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Alternative Powering Methods for Miniature Wireless Sensors

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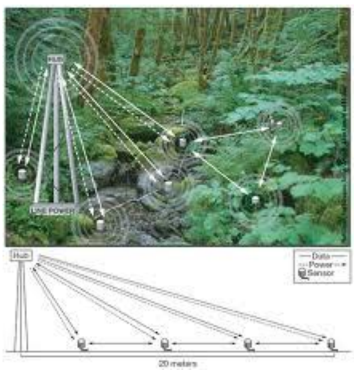
EnerHarv 2018

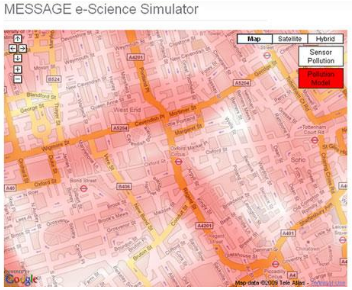
Cork, 29-31 May

PERVASIVE SENSING

- ubiquitous
- wireless



MESSAGE e-Science Simulator



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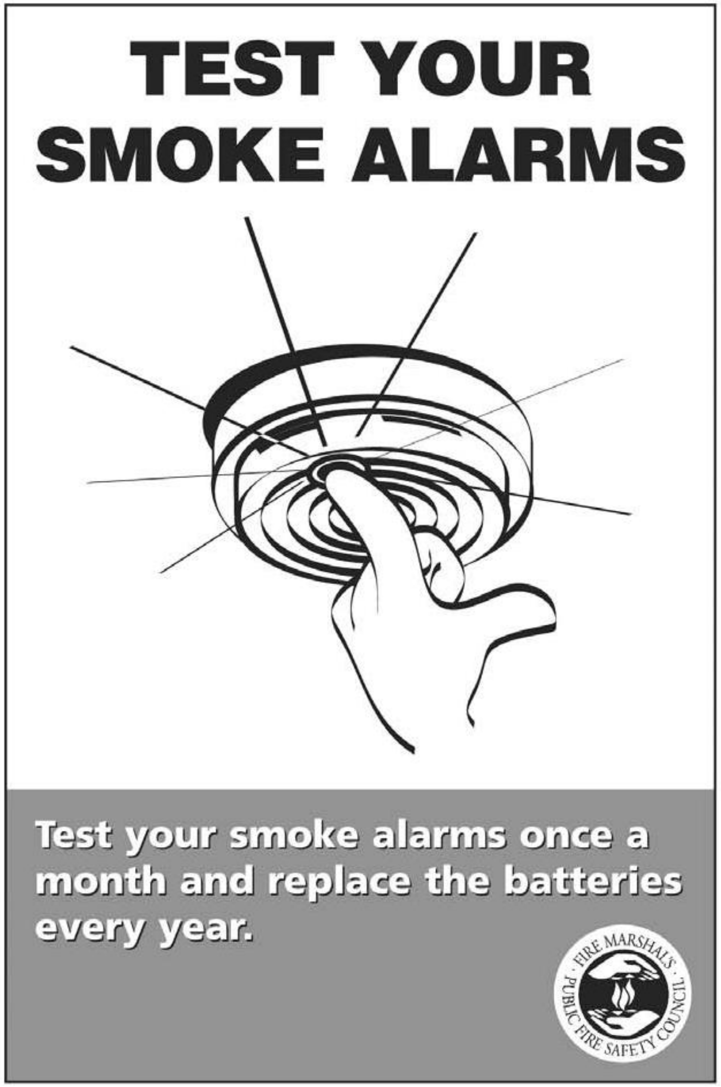
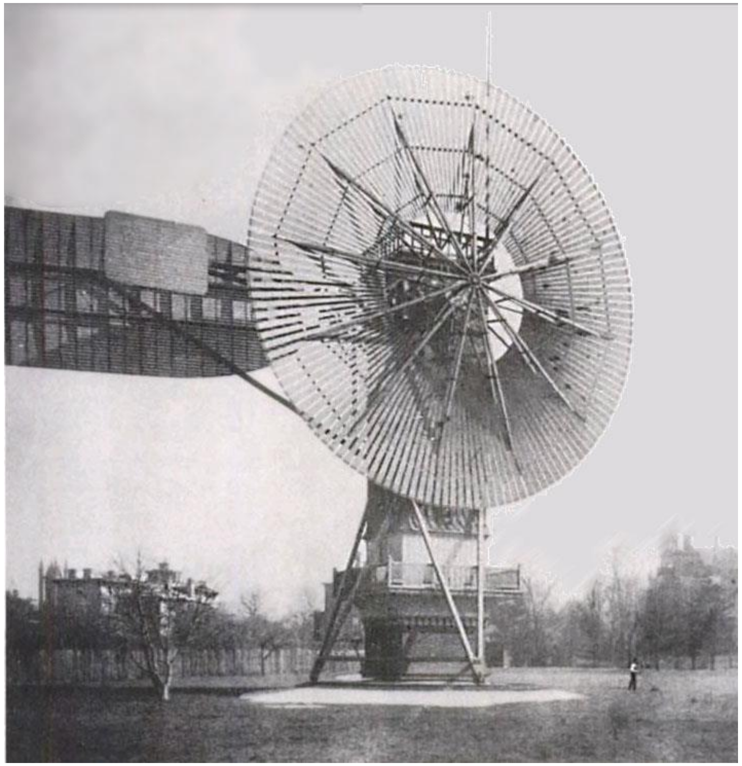
PERVASIVE SENSING

- The power issue





Power From Ambient Motion

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How is Harvesting Different?

- Local generation for local use
- Miniaturisation
- *Generator not necessarily anchored to ground*

Two scenarios:

- Direct force, e.g. heel strike, finger press
- Moving object or structure but no counter-force

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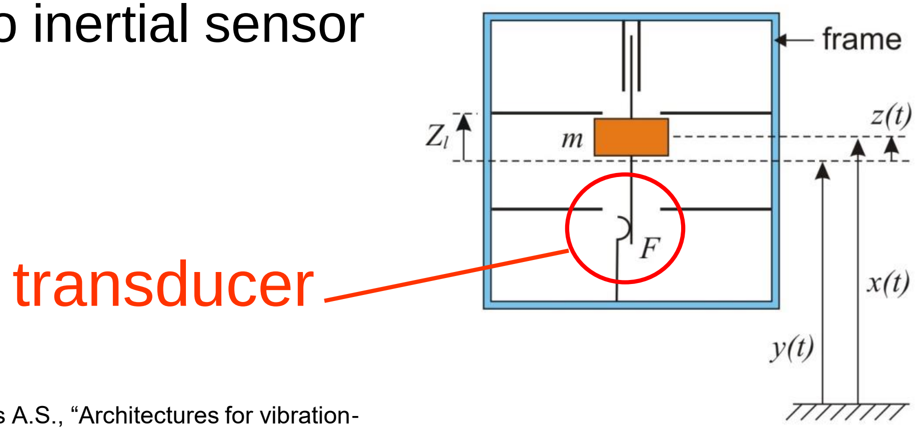
INERTIAL ENERGY HARVESTERS

- Mass mounted on a spring within a frame
- Frame attached to moving "host" (person, machine…)
- Internal inertial mass (proof mass) replaces fixed connection
- Host motion vibrates internal mass
- Internal transducer extracts power
- Structure similar to inertial sensor



Mitcheson P.D., Green T.C., Yeatman E.M., Holmes A.S., "Architectures for vibration-driven micropower generators", IEEE/ASME J. Microelectromechanical Systems 13(3), (2004), 429-440.

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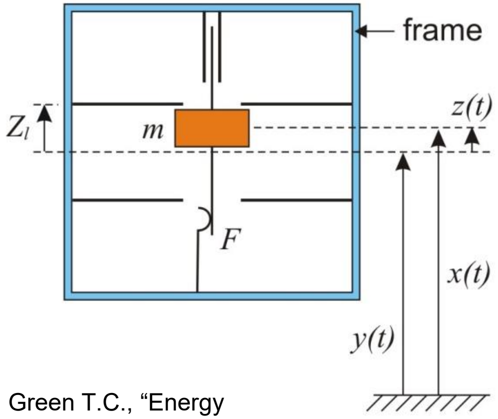
Inertial Energy Harvesters: Available Power

assume:

- source acceleration amplitude $\mathbf{a_o}$ and frequency $\mathbf{f}$
- Proof mass $\mathbf{m}$, max internal displacement $\mathbf{\Delta z}$
- then maximum power $P = 2m\Delta z \cdot a_o f$



Mitcheson P.D., Yeatman E.M., Kondala Rao G., Holmes A.S., Green T.C., "Energy harvesting from human and machine motion for wireless electronic devices", Proc. IEEE 96(9), (2008), 1457-1486.

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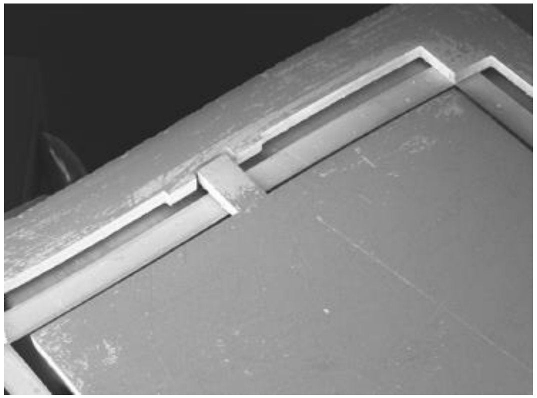
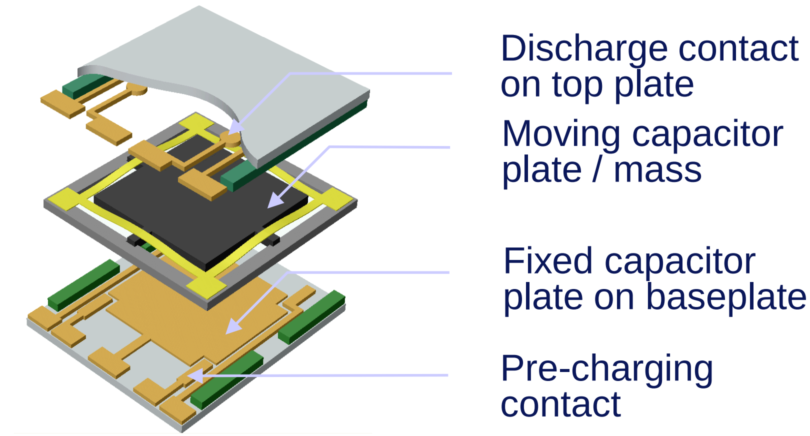
Early Non-Resonant Electrostatic Harvester





- Capacitor pre-charged when mass at bottom (max capacitance)
- Under sufficiently large frame acceleration, capacitor plates separate *at **constant charge***, work is done against electrostatic force

  $\Rightarrow$ stored electrostatic energy and plate voltage increase
- Charge transferred (at higher voltage) to external circuit when moving plate reaches top plate
- ***Whole wafer thickness maximises inertial mass!***

Miao P., Mitcheson P.D., Holmes A.S., Yeatman E.M., Green T.C., Stark B.H., "MEMS inertial power generators for biomedical applications", Microsystem Technologies, 12, (2006), 1079-1083.

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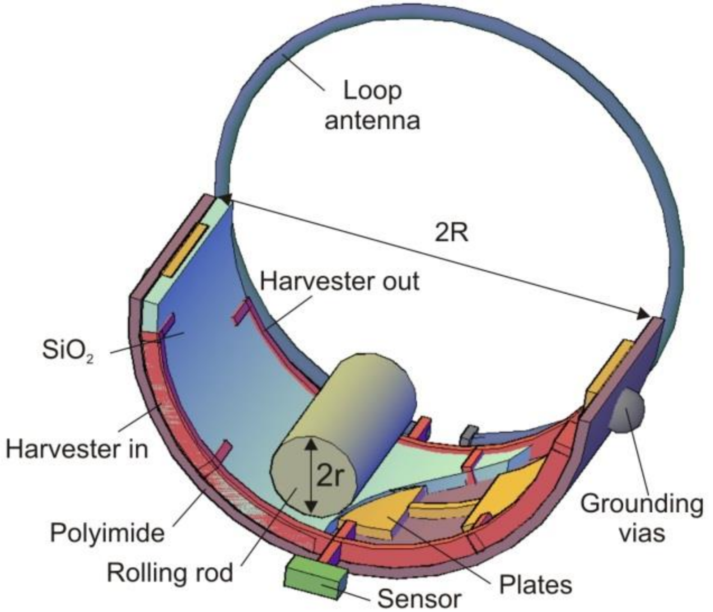
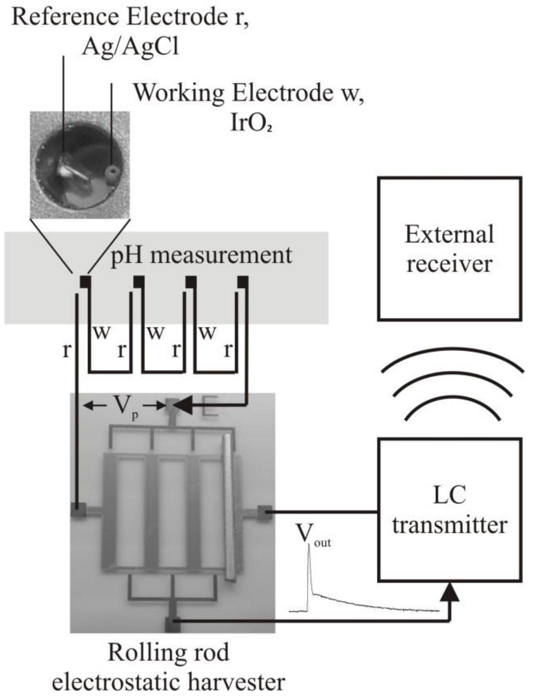
Rolling Element Harvester





- Electrostatic harvester with rolling inertial element
- Output coupled directly to resonant transmitter
- Priming voltage provided by sensor; no processing electronics

He C., Kiziroglou M.E., Yates D.C., Yeatman E.M., "A MEMS self-powered sensor and RF transmission platform for WSN nodes", IEEE Sensors Journal, 11(12), (2011), 3437-3445.

