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

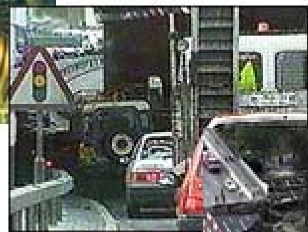
- **Tunnels**
  London Underground (LUL)
  - Tunnels 75 – 100 yrs old
  - Deterioration of linings
  - Minimal clearance to tunnel wall
  - Risks from 3rd party construction

- **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

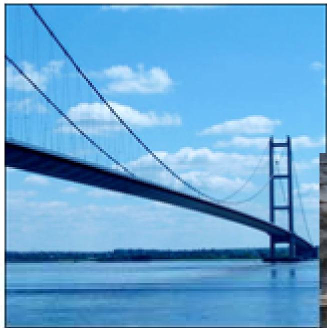
Oxford Street

LUL tunnel



Blackwall Tunnel

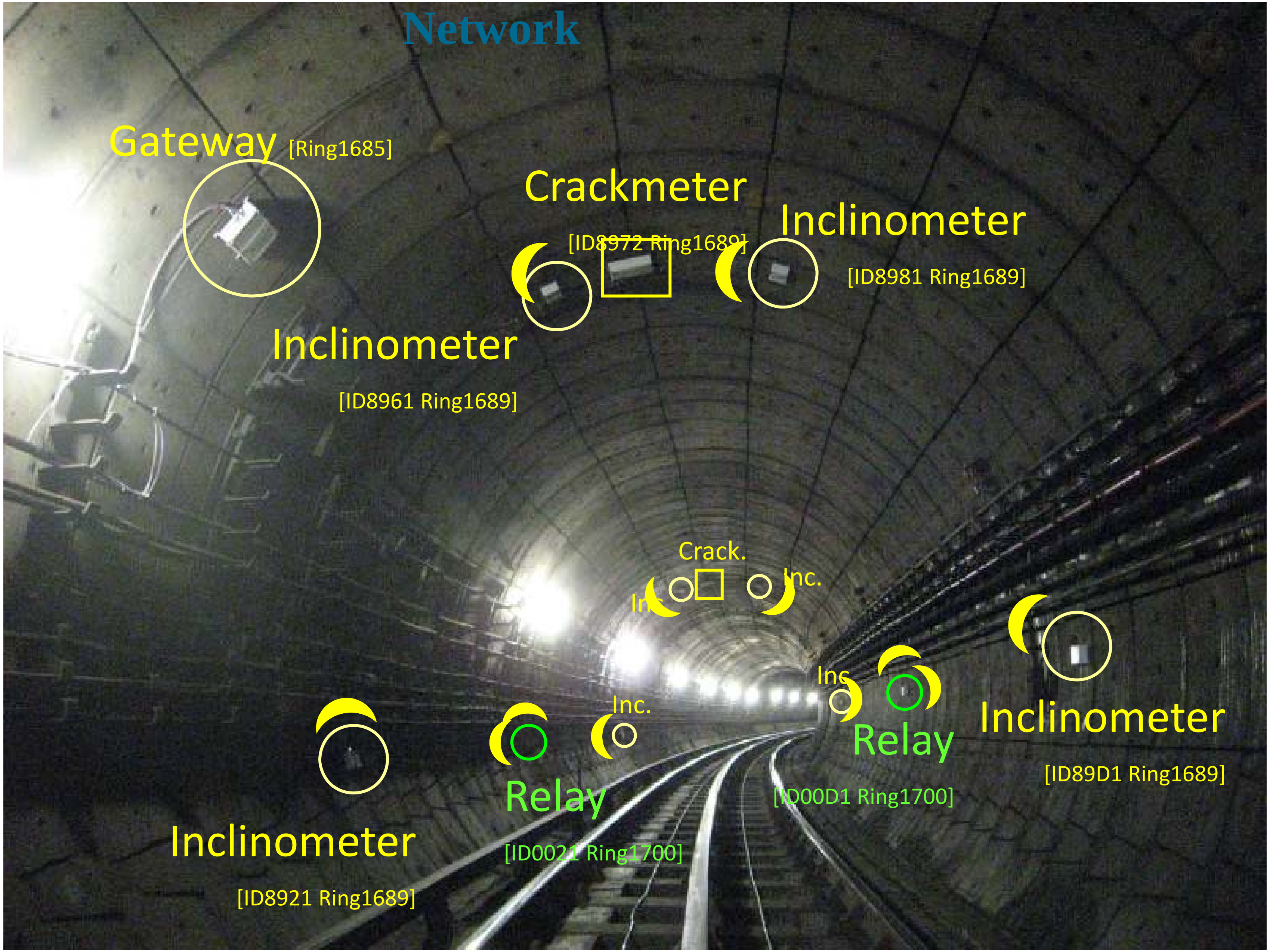
Collapsed Tunnel

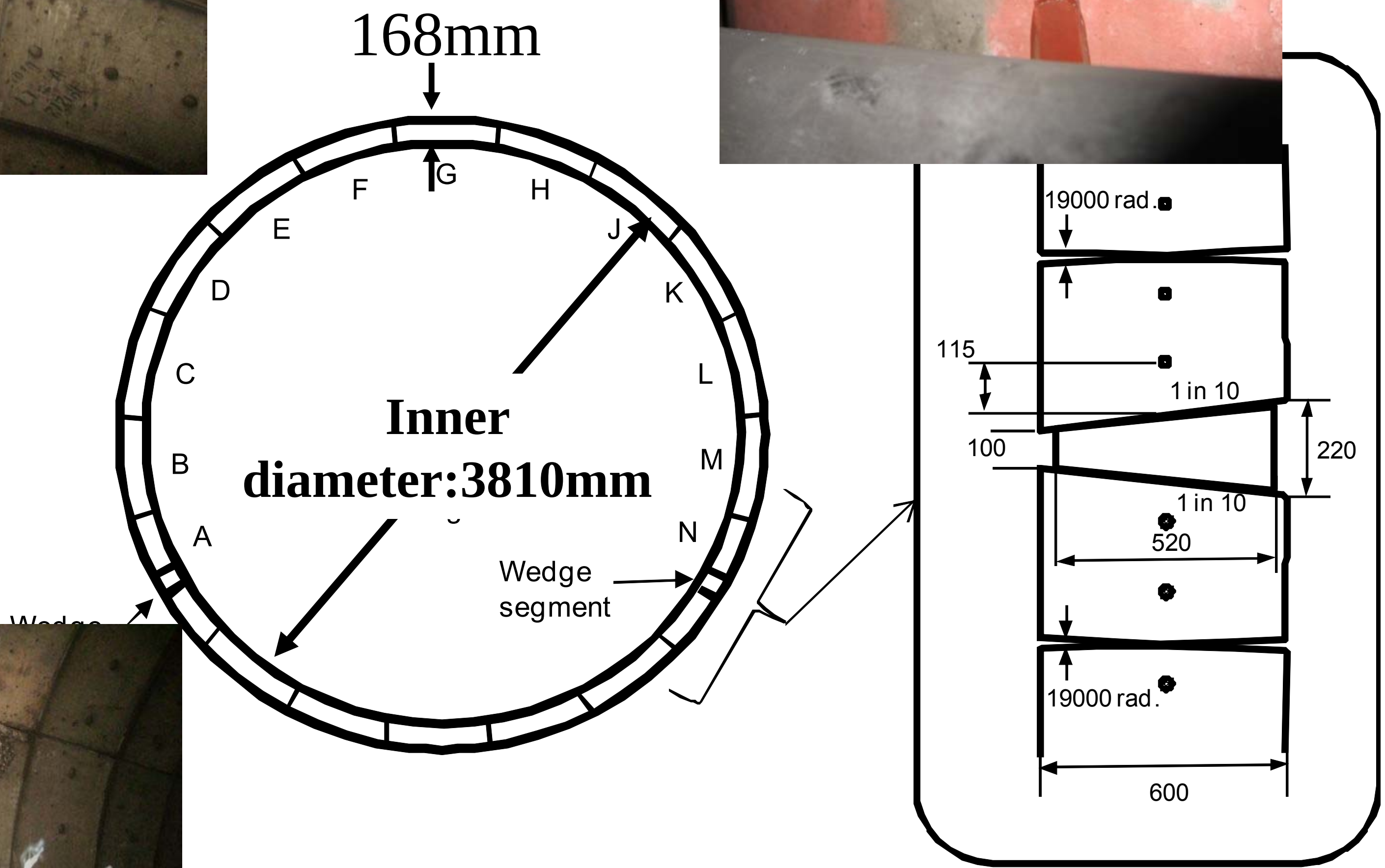


The Humber Bridge

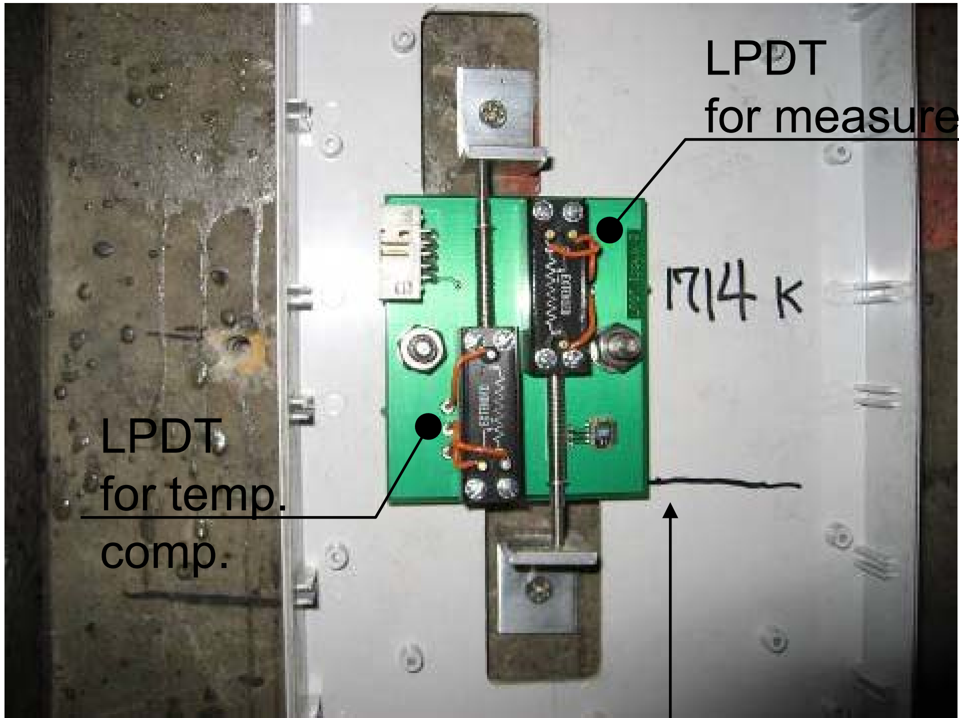
Tunnels

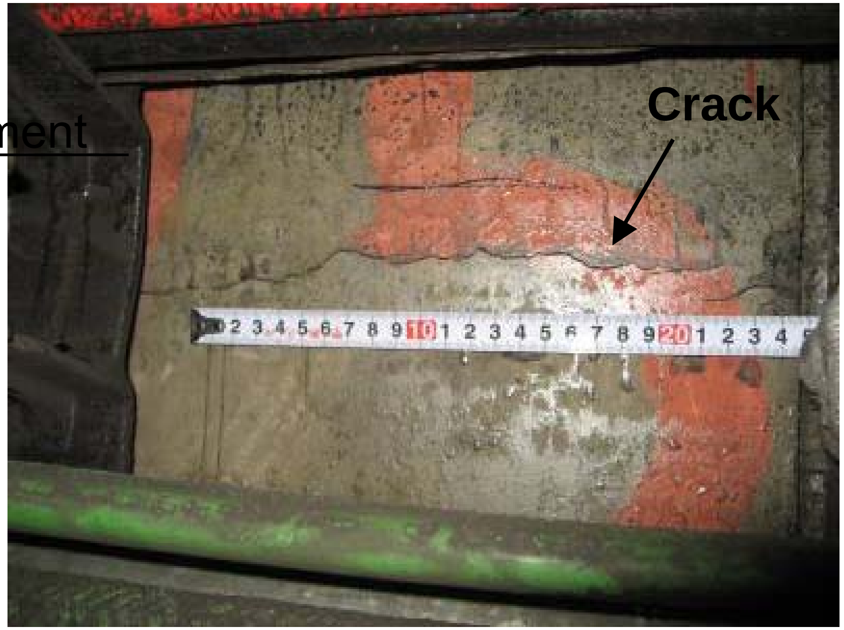
Wireless Sensor Network

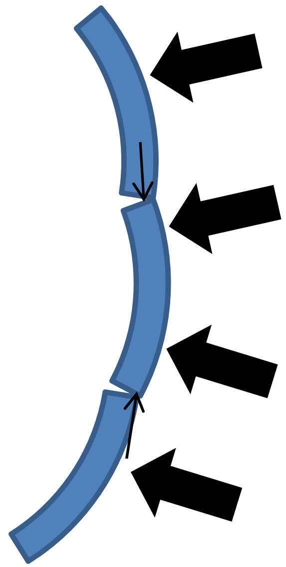



168mm
G
F
H
E
J
D
K
C
L
Inner
diameter:3810mm
B
M
A
N
Wedge
segment
19000 rad.
115
1 in 10
100
220
1 in 10
520
19000 rad.
600

