Powering tomorrow's sensor: a review of technologies – part 2

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Abstract

Purpose – The paper aims to provide a technical review of new and emerging power sources and their application to sensors.

Design/methodology/approach – This is the second part of a two-part paper. Following a brief introduction, recent developments and research into fuel cell, energy harvesting, microgenerator and wireless power transmission technologies are considered.

Findings – All of these technologies are the topic of a major research effort and offer prospects to power future generations of sensors. Several pose strong competition to rechargeable batteties.

Originality/value – The paper provides a detailed insight into new and improved sensor power sources.

Keywords Sensors, MEMS, Electric cells, Energy management, Electric power generation

Paper type Technical paper

Introduction

As noted in the first part of this paper (Vol. 30, No. 3), the proliferation of portable electronic devices has led to enormous interest in novel power sources. This has been further stimulated by the expanding uses of wireless sensors and sensor networks. Accordingly, a diversity of technologies are being developed by a global research effort. Part 1 of this paper discussed batteries, betavoltaics and supercapacitors; this second part considers fuel cells, energy harvesting, microgenerators and wireless power transmission.

Fuel cells

Fuel cells are electrochemical devices which generate electricity through the reaction between a fuel on the anode side of the cell and an oxidant on the cathode, in the presence of an electrolyte and a catalyst. They differ from conventional batteries in that they consume reactant from an external source which must be replenished. Numerous different combinations of fuels, oxidants and catalysts have been investigated, and fuel cells are the topic of a global research effort. They are used as power sources in remote and rural locations, in spacecraft and in certain military applications, but the most significant potential lies in portable electronic devices such as laptops, phones and music players. Numerous companies are rushing to develop products, often termed micro fuel cells, to address these multi-billion dollar markets. In 2009, Toshiba announced the "Dynario" product that serves as an external power source for mobile devices. It runs on methanol and ambient oxygen and produces 400 mA at 5 V. A key benefit of the technology that overcomes one of the limitations of conventional batteries is the recharge speed: reactivating a depleted cell simply involves inserting a new fuel cartridge.

Many companies are expected to launch micro fuel cells in the next few years, but some academic groups are developing truly miniature devices with millimetre dimensions. A research group at the University of Illinois recently announced what is claimed to be the smallest fuel cell yet developed (Moghaddam *et al.*, 2008). With dimensions of just 3 × 3 × 1 mm (Figure 1), this features a thin, porous membrane which separates a water reservoir from another containing a metal hydride ($LiAlH_4$), below which is an arrangement of electrodes. Water molecules pass through the membrane as vapour and then react with the hydride to yield hydrogen. This leaves the reactor through a nanoporous silicon wall to reach a hybrid silicon and Nafion (a sulphonated tetrafluoroethylene-based copolymer) membrane electrode. A passive microfluidic system regulates hydrogen generation through the controlled delivery of water vapour to the hydride. The original cell generated 0.7 V and 0.1 mA for about 30 h but a more recent design produced ~1 mA at a similar voltage. This work is part of a broader research programme which aims to develop new types of microfabricated, silicon fuel cells to power micro-electromechanical system (MEMS) devices operating in remote locations. In addition to hydrogen, other fuels including methanol and formic acid are being studied. A fuel cell based on silicon MEMS technology has been developed by a group from Japan's Waseda University (Tominaka *et al.*, 2009). This can operate with a variety of fuels, including methanol and less toxic ethanol and 2-propanol and uses ambient oxygen as the oxidant. In the future, the group hopes to integrate the cell with other micro-devices, thus yielding MEMS structures with on-chip power sources. A possible

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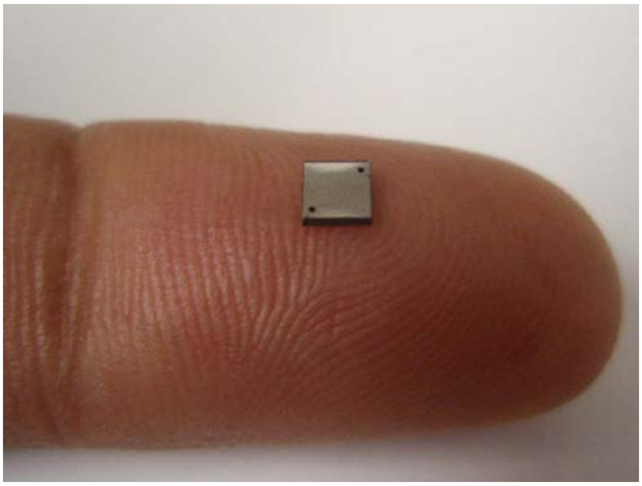
Figure 1 The microminiaturised fuel cell developed at the University of Illinois



Source: Saeed Moghaddam, University of Illinois

future goal would be the development of an integrated blood-screening sensor powered by a cell fuelled by blood glucose.

