Making Sense of Sensors

Markets and Technologies

Produced by the Institute of Bio-Sensing Technology for the Microelectronics iNet

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EXECUTIVE SUMMARY

This report is in two distinct but interrelated parts. Firstly, there is an introduction to how sensors may be deployed and the main technologies used to manufacture them. Secondly, the current and emerging markets for sensors across different application sectors are described.

A sensor is ‘a device with provides a useful output in response to a specified measurand’, which is classified as either physical, chemical or biological. A sensor system is ‘an integration of sensors and other enabling technology to gather, process, and present information for action from sensed data’. There are significant opportunities in all aspects of the manufacture and application of both sensors and sensor systems.

The ability to microstructure materials at the micro- and nano-scale together with the availability of new materials technologies has led to the emergence of a number of disruptive sensor technologies. Foremost amongst these are MicroElectroMechanical Systems (MEMS), biosensors and fibre optic sensors. Nanotechnology based sensors will probably play an increasing role in new sensor technologies over the next decade.

There is a need for sensors across all market sectors. The current market drivers for sensors and associated packaging and electronics are for increased performance, and functionality (multi sensor fusion) combined with reduced size, weight and cost and low power operation together with wireless communications.

In terms of growth in the markets for specific sensor types the following are experiencing growth in the 15-20% (CAGR) range: humidity sensors, torque sensors, distance sensors, acoustic sensors and pH sensors. Healthy growth rates (>10%) for biosensors and gas sensors are also noted by various analysts.

Principal market needs include point of care systems for medical diagnostics, sensors for automotives, biosensors and chemical sensors. One of the most dynamic sensors markets is wireless sensors with a projected CAGR of 48.5% between 2008 and 2013. This will in turn stimulate a growth in energy harvesting technologies.

The UK has a strong presence in the sensors market: in 2009, the UK had a £3b share (6%) of the current £50b world sensors market and a £7.5b (6%) share of the current £124.5b world instrumentation market. Overall, the world sensors market has been unaffected by the worldwide recession with the market growing at around 10% p.a.

Further along the value chain, the sensor systems market looks likely to be around $490b by 2013.

Thus both the sensors and sensor systems markets offer significant opportunities, which UK industry is well placed to take advantage of.
INTRODUCTION AND SCOPE OF THE REPORT

This report is divided into two highly related but distinct parts:

- Part I – is concerned primarily with sensor technology, describing the measurands of interest and current and emerging technologies to quantify these measurands.
- Part II – describes sensor requirements for different market sectors, opportunities for new products and sources of potential funding.

In terms of measurands, the report covers physical, chemical and biological quantities and includes a generalised description of how these quantities can be measured. Some key current and emerging potentially disruptive technologies are described. The value chain for these sensors is described: this ranges from the bare sensor to a fully packaged device with integrated electronics and signal processing and an appropriate communications interface.

The report describes the sensors market in general and the specific drivers and requirements across different market sectors. The future trends in sensor systems to meet these requirements are discussed. Sources of potential funding for sensor and system development are described. Some of the certification and regulatory issues associated with sensors are also discussed.

The report does not cover imaging technologies.

Who should read this report?

Technical Leaders:

- to gain a broad appreciation of the all pervasive nature of sensors and current and potentially emerging sensors technologies. This will help to inform the choice of a sensor technology for a particular application. The report also discusses the metrics to be considered when choosing a sensor technology.

- to highlight disruptive technologies which could potentially make a current product uncompetitive or alternatively be used to give a competitive advantage.

Business leaders:

- to appreciate the market drivers for current and emerging applications across the different market sectors.

- to identify where a technology currently used in one sector might be successfully applied in different sector. To appreciate where their product fits in the sensor system value chain.

- to aid in the identification of some funding sources for projects to develop sensing technology and products.
PART I MEASURANDS AND SENSORS

In 1975, the Instrument Society of America defined a sensor as:

‘a device which provides a useful output in response to a specified measurand’.

