Smart Infrastructure and buildings
- why energy harvesting is needed -

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The Problems

• Poor understanding of performance of infrastructure, during construction and after completion

• Construction industry
  – Expensive
  – Old and slow, not always safe
  – Produces lots of waste

• Ageing infrastructure
  – Typical lifespan in range 15-60 years
  – Much of UK infrastructure considerably older
The Vision

- Cradle-to-grave through whole life cycle
- Develop and commercialise emerging technologies
  - latest sensor technologies
  - data management tools
  - manufacturing processes
  - supply chain management processes
  - management of the built environment
- Interdisciplinary
Ageing Engineering Infrastructure

• **Tunnels**
  - *London Underground (LUL)*
    - Tunnels 75 – 100 yrs old
    - Deterioration of linings
    - Minimal clearance to tunnel wall
    - Risks from 3rd party construction

• **Water Supply and Sewer Systems**
  - *Thames Water*
    - 31,000 km of pipelines
    - ½ more than 100 yrs old, 1/3 more than 150 yrs old, ~30% leakage

• **Bridges**
  - *Highway Agency/LUL/ Humber Bridge*
    - ~150,000 bridges in UK
    - Critical links in road/rail infrastructure
    - Deterioration
    - Many structures below required strength
Tunnels
Wireless Sensor Network

- Gateway [Ring1685]
- Crackmeter [ID8972 Ring1689]
- Inclinometer [ID8961 Ring1689]
- Crackmeter [ID891 Ring1689]
- Inclinometer [ID8961 Ring1689]
- Relay [ID0001 Ring1700]
- Inclinometer [ID891 Ring1689]
- Inclinometer [ID8921 Ring1689]
- Relay [ID0001 Ring1700]
- Inclinometer [ID891 Ring1689]
- Inclinometer [ID8961 Ring1689]
- Crackmeter [ID8972 Ring1689]
- Inclinometer [ID8961 Ring1689]
Inner diameter: 3810mm

Wedge segment

Inner diameter: 3810 mm

19000 rad.

Wedge segment

1 in 10

115

100

520

19000 rad.

600
Crackmeter (LPDT) for measurement

LPDT for temp. comp.

Crack Location

Range 12.5mm
MicaZ 10 bit ADC
Resolution ~12μm
Inclinometer

- Resolution 0.001°
- Range ±15°
- External 16 bit ADC

Temperature & Humidity sensor
3.6v battery, battery capacity: 19 Ah (amp hour)

3mins/sample frequency > 500 days.

The average power consumption 4.6mW
Design of Energy Efficient WSN system

Use of relay motes

Energy Usage : 100

Energy usage : 50

Energy usage : 50
London WSN case

By placing relay nodes at optimised locations, the battery usage of the motes will be more evenly spread and the life of the Bond Street WSN can be extended for another 30%. 
Energy harvesting target

<table>
<thead>
<tr>
<th>Device</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laptop</td>
<td>10</td>
</tr>
<tr>
<td>Sensor board</td>
<td>1</td>
</tr>
<tr>
<td>Ipod nano</td>
<td>100's mW</td>
</tr>
<tr>
<td>Wireless communication</td>
<td>5-15 mW</td>
</tr>
<tr>
<td>MEMS Sensor</td>
<td>1-10 (\mu)W</td>
</tr>
<tr>
<td>Electronic Watch</td>
<td>1 (\mu)W</td>
</tr>
</tbody>
</table>

**Target:** 1\(\mu\)W, 15mW, 1W
RF / Sound / Solar energy harvester

RF electromagnetic wave power density =
1\mu W/cm^2 @ 50 cm distance from the transmitter (WLAN)

Sound wave power density =
1\mu W/cm^2 @ 100 dB sound noise
(10\% traffic ports have such noise level)

Solar cell power density =
100 mW/cm^2 @ strong sunlight
100 \mu W/cm^2 @ office
Data from London Underground monitoring

Air flow velocity in tunnel

When a train is passing (300s-400s)

Tunnel acceleration

(m/s)

(m/s/s)
Air-flow energy harvester power simulation

\[ P = \frac{1}{2} \rho A V^3 C_p \]

\( P \): power, \( \rho \): flow density, \( A \): area of turbine, \( V \): flow velocity
\( C_p \): power coefficient, (theoretical maximum = 0.593, Betz limit)

Fig: Calculated power output using 1cm\(^2\) area turbine considering real air flow velocity in tunnels

\( P_{\text{peak}} = 0.3 \text{mW} \)

Time \(*\) 10 s
Train 1

Train 2

Peak Frequency = 278 Hz

Peak Frequency = 279 Hz
Piezoelectric Energy Harvester

\[ M \ddot{u}(t) + D \dot{u}(t) + Ku(t) + Av(t) = -M \ddot{y}(t) \]
\[ v(t) = RA \dot{u}(t) - RC \dot{v}(t) \]

