Theme C Technical Seminar
Accelerating EH simulation and design exploration

Holistic energy-harvesting project workshop and showcase
Imperial College, 11 Feb 2013

T J Kazmierski, University of Southampton
tjk@ecs.soton.ac.uk
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:

\[ f(\dot{x}(t), x(t), t); \quad x(0) = x_0 \]

State equations:

\[ \dot{x}(t) = f(x(t), t); \quad x(0) = x_0 \]

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 $t_k$, $k = 0, 1, \ldots$

  $$\dot{x}_{k+1} = -J_k(x_k - x_{k-1}) + f(x_k, t_{k+1})$$

  $J_k$ is the Jacobian of $f$ at time point $t_k$.

- The linearised state equation can be presented as:

  $$\dot{x}_{k+1} = -C_k^{-1}G_k(x_k - x_{k-1}) + e_{k+1}$$

  $C_k$ - diagonal matrix representing energy storing components

  $G_k$ - diagonally dominant matrix representing resistive part of a passive electrical system, such as energy harvester electronics.
Step size control

Linearised state equation:

\[ \dot{x}_{k+1} = -C_k^{-1} G_k (x_k - x_{k-1}) + e_{k+1} \quad (4) \]

**Theorem.** If \( G_k \) 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):

\[ x_{k+1} = x_k + h_{k+1} C_k^{-1} G_k \sum_{i=1}^{p} \beta_i (x_k - x_{k-i}) + e_k \quad (5) \]

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

\[ h_{max,1} = \frac{1}{\max_{r=1,\ldots,N} |a_{r,r}|}; \quad p = 1 \quad (6) \]

\[ h_{max,2} = \frac{1}{2 \max_{r=1,\ldots,N} |a_{r,r}|}; \quad p = 2 \quad (7) \]
Automatic elimination of terminal variables

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

\[
\begin{bmatrix}
\dot{\mathbf{x}}(t_k) \\
0
\end{bmatrix} =
\begin{bmatrix}
J_{xx,k} & J_{xy,k} \\
J_{yx,k} & J_{yy,k}
\end{bmatrix}
\begin{bmatrix}
\mathbf{x}(t_k) \\
\mathbf{y}(t_k)
\end{bmatrix} +
\begin{bmatrix}
e_x(t_k) \\
0
\end{bmatrix}
\]

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

- 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

- **Analogue part modelled using linearised state-space technique**
- **Digital part modelled as standard digital process**

**Vibration Source**

- **Energy Harvesting Transducer**
- **Power Processing Interface**
- **Electrical Energy Storage**
- **Voltage Regulation**

**Harvester Control**

- **Performance Demand**

**Accelerometer**

- **Frequency Tuning Actuator**
- **Power/Voltage Measurements**

**Power consumption model**
Microgenerator

**Mechanical part**

**Electrical part**

- Implicit equations:
  \[ m \frac{d^2 z(t)}{dt^2} + c_p \frac{dz(t)}{dt} + k_s z(t) + \Phi i_L(t) + F_{t-z} - F_a = 0 \]
  \[ \Phi \frac{dz(t)}{dt} + R_c i_L(t) + L_c \frac{di_L(t)}{dt} + V_m = 0 \]

- Explicit equations:

**State variables**

**Terminal variables**

\[
\begin{bmatrix}
\frac{dz(t)}{dt} \\
\frac{di_L(t)}{dt}
\end{bmatrix}
= \begin{bmatrix}
\frac{-c_p}{m} & \frac{-k_s}{m} & \frac{-\Phi}{m} & \frac{-R_c}{L_c} \\
1 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\frac{dz(t)}{dt} \\
\frac{di_L(t)}{dt}
\end{bmatrix}
+ \begin{bmatrix}
0 & \frac{-\Phi}{m} & 0 & 0 \\
0 & \frac{-1}{L_c} & 0 & 0
\end{bmatrix}
\begin{bmatrix}
V_m \\
I_m
\end{bmatrix}
+ \begin{bmatrix}
\frac{F_a - F_{t-z}}{m} \\
0 \\
0
\end{bmatrix}
\]
Power processing

5-stage Dickson voltage multiplier

\[ I_d = I_s \left( e^{V_d/V_t} - 1 \right) \Rightarrow I_d = GV_d + J \]

Linearised diode model:

- **Linearised State Equations**

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

Three-branch model by Zubieta and Bonert (2000)