Many definitions limit measurands to physical stimuli such as pressure or acceleration. However, for the purposes of this report, we consider a much wider range of measurands which we categorise as:

- Physical, e.g. temperature or movement.
- Chemical, e.g. the concentration of a chemical vapour or of a compound in solution.
- Biological, e.g. the identity and number of bacteria present in a sample or the presence of a marker for cancer in a blood sample.

These three classes of measurand present quite different challenges, thus it is convenient to address them separately when discussing sensor technologies.

Introduction to measurands in different market sectors

There are many current and emerging needs for all three classes of measurands across all market sectors. Some examples of the measurands for different market sectors are given in table 1.

<table>
<thead>
<tr>
<th>Healthcare</th>
<th>Physical</th>
<th>Chemical</th>
<th>Biological</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blood pressure</td>
<td>Glucose</td>
<td>Presence of infectious agents, e.g. sepsis due to bacteria.</td>
</tr>
<tr>
<td></td>
<td>Sound for aiding hearing. Vision</td>
<td>Blood gases</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for retinal implant.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>Air flow at wind turbines</td>
<td>Pollutants: NOx, SOx from</td>
<td>Composition of biomass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>power stations</td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td>Noise pollution</td>
<td>Pollutants, pesticides</td>
<td>E.coli in water courses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy metals in the</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>marine environment.</td>
<td></td>
</tr>
<tr>
<td>Aerospace</td>
<td>Turbine tip clearance</td>
<td>Engine exhaust products</td>
<td>Bacteria in fuel tanks</td>
</tr>
<tr>
<td>Security</td>
<td>Biometrics, e.g. face recognition,</td>
<td>Explosives and drugs at</td>
<td>Pathogenic biological agents</td>
</tr>
<tr>
<td></td>
<td>iris pattern.</td>
<td>airports.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Signals due to an intruder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>Level and pressure sensors in</td>
<td>Oxygen sensor in the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>automotives.</td>
<td>exhaust gases.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inertial components for navigation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>and comfort control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Built environment</td>
<td>Temperature</td>
<td>CO₂ levels for comfort</td>
<td>Legionella in air conditioning units.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>control</td>
<td></td>
</tr>
<tr>
<td>Leisure / consumer</td>
<td>Movement for Nintendo Wii systems</td>
<td>Self-testing, e.g. alcohol</td>
<td>Testing food safety, e.g. are bacteria or toxins present?</td>
</tr>
<tr>
<td></td>
<td>Microphones for mobile phones</td>
<td>in breath.</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Examples of measurands for different application sectors
Reference to table 1, which contains only a few measurands, highlights how all pervasive sensor technology is. Considering the measurement of sound to aid hearing as an example, the specification of the sensor ranges from a relatively simple microphone for an external hearing aid to a very high specification miniaturised sensor for a cochlear implant. The cochlear implant then raises the issue of packaging for compatibility with implantation in the body and conditioning the minute electrical signals for interfacing with the host’s nervous system and finally the brain.

One of the current major biological detection challenges refers to infectious agents, e.g. bacteria such as MRSA, which may be present at very low concentrations. The presence of even a few organisms can lead to serious infection especially in immuno-compromised individuals. There is a strict EU level for *E.coli* in drinking water of less than 1cfu/100ml. Rapid and specific detection at this level requires the development of a very sensitive detection platform.

Application drivers in the development of sensors to meet current market needs include: high sensitivity and specificity, small footprint, low power and low cost. There are many opportunities in all these markets and also many important challenges to be solved in developing sensor technology.
Figures of merit for sensor technologies

In choosing a sensor or sensor technology, we must ensure that it is fit for purpose. The commonly used parameters used to specify a sensor are described in Table 2, together with some important factors to consider, together with illustrative examples showing the range of specifications required to meet a diverse range of applications.