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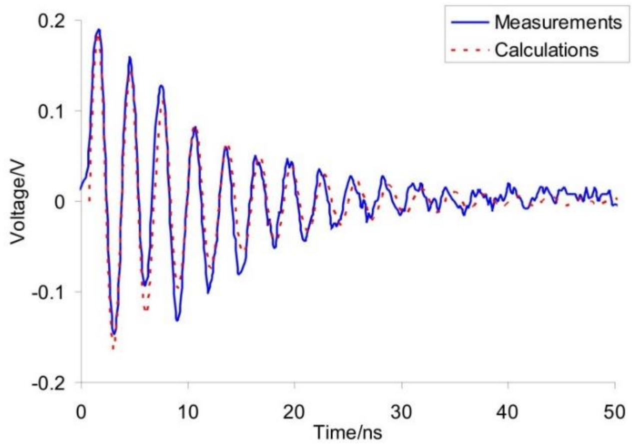
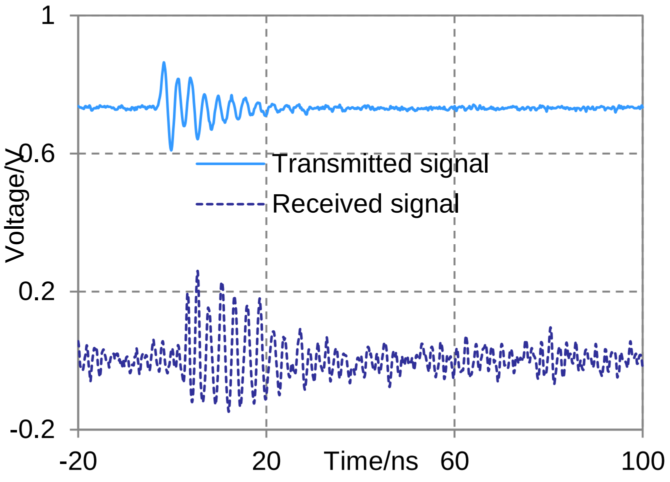
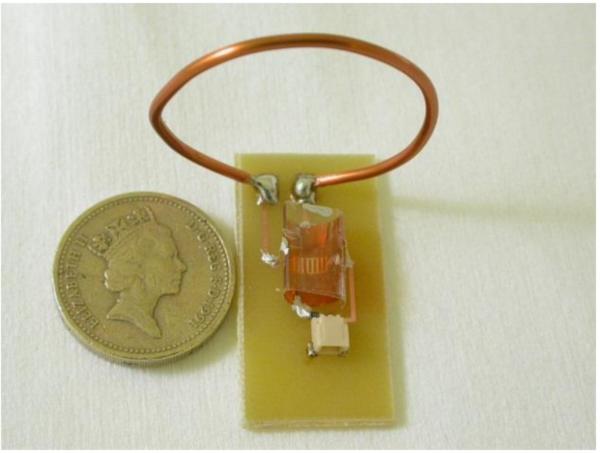
Rolling Element Harvester



Capacitively tapped measurement harvester discharging through the loop antenna, showing oscillation at 330 MHz.



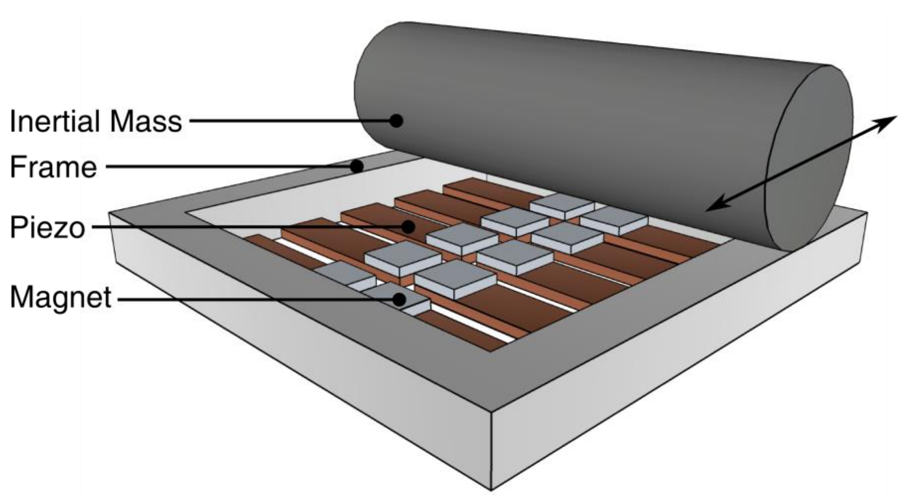
Transmitted and received signals (with very different levels of amplification)

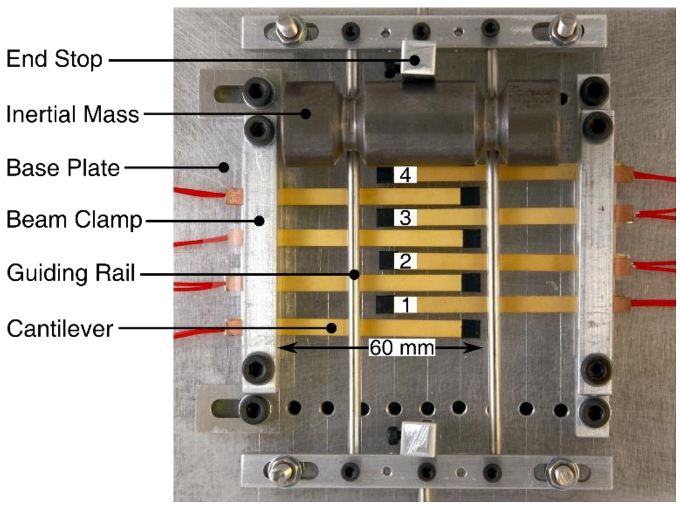


- Transmission over 1 m range successfully demonstrated
- Minimum detected pulse energy ~42 pJ

Impulse-Excited Rolling Element Harvester

- Alternative design of rolling element harvester, also designed for large amplitude, low frequency, non-harmonic excitation
- Distributed transduction via an array of piezoelectric beams
- Permanent magnets attached to beams snap to the proof mass as it passes, and then suddenly release leaving beams to resonate at natural freuency
- Frequency up-conversion improves electromechanical coupling





Pillatsch P., Yeatman E.M., Holmes A.S., “A scalable piezoelectric impulse-excited generator for random low frequency excitation”, Proc. IEEE MEMS 2012, Paris, 29 Jan – 2 Feb 2012, 1205-1208.

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Overcoming Displacement Limit: Rotational Harvesters

Inertial Harvesters: power is limited by proof mass and travel range

- Maximum power = $2m\Delta z \cdot a_o f$

Any alternatives?

yes, *rotating* (not rolling) proof mass:
limited motion range not inherent

E.M Yeatman, "Energy Harvesting from Motion Using Rotating and Gyroscopic Proof Masses", J. Mechanical Engineering Science **222** (C1), pp. 27-36 (2008).

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Seiko Kinetic

- First introduced in 1986
- Electromagnetic generator powers a quartz movement
- High gear ratio necessary to achieve the required voltage, involves many interacting precision parts
- Storage capacitor in later models replaced by rechargeable battery
- Estimated power output around 5 μW

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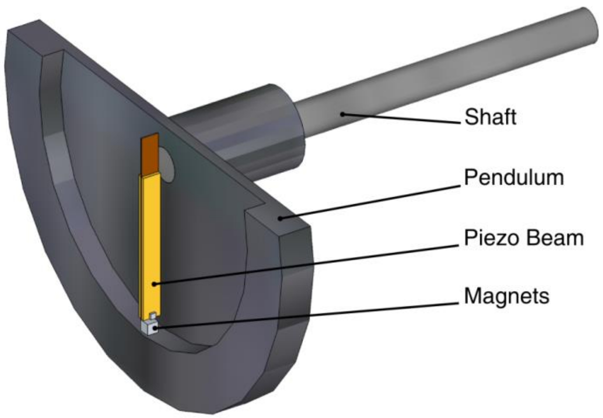
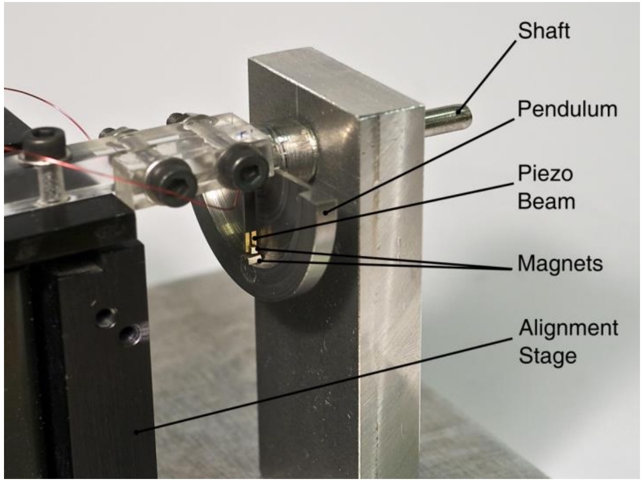
Impulse-Excited Rotating Element Harvester



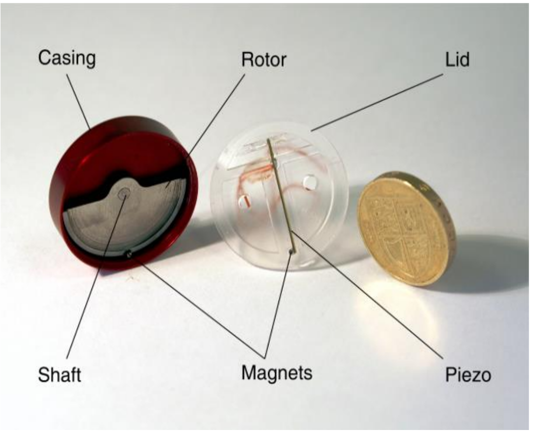


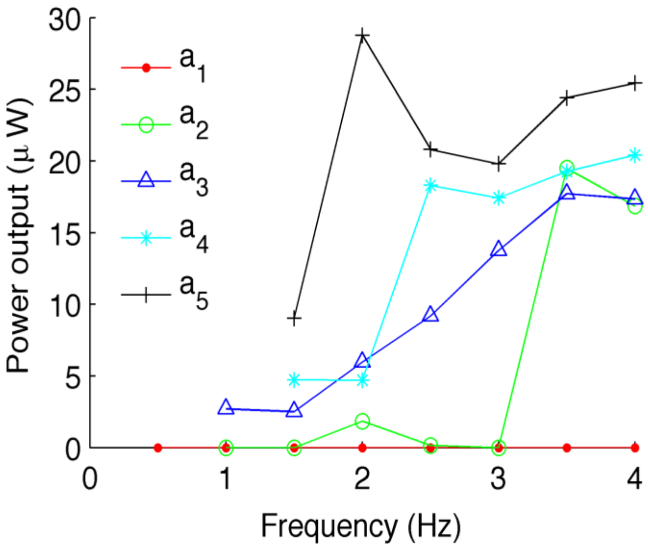
- Operation in any orientation
- Rotational and linear excitation
- No inherent displacement limit for the proof mass travel
- Compared to wristwatch generators:
  - No gears necessary
  - No mechanical contact due to magnetic coupling, good for long lifetime
  - Small number of parts, reduced cost
  - Convenient for miniaturization

P. Pillatsch, E.M. Yeatman, A.S. Holmes, “Piezoelectric Rotational Energy Harvester for Body Sensors Using an Oscillating Mass”, Proc. Body Sensor Networks, London, May 2012, pp. 6-10.

Impulse Excited Piezoelectric Generator

- Wristwatch sized device
- Increased power output
- Real-world evaluation





P. Pillatsch, E.M. Yeatman and A.S. Holmes, "Real World Testing Of A Piezoelectric Rotational Energy Harvester for Human Motion", PowerMEMS 2013, London, Dec 3-6, 2013.

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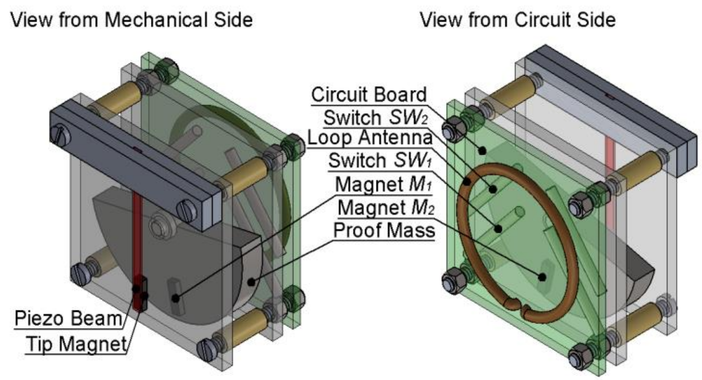
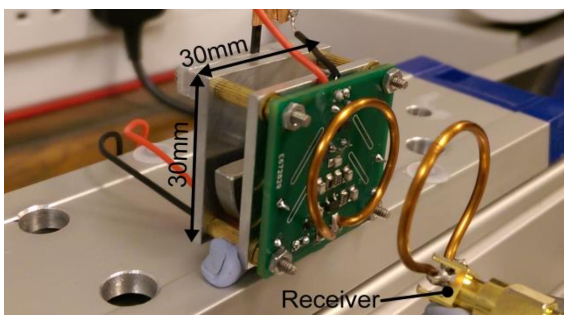
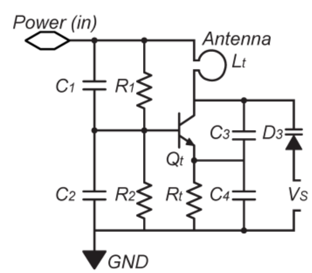
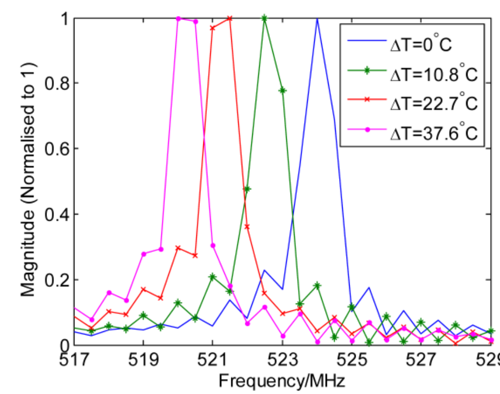
Piezoelectric Self-Powered Wireless Sensor

- Excitation of piezoelectric beam by external motion produces RF pulse
- Input sensor voltage modulates pulse frequency
- FM output, no on-board storage or digital processing









H. Jiang, M. Kiziroglou, D.C. Yates and E.M. Yeatman, “A Non-harmonic Motion-powered Piezoelectric FM Wireless Sensing System”, Transducers 2015, Anchorage, June 21-25.

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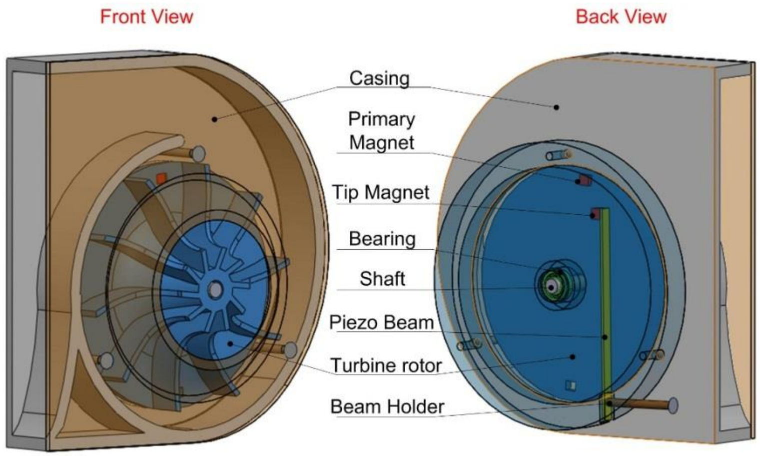
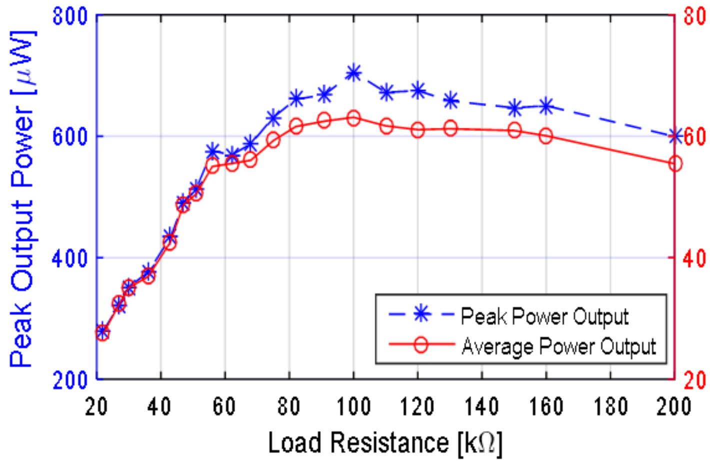
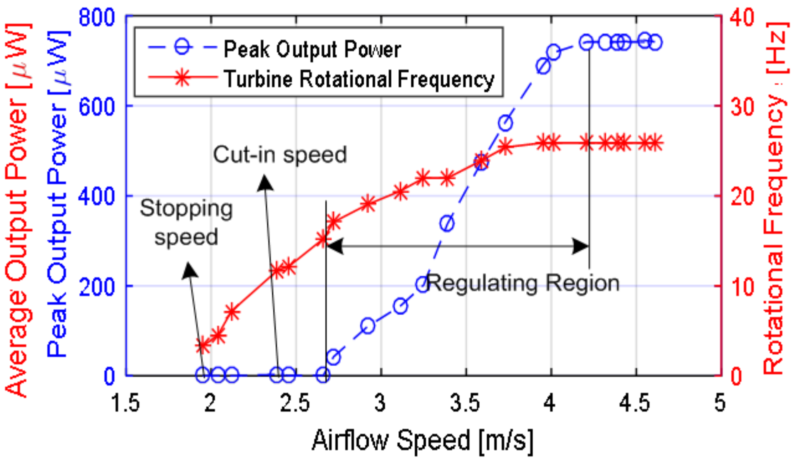
Micro Turbine with Piezoelectric Transduction



- 3D printed turbine and casing, low cost bearing
- Magnet on rotor plucks magnet on piezo beam tip
- Frequency upconversion from rotation speed to beam oscillation: broadband operation with high Q, high efficiency transduction
- Centrifugal regulator added for low cut-in speed





H. Fu & E.M. Yeatman, “A Miniature Radial-Flow Wind Turbine Using Piezoelectric Transducers and Magnetic Excitation”, Proc. PowerMEMS 2015.

H. Fu and E.M. Yeatman, A miniaturized piezoelectric turbine with self-regulation for increased air speed range, Applied Physics Letters, 2015, in press.

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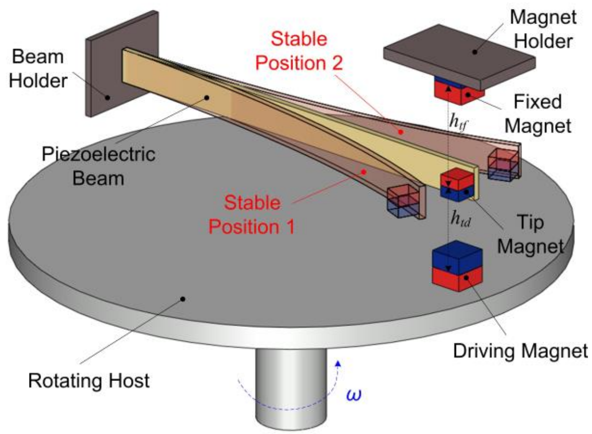
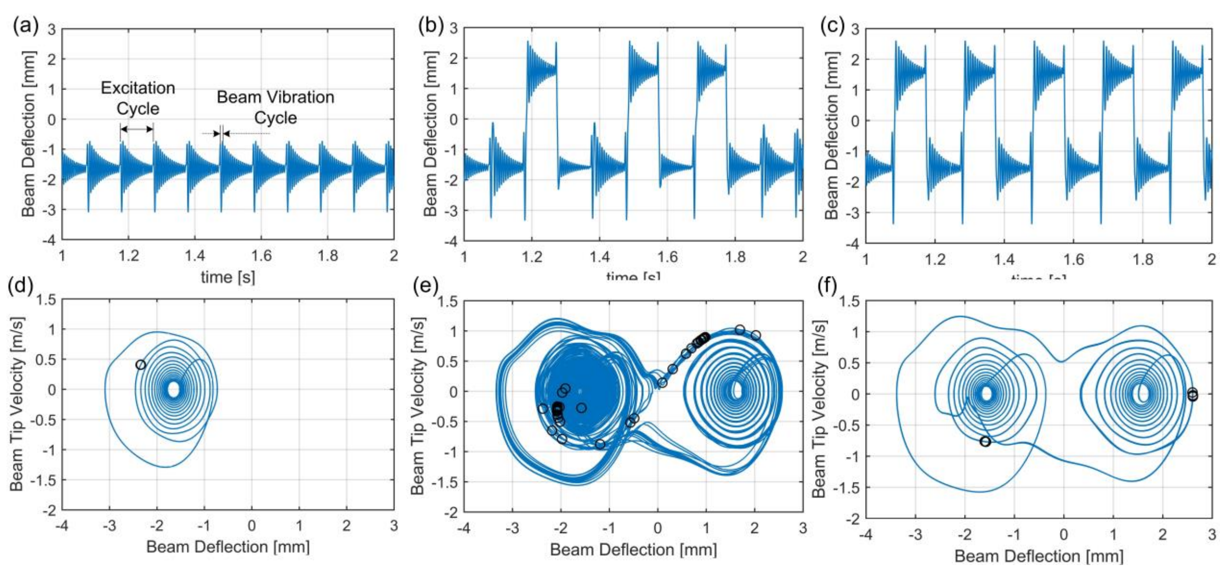
PIEZOELECTRIC ROTATING GENERATORS WITH BISTABILITY





H. Fu and E. M. Yeatman, Mechanical Systems and Signal Processing, 2018.

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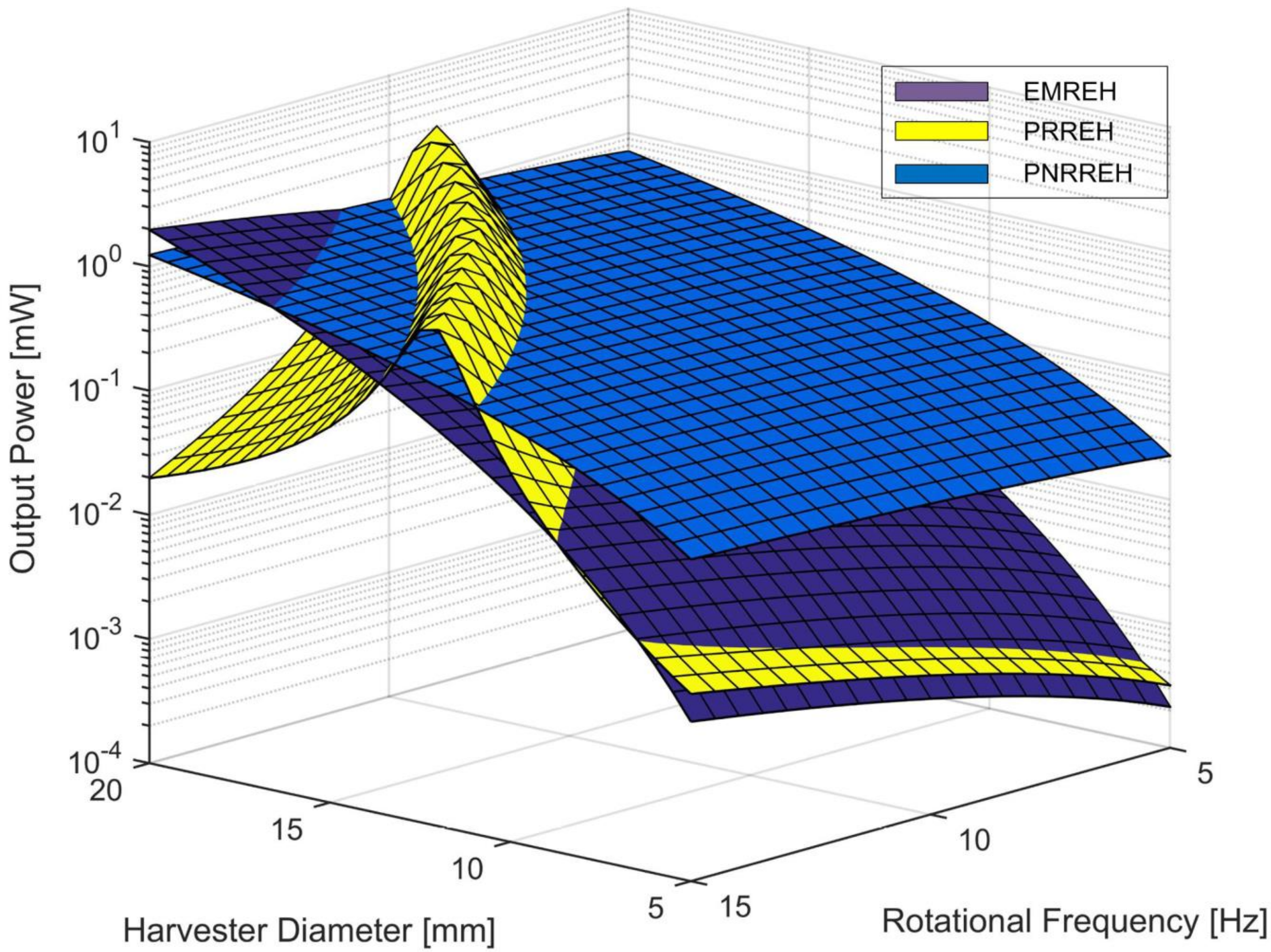
PIEZOELECTRIC VS ELECTROMAGNETIC ROTATING GENERATORS



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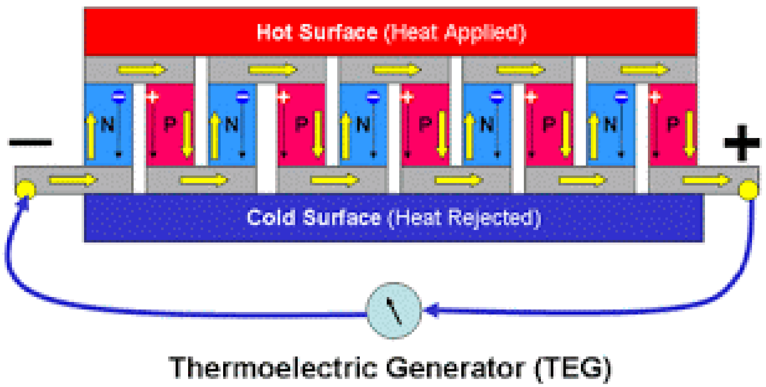
H. Fu and E. M. Yeatman, *Energy Technology, in press.*

DYNAMIC THERMOELECTRIC HARVESTING

Thermoelectric Generation: Challenge of Miniaturisation

- Need a high ΔT across short distance
- Need good thermal contact to heat source and heat sink
- Need minimal parallel heat paths



Myprojectscope.blogspot.co.uk

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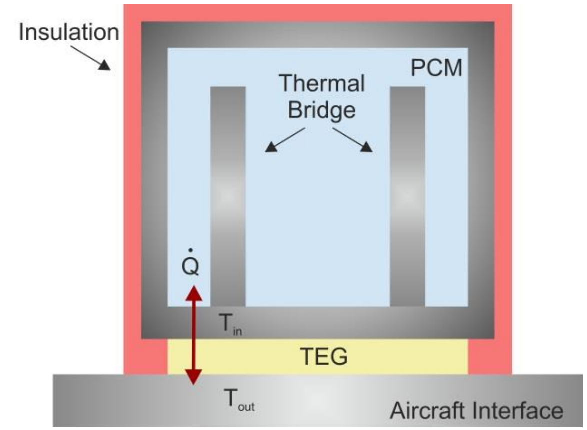
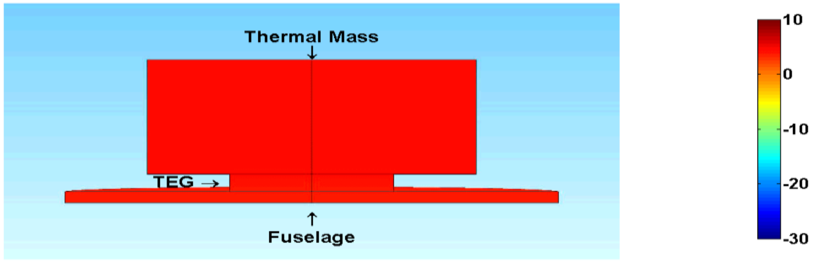
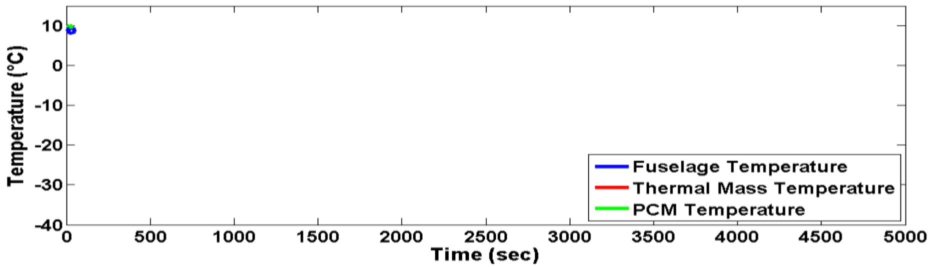
DYNAMIC THERMOELECTRIC HARVESTING

Dynamic thermoelectric energy harvesting

- Exploitation of temperature variation in time
- Heat storage unit (HSU), thermally insulated from environment
- TEG between the HSU and the environment
- T_{IN} follows T_{OUT} with a delay
- Phase Change Material (PCM) boosts heat storage







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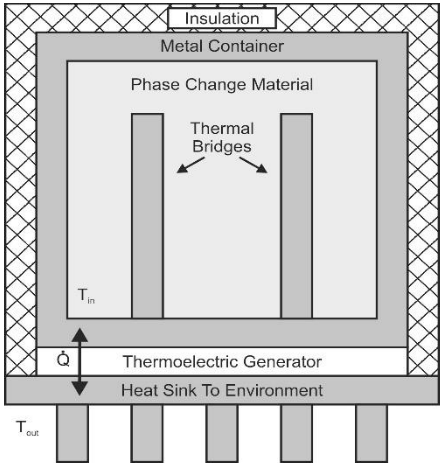
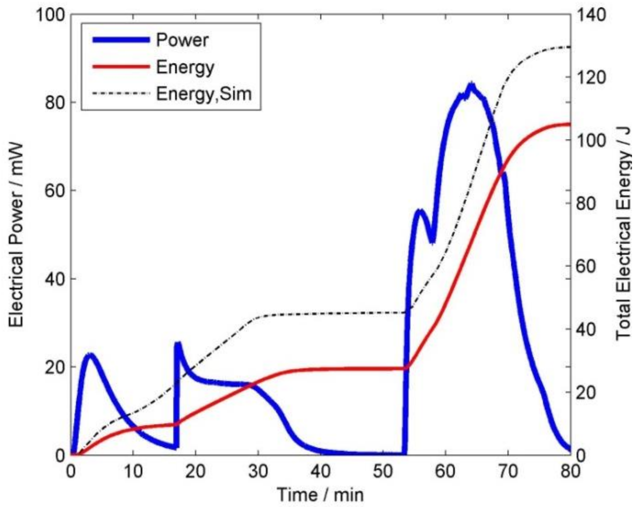
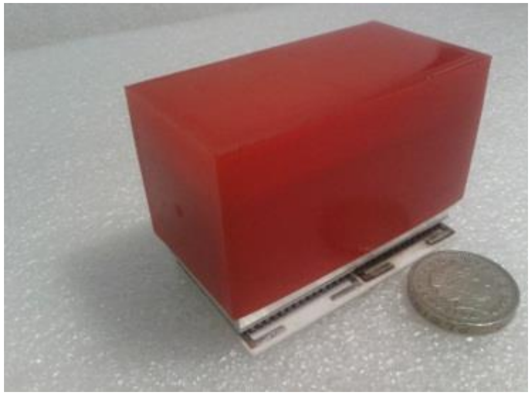
Comsol simulation: Elefsiniotis et al, Journal of Physics: Conference Series 476 (1), 012020

Thermal Harvester for Aircraft Structure Monitoring





- Wireless strain sensors in wings, fuselage
- Hard to access
- Use temperature change from ground to flight to harvest thermal energy
- Phase change material provides thermal inertia on one side of generator



Kiziroglou, M.E.; Wright, S.W.; Toh, T.T.; Mitcheson, P.D.; Becker, T.; Yeatman, E.M., "Design and Fabrication of Heat Storage Thermoelectric Harvesting Devices," IEEE Trans Industrial Electronics 61, pp.302,309, Jan. 2014

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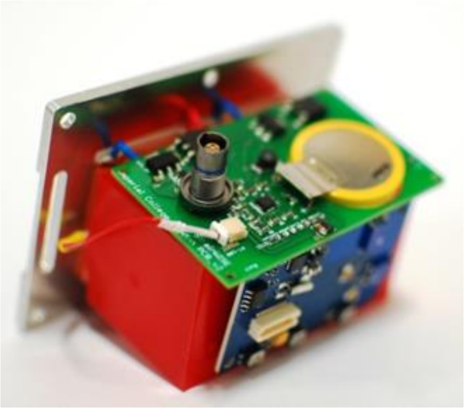
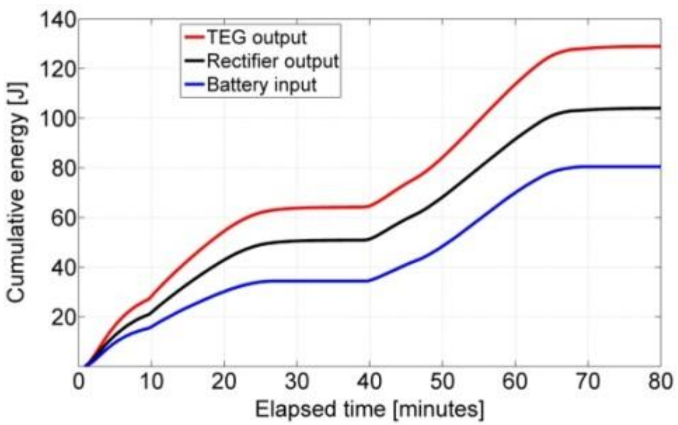
Harvesting Powered Wireless Aircraft Strain Sensor



- Consortium: CSEM, Imperial, Serma
- Application coordinator: Airbus
- Energy demand < 28 J / flight
- Energy availability > 60 J / flight
- Power management and storage > 60% efficient



JEM, 42 (7), 2301, 2013

Toh, T.T.; Wright, S.W.; Kiziroglou, M.E.; Mitcheson, P.D.; Yeatman, E.M. "A Dual Polarity, Cold-Starting Interface Circuit for Heat Storage Energy Harvesters" Sensors and Actuators, 2014.

M. E. Kiziroglou, A. Elefsiniotis, S. W. Wright, T. T. Toh, P. D. Mitcheson, T. Becker, and E. M. Yeatman, "Performance of phase change materials for heat storage thermoelectric harvesting" Applied Physics Letters, vol. 103, pp. 193902-193902-5, 2013.

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Conclusions

- Differential transduction doesn't miniaturise well, limits application scenarios
- Inertial units can enable single point energy harvesting, for both motion and heat
- Extract power by the time variation of position or temperature at a single location
- Power limit depends on rate and amplitude of change, and size of inertial unit

What if Harvesting Isn't Enough?

- Sensor networks are discussed much more than they are deployed
- Reliability in harsh environments and power consumption remain obstacles
- Harvesting and mesh networks with relaying has gone some way to solve these issues

- However, availability of power with harvesting can be insufficient for many operational scenarios

A possible solution is ***Synthsense:*** Synthetic Sensor Networks.

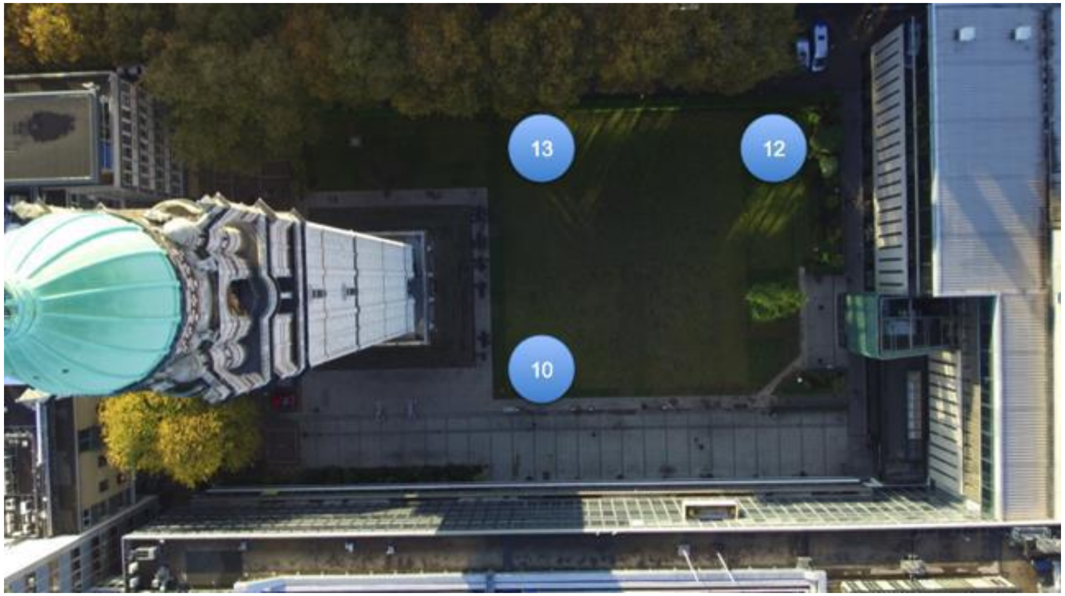
Synthsense Concept

- Use UAVs to read time sequences of data from embedded sensors without long range comms
- Between "visits", sensors can keep accumulating data with very low power requirements
- This power can be "injected" by the UAV

Some research challenges:

- improve reading speed and power transfer efficiency, to get required range, stealth and operating time
- Combined data and power link
- Wireless charging of the UAV to enable unmanned charging stations
- Would like much less than 1% duty cycle for wireless powering

Proof of Concept - Data Transfer



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Sensor Data Collection

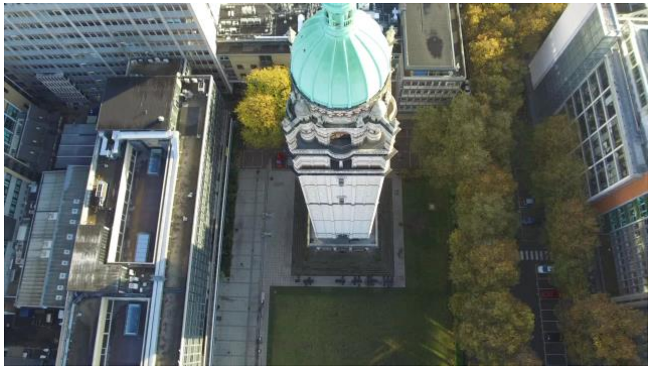
- First steps on the Queen's Lawn at IC:
  - Drone: DJI Matrice 100
  - 'TelosB' wireless sensor nodes
    - One mounted underneath drone
    - Sensor data periodically stored on device
  - IEEE 802.15.4-2003 2.4GHz wireless links

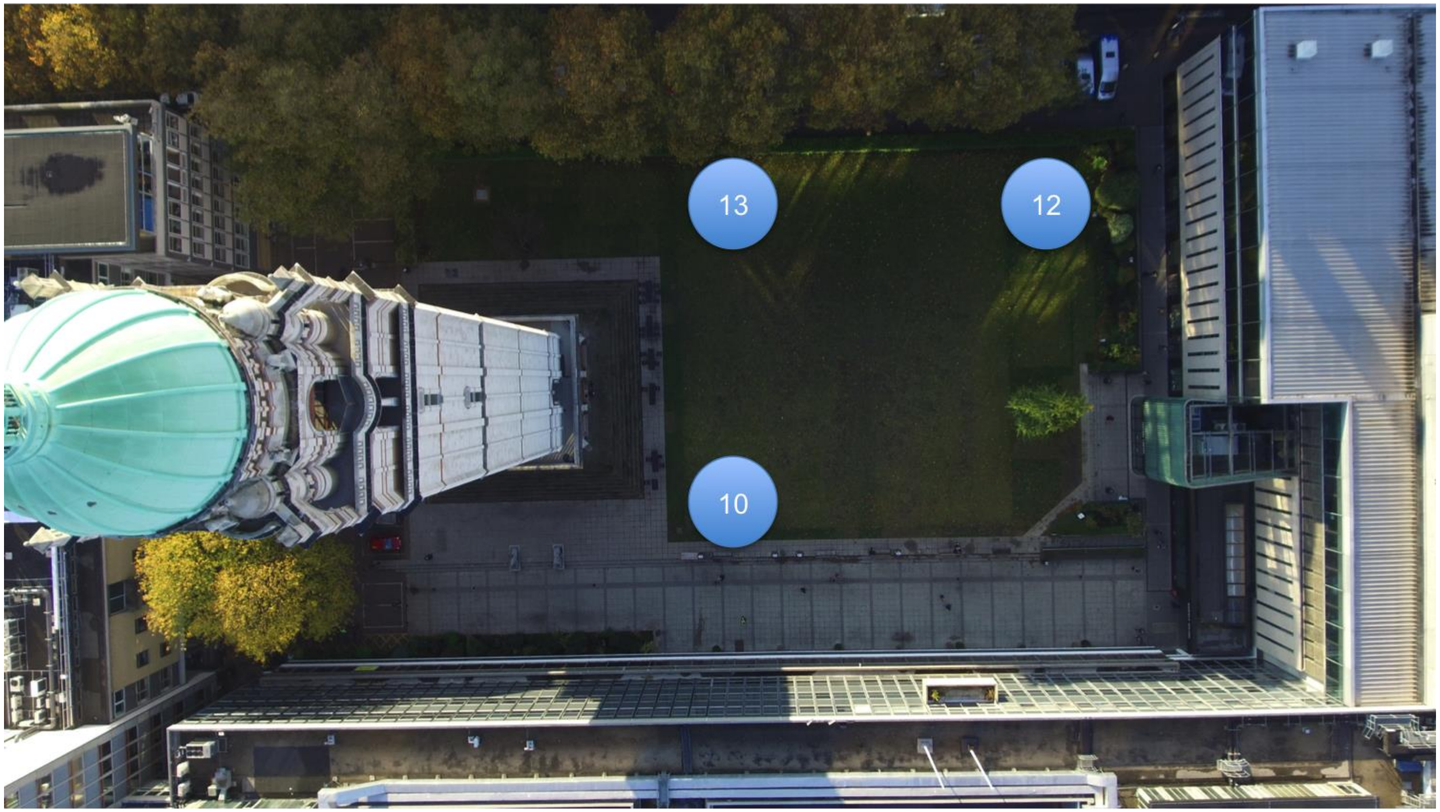
Drone's view

Data Collection

Sensor Data Collection

- Small deployment of 3 sensing nodes





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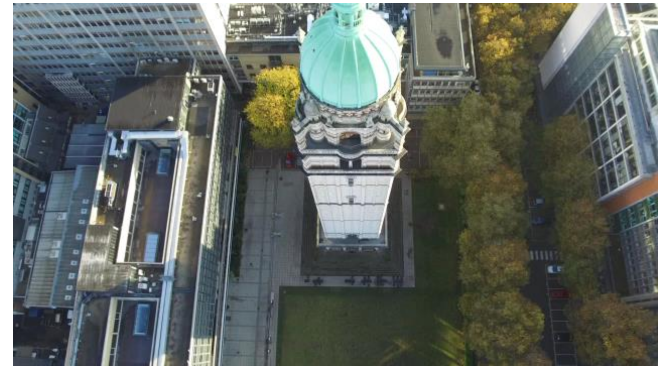
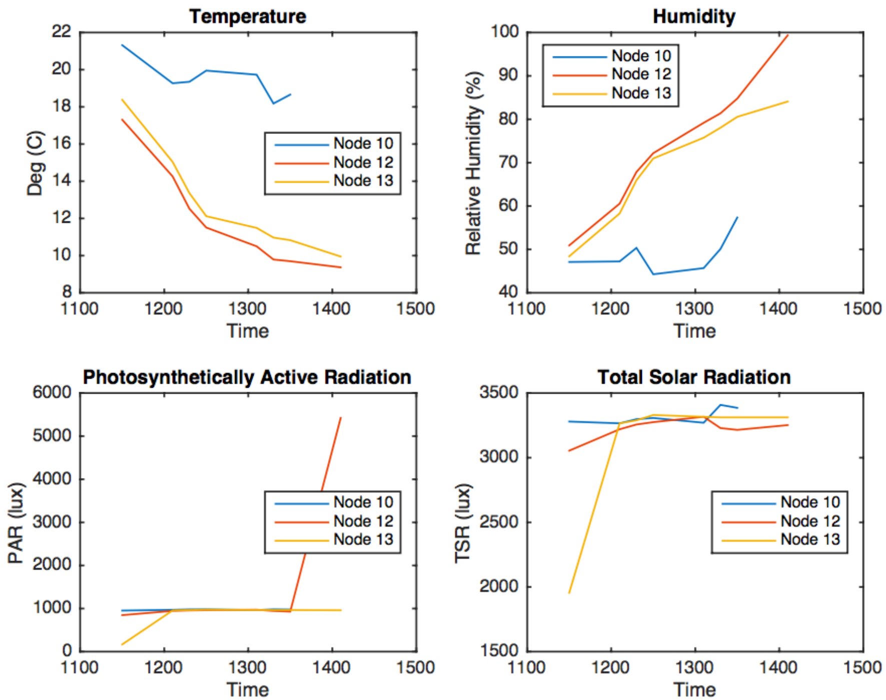
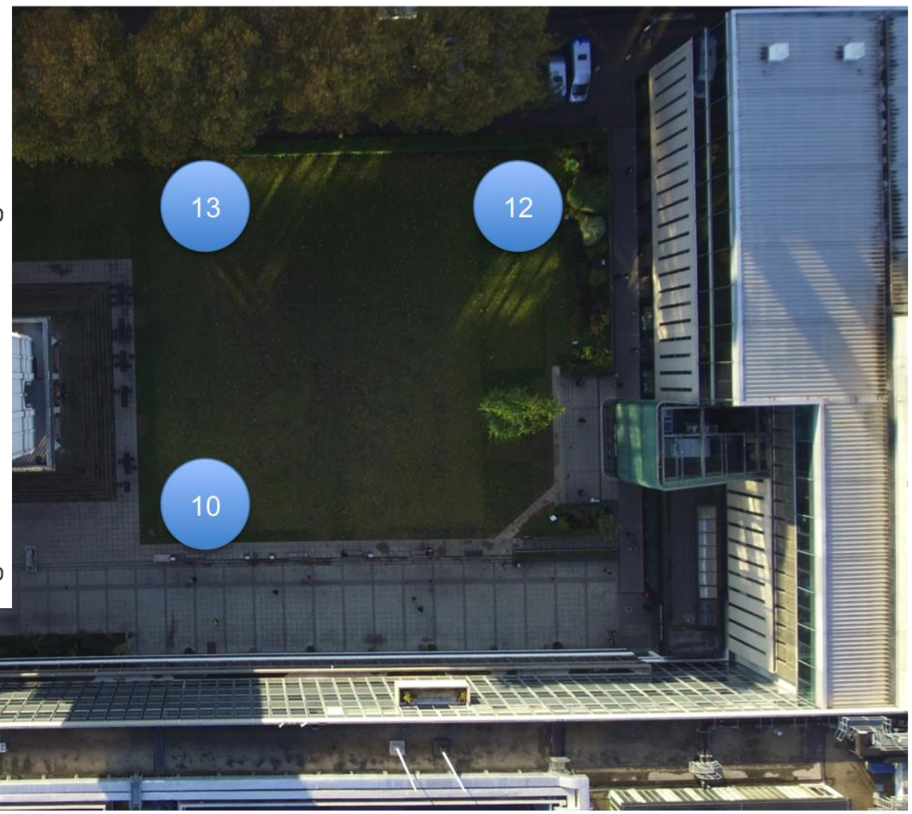
Sensor Data Collection

- Small deployment of 3 sensing nodes







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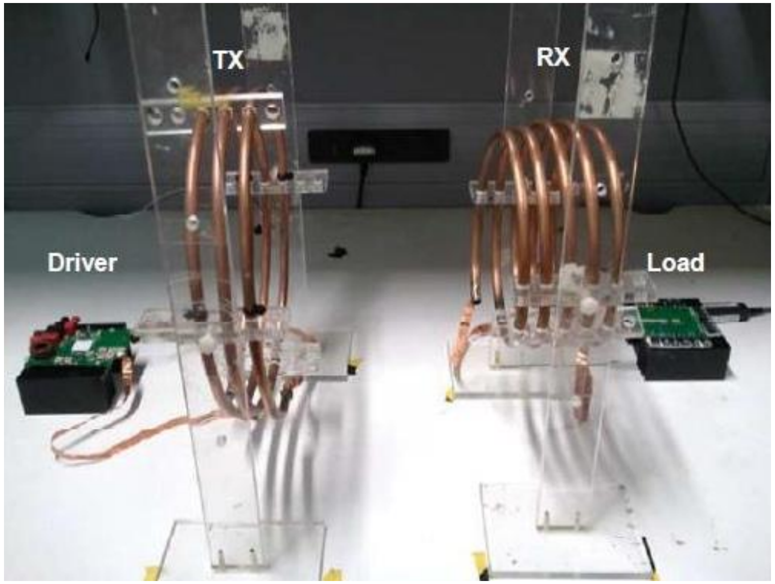
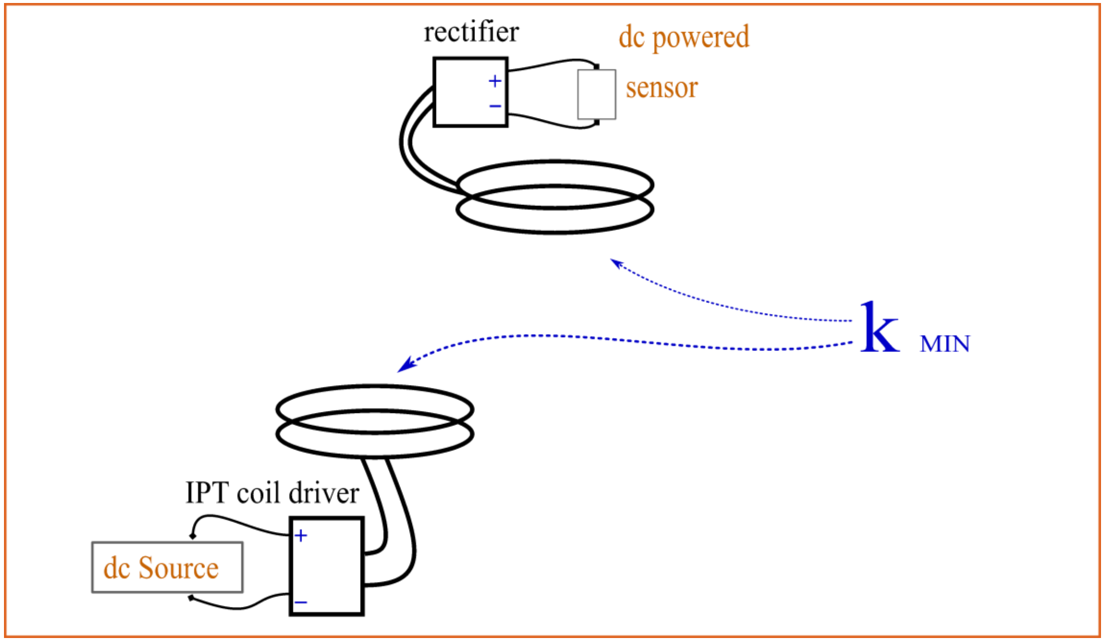
Wireless Power Delivery



Challenges for Synthsense Charging



Dynamic system challenges:

1. Light weight system
2. High link efficiency capability independent of k
3. Optimal reflected load with varying k
4. High efficiency of the inverter and rectifier with varying k and varying power throughput

We need longer range and much better tolerance to misalignment than other IPT systems – and very light weight.

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Commercial systems: Automotive and phones

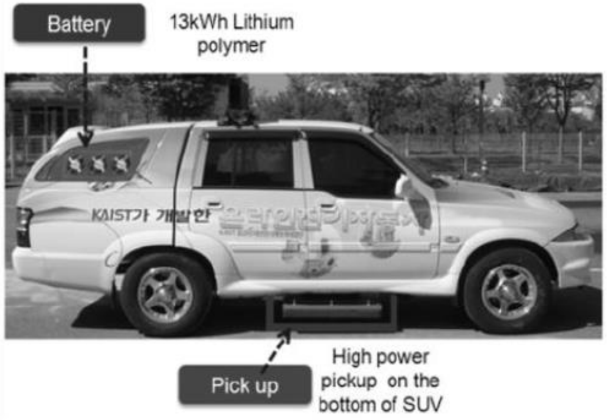
Most use ferrite to enhance coupling: too heavy

Witricity EV charger

- RX ~10 kg, TX ~30 kg, 85 kHz

Qualcomm Halo

- 20 kW, 20 kg, 20kHz

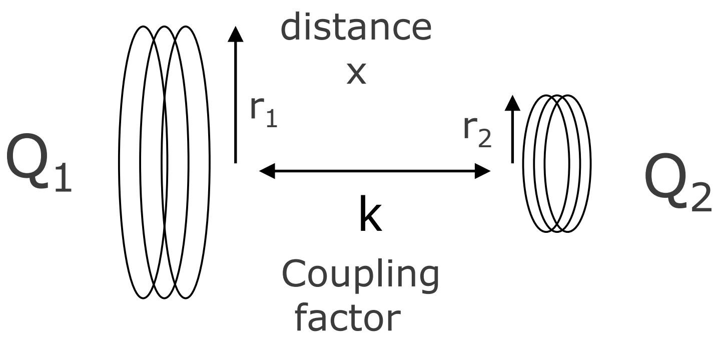


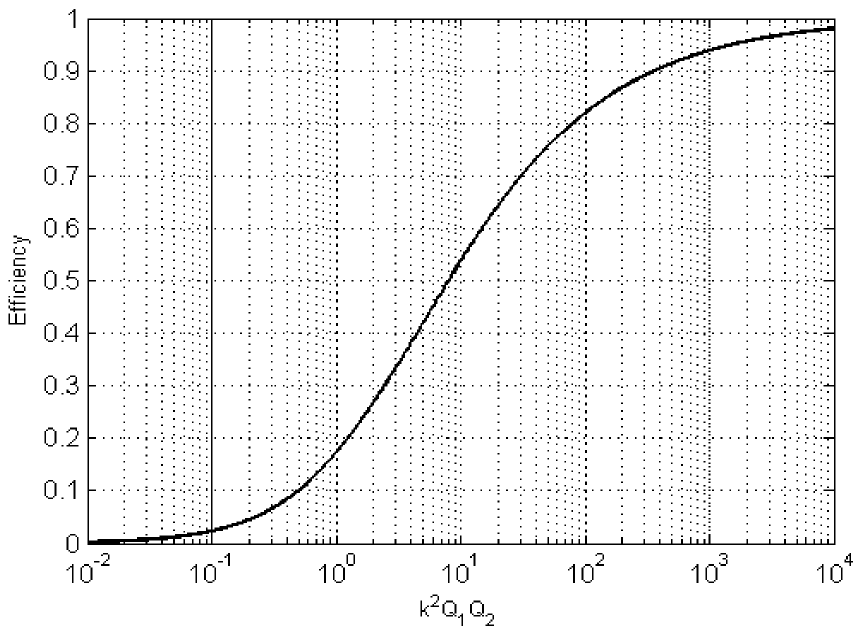
- Qi standard very short range
- Limited power levels
- Other systems are too heavy

Reliance on High Q, not high k

Efficiency given by: $$\eta = \frac{k^2 Q_1 Q_2}{\left(1+\sqrt{1+k^2 Q_1 Q_2}\right)^2}$$

Secondary resonance
Optimal load





Need to maximise $k^2Q_1Q_2$

$k^2Q_1Q_2 > 10$ for $\eta > 50\%$

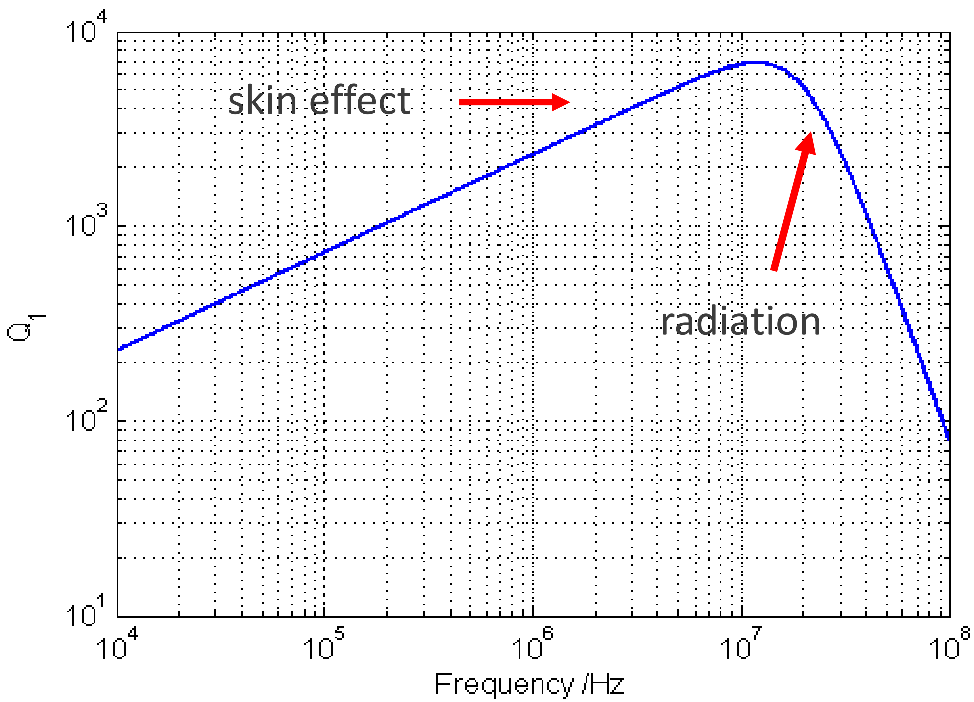
$k^2Q_1Q_2 > 350$ for $\eta > 90\%$

Most systems are reliant on maximising k. This leads to heavy systems with poor alignment tolerance

High Frequency is Key

Efficiency given by: $$\eta = \frac{k^2 Q_1 Q_2}{\left(1+\sqrt{1+k^2 Q_1 Q_2}\right)^2}$$

Secondary resonance
Optimal load



- High frequency (MHz) allows high Q
- High frequency allows removal of ferrite
- Skin effect allows very thin conductors
- If Q is high enough, we don’t need to worry about k – longer range

Light weight and varying k capability are possible with high frequency, high Q coils

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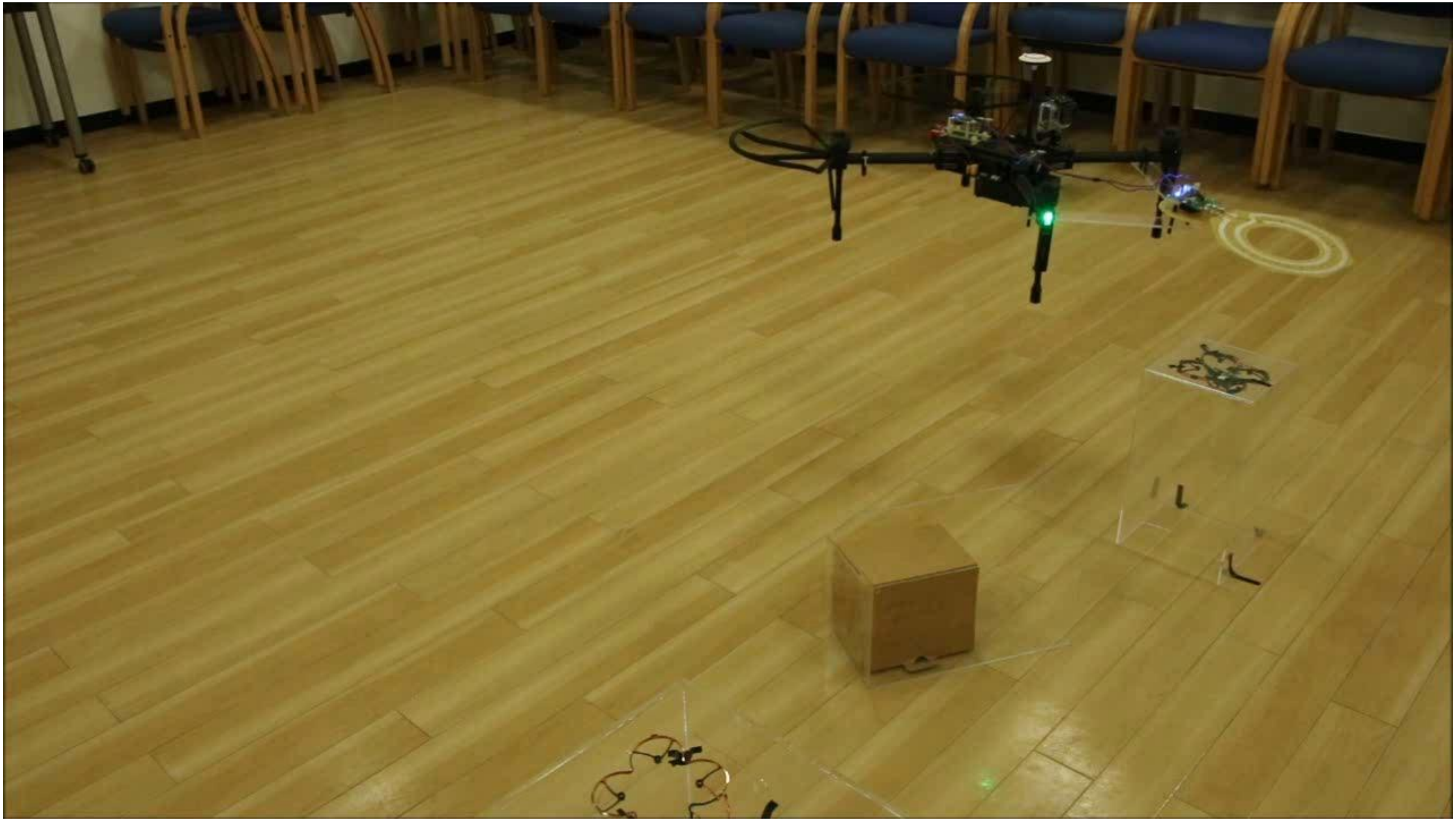
Drone charging a sensor



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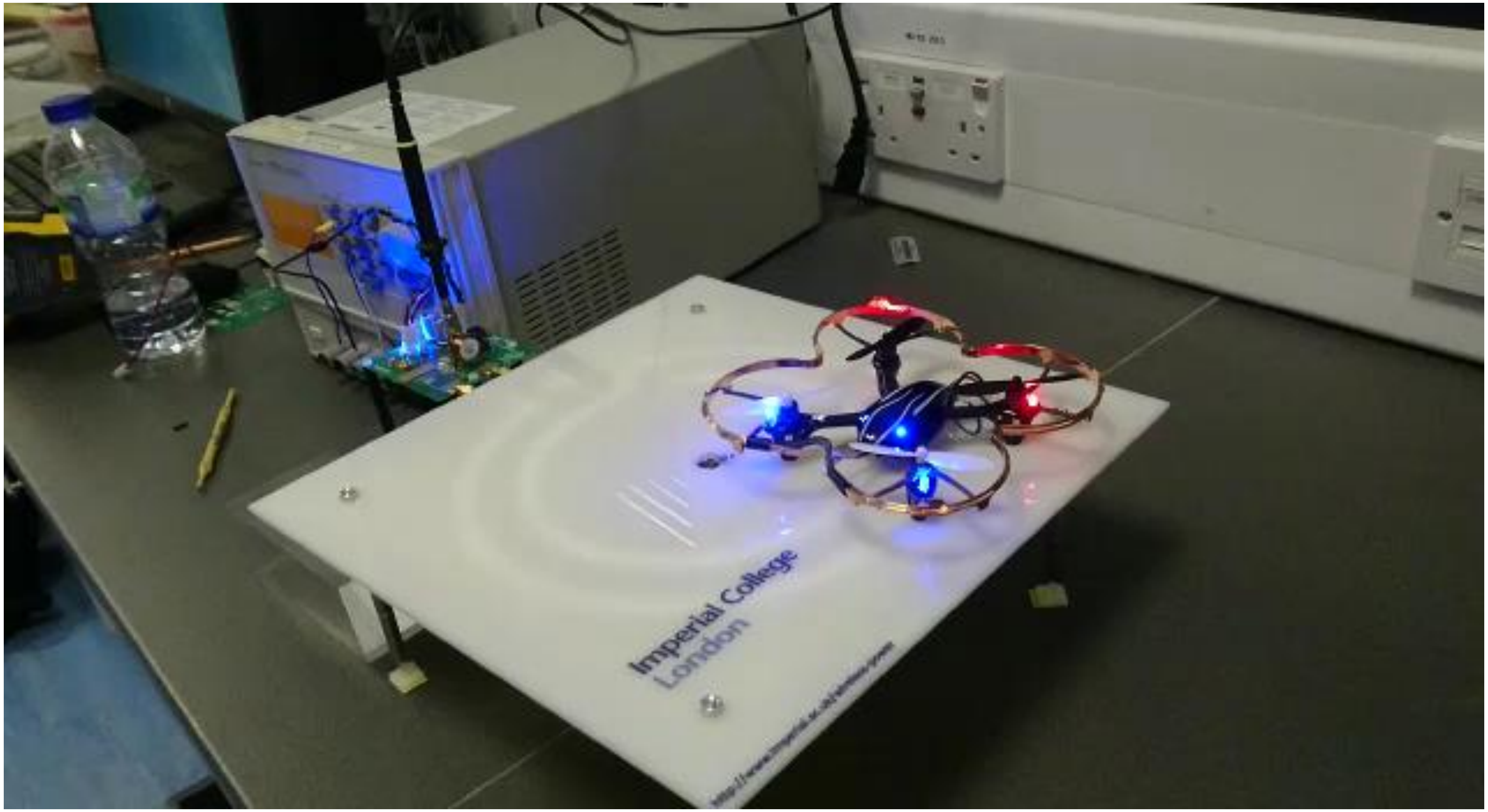
Drone With No Battery



Drone Charging Drone!

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Conclusions

- A new paradigm for WSNs, inspired by SAR, called Synthsense
- Autonomous drones can visit remote sensors and exchange data and supply power inductively.

- Wireless powering is possible using MHz operation for light weighting the system and attaining longer range
- Additional technical difficulty is coping with changes in load and coupling factor as the drone hovers next to the sensor
- Solved by several circuit topologies

- As we can charge at 50 W, and the average node consumption is under 1 mW, our charging duty cycle is 0.002%! (or 7s every hour)

Wireless Charging References

- Modeling and Analysis of Class EF and Class E/F Inverters With Series-Tuned Resonant Networks, S Aldhaher, DC Yates, PD Mitcheson, Power Electronics, IEEE Transactions on 31 (5), 3415-3430

- Link efficiency-led design of mid-range inductive power transfer systems, CH Kwan, G Kkelis, S Aldhaher, J Lawson, DC Yates, PCK Luk, Emerging Technologies: Wireless Power (WoW), 2015 IEEE PELS Workshop on, 1-7

- Maximizing DC-to-load efficiency for inductive power transfer, M Pinuela, DC Yates, S Lucyszyn, PD Mitcheson, Power Electronics, IEEE Transactions on 28 (5), 2437-2447

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THANK-YOU!

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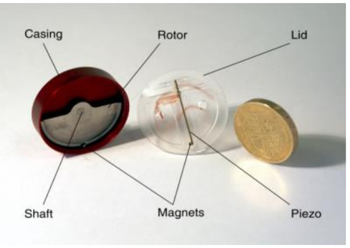

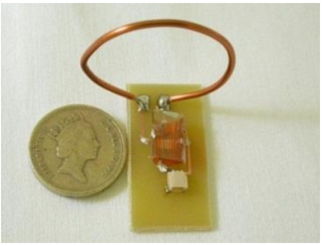

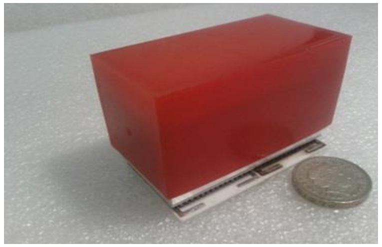

Extra Slides for Questions etc

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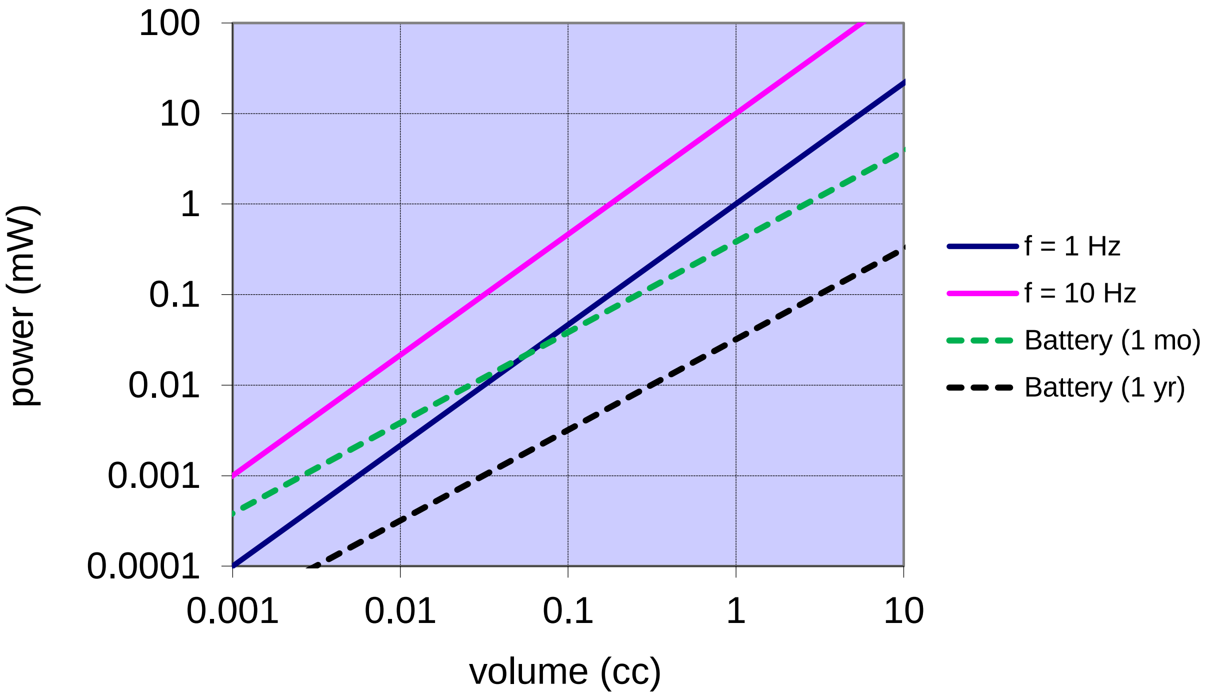
Inertial Harvesters Compared to Batteries



Plot assumes:

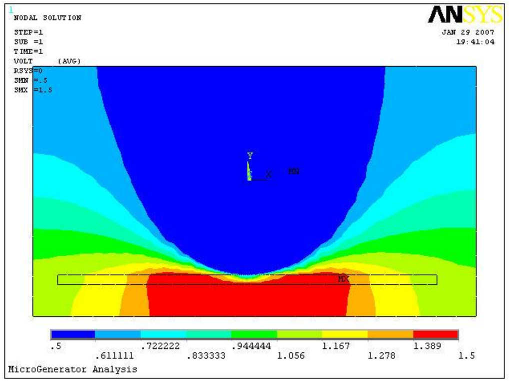
- proof mass 10 g/cc
- source acceleration 1g
- Li battery 1 kJ/cc

External Mass Electrostatic Harvester

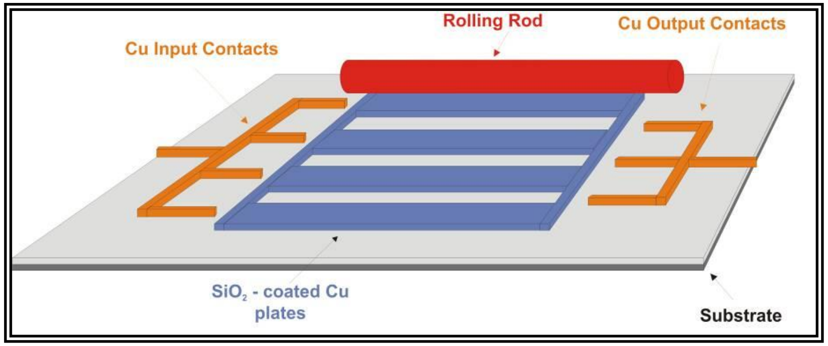
- Proof mass rolls on substrate
- Multiple charge-discharge cycles per transit
- No deep etching: fabrication simplicity
- Large mass and internal travel range

But:

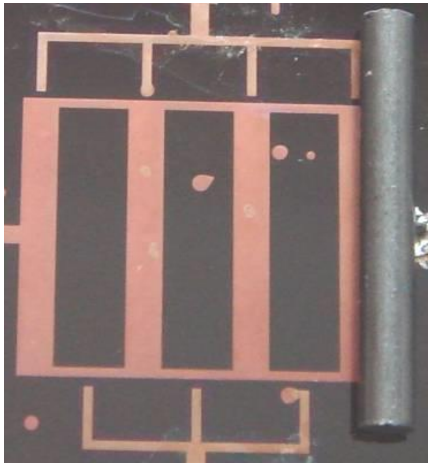
- Very low capacitances & capacitance ratios
- Thus, low power for given priming voltage



Electrostatic simulation



Schematic illustrating concept



Rolling mass on prototype device

M. Kiziroglou, C. He and E.M. Yeatman, “Rolling Rod Electrostatic Microgenerator”, IEEE Trans. Industrial Electronics **56**(4), pp. 1101-1108 (2009).

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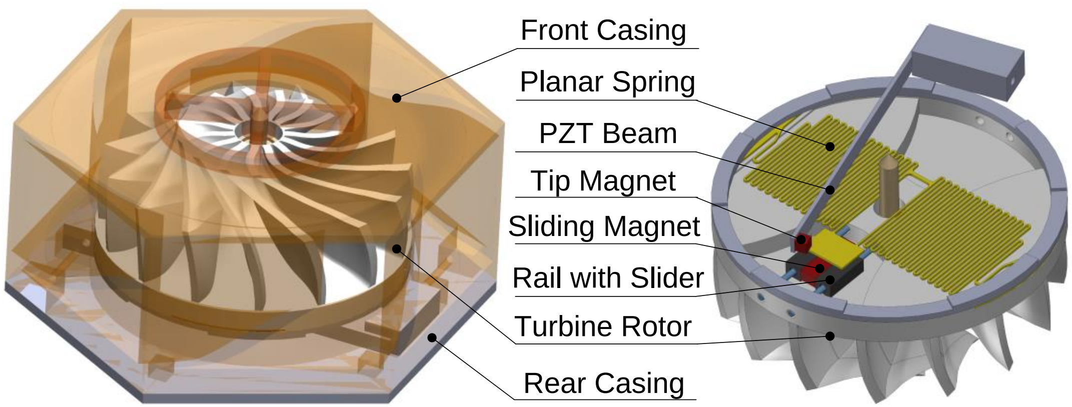
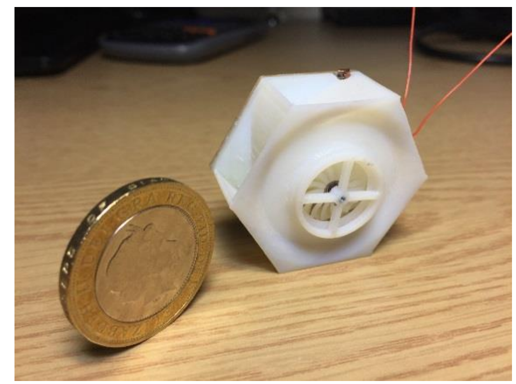
SELF-REGULATION

Solution to high cut-in speed:

- ✓ Passive self-regulation
- ✓ Centrifugal force
- ✓ Regulating magnetic coupling
- ✓ Ultra-flexible planar spring





Piezoelectric turbine with self-regulation Ø37 mm×18 mm[1,2]

1. H. Fu and E. M. Yeatman, *Applied Physics Letters,* vol. 107, p. 243905, 2015.
2. H. Fu, M. D'Auria, G. Dou, and E. M. Yeatman, in *2016 IEEE 29th International Conference on Micro Electro Mechanical Systems (MEMS)*, 2016, pp. 1220-1223.

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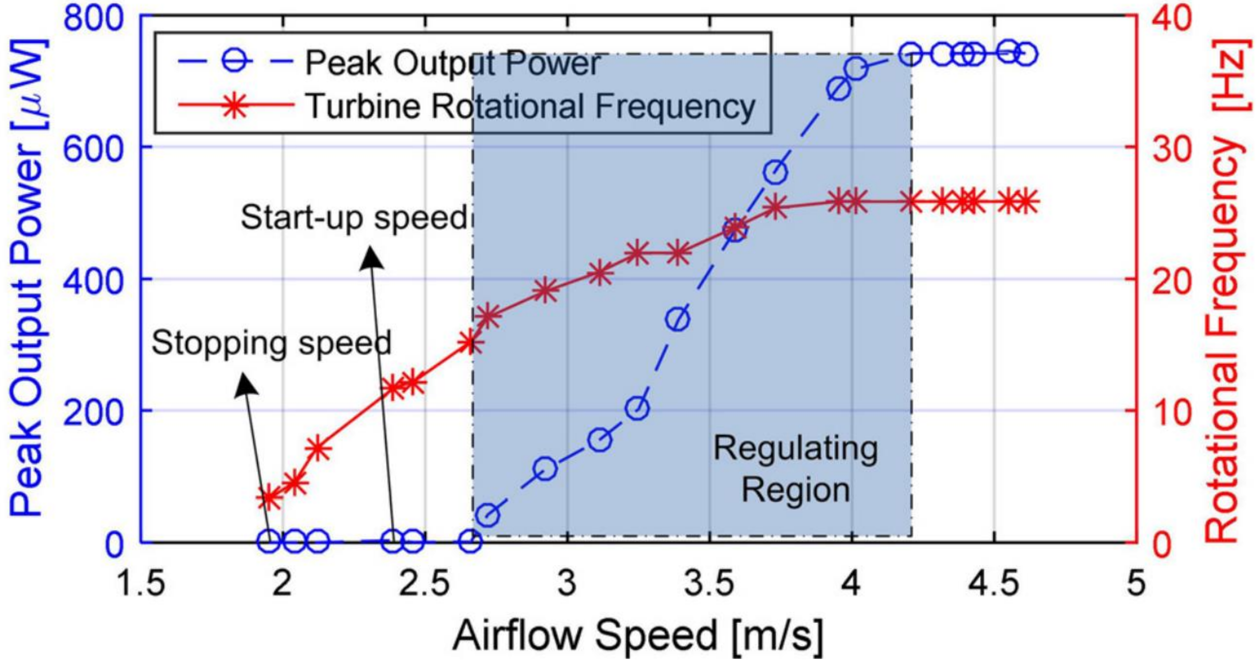
RESEARCH PROGRESS



Output power and frequency against airspeed[1,2]

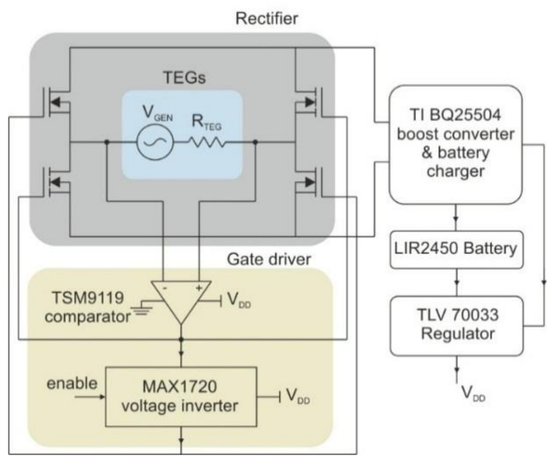
Advantages

- ✓ Lower cut-in speed
- ✓ 30% improvement against a non-regulated harvester

1. H. Fu and E. M. Yeatman, *Applied Physics Letters,* vol. 107, p. 243905, 2015.
2. H. Fu, M. D'Auria, G. Dou, and E. M. Yeatman, in *2016 IEEE 29th International Conference on Micro Electro Mechanical Systems (MEMS)*, 2016, pp. 1220-1223.

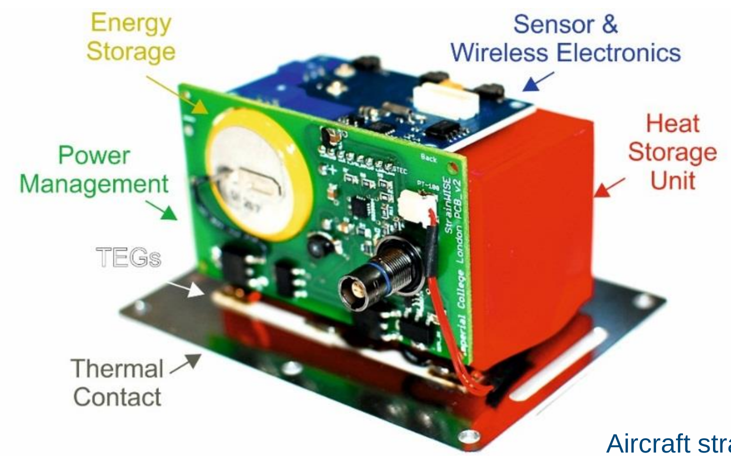
Harvesting Powered Wireless Aircraft Strain Sensor

Cold-starting, bipolar power management



Sensors and Actuators, 211, 38-44, 2014

Sensor node integration and flight testing



Custom TDMA low power protocol

Energy demand < 28 J / flight

Energy availability > 60 J / flight

Power management and storage > 60% efficient

Aircraft strain WSN powered by heat storage harvesting, IEEE Trans. Industr. Electr, 2017

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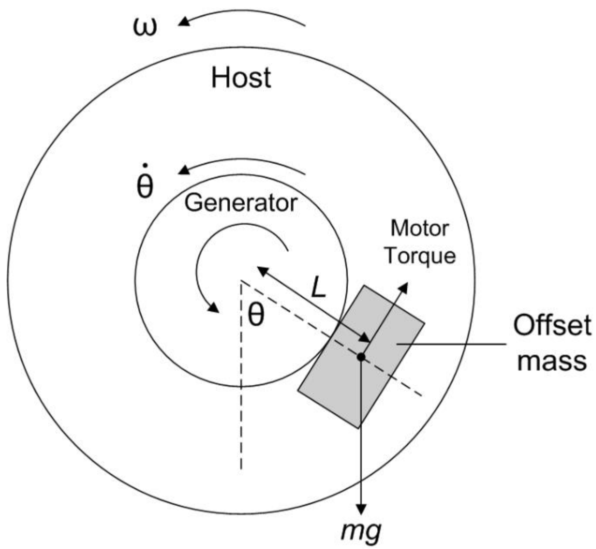
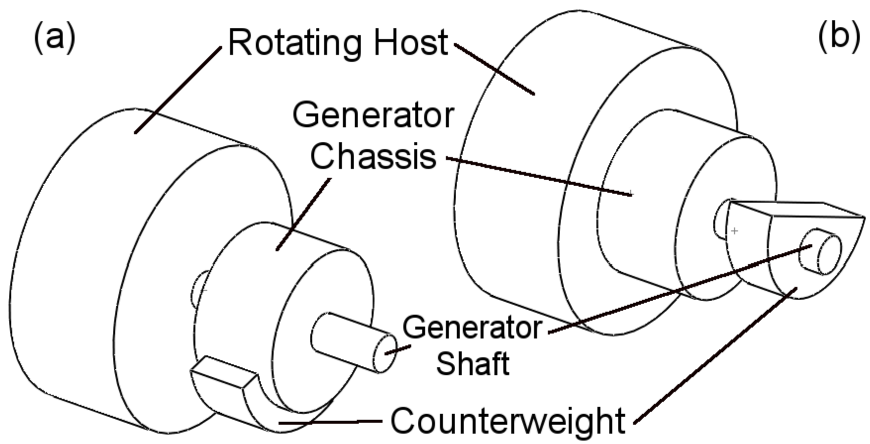
Harvester for *Continuously* Rotating Source

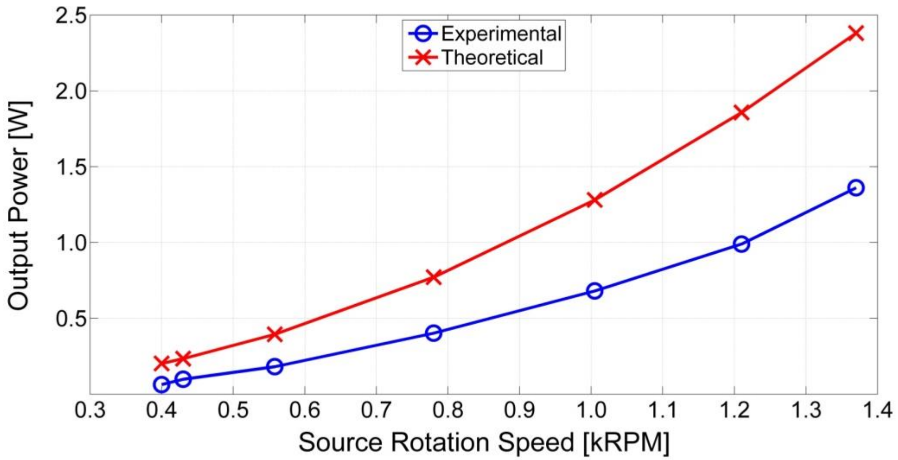


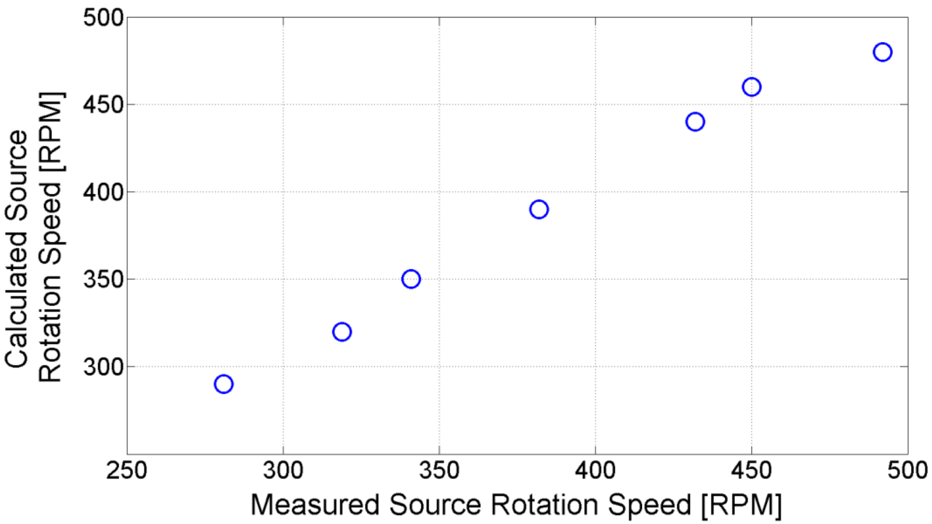


- Single point-of-attachment system for energy harvesting from rotation
- DC machine used for transduction
- Gravitational force on offset mass used to prevent rotation of one side of transducer (either casing or shaft)

Wireless Tachometer

TT Toh, PD Mitcheson, AS Holmes, EM Yeatman, "A continuously rotating energy harvester with maximum power point tracking", J. Micromechanics and Microengineering 18 (10), 104008





Compare: Rotating vs Linear resonant generator

Example: upper limb swinging at 1 Hz

- Linear: Y_o = 5 cm
- Rotating: θ_o = 25 deg
- Use mass of 1 g, radius = travel range = 0.5 cm

$$P_{\max} = \frac{mY_o Z_o \omega^3}{\pi} \quad \text{vs.} \quad P_{\max} = \frac{mR^2\theta_o^2\omega^3}{8}\sqrt{Q}$$

Result:

P_{lin} = 13 uW $\quad$ P_{rot} = 0.2 uW $\sqrt{Q}$

E.M Yeatman, "Energy Harvesting from Motion Using Rotating and Gyroscopic Proof Masses", J. Mechanical Engineering Science 222 (C1), pp. 27-36 (2008).

Rotating vs Linear resonant generator

P_{lin} = 13 uW P_{rot} = 0.2 uW $\sqrt{Q}$

P_{rot} higher for Q > 4000

Technical Challenge:

- High Q for resonant rotating device requires spring with very high number of turns

Practical Challenge:

- High Q means high drive frequency dependence

Gyroscopic power generation

How to implement in MEMS? High quality spinning bearings not really available.

E.M Yeatman, "Energy Harvesting from Motion Using Rotating and Gyroscopic Proof Masses", J. Mechanical Engineering Science 222 (C1), pp. 27-36 (2008).

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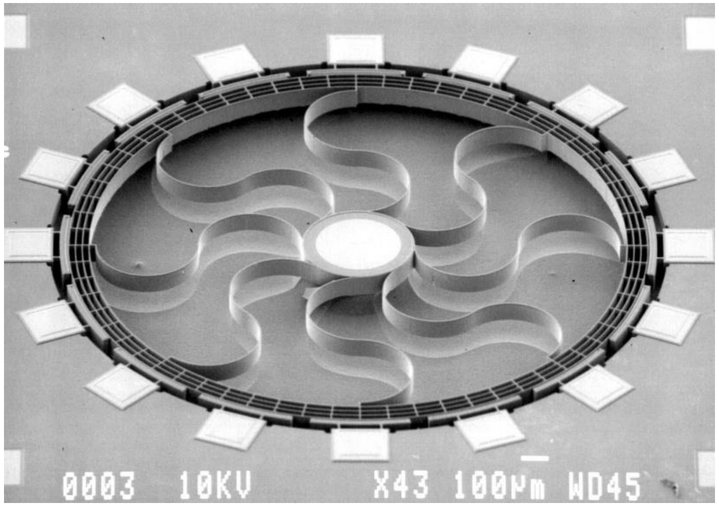
Gyroscopic power generation

How to implement in MEMS? High quality spinning bearings not really available.

- Solution: well known format for MEMS gyros
  - Vibrating gyro



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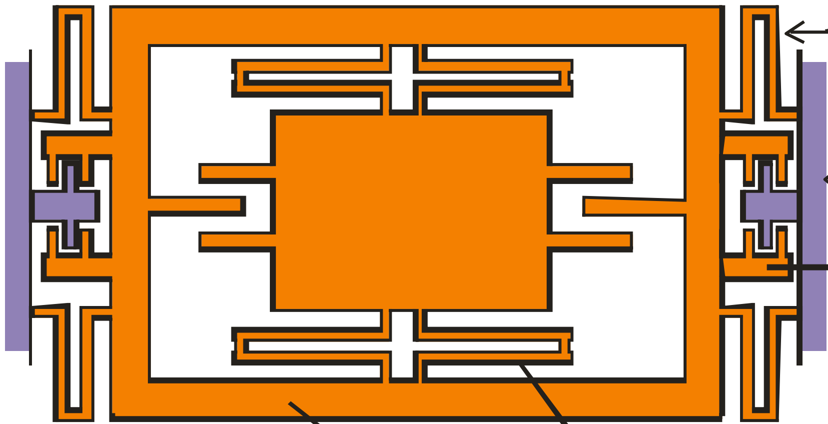
Gyroscopic power generation

- Proposed format: linear vibration on two axes, one for drive, one for pick-off;
- Same as gyro sensor except pick-off extracts energy, not signal



after Fedder et al