ELEC6233
Digital System Synthesis

5. Design space exploration and synthesis
Design space exploration - an interesting history

- Sir Ronald A. Fisher pioneered the concept of “design of experiments” in 1920s in agriculture which resulted in Response Surface Modelling (RSM).
  - Now used in many areas of science and engineering

Limited number of experiments (or simulations!)

Polynomial model (Response Surface)

FAST DESIGN SPACE EXPLORATION!
Design Space Exploration and Hardware Synthesis

- Application
- Select implementation
- Map design to H/W
- Evaluate performance metrics
- Best design?
- Done

This process is carried out on several levels of abstraction.
Design Space Exploration

1. Application
2. Select implementation
3. Map design to H/W
4. Evaluate performance metrics
5. Best design?
   - Yes: Done
   - No: Semi-automated design space exploration

This process is carried out on several levels of abstraction.
Design Space Exploration

1. Application
2. Select implementation
3. Map design to H/W
4. Evaluate performance metrics
5. Best design?
   - Yes: Done
   - No: Repeat steps 2-5

Semi-automated design space exploration
Real-time simulation-based, or RSM based (off-line simulations)

This process is carried out on several levels of abstraction
Performance analysis is difficult

• Simulation is difficult due to complexity

• Several levels of abstraction
  – Low-fidelity (less accurate) and high-fidelity (more accurate) models

• Behaviour is complex, data dependent

• Constraints
  – Limited resources
  – Limited time to evaluate performance accurately

• Multiple applications
  – Resources even more limited
  – Mapping/scheduling/arbitration very hard
Optimisation

• Optimisation goal: find the best design in the design space

• Optimisation often has conflicting objectives
  – Typical trade offs:
    • Speed, power, size, cost
  – Multi-objective optimisation techniques exist

• A number of optimisation techniques are used in high-level synthesis
  – Evolutionary optimisation (genetic optimisation)
  – Simulated annealing
  – Integer Programming
Design space exploration response surface models (RSM)

1. Let the designer select ‘a best’ design by exploring the design space quickly.
2. RSM approach only needs a limited number of expensive simulations to build the response surface model.
3. RSM uses low-order polynomials, hence is fast.
4. Need to build a separate RSM for each performance metric – but one set of simulations is sufficient.

Limited number of experiments (or simulations!)

Polynomial model (Response Surface)

**FAST DESIGN SPACE EXPLORATION!**
RSM concept will be explained using an example

- Challenge: find an optimal design of a complex energy-harvester-powered sensor node
  - High-speed vibration microgenerator: small simulation time step (0.1ms)
  - Low-speed storage: supercapacitor can take tens of hours to charge

System simulation and validation

Scenario 1: tuning by 1Hz

Recovery time/duty cycle - 600 seconds

Output power from microgenerator:

Supercapacitor voltage:
Simulation and validation (2)

Scenario 2: tuning by 14Hz

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

Supercapacitor voltage:
## Simulation complexity

Comparison of CPU times

Two order of magnitude acceleration was needed to make RSM approach feasible

<table>
<thead>
<tr>
<th>HDL</th>
<th>Existing technique</th>
<th>New accelerated technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHDL-AMS</td>
<td>SystemC-A</td>
<td>SystemC-A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Integration method</th>
<th>Existing technique</th>
<th>New accelerated technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newton-Raphson based</td>
<td>Newton-Raphson based</td>
<td>Linearised state-space</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CPU time for Scenario 1</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2185 sec</td>
<td>2386</td>
<td>20.3 sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CPU time for Scenario 2</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7 hours</td>
<td>8 hours</td>
<td>228 sec</td>
</tr>
</tbody>
</table>
## System diagram

![System diagram](image.png)

### Component Table

<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>
Performance metric: energy consumption of sensor node

- Measure the current draw of sensor node at various modes

![Current vs Time Graph](image)

- Supply voltage is 2.8V, total energy of 116 uJ during 2.75 ms of transmission
- Power and energy consumption can be calculated.
Response surface model (1)

• 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:

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

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

\[ \hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j \]
Response surface model (2)

- Low order polynomial equation:

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

- To characterise the RSM is to find coefficients \( \beta \) that give the minimum sum of squared residuals (SSE), i.e. minimise the approximation error:

\[
SSE = \sum_{i=1}^{n} \epsilon^2 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2
\]

- A number of simulations with different parameter values within the design space are carried out to calculate coefficients \( \beta \) using least squares method (LSM):

\[
\frac{\partial SSE}{\partial \beta} = 0
\]

- Optimum design (matrix \( X \) that maximises the polynomial) can then be found quickly.