<table>
<thead>
<tr>
<th>Sensor attribute</th>
<th>Factors to consider</th>
<th>Illustrative example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>A key initial factor to consider in determining choice of technology. The key driver behind much basic sensor development.</td>
<td>Detection of alcohol in breath at one part in 10^15. Detection of explosives via the presence of vapour at the part per trillion level (parts per 10^15).</td>
</tr>
<tr>
<td>Resolution</td>
<td>Consider combined sensor and electronics package. Signal processing is one approach to increasing resolution.</td>
<td>Identification of a certain bacteria in a wound – low resolution. Cholesterol in blood – high resolution.</td>
</tr>
<tr>
<td>Specificity</td>
<td>Are there other stimuli which could give a false positive reading.</td>
<td>Detection of low levels of bacteria in food – ensuring that other materials in the food do not give false positives.</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>Upper and lower levels of detection set dynamic range</td>
<td>Microphone for calibration of sound levels - very high dynamic range. Microphone for mobile phone use - limited dynamic range acceptable.</td>
</tr>
<tr>
<td>Speed of response</td>
<td>Insufficient speed of response will greatly limit market attractiveness</td>
<td>Detection of metal objects on an airline passenger – 1 second. PSA (prostate cancer marker) level in blood – turnaround of hours is acceptable.</td>
</tr>
<tr>
<td>Recovery time</td>
<td>Clear down time to the next measurement. Especially important in chemical and biological detection.</td>
<td>Avoid carry over – often leads to disposable sensors, e.g. for healthcare or forensic applications.</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>Is regular calibration needed – especially important for legislative compliance or law enforcement.</td>
<td>Key for measurement of breath alcohol for law enforcement of drink / driving levels. Glucose in blood.</td>
</tr>
<tr>
<td>Size / weight</td>
<td>Larger may be cheaper or higher specification. Portability and size are important for many emerging applications.</td>
<td>For space applications size and weight must be minimised. For automotive, weight might be less of an issue.</td>
</tr>
<tr>
<td>Lifetime / stability</td>
<td>Is failure / replacement of a sensor viable. The sensor could be a consumable product.</td>
<td>Sensors on a spacecraft or in a remote location cannot be replaced or serviced. Failure of oxygen sensor in engine management can have a costly effect on fuel consumption.</td>
</tr>
<tr>
<td>Immunity to environment, including temperature, humidity</td>
<td>The environment must not perturb the sensor response and vice versa. Also need to consider getting the signal from the sensor to the observer.</td>
<td>High pressure in an oil well. Getting signals from an electrically noisy environment. Corrosive materials present. Sensors In the body.</td>
</tr>
<tr>
<td>Availability / IP position</td>
<td>Freedom to operate. Security of supply.</td>
<td>Is a licence required. Is the sole supplier on a critical path?</td>
</tr>
<tr>
<td>Cost</td>
<td>Increased specification almost always leads to greater cost. Although disruptive technologies and volume production can give great cost reductions.</td>
<td>MEMS technology offers cheap high specification physical sensors. The effect of emerging technologies should be continually assessed.</td>
</tr>
</tbody>
</table>

Table 2 Important figures of merit for sensors
In practice, there will often be a trade off in the sensor specification. For example, increased sensitivity often comes at the expense of increased cost and larger footprint. Performance against all of the specifications must be considered in sourcing or developing a sensor. Failure to achieve one specification can lead to the failure of the product in the commercial marketplace. Disruptive technologies may also open up a whole new market, e.g. silicon carbide offers sensor technology which operates at 600°C.

**Discussion of physical measurands**

We now move to consider the measurands in more detail, starting with physical stimuli. These range from simple measurement of core temperature of the human body to 3 axis measurement of acceleration and rotation of a moving object. Some physical measurands together with examples of their applications are given in table 3.

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Examples of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Controlling efficiency of industrial processes. Human body core temperature</td>
</tr>
<tr>
<td>Position</td>
<td>Control of a catheter or surgical tool in the body.</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Crash sensor in an airbag. Movement of limbs in assistive living or for orthotics.</td>
</tr>
<tr>
<td>Pressure</td>
<td>Blood pressure, pressure in an artery during angioplasty, tyre pressure, pressure in an oil well.</td>
</tr>
<tr>
<td>Strain / bending</td>
<td>Flexing of an aircraft wing or bridge.</td>
</tr>
<tr>
<td>Rotation, orientation</td>
<td>Stability control system for an automotive. In an inertial navigation system.</td>
</tr>
<tr>
<td>Mass / density</td>
<td>Density of a liquid for industrial process control</td>
</tr>
<tr>
<td>Torque</td>
<td>Any rotating system: drilling for oil, helicopter operations, steering systems.</td>
</tr>
<tr>
<td>Flow and level</td>
<td>Level sensors in fuel and other tanks. Gas flow in industrial process control; air flow around wind turbines for optimum efficiency.</td>
</tr>
<tr>
<td>Electric fields / potential</td>
<td>RFID tags; ECG for pacemakers; EEG –measurement of brain activity</td>
</tr>
<tr>
<td>Optical radiation</td>
<td>To measure light levels, to analyse spectral distribution of light.</td>
</tr>
<tr>
<td>Electromagnetic radiation</td>
<td>From x-ray for medical imaging to thermal imaging for ‘seeing in the dark’.</td>
</tr>
<tr>
<td>Magnetic fields</td>
<td>For navigation, correction of compass readings near to metal objects.</td>
</tr>
<tr>
<td>Shape/ roughness</td>
<td>Biometric imaging of the face for access control.</td>
</tr>
<tr>
<td>Viscosity</td>
<td>Process control.</td>
</tr>
<tr>
<td>Optical properties</td>
<td>Refractive index for process control. To measure stress via birefringence.</td>
</tr>
</tbody>
</table>

Table 3 Some important physical measurands

The challenge for the sensor designer and manufacturer is to develop a product to sense one or more of these measurands which also meets the specifications described in Table 2. The output of the sensor should be in a useful form, often an electrical output.
Discussion of chemical measurands

We define a chemical measurand as a substance with a distinct molecular composition that is produced by or used in a chemical process. Chemical measurands of importance to the commercial market tend to be small molecules, e.g. less than ~ 200 mass units. In contrast, biological compounds and entities are generally much larger molecules or complete micro-organisms. Some important classes of chemical measurand together with examples are given in table 4.

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour – high concentrations</td>
<td>Oxygen in car exhaust for engine management. Concentrations of gases in anaesthesia. Environmental pollutants, e.g. H₂S, NO, NO₂, SO₄ in factory exhausts. Alcohol in breath.</td>
</tr>
<tr>
<td>Vapour – low concentrations</td>
<td>Explosives for security applications. Toxic industrial chemicals, e.g. HCN. Volatile organic compounds, e.g. in emission from industrial processes. Chemical warfare agents: e.g. nerve agents such as sarin.</td>
</tr>
<tr>
<td>Organic molecules in solution</td>
<td>Pesticides e.g. organophosphates Glucose level in blood</td>
</tr>
<tr>
<td>Gases in solutions</td>
<td>Blood gases for medical diagnosis, e.g. in intensive care. Oxygen in solution for process control.</td>
</tr>
<tr>
<td>Ionic chemicals in solution</td>
<td>pH – important for the efficiency of many processes. Heavy metals, e.g. Cd, in the food chain or marine environment.</td>
</tr>
<tr>
<td>Solids</td>
<td>Small particulates of explosives or drugs at airports.</td>
</tr>
</tbody>
</table>

Table 4 Important classes of chemical measurands together with examples.

The quantification of chemical measurands offers an additional level of complexity in comparison to physical quantities. For example, specificity of detection may now be key as some compounds will be present at very low levels (e.g. sub parts per billion) in the presence of other compounds at considerably higher levels. A poorly designed sensor with insufficient specificity might give a false positive reading.
Discussion of biological measurands

We define a biological measurand as relating to, caused by, or affecting life or living organisms. We also include the organisms themselves as a biological measurand.

Biological measurands are thus very large molecules or complete micro-organisms. For example the enzyme, glucose oxidase, involved in catalysing the oxidation of glucose, has a molecular weight of 160,000 atomic mass units. This contrasts with chemical measurands which are much smaller molecules. Some classes of biological measurands are listed in table 5 to illustrate the wide range of materials for which a sensor might be required.

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enzymes</td>
<td>Biology’s catalyst</td>
<td>Glucose oxidase – catalyses oxidation of glucose. Salivary amylase – key in digestion</td>
</tr>
<tr>
<td>Hormones</td>
<td>Messenger compound</td>
<td>HCG - pregnancy testing. Insulin – important in diabetes</td>
</tr>
<tr>
<td>Viruses</td>
<td>A virus is a small infectious agent that can replicate only inside the living cells of organisms</td>
<td>Norovirus – gastroenteritis Human papilloma virus – important in cervical cancer</td>
</tr>
<tr>
<td>Bacteria</td>
<td>Microscopic single celled organism. Some produce infectious disease. Some are beneficial, e.g. bacteria in the gut.</td>
<td>Food spoilage Infections, sepsis in healthcare Biological weapons Legionella in air conditioning systems.</td>
</tr>
<tr>
<td>Proteins</td>
<td>Linear polymer built from amino acids. The sequence controls the structure and function.</td>
<td>Antibodies which bind targets with high specificity. Prostate specific antigen – a marker for prostate cancer.</td>
</tr>
<tr>
<td>Nucleic acids</td>
<td>Contain the genetic information for all cellular functions.</td>
<td>Identification of individuals, e.g. forensic / paternity. Presence of genetically modified organisms (GMOs). Identification of presence of a particular strain of bacteria.</td>
</tr>
</tbody>
</table>

Table 5 Some important biological measurands

One of the major current drivers to develop methods for the detection of biological material is for the healthcare market. Applications include:

- Diagnosis of disease and monitoring the efficacy of therapy.
- Diagnosis of infection, including sepsis, and selecting suitable antibiotics.
- Wound assessment and monitoring the efficacy of treatment.
- Personalised medicine, stratified medicine.
- Toxicity testing of potential new drug compounds for the pharmaceutical market.
- Development of low cost point of care diagnosis systems for developing nations.
SENSOR SYSTEMS

We define a sensor system as

‘an integration of sensors and other enabling technology to gather, process, and present information for action from sensed data’.

We now consider the development of sensor systems for the gamut of measurands that we described in the previous sections. We will approach this in two stages:

- Firstly, we describe the basic principles which underpin some of the principal detection methodologies.
- Secondly, we will describe some of the current and emerging technologies which turn these basic detection methodologies into practical sensors and sensor systems.

Sensors for physical measurands

The function of a sensor is to ‘give a useful output in response to the stimulus of the measurand’. In many cases, the preferred output is electrical. Figure 1 shows the overall concept of a sensor in which an electrical output is obtained. Reading the figure from left to right: stimulus by the measurand M produces a response R via the primary transduction mechanism. In some cases, the primary transduction mechanism gives an electrical output, e.g. the bending of a piezoelectric material produces a voltage across the material, which may be used as a direct read out of the bending.

![Figure 1 Sensor operation: the input stimulus is the measurand (M) and the output from the sensor is the signal S, here shown as a voltage.](image)
In many cases, the primary transduction mechanism gives a non-electrical response. In this case a secondary transduction mechanism is needed to transform the intermediate signal, R, into the electrical domain, S. An example of a non-electrical response would be the deflection of a thin membrane caused by a change of pressure or in response to an acoustic signal. A secondary transduction mechanism could be achieved by making the membrane one electrode of a parallel plate capacitor and measuring the changes in capacitance (see figure 2). Such an approach is used in the miniature microphones used in the newest generation of mobile phones.

It is important to choose appropriate primary and secondary transduction mechanisms to give the required performance and to avoid interferences caused by other stimuli that might be present, for example in a noisy or high temperature environment.

Some of the many primary transduction mechanisms used in sensors are given in table 6. A more complete description of primary transduction principles is given in 1.

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Primary Transduction (R)</th>
<th>Conversion from R to V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement / pressure</td>
<td>A beam or membrane moves - the basis of many sensors.</td>
<td>Piezoelectric material. Moving element is made one element of a capacitor.</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>Voltage generated by Hall effect in a semiconductor.</td>
<td>Gives V directly via high impedance voltmeter.</td>
</tr>
<tr>
<td>Electrical fields</td>
<td>Optical properties change via the Kerr effect ($E^2$).</td>
<td>Rotation of plane of polarisation. Measured using optical system with a light source, an optical detector and polarisers.</td>
</tr>
<tr>
<td>Temperature</td>
<td>Peltier / thermoelectric effect. Bimetallic strip bending.</td>
<td>A thermocouple generates a voltage output. The bending of the bimetallic strip could be read out optically.</td>
</tr>
</tbody>
</table>

Table 6 Some physical effects used as the transduction processes in physical sensors

**Sensors for chemical measurands**

The general approach to the measurement of chemical measurands is similar to that for physical measurands described in figure 1. However, the primary transduction element must also now have the element of chemical selectivity. Approaches that can be adopted to achieve chemical selectivity include:

- Those based on the intrinsic properties of the compound, e.g. a spectroscopic signature (infra-red absorption, fluorescence, Raman) or more sophisticated techniques such as mass spectrometry.

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Those based on a specific chemical interaction; these range from the specific interaction of a compound with an enzyme or the less specific interaction of a chemical vapour with the surface of a heated doped semiconducting material.

Some of the approaches adopted to implement these approaches to chemical selectivity are summarised in table 7 for a range of chemical analytes.

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Transduction mechanism</th>
<th>Selective element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour – high concentrations</td>
<td>Conduction of semiconductor, e.g. SnO₂, ZnO</td>
<td>Dopants in the semiconductor, temperature of operation.</td>
</tr>
<tr>
<td></td>
<td>Pellistor - vapour combusts on a hot surface to release heat which raises the temperature. This changes the resistance of a temperature sensitive element.</td>
<td>The sensor only responds to the presence of combustible gases.</td>
</tr>
<tr>
<td></td>
<td>Resistance of polymeric semiconductors (chemiresistors)</td>
<td>Chemical groups in the polymer, dopants, temperature of operation.</td>
</tr>
<tr>
<td></td>
<td>Absorption of infra-red radiation.</td>
<td>Specific wavelengths correspond to particular chemical bonds.</td>
</tr>
<tr>
<td>Vapour – low concentrations</td>
<td>Ionise the gas and measure the resulting ion current</td>
<td>Mass filter, e.g. quadrupole mass filter.</td>
</tr>
<tr>
<td></td>
<td>Quenching of fluorescence of a polymer</td>
<td>Gas chromatograph before the mass filter.</td>
</tr>
<tr>
<td></td>
<td>Change in resonant frequency, e.g. of a surface acoustic wave device.</td>
<td>Chemical groups in the polymer are tailored to interact with the target.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The analyte binds to chemoselective polymers. An array of such sensors with a range of polymer coatings is an ‘electronic nose’.</td>
</tr>
<tr>
<td>Organic molecules in solution</td>
<td>Fluorescence signature</td>
<td>Selection of excitation and detection wavelengths.</td>
</tr>
<tr>
<td></td>
<td>Electrochemical</td>
<td>Enzymes react specifically with the target to produce electrochemically detectable products, e.g. glucose oxidase. Choice of electrode materials and the potential of the electrodes.</td>
</tr>
<tr>
<td>Gases in solution</td>
<td>Electrochemical</td>
<td>Choice of electrode materials and setting the potentials on the electrodes for selectivity. Selective membranes are added to the electrode surface.</td>
</tr>
<tr>
<td>Ions in solution, e.g. heavy metals</td>
<td>Electrochemical</td>
<td>Choice of electrode material and potentials.</td>
</tr>
<tr>
<td></td>
<td>Colourimetric</td>
<td>Reaction of the ions with a dye leads to a colour change – detection can then be by absorption spectroscopy.</td>
</tr>
<tr>
<td>Solids</td>
<td>Fluorescence</td>
<td>Selection of excitation and detection wavelengths.</td>
</tr>
<tr>
<td></td>
<td>Infra red, Raman spectroscopy</td>
<td>Specific wavelengths correspond to specific chemical bonds.</td>
</tr>
</tbody>
</table>

Table 7 Some fundamental processes used as the transduction mechanism for chemical detection
Sensors for biological measurands

Biological measurands are very diverse in nature and include:
- Living micro-organisms such as yeasts, bacteria and viruses.
- Large biological molecules., e.g. DNA, antibodies, proteins.

It is becoming increasingly important to quantify the presence of such biological entities for a wide range of application sectors. Many of these requirements are driven by legislation, e.g. the Water Framework Directive\(^2\) and the need to improve services and save money, e.g. in the treatment of patients in the NHS. A number of sensing methodologies have evolved for detecting these bio-entities:

i) Detecting the complete entity, e.g. a complete bacterium or hormone.

ii) Detecting the presence of some specific characteristic of the entity. This could be either chemical, e.g. a DNA sequence which characterises the species or some physical characteristic, e.g. an optical spectrum, of the entity.

A number of technologies have been developed to implement these two sensing methodologies. Two of the most important are:

- Biosensors: these exploit receptors, e.g. antibodies, which interact with the species of interest with high specificity. The analyte – receptor interaction is then measured via a transducer.
- Measurement of the physical properties which characterise the target, e.g.
  - Optical response, e.g. infra-red or Raman spectrum or fluorescence.
  - Electrical properties, e.g. frequency dependent dielectric properties.

Miniaturisation also offers the possibility of complete portable detection systems which use the alternative approach of carrying out many of the operations traditionally carried out in a laboratory in a complete portable micro-system. These are often grouped together under the epithet: ‘Lab on a chip’ or more correctly: a ‘micro total analysis system’ as proposed by Andreas Manz.

IMPORTANT CURRENT AND EMERGING TECHNOLOGIES FOR SENSORS

Many methods of transforming a measurand into an electrical signal have been developed leading to a wide range of products which are now available commercially. However, over the last decade, a number of disruptive technologies have either been developed or are now emerging into the market place. These advances in sensors are themselves built on significant advances in the underpinning enabling technologies, e.g.

- Microfabrication techniques allowing the control of critical dimensions from millimetres down to nanometres\(^3\).
- New materials to form the basis of transducers and also for use in other parts of the value chain such as packaging.
- The availability of small highly sophisticated signal conditioning and signal processing chips, e.g. as bespoke Application Specific Integrated Circuits (ASICS).
- Significant steps forward in communications, e.g. wireless and optical techniques together with efficient energy generation and energy storage technologies.

Some of the major sensor technologies and emerging potentially disruptive technologies are now described in more detail. General descriptions of these technologies can be found in the CRC series edited by Richard C Dorf\(^4\).

**MicroElectroMechanical Systems (MEMS)**

MicroElectroMechanical Systems\(^5\), referred to as MEMS, offers sensors for most of the physical measurands, e.g. pressure, sound, magnetic fields and acceleration. The size of the bare sensor dye is of order millimetres with critical feature sizes of order one micron.

MEMS technology has emerged from the technology used to manufacture silicon Integrated Circuits. The starting point is a silicon wafer, typically of diameter 20 cm. The use of IC technology allows sophisticated three dimensional structures to be fashioned to tolerances of a few nanometres in the silicon and also in a wide range of other materials such as metals for electrodes and insulating dielectric materials which may be deposited, in thin film form, onto the silicon wafer. These techniques allow the manufacture of free standing beams and membranes which move in response to physical measurands. The movement of these structures is then read out by a variety of techniques, e.g. through the changing capacitance read out via electrodes integrated into the structures (see figure 2).