**Variables**
- \( u \): displacement of the mass
- \( y \): external excitation displacement
- \( v \): outgoing voltage

**Parameters**
- \( M \): mass
- \( K \): stiffness of the spring
- \( D \): damper
- \( A \): piezoelectric coefficient
- \( C \): piezoelectric capacitance
- \( R \): resistive load

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A ) (V/N)</td>
<td>0.00047</td>
</tr>
<tr>
<td>( C ) (F)</td>
<td>( 1.27 \times 10^{-7} )</td>
</tr>
<tr>
<td>( D ) (N/ms)</td>
<td>0.042</td>
</tr>
<tr>
<td>( K ) (N/m)</td>
<td>4320</td>
</tr>
</tbody>
</table>

For \( M = 0.02 \) g.

1 uW per kg.
Water Mains
Water Mains monitoring

Manhole covers in a UK road. (Southport)

A water pipe inside a manhole. There may be some wireless sensors to measure water flow and pressure.
Manhole Cover Vibration Data

• Broadband vibration

• Multiple frequency peaks:
  10-60 Hz and 280-330 Hz

(impulse response of the manhole cover)
Sinusoidal Excitation based Optimisation

<table>
<thead>
<tr>
<th>F (Hz)</th>
<th>M (g)</th>
<th>R (KΩ)</th>
<th>Power (uJ/Vehicle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>304</td>
<td>1</td>
<td>4.1</td>
<td>$1.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>20.8</td>
<td>$6.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>10</td>
<td>1090</td>
<td>125</td>
<td>0.76</td>
</tr>
</tbody>
</table>
Hydraulic power generation using bypass pipes

- 15 mW Power  ➡️  85 – 96 Litres/Day

- 0.07 – 0.32 mW < 1 mW
  Pressure Difference: 63 Pa << 20 KPa

- < 1 μW

<table>
<thead>
<tr>
<th></th>
<th>Water Velocity (m/s)</th>
<th>Pressure Diff. (Pa)</th>
<th>Electric Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sys. 1</td>
<td>20.9 – 23.2</td>
<td>350K</td>
<td>144 – 196 W</td>
</tr>
<tr>
<td>Sys. 2</td>
<td>0.17 – 0.27</td>
<td>63</td>
<td>0.07 – 0.32 mW</td>
</tr>
<tr>
<td>Sys. 3</td>
<td>0.004 – 0.033</td>
<td>50</td>
<td>&lt; 1 μW</td>
</tr>
</tbody>
</table>
Thermoelectric generation

Average Temperature Difference:
3 °C

Dimension:
40 x 40 x 4.5 mm

Costs: 10 USD

Power: 2.8 mW

A 15 mW System:
6 Pcs → 60 USD
Thermoelectric generation

Outside Air → Thermoelectric Generator → Manhole Chamber

V = 20 cm/s

Valve → Thermal-Isolated Tube

V = 2 cm/s

Main pipe

System 1

System 2
Power harvesting from water pressure fluctuation

The Simulated Result of an Optimised Generator:

<table>
<thead>
<tr>
<th>Piston Area: 1 cm²</th>
<th>M (Kg)</th>
<th>K (N/m)</th>
<th>D (Ns/m)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>17.3</td>
<td>25.2</td>
<td></td>
<td>3.28</td>
</tr>
</tbody>
</table>
**Main pipe**

**Piston**

**Resonance**

\[
\text{Ave Power} = 8.1136 \text{ mW}
\]

**Non-Resonance**

\[
\text{Ave Power} = 3.4331 \text{ mW}
\]

<table>
<thead>
<tr>
<th></th>
<th>M (Kg)</th>
<th>K (N/m)</th>
<th>D (Ns/m)</th>
<th>0.1 Hz Sine Data</th>
<th>Recorded Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave. Power (mW)</td>
<td>P2P Disp (metre)</td>
<td>Ave. Power (mW)</td>
<td>P2P Disp (metre)</td>
<td></td>
</tr>
<tr>
<td>Resonant</td>
<td>3.60</td>
<td>1.42</td>
<td>31.83</td>
<td>15.65</td>
<td>0.10</td>
</tr>
<tr>
<td>Non-Res</td>
<td>3.60</td>
<td>15.56</td>
<td>22.51</td>
<td>10.83</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Per cm²
Bridges
Humber Bridge
Ferriby Road Bridge
(part of Humber Bridge)
WSN Layout

Gateway with 12V 100Ah battery & Mobile Phone Modem
New technologies
MEMS resonant power harvester

Figure 1. Illustration of the power harvester

Figure 2. Displacement amplification

Figure 3. Equivalent mechanical model

$\text{Displacement}$

$\text{Frequency}$

$f_1 = 1.4\text{kHz}$, $f_2 = 1.8\text{kHz}$, $f_3 = 2.3\text{kHz}$
MEMS power harvester experimental result