State equations:

$$\frac{d}{dt} \begin{bmatrix} V_i \\ V_d \\ V_l \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_i \ast (C_{i0} + C_{i1})} & 0 & 0 \\ 0 & -\frac{1}{R_d \ast C_d} & 0 \\ 0 & 0 & -\frac{1}{R_i \ast C_l} \end{bmatrix} \begin{bmatrix} V_i \\ V_d \\ V_l \end{bmatrix} + \begin{bmatrix} \frac{1}{R_i \ast (C_{i0} + C_{i1})} \\ \frac{1}{R_d \ast C_d} \\ \frac{1}{R_i \ast C_l} \end{bmatrix} \begin{bmatrix} V_c \\ I_c \end{bmatrix}$$
Complete model of analogue part

Terminal variables are eliminated

\[
V_m = ((G_1 + G_2)V_1 + (G_2 + G_3)V_2 + (G_3 + G_4)V_3 + (G_4 + G_5)V_4 + G_5 V_5 \\
- J_1 - J_3 - J_5 + J_2 + J_4 - I_L(t))/(G_1 + G_2 + G_3 + G_4 + G_5)
\]

\[
I_m = I_L(t) \\
V_c = V_5 \\
I_c = \left( \frac{1}{R_i} + \frac{1}{R_d} + \frac{1}{R_l} + \frac{1}{R_{eq}} \right)
\]

Complete linearised state-space equations

\[
\begin{bmatrix}
\dot{v}_m \\
\dot{v}_c \\
\dot{v}_s
\end{bmatrix} = \begin{bmatrix}
J_1 & 0 & 0 \\
0 & J_2 & 0 \\
0 & 0 & J_3
\end{bmatrix} \begin{bmatrix}
v_m \\
v_c \\
v_s
\end{bmatrix} + \begin{bmatrix}
B_1A \\
B_2A \\
B_3A
\end{bmatrix} \begin{bmatrix}
v_m \\
v_c \\
v_s
\end{bmatrix} + \begin{bmatrix}
e_1 + B_1e_t \\
e_2 + B_2e_t \\
e_3 + B_3e_t
\end{bmatrix}
\]

Combination of blocks

- Microgenerator
- Voltage booster
- Supercapacitor
Microcontroller

- **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**

$R_{eq} = \begin{cases} 
1.0 \times 9\Omega & \text{when microcontroller is in sleep mode} \\
33\Omega & \text{when microcontroller wakes up} \\
16.7\Omega & \text{when actuator performs tuning}
\end{cases}$
State-space modelling of boost converter

- Switch is modelled as

\[ R_{SW} = \begin{cases} 
1.0 \times 10^9 \Omega & \text{when the switch is off} \\
4 \Omega & \text{when the switch is on}
\end{cases} \]

- State-space matrix

\[
\frac{d}{dt} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ i_L \end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 & 0 \\
-\frac{G_2}{C_2} & -\frac{G_2}{C_2} & 0 & 0 \\
0 & 0 & -\frac{G_3}{C_3X} & -G_3R_{SW} \\
0 & \frac{1}{L} & -\frac{1}{C_3} & -R_{LX} - R_{SW} \\
\end{bmatrix} \begin{bmatrix}
V_1 \\ V_2 \\ V_3 \\ i_L \\
\end{bmatrix} + \begin{bmatrix}
0 \\
\frac{1}{C_1} \\
0 \\
0 \\
\end{bmatrix} \begin{bmatrix}
V_m \\ I_m \\ V_s \\ I_s \\
\end{bmatrix}
\]

\[
+ \begin{bmatrix}
\frac{J_2}{C_2} \\
-\frac{1}{C_3} \\
0 \\
0 \\
\end{bmatrix} \begin{bmatrix}
0 \\
J_3(X + G_3R_{SW}) \\
0 \\
J_3R_{SW} \\
\end{bmatrix} \]
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
    \[
    \frac{di_L(t)}{dt} + \frac{i_L(t)}{\tau} = I_0
    \]
  – General solution to a first-order linear equation
    \[
    i_L(t) = I_0\tau + Ce^{-t/\tau}
    \]
  – Initial condition (present time-point value)
    \[
    t = 0, \quad i_L(0) = i_n \quad \Rightarrow \quad C = i_n - I_0\tau
    \]
  – 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

<table>
<thead>
<tr>
<th>HDL</th>
<th>Existing technique</th>
<th>Proposed technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHDL-AMS</td>
<td>SystemC-A</td>
<td>SystemC-A</td>
</tr>
<tr>
<td>Integration method</td>
<td>Newton-Raphson based</td>
<td>Newton-Raphson based</td>
</tr>
<tr>
<td>CPU time for Scenario 1</td>
<td>2185 sec</td>
<td>2386</td>
</tr>
<tr>
<td>CPU time for Scenario 2</td>
<td>7 hours</td>
<td>8 hours</td>
</tr>
</tbody>
</table>
Why fast design space exploration?