Crackmeter (LPDT)





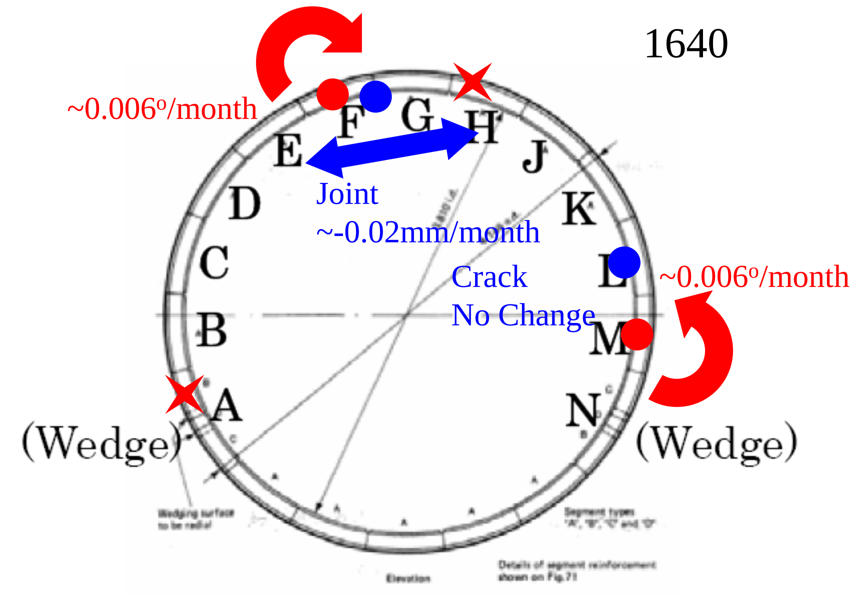


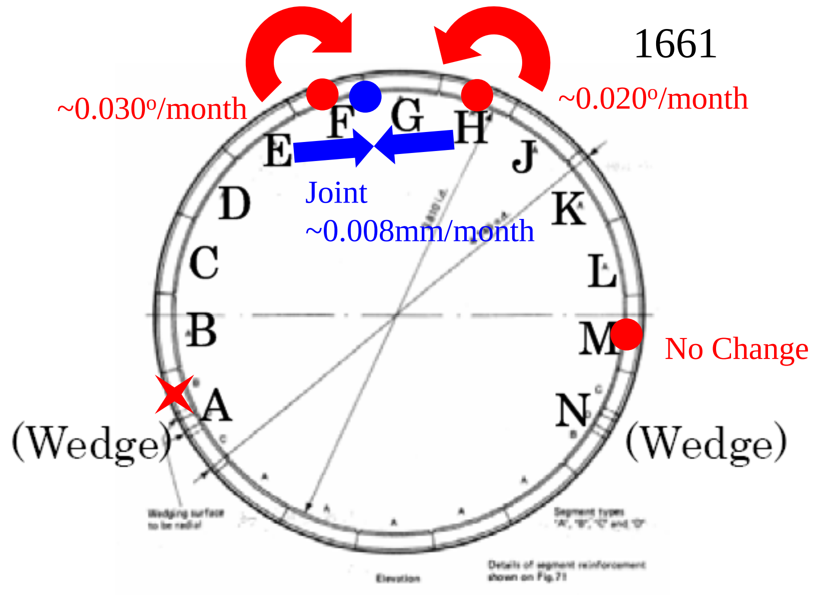
Range 12.5mm
MicaZ 10 bit ADC
Resolution ~12μm

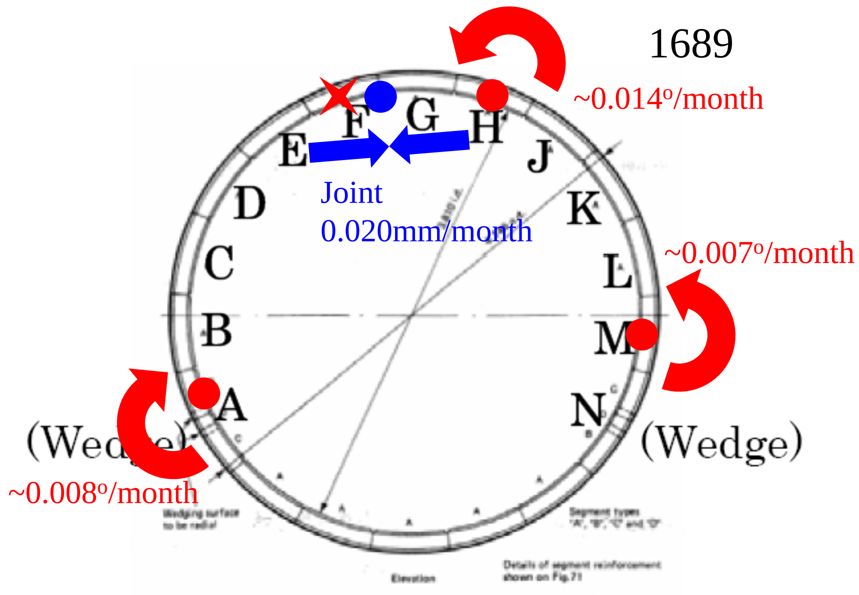
Inclinometer

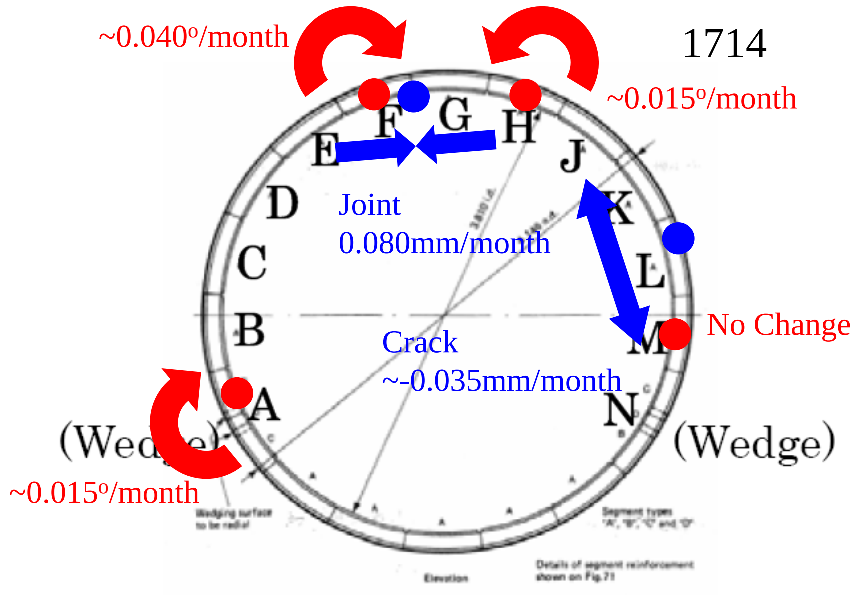
Resolution 0.001°
Range ±15°
External 16 bit ADC