Current device: \( Area = 0.135 \text{cm}^2 \), \( Thickness = 25 \text{um} \), \( gap = 2 \text{um} \), \( f = 1.43 \text{kHz} \) \( \Rightarrow \) Power = 0.113\( \mu \text{W} \)

Future work: \( Area = 1 \text{cm}^2 \), \( Thickness = 400 \text{um} \), \( gap = 10 \text{um} \), \( f = 130 \text{Hz} \) \( \Rightarrow \) Power = 2.23\( \mu \text{W} \)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Mass (g)</th>
<th>Acceleration (ms(^2))</th>
<th>Power ((\mu\text{W}))</th>
<th>Power/Mass/Acceleration ((\mu\text{W}/\text{g/}\text{ms}^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ma [3]</td>
<td>0.0002</td>
<td>766</td>
<td>0.065</td>
<td>0.42</td>
</tr>
<tr>
<td>Mitcheson [4]</td>
<td>0.1</td>
<td>50</td>
<td>3.7</td>
<td>0.74</td>
</tr>
<tr>
<td>Despese [5]</td>
<td>104</td>
<td>8.8</td>
<td>1052</td>
<td>1.15</td>
</tr>
<tr>
<td>Arakawa [6]</td>
<td>0.65</td>
<td>3.9</td>
<td>6</td>
<td>2.37</td>
</tr>
<tr>
<td>This work (in air)</td>
<td>0.000734</td>
<td>1.76</td>
<td>0.017</td>
<td>13.16</td>
</tr>
<tr>
<td>This work (in vacuum)</td>
<td>0.000734</td>
<td>1.75</td>
<td>0.113</td>
<td>87.97</td>
</tr>
</tbody>
</table>

Yellow: acceleration   Green: power output (voltage)
EnOcean switches and sensors for buildings

Solar cells

electromagnetic

thermocouples

From EnOcean website
## Motivation Concept: Transparent PV cells
(Currently amorphous Si)

<p>| | | |</p>
<table>
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<tr>
<td>ASI glas - Schott Solar</td>
<td><a href="http://www.schottSolar.com">www.schottSolar.com</a></td>
<td></td>
</tr>
<tr>
<td>See-Through PV module - Kaneka</td>
<td><a href="http://www.pv.kaneka.co.jp">www.pv.kaneka.co.jp</a></td>
<td></td>
</tr>
<tr>
<td>Suntech See Thru - Suntech</td>
<td><a href="http://www.suntech-power.com">www.suntech-power.com</a></td>
<td></td>
</tr>
</tbody>
</table>
• seamless built-in technology

• light shade decreases incoming heat
  → less A/C usage
  → environmental friendly

• aperture / yield trade-off
  (similar to LCD trade-off)
The Idea

See through solar cells

• amorphous selenium (a-Se)
  wide band gap $\rightarrow$ *transparent to visible light*

• inexpensive and easy to fabricate
  thermal evaporation electrolysis

Saito et al. (2011) Appl. Phys. Lett. 98, 152102 (2011);
doi:10.1063/1.3579262 (3 pages)
Large-Scale Deployment

Monitor station before, during and after new development

Monitor Flyover in parallel with commercial monitoring system
Innovation and Knowledge Centre for Smart Infrastructure and Construction

- Develop and commercialise emerging technologies such as latest sensor technologies, data management tools, manufacturing processes, supply chain management processes and management of the built environment.
- Starting April 2011 for five years.
- £10M from EPSRC/TSB and £7M from Industry

**Construction Sector**

- Laing O’Rourke
- ARUP
- SKANSKA
- ITM
- Sol Dextra
- Atkins
- Costain
- WSP
- PB
- Mott MacDonald
- Symonds
- Brey
- Halcrow

**Infrastructure Sector**

- Thames Water
- Transport for London
- Highways Agency
- Tube Lines
- Underground
- Humber Bridge Board
- Transport Scotland
- IRL

**Manufacturing, Electrical & Information Sectors**

- Toshiba
- IBM
- RedBite
- Thales
- OpenHub
Summary 1

• Motivation for infrastructure and building monitoring
  – Difficult-to-access locations
  – Risk assessment versus monitoring (long-term monitoring may not be what infrastructure owners want for existing infrastructure)
  – Minimum disturbance to existing infrastructure
  – Newly builds - Construction industry needs to shift to more service oriented industry
Summary 2

• Cheaper than battery
  – EH-Battery combined solution
  – Batch production (MEMS)
  – Sensor-communication electronics integration for lower power consumption

• Ease of use
  – Minimum training, off-the-shelf solution
  – Safe, safe and safe
Thank you

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EPSRC, London Underground, Tubelines, United Utilities, Humber Bridge, Transport for London