• Even with accelerated simulation – it still takes too 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

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Make</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller</td>
<td>PIC16F884</td>
<td>Microchip</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>LIS3L06AL</td>
<td>STMicroelectronics</td>
</tr>
<tr>
<td>Linear actuator</td>
<td>21000 Series Size 8 stepper motor</td>
<td>Haydon</td>
</tr>
<tr>
<td>Radio transceiver</td>
<td>eZ430-RF2500</td>
<td>Texas Instruments</td>
</tr>
</tbody>
</table>
System photos
Simulation vs experiment

- Transmission frequency of sensor node depends on supercap voltage:

<table>
<thead>
<tr>
<th>Supercapacitor voltage</th>
<th>Wireless transmission interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 2.7 V</td>
<td>No transmission</td>
</tr>
<tr>
<td>Between 2.7 and 2.8 V</td>
<td>Transmit every 1 minute</td>
</tr>
<tr>
<td>Between 2.8 and 2.9 V</td>
<td>Transmit every 5 seconds</td>
</tr>
<tr>
<td>Above 2.9 V</td>
<td>Transmit every 1 second</td>
</tr>
</tbody>
</table>

![Graph showing supercapacitor voltage over time with transmission intervals marked]
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:

\[ y = \hat{y}(a_1, a_2, \ldots, a_k) + \epsilon \]

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

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

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

\[
\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j
\]
Design space explorer (Theme C demonstrator)

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

- User parameters and performance indicators

<table>
<thead>
<tr>
<th>User parameters</th>
<th>Vibration source</th>
<th>Micro-generator</th>
<th>Power processing</th>
<th>Storage</th>
<th>Sensor node</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude of sine wave</td>
<td>Proof mass</td>
<td>Diode bridge rectifier</td>
<td>Super-capacitor value</td>
<td>Threshold when transmission frequency changes</td>
</tr>
<tr>
<td></td>
<td>Stiffness of cantilever</td>
<td>4-stage VM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of sine wave</td>
<td>Number of coil turns</td>
<td>Boost converter</td>
<td>Inductor value</td>
<td>Switching Freq</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical Q factor</td>
<td></td>
<td>Duty cycle</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance indicators</th>
<th>Generated power</th>
<th>Power consumption</th>
<th>Super-capacitor voltage</th>
<th>Number of transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum displacement</td>
<td>Transfer efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</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](http://cmg.soton.ac.uk/iridis))

- **Message Passing Interface (MPI) library for programming**
  - OpenMPI: Open Source High Performance Computing
Theme C demonstrator GUI

Performance estimator of wireless sensor powered by kinetic energy harvester

- **Diode bridge**
  - 4-stage voltage multiplier
  - Switching boost converter

- **Power Processing**
  - **Generated Power**: 10.91 mW
  - **Power Consumption**: 1.41 mW
  - **Max Displacement**: 7.48 mm
  - **Transfer Efficiency**: 87.10%

- **Energy Storage**
  - **SuperCap Voltage**: 2.70 V

- **Sensor Node**
  - Estimated Number of Transmissions: 6565/min
  - Transmission duty cycle depends on supercap voltage ($V_c$) and threshold voltage ($V_{th}$):
    - $V_c < 2V$: no transmission
    - $2V < V_c < V_{th}$: transmit every 1 min
    - $V_{th} < V_c < 3.5V$: transmit every 1 sec
    - $V_c > 3.5V$: transmit every 3 ms

**User parameters**

- **Peak Amp**: 700 mg (100~1000mg)
- **Freq**: 50.00 Hz (50~250Hz)
- **Proof mass**: 2.0 g (2~12g)
- **Number of coil turns**: 2000 (500~5000)
- **Mechanical Q**: 200 (100~500)
- **Cantilever**
  - Length: 10.00, 2.00, 1.00 mm
  - Width: 150.00, 200.00 mm
  - Thickness: Copper
- **Resonant Frequency**: 50.01 Hz
- **Operating Freq Range**: 49.750 to 50.250 Hz

**Energy consumption per transmission (100~1000μJ)**

- SuperCap threshold voltage (2.5~3V): 2.50 V
- SuperCap capacitor value (0.1~1F): 0.55 F

The resonant frequency of cantilever is close to the input frequency. Performance indicators updated.
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.
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