Movement Overview



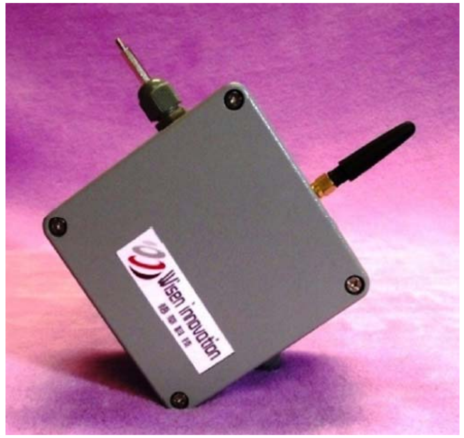






Gateway

Inclinometer mote

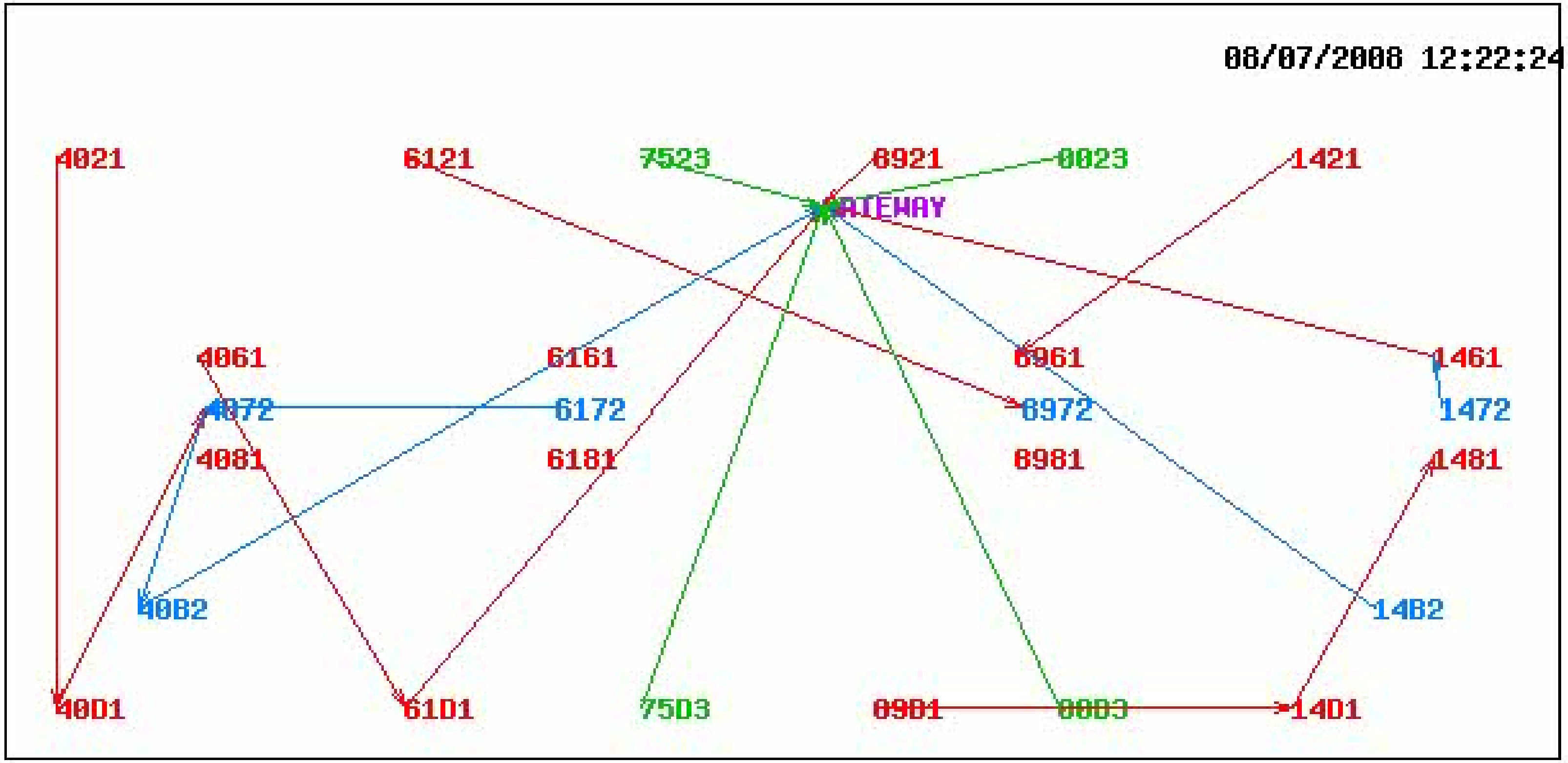


Displacement mote

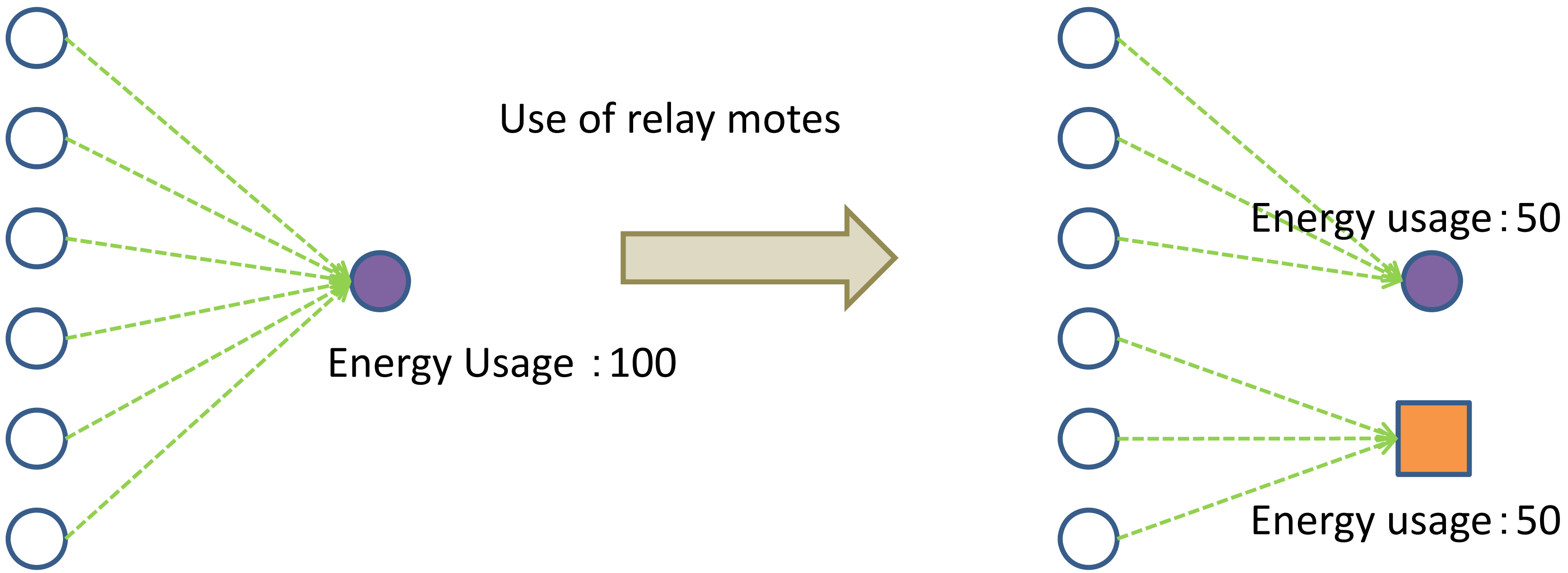
3.6v battery, battery capacity: 19 Ah (amp hour)

3mins/sample frequency > 500 days.

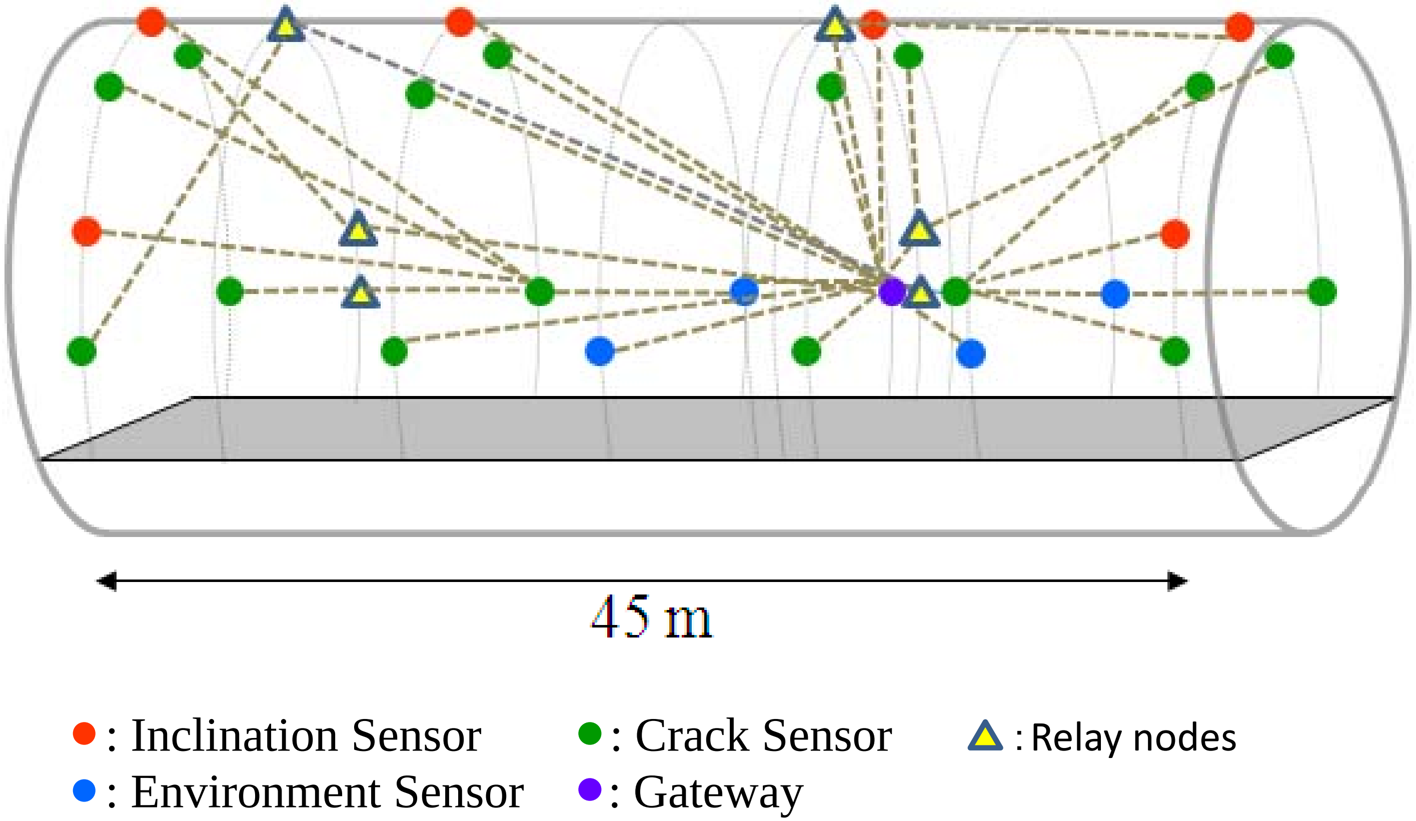
The average power consumption 4.6mW


08/07/2008 12:22:24
4021
6121
7523
6921
0023
1421
ATEWAY
4061
6161
6961
1461
4072
6172
6972
1472
4081
6181
6981
1481
40B2
14B2
40D1
61D1
75D3
69D1
00D3
14D1

Design of Energy Efficient WSN system



London WSN case

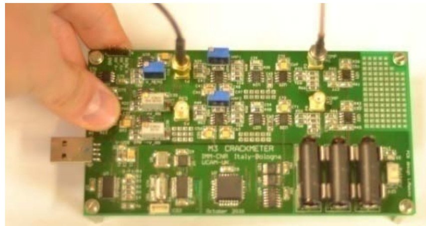


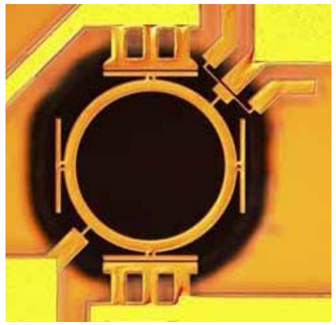
By placing relay nodes at optimised locations, the battery usage of the motes will be more evenly spread and the life of the Bond Street WSN can be extended for another 30%.

Energy harvesting target

Laptop	10 W
Sensor board	1 W
Ipod nano	100's mW
Wireless communication	5-15 mW
MEMS Sensor	1-10 µW
Electronic Watch	1 µW

Target: 1µW, 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 =

$1\mu W/cm^2$ @ 100dB sound noise

(10% traffic ports have such noise level)

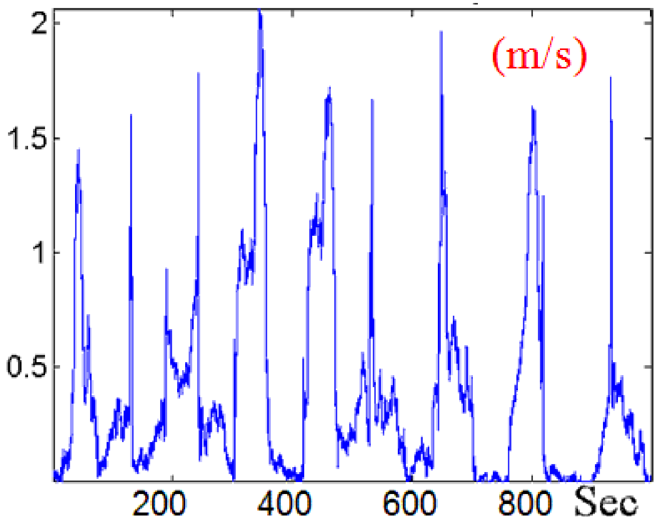
Solar cell power density =

$100 mW/cm^2$ @ strong sunlight

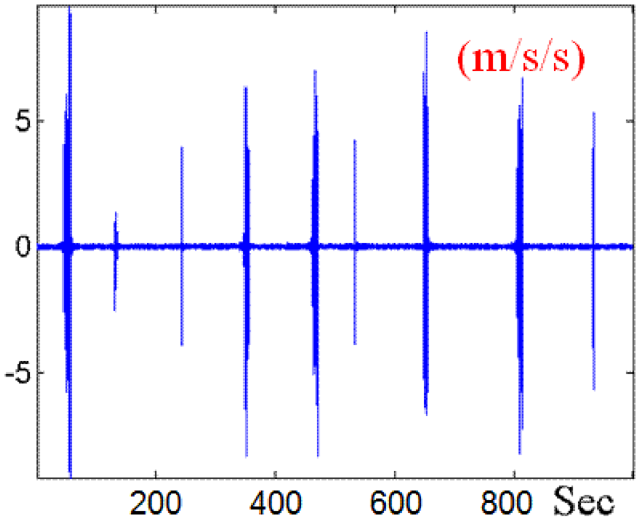
$100\mu W/cm^2$ @ office

Data from London Underground monitoring

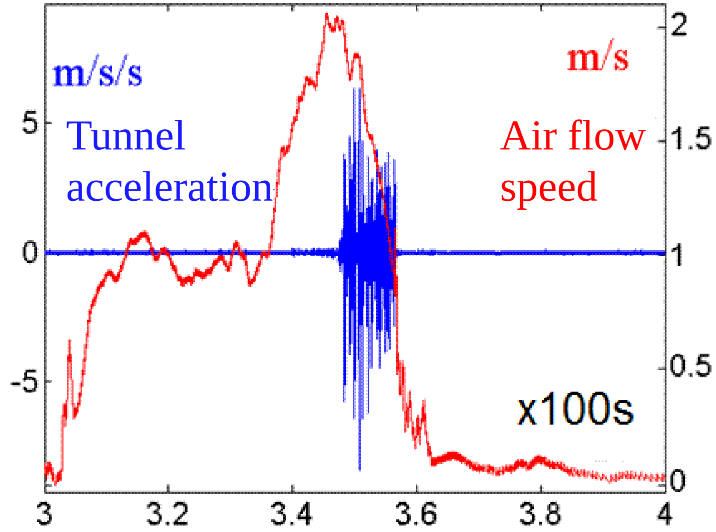
Air flow velocity in tunnel



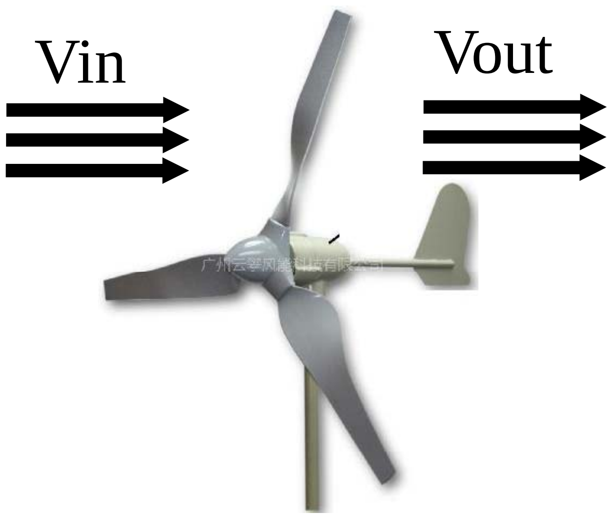
Tunnel acceleration



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



Air-flow energy harvester power simulation



$$P = \frac{1}{2}\rho A V^3 C_P$$

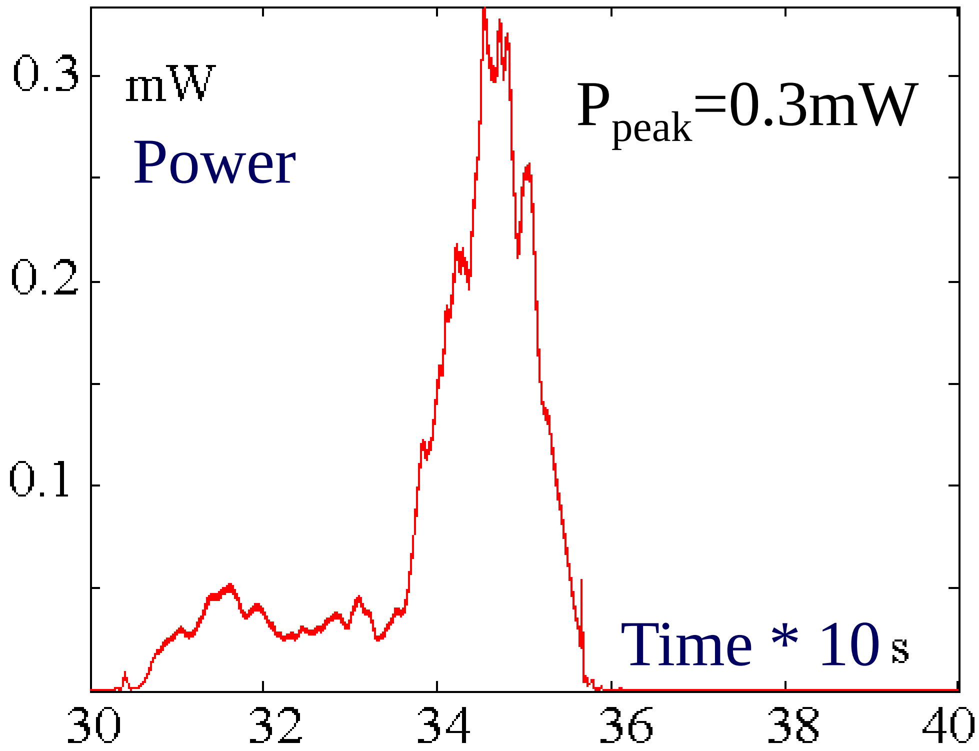
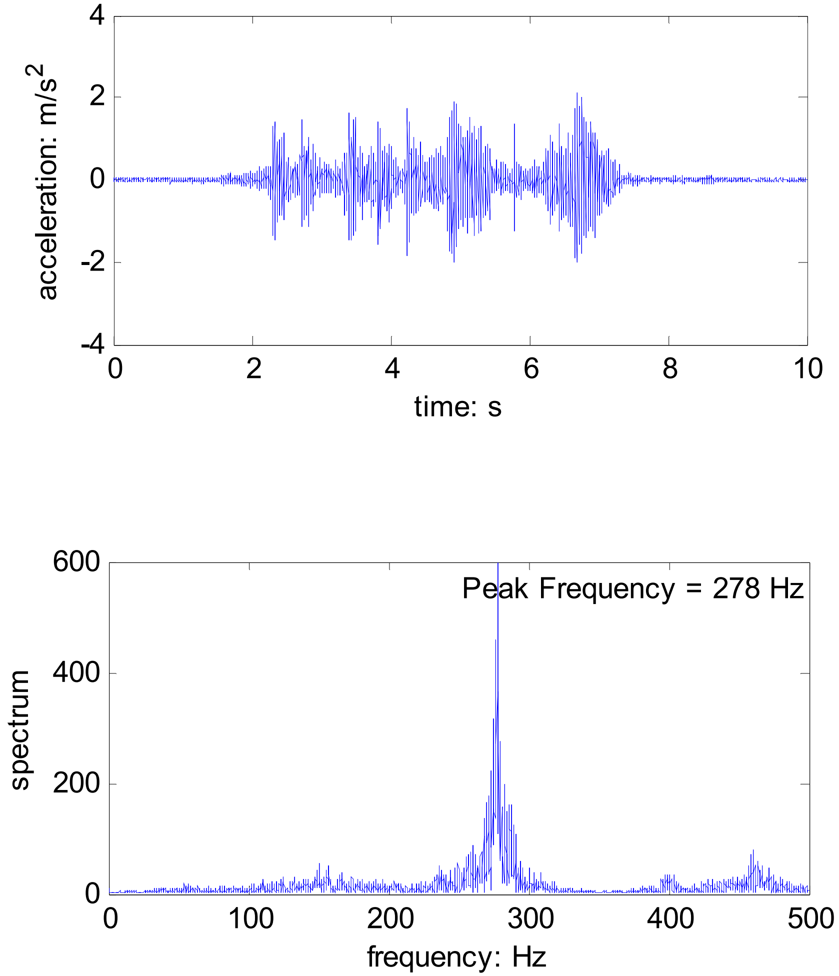


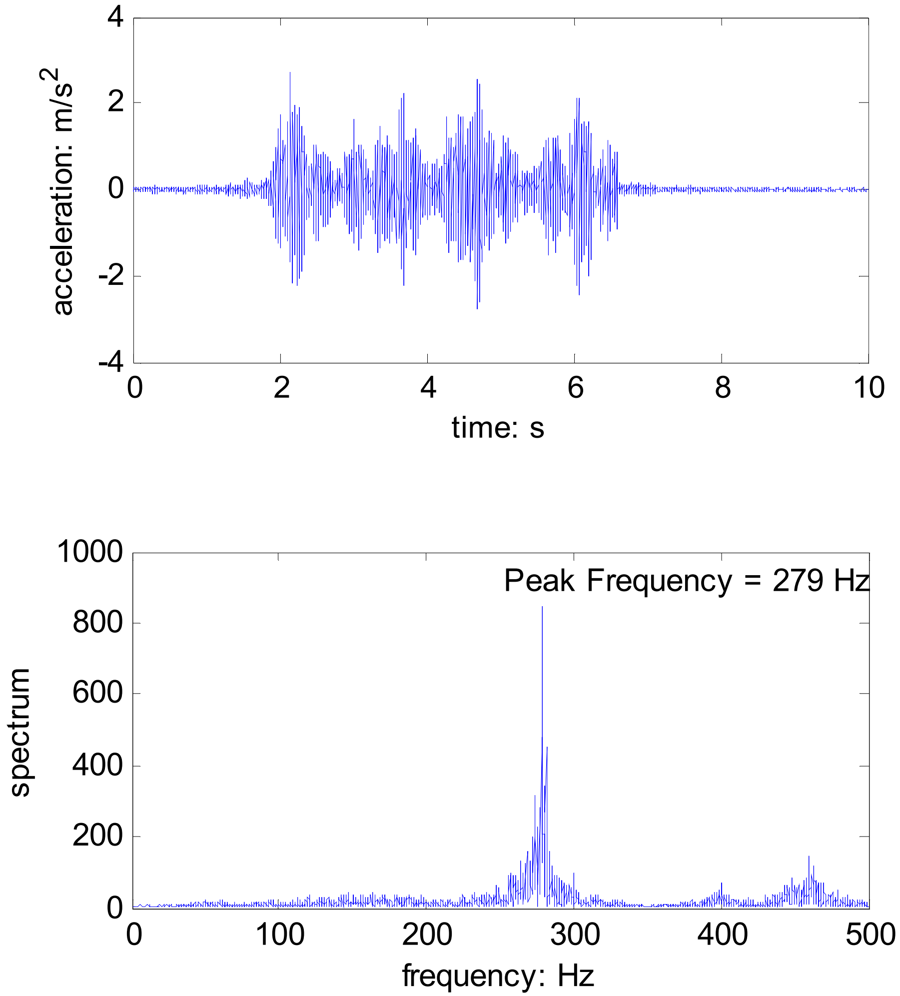
Fig: Calculated power output using 1cm^2 area turbine considering real air flow velocity in tunnels

P: power, , *ρ:* flow density, *A:* area of turbine, *V:* flow velocity
Cp: power coefficient, (theoretical maximum = 0.593, Betz limit)

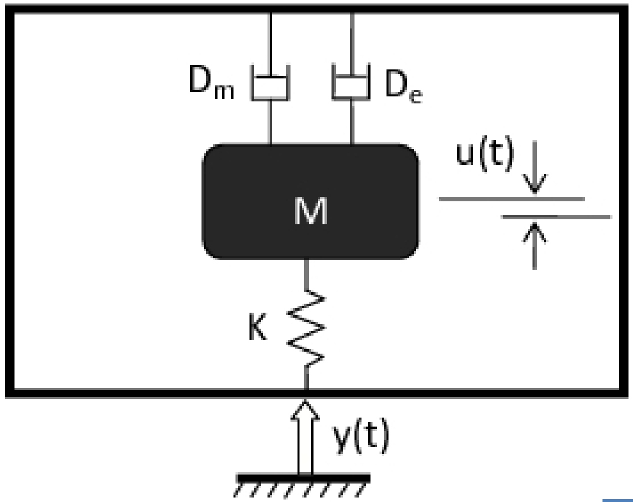
Train 1



Train 2



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

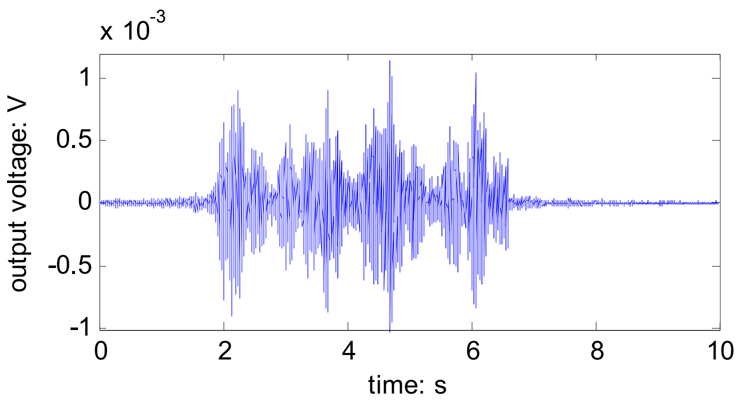
D: damper

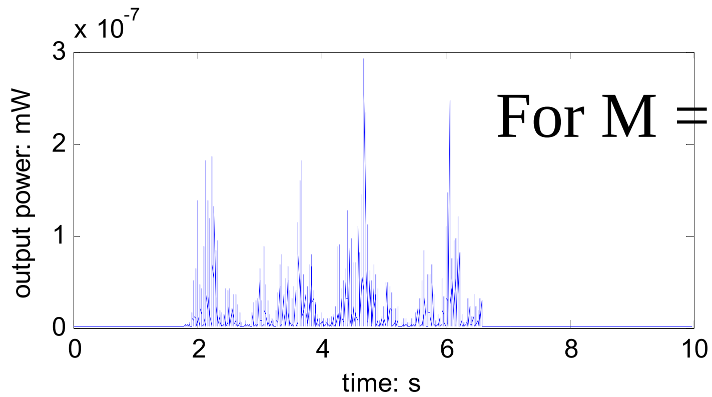
A: piezoelectric coefficient

C: piezoelectric capacitance

R: resistive load

A (V/N)	C (F)	D (N/ms)	K (N/m)
0.00047	1.27 X 10-7	0.042	4320





For M = 0.02 g.

1 uW per kg.

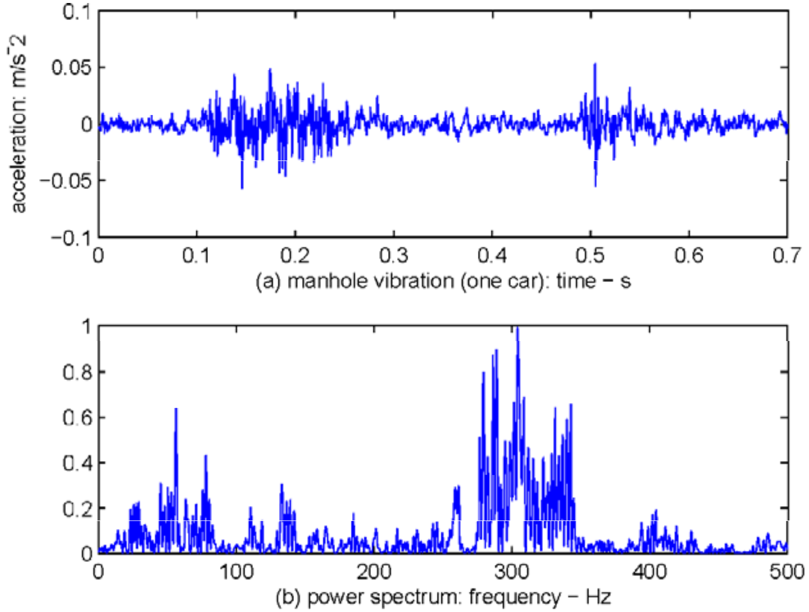
Water Mains

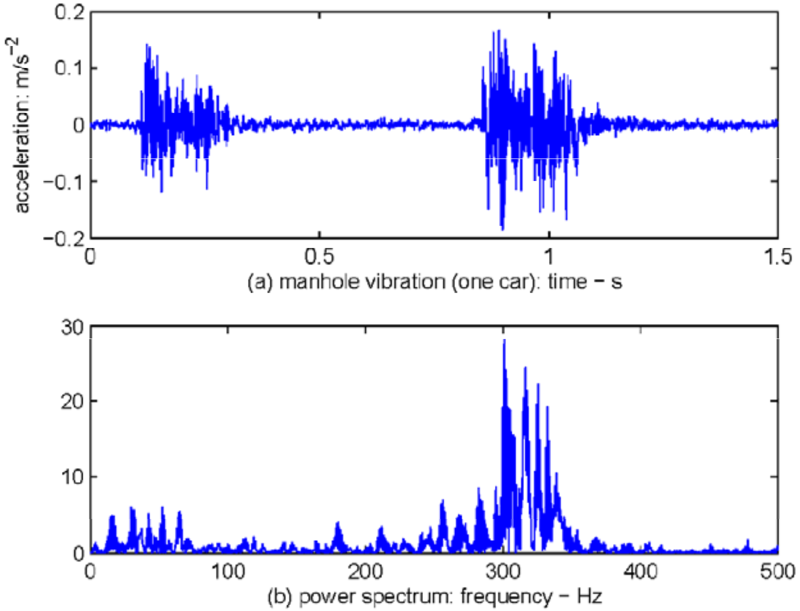
Water Mains monitoring

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





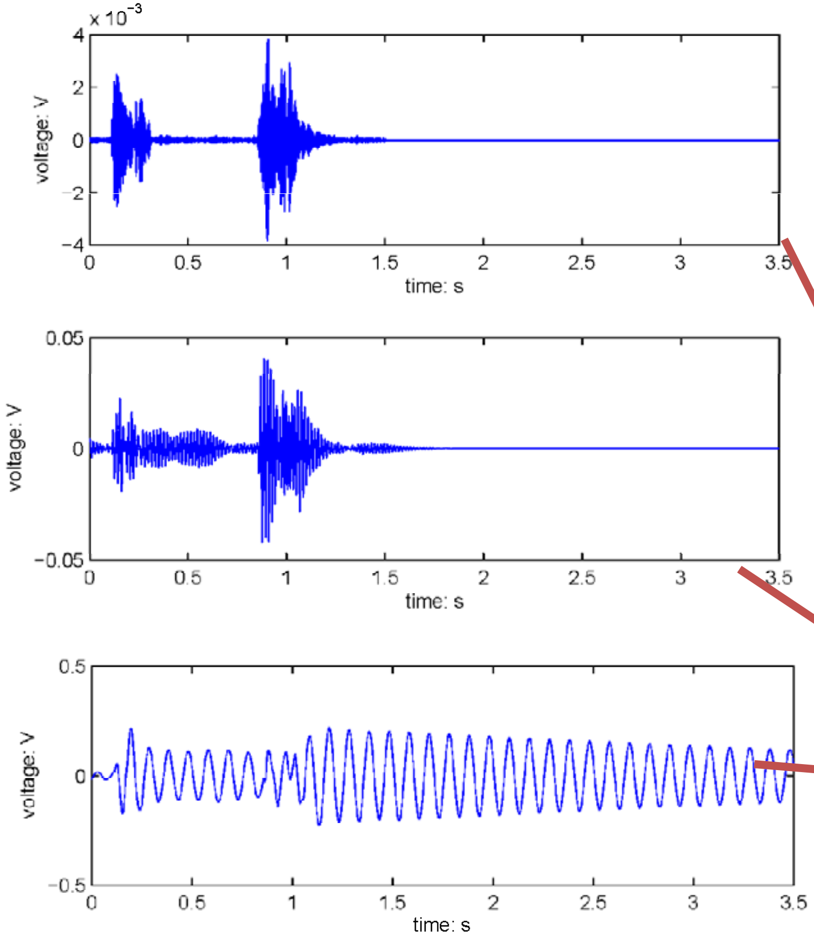
•Broadband vibration

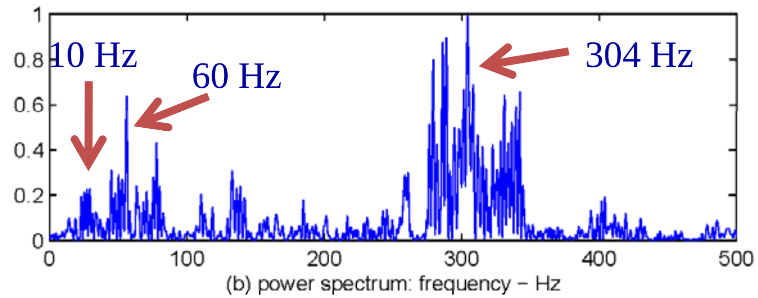
•Multiple frequency peaks:

10-60 Hz and 280-330 Hz

(impulse response of the manhole cover)

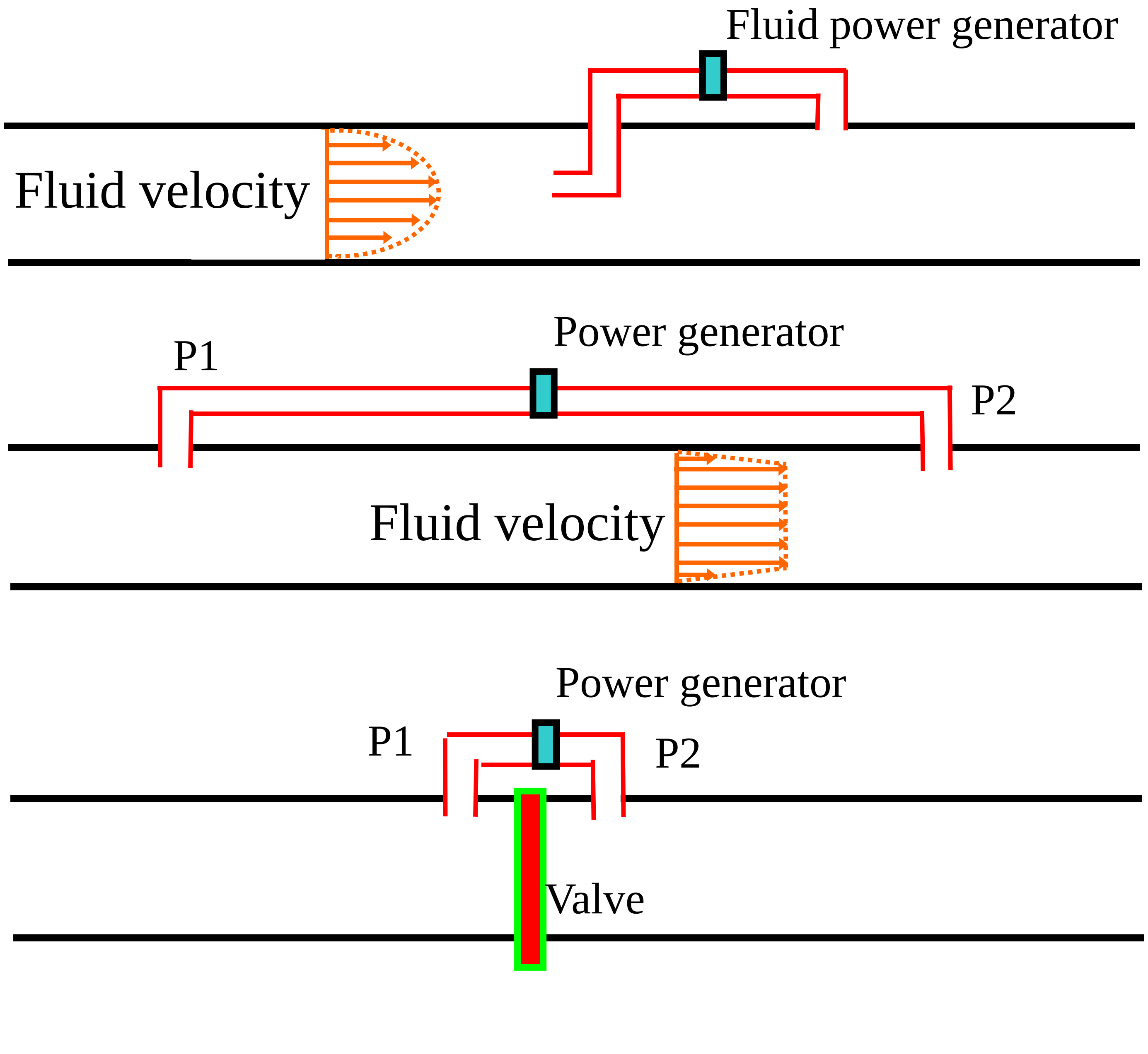
Sinusoidal Excitation based Optimisation





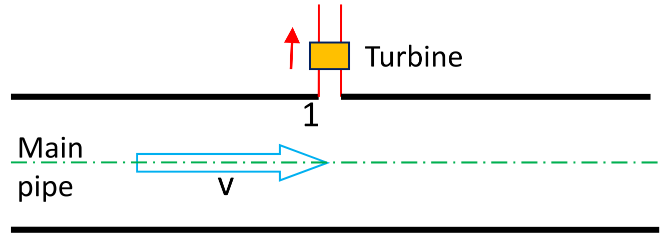
F (Hz)	M (g)	R (KΩ)	Power (uJ/Vehicle)
304	1	4.1	1.2×10^{-4}
60	30	20.8	6.4×10^{-3}
10	1090	125	0.76

Water Pipe harvester

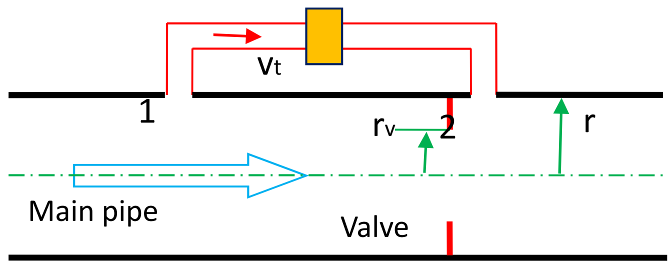


Hydraulic power generation

using bypass pipes

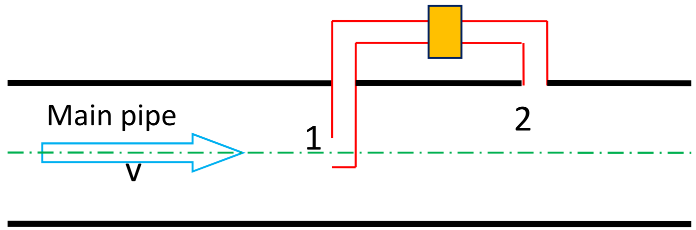


- 15 mW Power → 85 – 96 Litres/Day



- 0.07 – 0.32 mW < 1 mW

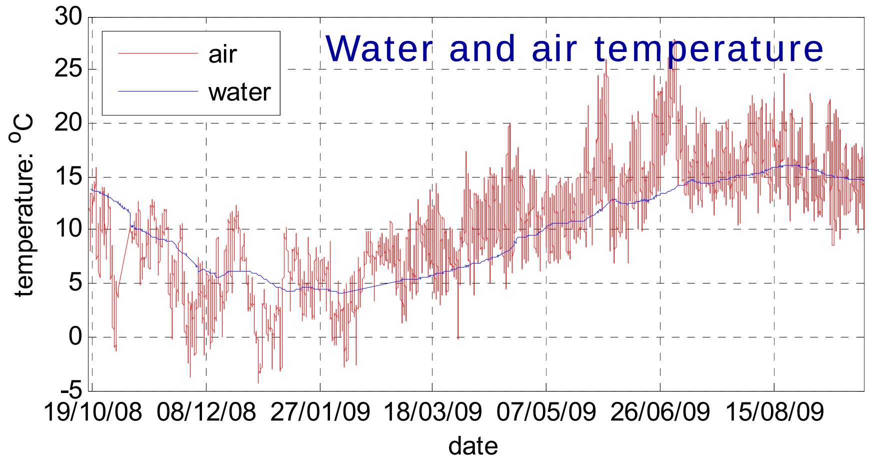
  Pressure Difference: 63 Pa << 20 KPa

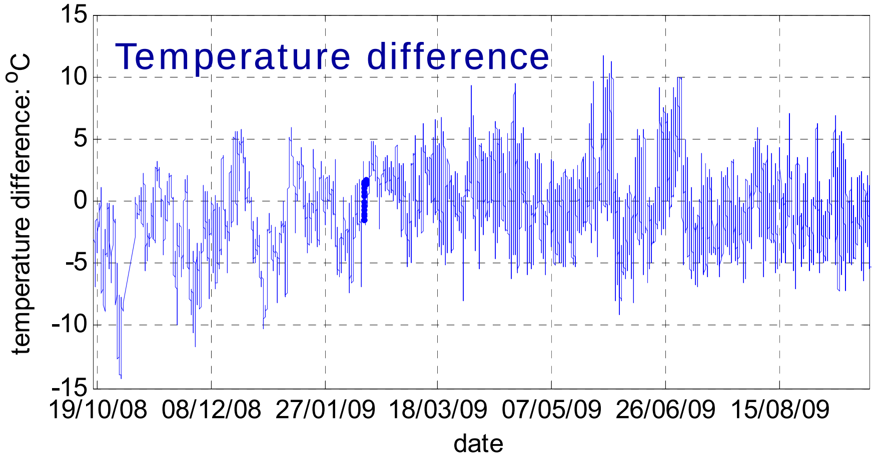


- < 1 uW

	Water Velocity (m/s)	Pressure Diff. (Pa)	Electric Power
Sys. 1	20.9 – 23.2	350K	144 – 196 W
Sys. 2	0.17 – 0.27	63	0.07 – 0.32 mW
Sys. 3	0.004 – 0.033	50	< 1 μW

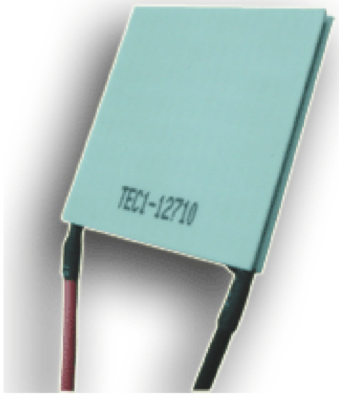
Thermoelectric generation





Average Temperature Difference:
3 °C

Thermoelectric Generator



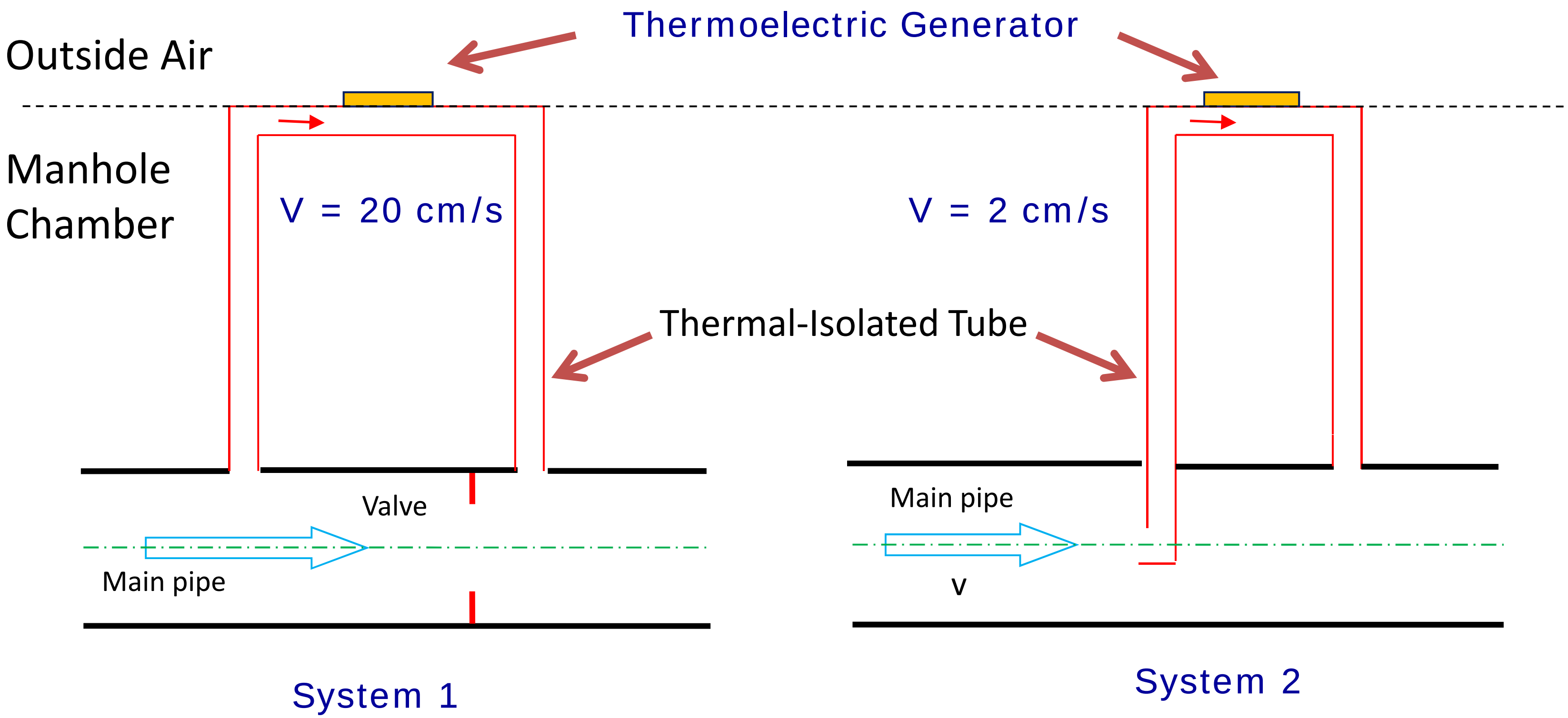
Dimension:
40 x 40 x 4.5 mm

Costs: 10 USD

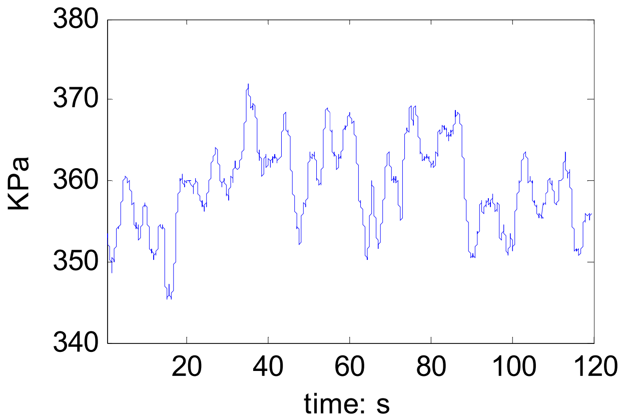
Power: 2.8 mW

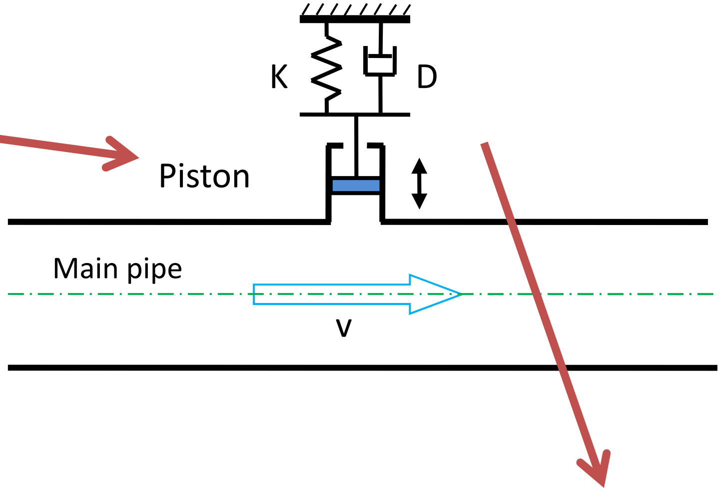
A 15 mW System:
6 Pcs → 60 USD

Thermoelectric generation



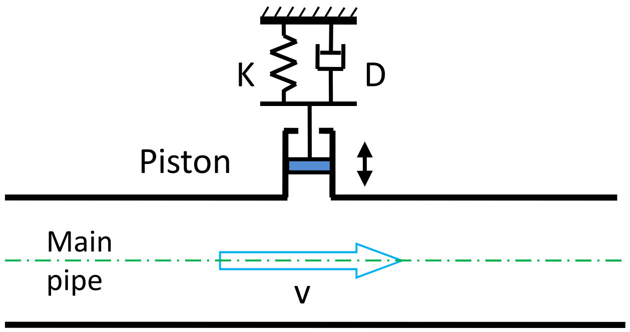
Power harvesting from water pressure fluctuation

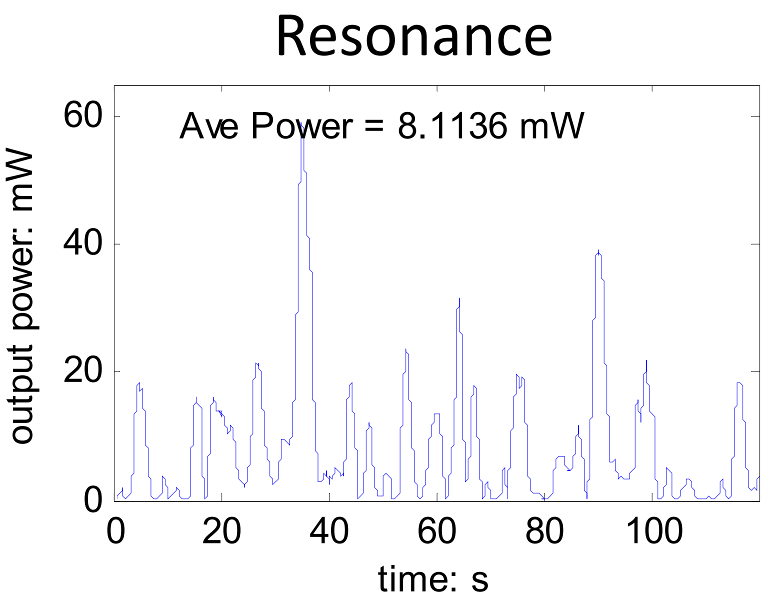


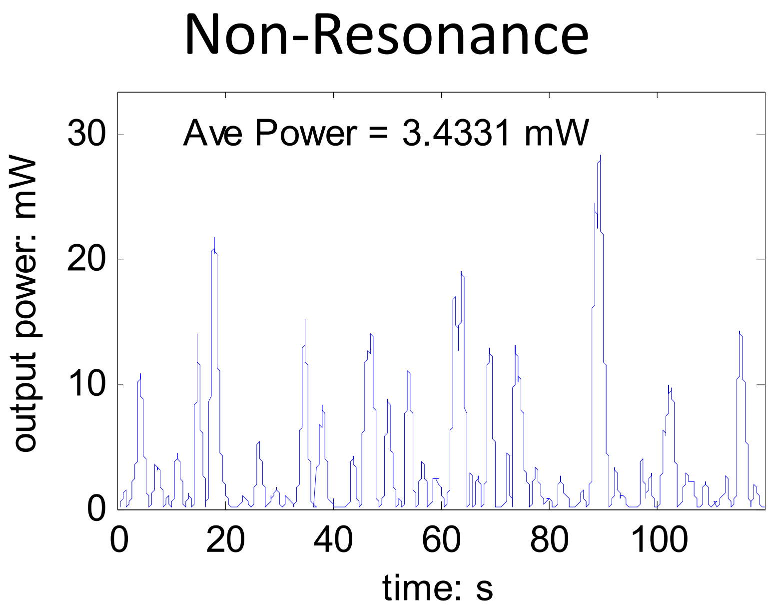


The Simulated Result of an Optimised Generator:

	M (Kg)	K (N/m)	D (Ns/m)	Power (mW)
Piston Area: 1 cm2	3.7	17.3	25.2	3.28





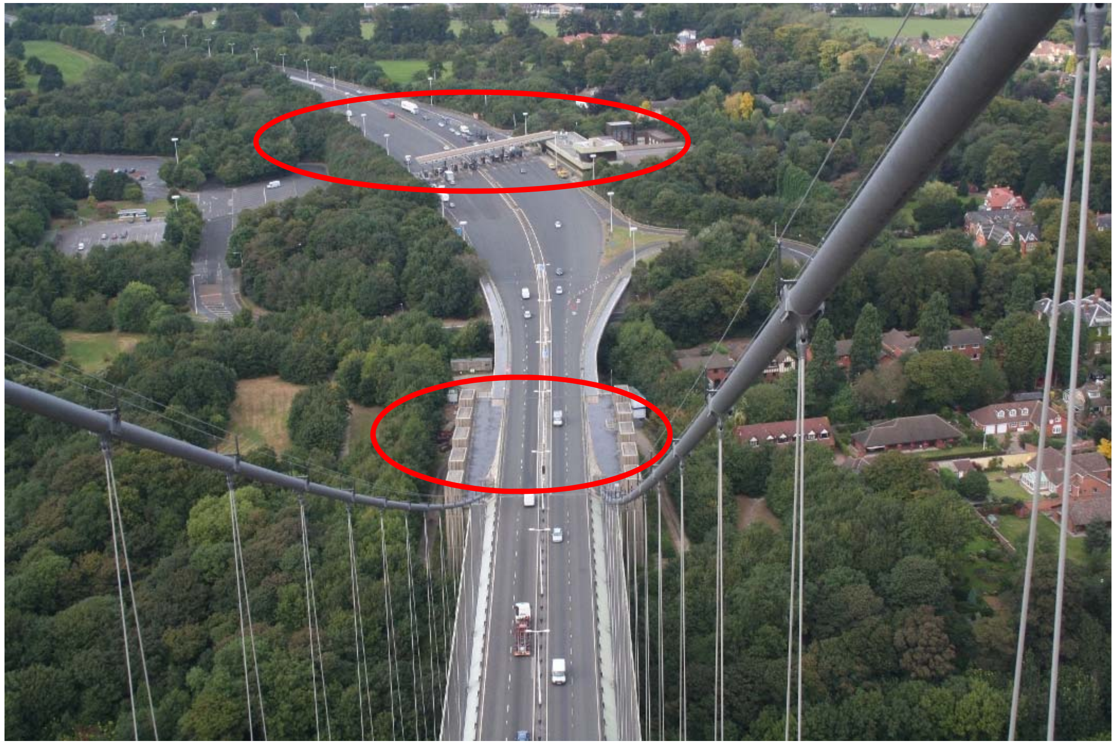


	M (Kg)	K (N/m)	D (Ns/m)	0.1 Hz Sine Data		Recorded Data	
				Ave. Power (mW)	P2P Disp (metre)	Ave. Power (mW)	P2P Disp (metre)
Resonant	3.60	1.42	31.83	15.65	0.10	**8.11**	**0.73**
Non-Res	3.60	15.56	22.51	10.83	0.10	**3.43**	**0.13**

Per cm^2

Bridges

Humber Bridge



Ferriby Road Bridge
(part of Humber Bridge)

Bearing Inclination

Cracks in Soffit

WSN Layout

Gateway with 12V 100Ah battery & Mobile Phone Modem

New technologies

MEMS resonant power harvester

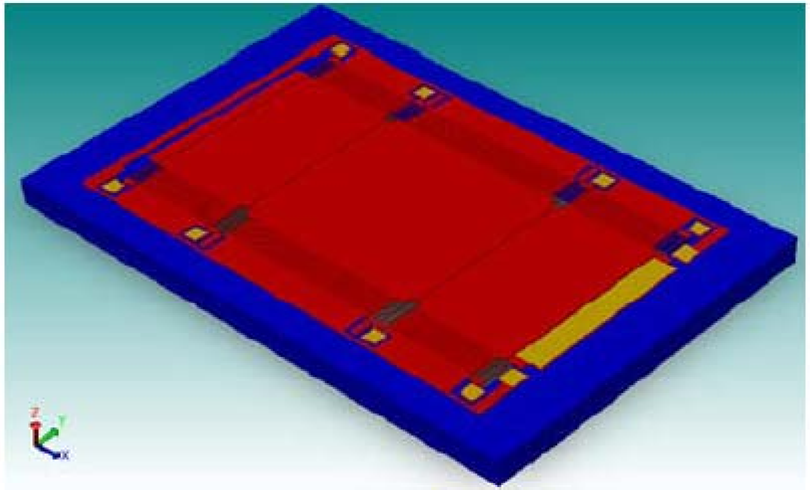


Figure 1. Illustration of the power harvester

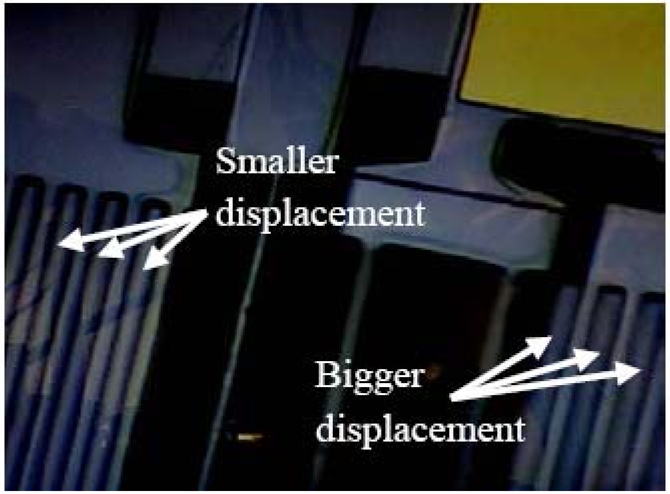


Figure 2. Displacement amplification

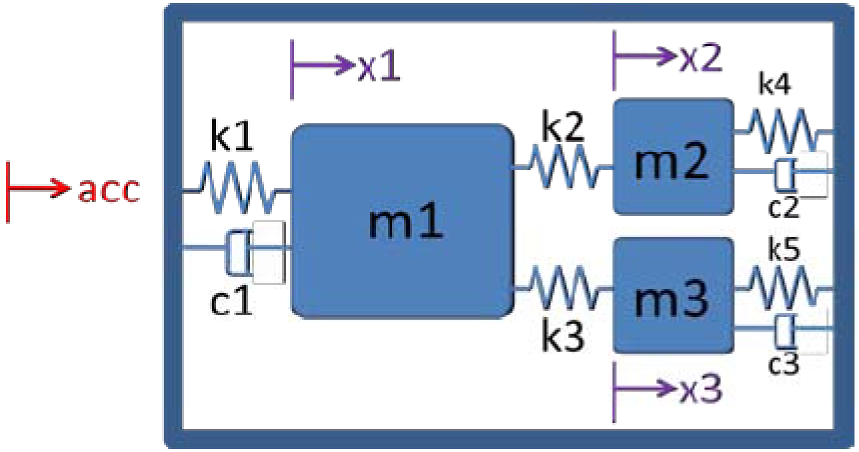
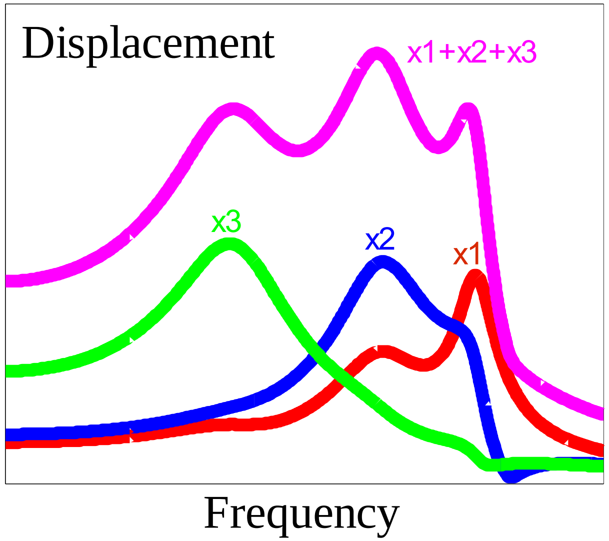
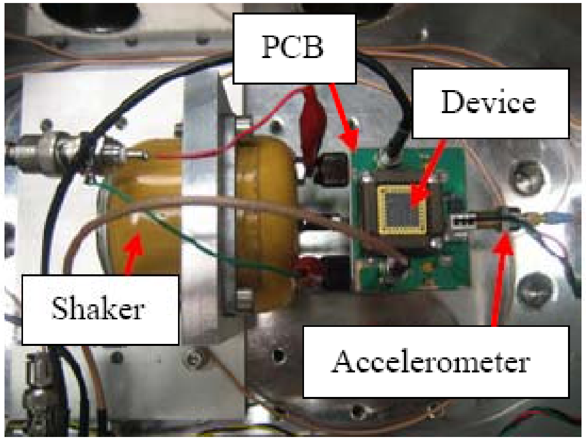


Figure 3. Equivalent mechanical model

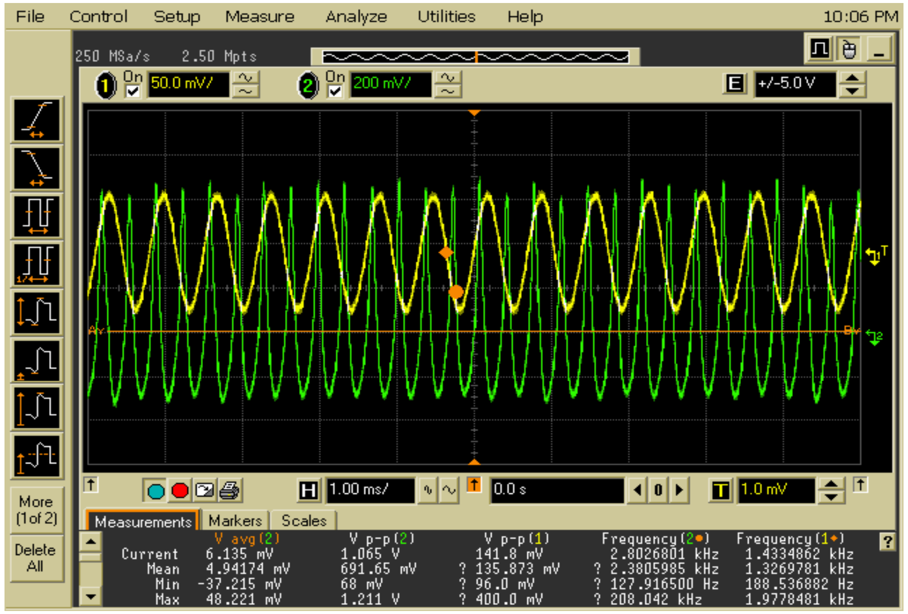


f1=1.4kHz, *f2*=1.8kHz, *f3*=2.3kHz

MEMS power harvester experimental result



Reference	Mass (g)	Acceleration (ms^{-2})	Power (μW)	Power/Mass/Acceleration ($\mu W/g/ms^{-2}$)
Ma [3]	0.0002	766	0.065	0.42
Mitcheson [4]	0.1	50	3.7	0.74
Despesse [5]	104	8.8	1052	1.15
Arakawa [6]	0.65	3.9	6	2.37
This work (in air)	**0.000734**	**1.76**	**0.017**	**13.16**
This work (in vacuum)	**0.000734**	**1.75**	**0.113**	**87.97**