- The best design is that which maximises the polynomial.
Design points choice for simulations - D-optimal design

• How to choose the predefined design points to cover the design space efficiently is the essence of the Design Of Experiment (DOE) methodology:

\[ \hat{y} = X\beta \]  
(matrix form of the polynomial, \( X \) – information matrix)

• Different types of DOE method: full factorial, central composite design (CCD), Box Behnken design (BBD) and computer generated designs such as D-optimal design

• D-optimal design is chosen because it requires minimum number of simulation runs

• D-optimal design is obtained by maximising the determinant of information matrix:

\[ \max(X \, X') \]
RSM model of the sensor node system

- 3 system configuration parameters are chosen for optimisation

<table>
<thead>
<tr>
<th>Description</th>
<th>Value range</th>
<th>Coded variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller clock frequency (Hz)</td>
<td>125k ~ 8M</td>
<td>$x_1$</td>
</tr>
<tr>
<td>Watchdog timer wakeup time (sec)</td>
<td>160 ~ 600</td>
<td>$x_2$</td>
</tr>
<tr>
<td>Transmission time interval (sec)</td>
<td>0.005 ~ 10</td>
<td>$x_3$</td>
</tr>
</tbody>
</table>

- Test scenario: vibration level 60mg, input frequency changed by 5Hz every 25 minutes
- System performance: total no of transmissions made during 1 hour (related to harvested energy)
- 27 simulations were carried out using accelerated simulation technique developed before
- RSM model (full quadratic equation):

$$
\hat{y}(x_1, x_2, x_3) = 469.167 - 108.833x_1 - 18.833x_2 - 209.5x_3 \\
+ 71.833x_1^2 + 90.5x_2^2 - 39.0x_3^2 - 32.333x_1x_2 - 71.333x_1x_3 + 43.333x_2x_3
$$
**Optimisation within RSM**

- Two algorithms from MATLAB toolbox are used for optimisation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original design</th>
<th>Simulated annealing</th>
<th>Genetic algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller clock frequency(Hz)</td>
<td>4M</td>
<td>8M</td>
<td>125k</td>
</tr>
<tr>
<td>Watchdog timer wakeup time(sec)</td>
<td>320</td>
<td>60</td>
<td>600</td>
</tr>
<tr>
<td>Transmission time interval(sec)</td>
<td>5</td>
<td>0.005</td>
<td>3.065</td>
</tr>
<tr>
<td>Number of transmissions</td>
<td>405</td>
<td>899</td>
<td>894</td>
</tr>
</tbody>
</table>

- It is possible to investigate the effect of each parameter on system performance using RSM
Demonstrator tool – 6 RSMs

- Performance estimator of wireless sensor powered by kinetic energy harvester
- User parameters and 6 performance indicators (6 RSMs were built)

<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></td>
<td>4-stage VM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of sine wave</td>
<td>Number of coil turns</td>
<td></td>
<td>Boost converter</td>
<td>Inductor value</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical Q factor</td>
<td></td>
<td></td>
<td>Switching Freq</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Duty cycle</td>
<td></td>
</tr>
<tr>
<td>Performance indicators</td>
<td>Generated power</td>
<td></td>
<td>Power consumption</td>
<td>Super-capacitor voltage</td>
<td>Number of transmission</td>
</tr>
<tr>
<td></td>
<td>Maximum displacement</td>
<td></td>
<td>Transfer efficiency</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
RSM model of the sensor node system

• 11 continuous parameters and 3 circuit topologies – treated as a discrete parameter
• 6 system performance indicators
• Simulation scenario: 10 hours continuous operation

<table>
<thead>
<tr>
<th>Supercapacitor voltage</th>
<th>Node behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 2.0V</td>
<td>Wake up every 1 minute, no transmission</td>
</tr>
<tr>
<td>Between 2.0 and Vth</td>
<td>Wake up and transmit every 1 minute</td>
</tr>
<tr>
<td>Between Vth and 3.5V</td>
<td>Wake up and transmit every 1 second</td>
</tr>
<tr>
<td>Above 3.5V</td>
<td>Wake up and transmit every 3ms, preventing from over-charge</td>
</tr>
</tbody>
</table>

• For each circuit topology with \( n \) continuous parameters, the number of simulations \( (N) \) required by the D-optimal choice is given by:

\[
N = 1(\text{constant item}) + n(\text{linear items}) + n(\text{squared items}) + C_n^2(\text{interaction items})
\]

• Total of 200+ simulations needed to build the RSM
Simulations were done on a supercomputer

- 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
GUI was created for design space exploration

- User can set the design parameters and the resulting system performance will update instantly
  - Initial GUI, simplified diagram, energy harvester as black box
GUI was created for design space exploration (2)

- Expanded GUI, more detail and more controls for the user
Response surface models in high-level synthesis

- A new concept has been investigated in recent years:
  - Supervised high-level synthesis (SHLS)

- In SHLS, exploration strategies play the role of a supervisor for tuning an HLS engine.

- SHLS tools include not only architectural alternatives but also compiler transformations – high complexity problems

- Recent example published in 2015: a new exploration approach, called spectral-aware Pareto iterative refinement, that exploits response surface models (RSMs) and spectral analysis for predicting the quality of the design points without resorting to costly architectural synthesis procedures: