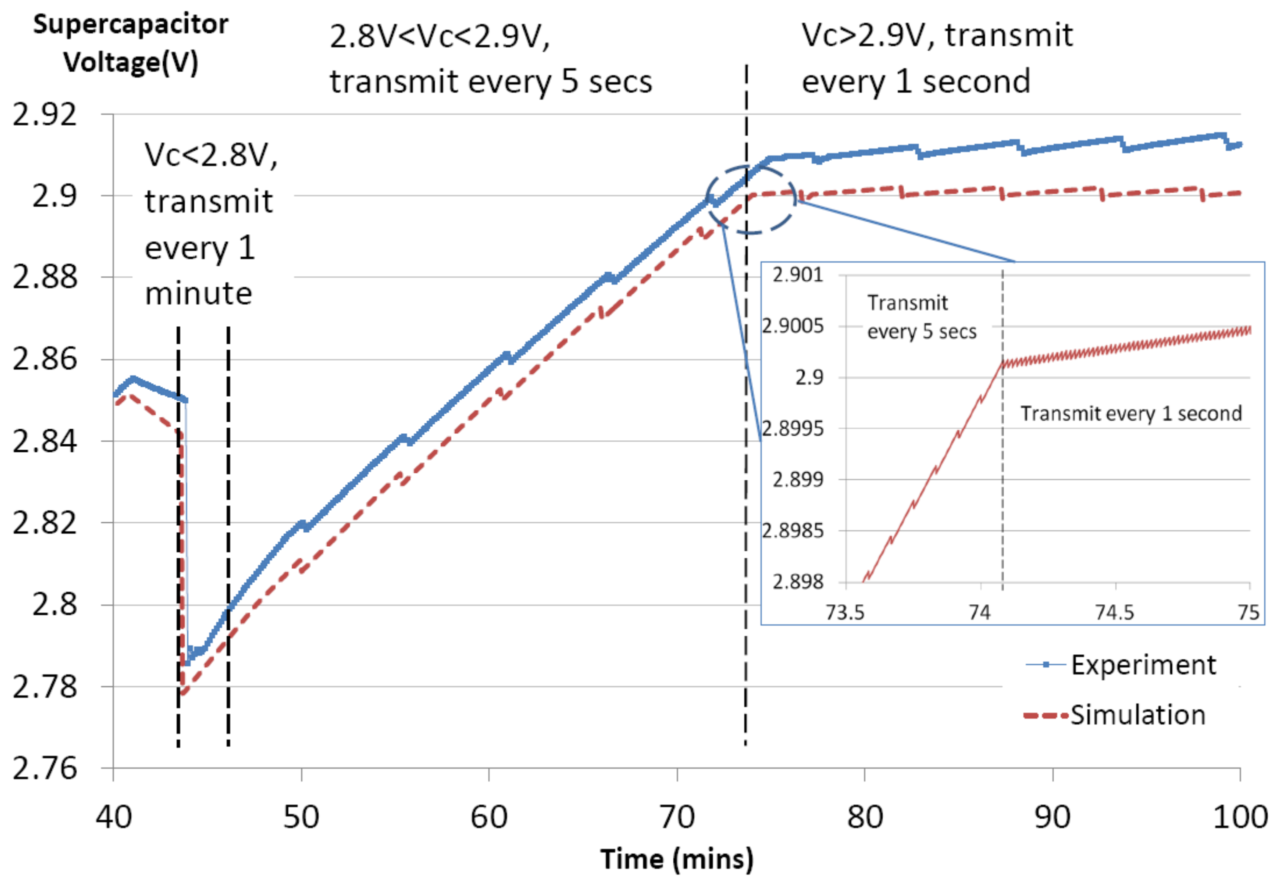




Simulation vs experiment

- Transmission frequency of sensor node depends on supercap voltage:

Supercapacitor voltage	Wireless transmission interval
Below 2.7 V	No transmission
Between 2.7 and 2.8 V	Transmit every 1 minute
Between 2.8 and 2.9 V	Transmit every 5 seconds
Above 2.9 V	Transmit every 1 second



Response surface model for fast design space exploration

- To relate the simulation result (the response) with a number of system parameters, a system function (the RSM) can be approximated as:

$$y = \hat{y}(a_1, a_2, ..., a_k) + \epsilon$$

- Coded variables with zero means are required to build RSM:

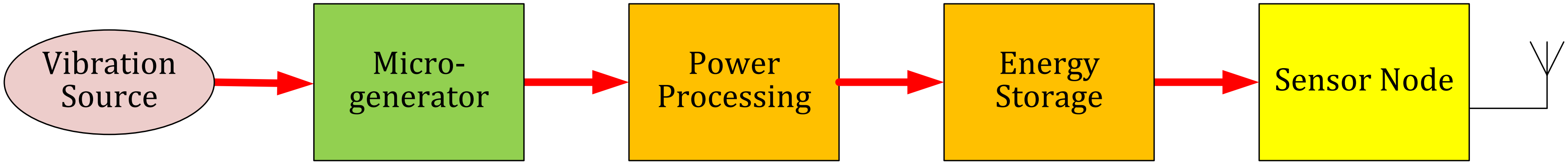
$$x = \frac{a - [a_{max} + a_{min}]/2}{[a_{max} + a_{min}]/2}$$

- A low order polynomial equation is often used as system function:

$$\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \sum \beta_{ij} x_i x_j$$

Design space explorer (Theme C demonstrator)

- Performance estimator of wireless sensor powered by kinetic energy harvester
- System diagram

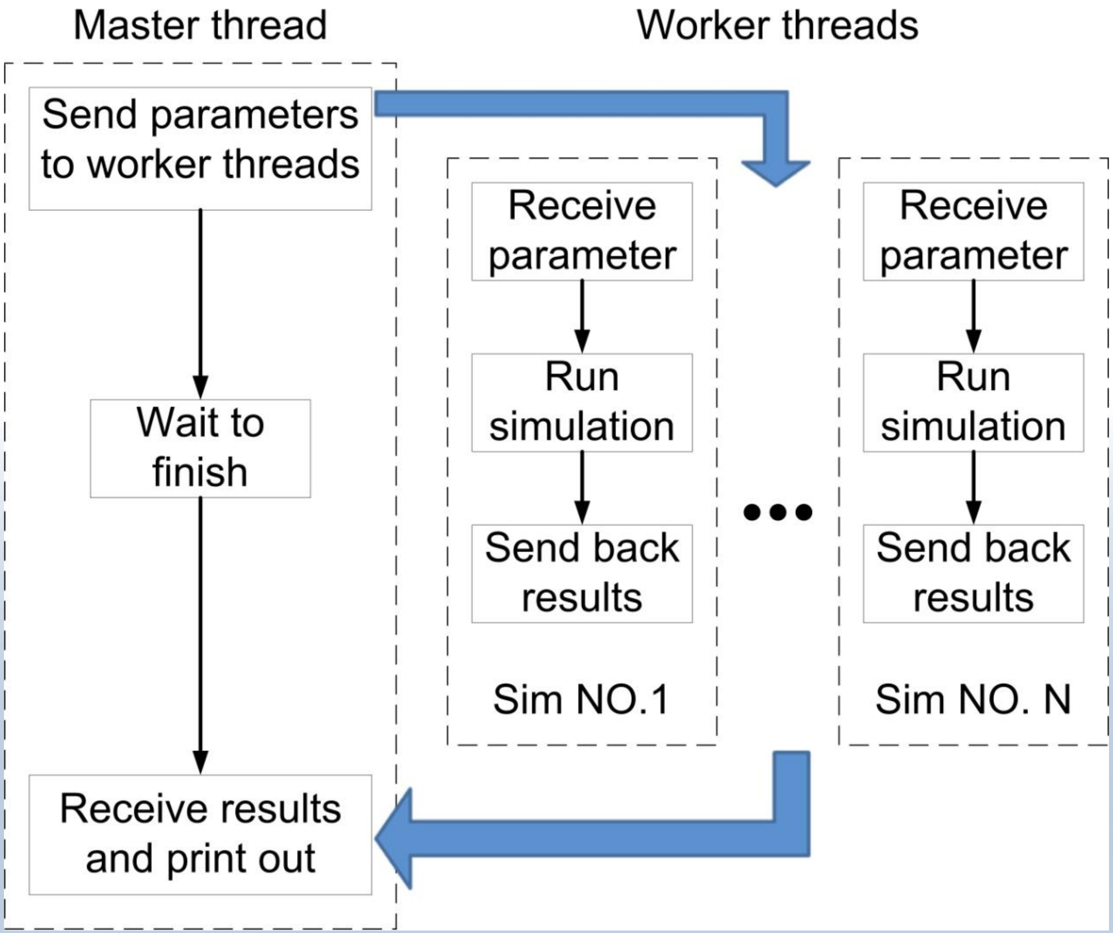


- User parameters and performance indicators

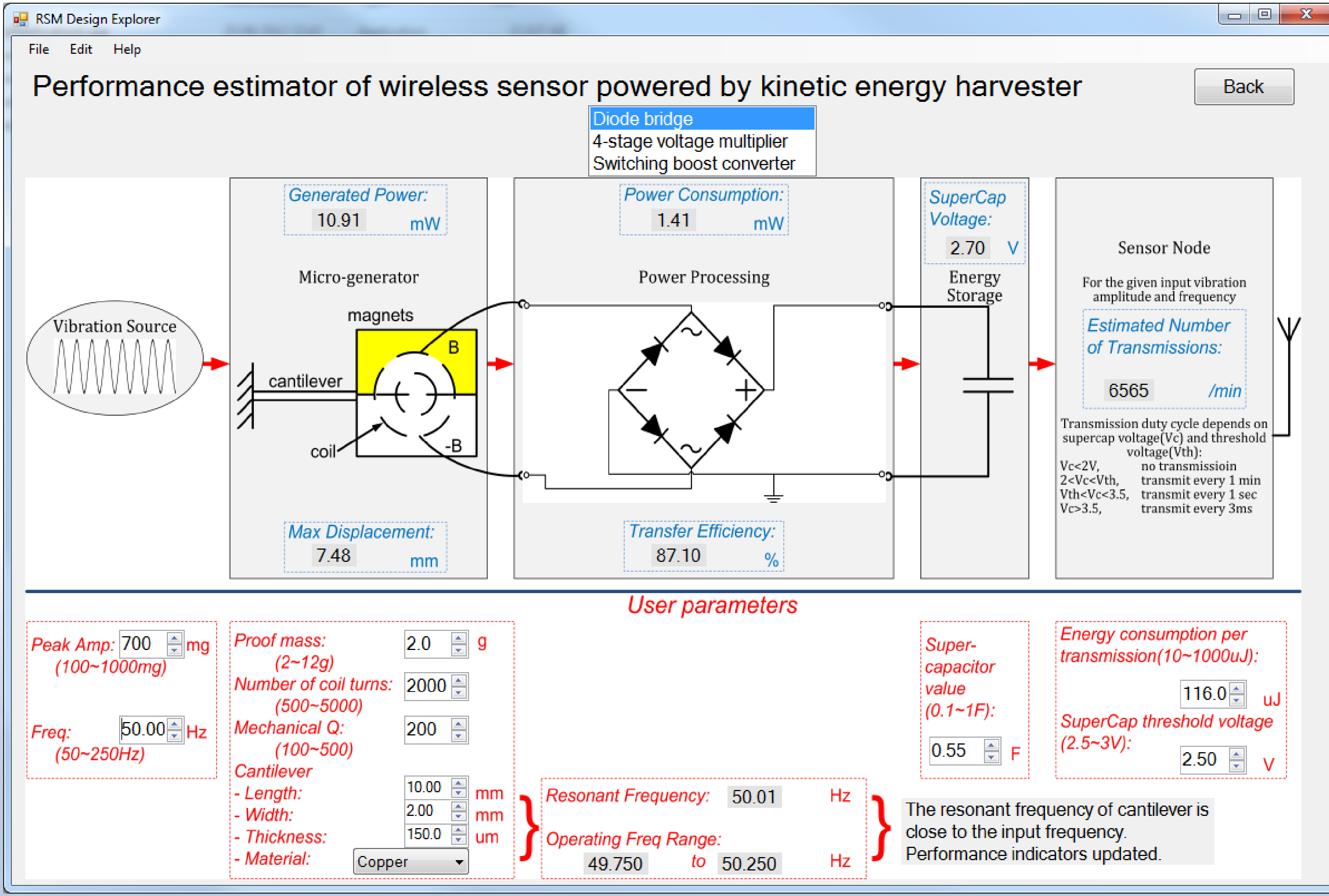
<table>
<tr><th></th><th>Vibration source</th><th>Micro-generator</th><th colspan="2">Power processing</th><th>Storage</th><th>Sensor node</th></tr>
<tr><td rowspan="5">User parameters</td><td rowspan="2">Amplitude of sine wave</td><td>Proof mass</td><td colspan="2">Diode bridge rectifier</td><td rowspan="5">Super-capacitor value</td><td rowspan="5">Threshold when transmission frequency changes</td></tr>
<tr><td>Stiffness of cantilever</td><td colspan="2">4-stage VM</td></tr>
<tr><td rowspan="3">Frequency of sine wave</td><td>Number of coil turns</td><td rowspan="3">Boost converter</td><td>Inductor value</td></tr>
<tr><td rowspan="2">Mechanical Q factor</td><td>Switching Freq</td></tr>
<tr><td>Duty cycle</td></tr>
<tr><td rowspan="2">Performance indicators</td><td rowspan="2"></td><td>Generated power</td><td colspan="2">Power consumption</td><td rowspan="2">Super-capacitor voltage</td><td rowspan="2">Number of transmission</td></tr>
<tr><td>Maximum displacement</td><td colspan="2">Transfer efficiency</td></tr>
</table>

Parallel simulations to build RSM model

- Southampton's Iridis 3 supercomputer
  - 1008 computing nodes each with 12 processing cores
  - Ranked 74 in the world (*http://cmg.soton.ac.uk/iridis*)
- Message Passing Interface (MPI) library for programming
  - OpenMPI: Open Source High Performance Computing



Theme C demonstrator GUI



RSM design explorer:

EPSRC
Engineering and Physical Sciences Research Council

holistic
energy harvesting

Newcastle University
Imperial College London
University of BRISTOL

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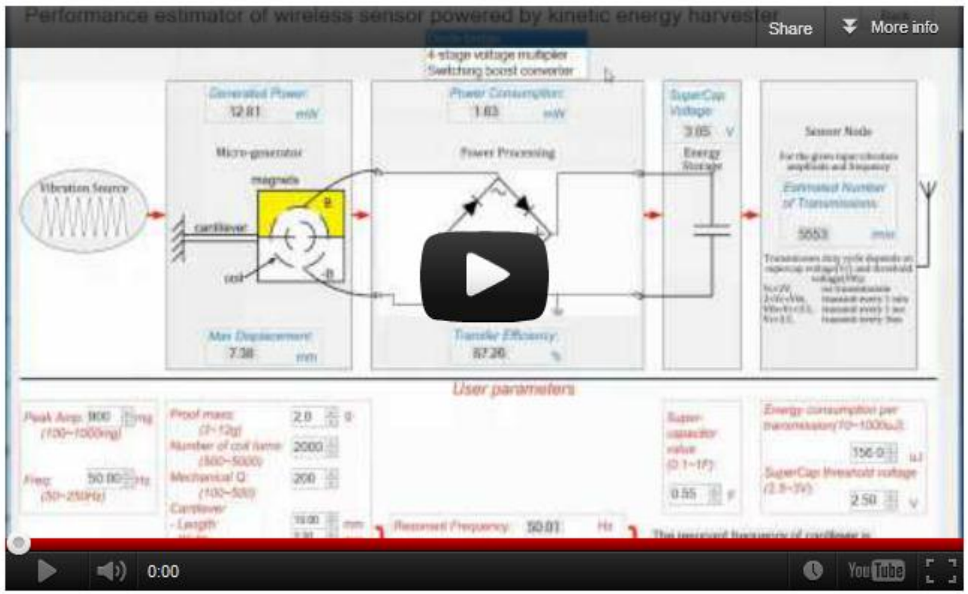
Design Space Exploration and Optimisation of Energy Harvesting Systems

Energy harvesting is the process by which ambient energy from the environment is captured and stored. Most mobile devices and wireless sensor nodes are now powered by batteries, which need charging or replacement after a period of time. If these devices could be self-powered by energy harvesters, great amount of cost in maintenance will be saved. In addition, some applications with limited accessibility such as biomedical implants and structure embedded micro-sensors will also benefit from energy harvesters. Various devices have been reported to scavenge energy from different sources, such as light, heat, RF, ocean wave, wind power and mechanical vibrations. Among all the available sources, kinetic based energy harvester seems to be the most popular since mechanical vibrations are widely present.



Typically the generated voltage from a vibration source is insufficient to power an electronic device directly because the voltage is AC and often too high/low for the target applications. Therefore external analogue circuits are needed to rectify and regulate the voltage and store the energy in a battery or a super-capacitor. Examples of such circuits include passive diode bridge, voltage multiplier, and AC/DC rectifier combining with an active switch-mode DC/DC converter. An energy harvester has normally three main components: the micro generator which converts ambient environment energy into electrical energy, the power processing circuit which rectifies and regulates the generated voltage, and the storage element.

http://www.holistic.ecs.soton.ac.uk/res/rsm.php

Conclusion

- Novel technique for accelerated simulation
  - 1 journal (IEEE TCAD), 1 conference (DATE'11)
- Accurate modelling of wireless sensor nodes powered by tunable energy harvesters: HDL-based approach
  - 1 journal (IEEE Sensors)
- Fast design space exploration and optimisation of complex systems
  - 2 conference (DATE'12, DATE'13), 1 journal under review (IEEE Sensors)
- Theme demonstrators
  - Simulation toolkit and RSM design explorer available for download: *www.holistic.ecs.soton.ac.uk/resources.php*