A similar use has been propsed for microbial fuel cells (MFCs), the idea being that they could extract glucose or other metabolites from body fluids for use as fuel, resulting in a renewable, long-term power source for implantable medical devices. MFCs differ from conventional cells in that they convert chemical to electrical energy through the catalytic activity of micro-organisms (bacteria). A typical MFC consists of anode and cathode compartments separated by a membrane. In the anode compartment, fuel is oxidised by the micro-organisms, generating electrons and protons. Electrons are transferred to the cathode through an external electrical circuit with a load resistor and the protons enter through the membrane. Both are consumed in the cathode compartment, combining with oxygen to form CO_2 and water. The bacteria can operate with a wide range of substrates (fuels), e.g. carbohydrates, fatty and amino acids, alcohols, proteins and inorganic compounds such as sulphides, mining drainages or even metals, in this case through the use of metal-reducing micro-organisms such as *Geobacter* and *Rhodoferax* species. At present, however, MFCs do not generally generate sufficient power for widespread applications and are, therefore, the topic of much research. For example, workers from the University of Massachusetts and the Naval Research Laboratory have used a strain of *Geobacter sulfurreducens* in the form of a thin biofilm in an MFC which produced current and power densities of $7.6\,\mathrm{A/m^2}$ and $3.9\,\mathrm{W/m^2}$; figures that were amongst the highest are yet to be reported (Yi *et al.*, 2009).

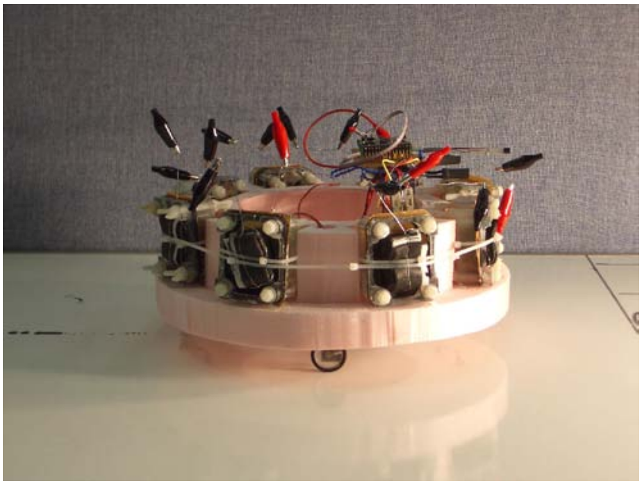
A key attraction of MFCs is their ability to operate continuously when located in environments rich in suitable bacterial metabolites, and in addition to the human body, these could include industrial waste streams or water courses. Sensors powered in this manner could be used to monitor pollutants in the waters. In 2008, a group from Washington State University reported the use of an MFC to power a suite of batteryless, wireless water quality sensors in the Palouse River (Donovan *et al.*, 2008). A very different application studied by a group from the University of Western England aimed to develop truly autonomous robots which scavenged their energy from the environment. MFCs were employed to extract electrical energy from refined and unrefined foods such as sugars, insects and fruit. To be truly autonomous, such robots will be required to incorporate actions that involve searching for, collecting and digesting food. The robots are designed to remain inactive until sufficient energy had been generated to complete the required task. So far, two such robots, EcoBots-I and II, have been developed which, to some extent, exhibit this type of behaviour. EcoBot-I employed *Escherichia coli* as the micro-organism and was fed with sugar while EcoBot-II (Figure 2) used eight MFCs based on activated sludge microbes and was fed with, amongst other substrates, dead insects and food waste. It was able to perform sensing, information processing, communication and actuation.

Microgenerators

Microgenerators are effectively the miniaturised versions of conventional devices such as gas turbines or reciprocating and rotary engines and are still at a very early stage of development. Many aim to exploit the capability of MEMS technology and are termed "power MEMS" devices. A key attraction of combustion-based systems is the high power densities: most liquid hydrocarbon fuels contain over 300 times more energy per unit weight than an NiCad battery and 100 times more than a Li-ion type (Table I).

Some of the most significant recent work was conducted at MIT under the Micro Engine project which later involved collaborations with the Georgia Institute of Technology, Clark Atlanta University and the University of Maryland. This started in the mid-1990s and aimed to develop a small, power-dense

Figure 2 The EcoBot-II



Source: IAS EcoBot Team

Table I Energy density comparisons

Energy source	Energy density (MJ/kg)
NiCad battery	0.14
Li-ion battery	0.46-0.72
Methanol	19.7
Gasoline	46.4

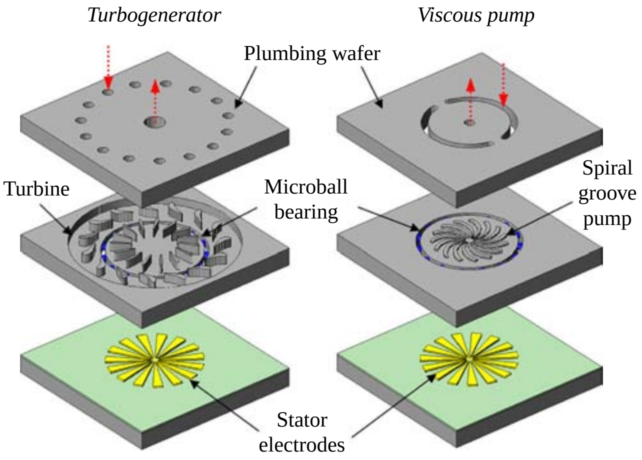
gas turbine generator based on MEMS fabrication technologies that would produce 20 W at 2.4 million rpm from a cubic centimetre-sized package. Fuel would be provided by a hydrogen cartridge. Much progress was made, but all manner of daunting technological challenges remain, such as extreme thermal management, rotor dynamics, bearing technology and tribology. As yet, no working devices have emerged, and although several European, Asian and other US academic groups have investigated the technology, interest has waned somewhat in recent years. However, lower level research continues. For example, the University of Maryland's MEMS Sensors and Actuators Lab recently reported the development of microscale pumps, motors and turbines which achieve rotational speeds of up to 87,000 rpm, supported on micro-ball bearings (Figure 3) (Ghalichechian *et al.*, 2008). A research group from the Berkeley Sensor & Actuator Centre at the University of California is working on the development of an MEMS-based rotary Wankel engine with a capacity of 1.5 cc. Operating with liquid hydrocarbon fuels such as kerosene, methanol, gasoline and diesel, this should achieve a far higher energy density than that obtained from batteries of a comparable size. Overall, the future prospects for microgenerators are unclear, but the motivation to develop high-energy density power sources, certainly in the military context, is as strong as ever. According to Bruce Geil, acting chief for the Power Components Branch of the US Army Research Laboratory, "The army needs small-scale, liquid-fuelled power generators that can provide higher energy, at lighter weight and lower cost, than current-fielded power sources".

Energy harvesting

Also termed energy scavenging, this involves technologies for converting various forms of energy in the environment into power. This may be used directly by the sensor or employed to charge a battery or capacitor. In addition to an ever-growing number of commercial products, it is the topic of a major research effort and plays a crucial role in wireless sensors and sensor networks. By way of a summary, Table II shows the major sources of harvested energy, the effects employed to convert them into power and the commercial status of each approach.