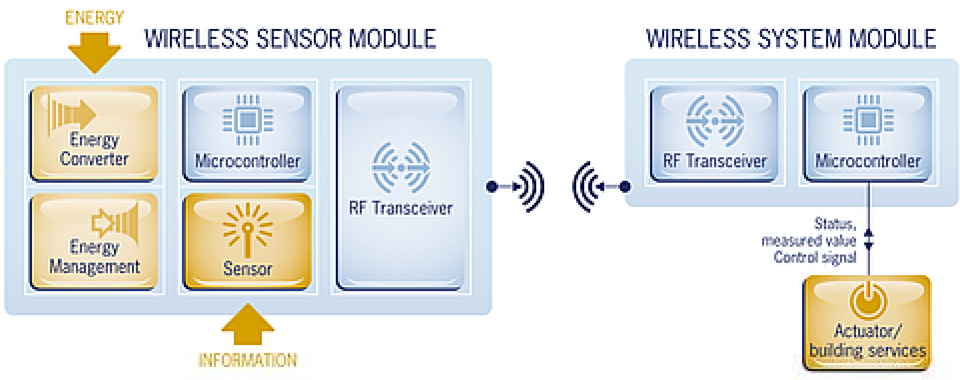


Current device: *Area*=0.135cm^2, *Thickness*=25um, *gap*=2um, *f*=1.43kHz → *Power*=0.113uW

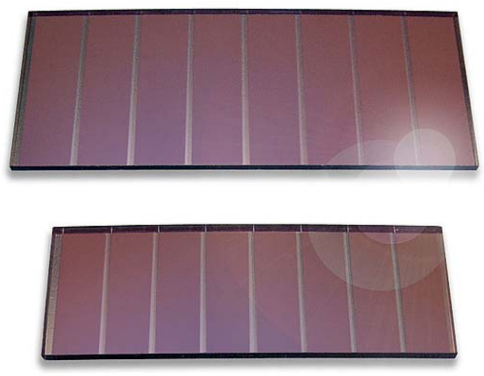
Future work: *Area*=1cm^2, *Thickness*=400um, *gap*=10um, *f*=130Hz → *Power*=2.23uW

Yellow: acceleration   Green: power output (voltage)

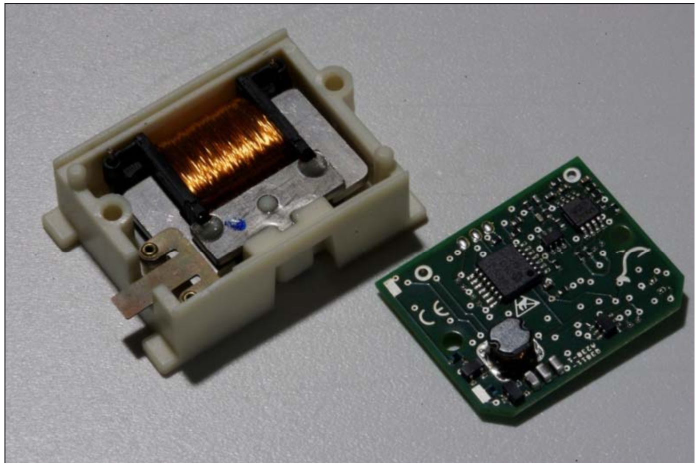
EnOcean switches and sensors for buildings



Solar cells



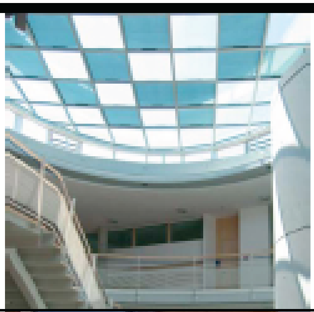
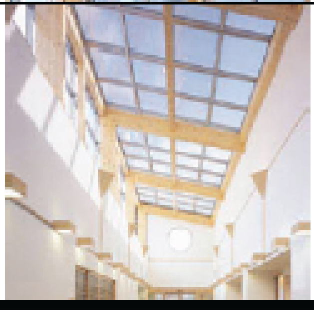
electromagnetic



thermocouples

From EnOcean website

Motivation Concept: Transparent PV cells (Currently amorphous Si)

	**ASI glas** - Schott Solar	www.schottsolar.com
	**See-Through PV module** - Kaneka	www.pv.kaneka.co.jp
	**Suntech See Thru** - Suntech	www.suntech-power.com

• seamless built-in technology

• light shade decreases incoming heat

→ less A/C usage

→ environmental friendly

• aperture / yield trade-off

(similar to LCD trade-off)

http://www.dansksolenergi.dk

The Idea

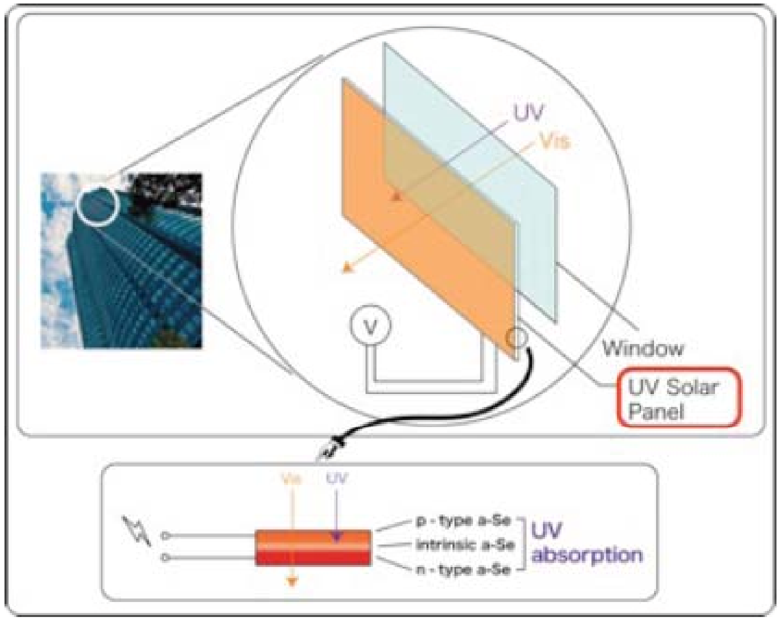
See through solar cells

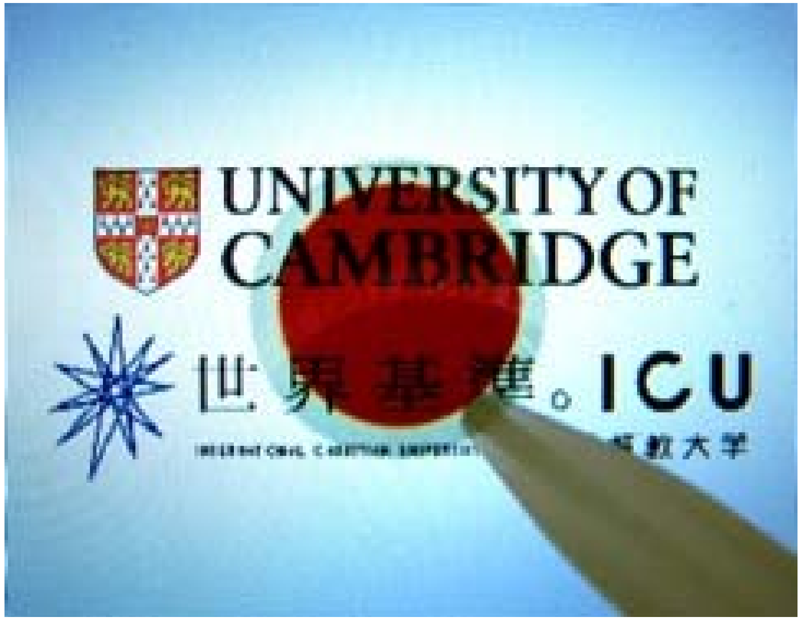
- amorphous selenium (a-Se)

wide band gap →***transparent to visible light***

- inexpensive and easy to fabricate

thermal evaporation electrolysis

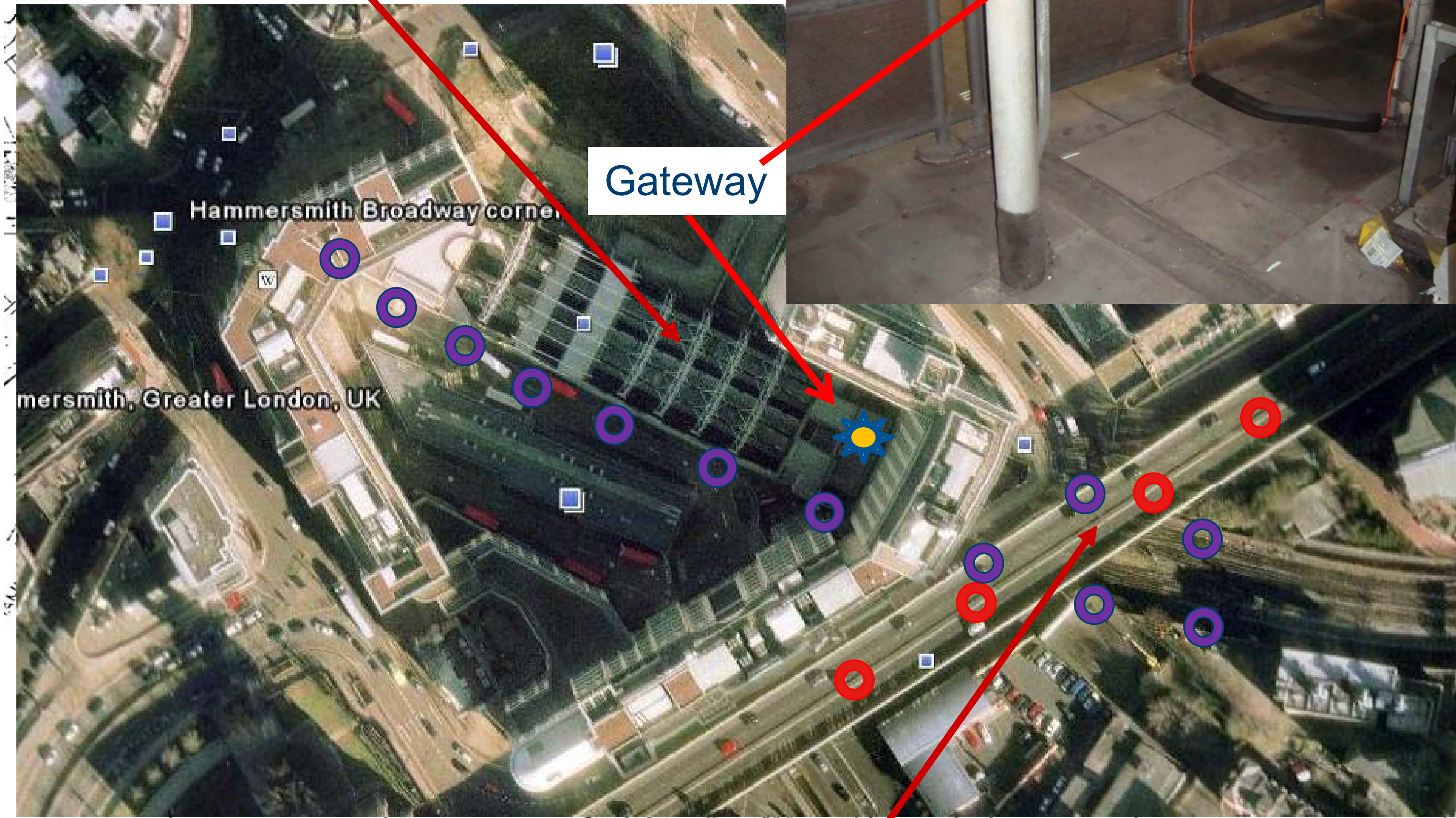




Saito et al. (2011) Appl. Phys. Lett. **98**, 152102 (2011); doi:10.1063/1.3579262 (*3 pages*)

Large-Scale Deployment

Monitor station before, during a



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 Instrumentation Testing & Monitoring Ltd Sol Data

geothermal international ATKINS COSTAIN WSP PB 125 YEARS Mott MacDonald

CAPITA SYMONDS bre Halcrow

Infrastructure Sector

Thames Water Transport for London HIGHWAYS AGENCY Tube Lines UNDERGROUND

HUMBERBRIDGEBOARD TRANSPORT SCOTLAND TRL

Manufacturing, Electrical & Information Sectors

RolaTube™ IBM RedBite THALES zühlke empowering ideas

TOSHIBA Leading Innovation GE Aviation Omnisense Senceive Jennic TECHNOLOGY FOR A CHANGING WORLD OpenHub digital architect digital developer

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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