Energy harvesting has recently been discussed in detail in this journal (e.g. Vol. 29, No. 3) and this section, therefore, concentrates on radio frequency (RF) techniques which were not previously considered. There is mounting interest in harnessing the ever-growing amount of RF energy in the environment, emitted from Wi-Fi transmitters, cell phone antennas, TV and radio masts and other sources. Toshiba hopes one day to charge mobile phone batteries in this way and has used a wide-band antenna (500 MHz-10 GHz) to harvest 3-5 mW. They aim to increase this to over 20 mW which would be sufficient to maintain a phone indefinitely in standby mode. A specific sensor application has been demonstrated by researchers at Intel's Seattle lab and a group from the University of Washington. They have developed the WARP (Wireless Ambient Radio Power) system which harvests electromagnetic energy from TV transmission towers. At a distance of 4.1 km from a 1 MW TV antenna operating at 674-680 MHz, it was possible to power a temperature sensor, a humidity sensor and an LCD (Figure 4). The team measured 0.7 V across an 8 kΩ load, corresponding to a harvested power of 60 μW. Although small, this could potentially be used with low-power sensors or Intel's wireless identification and sensing platform, a type of RF identification system that can remotely power sensors. Some companies are already offering commercial RF harvesting products and an example is Powercast Corp. With a claimed RF to direct current (DC) conversion efficiency of up to 70 per cent, the "Powerharvester" modules allow batteries or other energy storage devices to be recharged in close proximity to their RF transmitting devices and low-power devices, including wireless sensors, can be driven directly from the harvested energy. Indeed, battery-free, wireless sensing is the target application of the company's P2100 module (Figure 5). The amount of usable power arising from RF energy harvesting depends on several factors, including the source power, distance from the source, antenna gain and the RF to DC conversion efficiency but will typically be in the milliwatt and microwatt range. RF energy harvesting has great potential to power indoor sensor systems which monitor temperature, motion and light. Building interiors often have low-light conditions making solar energy harvesting methods unreliable; suitable thermal gradients are not likely to be available and vibration tends to be minimal.

Figure 3 The University of Maryland microgenerator



Source: University of Maryland

Wireless power transmission

In 2005, a team of MIT physicists led by Marin Soljačić developed the theoretical basis for wireless electrical power transfer and validated their theories experimentally in 2007 when they wirelessly powered a 60-W light bulb from a distance of over two metres (Figure 6) (Kurs *et al.*, 2007). This was achieved with a technique they dubbed "WiTricity", which is based on a resonant coupling principle. The design consists of two 60-cm diameter copper coils, each a self-resonant system. One of the coils, attached to the power source, is the transmitting unit but rather than irradiating the environment with electromagnetic waves, it fills the space around it with a non-radiative magnetic field, oscillating at MHz frequencies. This field mediates the power exchange with the other coil, the receiver, which is designed to resonate with the field. The resonant nature of the process ensures a strong coupling interaction between the transmission and the receiving units, while the interaction with the rest of the environment is weak.

Efforts are now underway to commercialise this principle. Intel has taken an interest in this type of technology and recently announced plans to develop a system that can be used to power a laptop wirelessly, which they refer to as Wireless Resonant

Table II Energy sources and conversion effects

Energy type/source	Conversion effects	Commercial status
Mechanical		
Vibration and motion	Piezoelectric Electrodynamic	Research/early stage commercialisation Commercially available
Radiant		
Ambient light	Photovoltaic	Widely used/mature
Thermal		
Temperature difference Temperature	Thermoelectric Pyroelectric	Early-stage commercialisation Research stage
Electromagnetic		
Ambient RF radiation	Induction	Research/early stage commercialisation

Figure 4 The RF-powered sensor

Source: Intel Corporation

Energy Link. In 2007, Witricity Corp. was founded to exploit the MIT technology through an exclusive licence. Some of the sensor-related applications anticipated by the company include uses on rotating components, in mobile robots and autonomous vehicles, in harsh or remote environments and in the many other areas where wireless operation is necessary. Most importantly, magnetic fields are regarded as benign, so it is unlikely that systems would pose a health threat. This is critical, as in addition to industrial uses, early wireless power applications are anticipated in the home, e.g. providing wireless power to TVs (demonstrated in 2009) and powering and recharging mobile devices such as laptops, phones and cameras.

Figure 5 Powercast's P2100 RF energy-harvesting module

Source: Powercast

Figure 6 The MIT research team pose between the two coils. Note the illuminated bulb

Source: Institute for Soldier Nanotechnologies, MIT/Aristeidis Karalis

Conclusions

The developments considered here and in the previous part of this paper all offer prospects as power sources in future generations of sensors and systems. Some, such as improved batteries, microgenerators and certain types of energy harvesters, may operate in stand-alone mode and power sensors directly. A major objective is the elimination of batteries, and this may well become possible by combining fuel cells or energy harvesters with energy storage devices such as advanced supercapacitors, or perhaps through the use of remote power transmission. In any event, future sensor and sensor system designers will have a wider and more versatile choice of power sources at their disposal than ever before.

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