As an example of MEMS technology, figure 2 shows a cross section (schematic) through a microphone manufactured using MEMS technology. At the heart of the device is a thin free standing membrane, of thickness order one micron, which moves in response to pressure changes generated by an incident sound wave. On one side of this membrane is a conducting electrode which is close

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\(^3\) Fundamentals of microfabrication and nanotechnology Marc J Madou (2011).

\(^4\) E.g. The electrical engineering handbook, 3rd edition, ed. R.C Dorf (2006), published CRC.

(within a few microns) to a second fixed electrode. The capacitance, $C$, measured between the two electrodes varies in response to the changing distance, $d$, between the two electrodes as the lower membrane moves, thereby giving a direct readout of the sound signal.

$$\text{Capacitance } C = \frac{k}{d}$$

**Transduction method: measure capacitance (C)**

Figure 2 MEMS microphone (schematic)

Signal conditioning electronics can be integrated with the sensors either as a hybrid, e.g. with an ASIC chip, or by monolithically manufacturing the circuitry in the silicon substrate on which the MEMS structure is made.

The production of such a microstructure involves great skill in (i) the design of the structure to give a flat response over the desired frequency range and (ii) controlling material properties such as stress. If the structure was to be scaled into the macro-domain – it would equate to two parallel plates of diameter one metre separated by a gap of just one millimetre.

Microphones similar to those shown in figure 2 are now to be found in a range of mobile phones, e.g. the current Apple iPhone4 model.

By exploiting the ability to make sophisticated structures such as these, MEMS technology offers a very wide range of sensors for physical measurands, e.g. accelerometers, gyroscopes, magnetometers, microphones and ultrasound sensors. It is now also possible to make more than one type of sensor on the same MEMS chip, e.g. accelerometers and gyroscopes integrated with magnetometers.

Major applications of MEMS currently in commercial products include:

- Accelerometers and gyroscopes in crash sensors and control systems in the automotive industry.
- Pressure sensors for oil pressure measurements, blood pressure monitors, and emerging applications such as measuring the pressure in an artery during angioplasty.
- Microphones and three axis accelerometers in mobile phones.
• In the leisure market to measure movement, e.g. for Nintendo Wii systems and to stabilise camera movements.

MEMS devices based on materials other than silicon are being developed to meet a range of technical challenges and market sectors, e.g.

• Diamond or silicon carbide MEMS for high temperature applications
• Polymer MEMS to give cheaper structures to be used as consumables in medical diagnostic systems.

**Bio-MicroElectroMechanical Systems - BioMEMS**

Initially the major applications of MEMS have been the measurement of physical quantities, often in engineering environments. In recent years, MEMS technology has found increasing applications in the life sciences. This has led to the adoption of a new term of BioMEMS. BioMEMS includes:

• the integration of MEMS with living systems, e.g. in-situ measurement of pressure in the body or the use of MEMS actuators for microsurgical procedures.
• the use of biological entities within physical MEMS structures, e.g. the use of receptors such as antibodies or living cells on a MEMS chip.

To address the wider range of applications covered by BioMEMS, new materials have been added to the manufacturing process such as hydrogels, biocompatible polymers and nanomaterials such as quantum dots.

This powerful combination of technologies and materials when combined with electronics and signal processing is spawning a whole range of new sensing systems which themselves are forming complete new fields of technology. These include:

• A whole new range of bio-sensors with improved performance which can potentially be mass produced at low cost.
• Lab on a Chip devices: here the analytical processes carried out in a sophisticated laboratory are condensed into a complete microsystem. These range from the commercially available pregnancy test devices to systems to detect low copy numbers of biological agents within twenty minutes.

**Semiconductor based sensors**

Semiconductors have a range of interesting properties, in particular their conductivity. The silicon integrated circuit industry is based on the fact that the application of an electric field can switch a thin layer of silicon material from a conducting (‘1’) state to a non-conducting (‘0’) one.

In sensor systems, this variable conductivity is influenced by an externally applied physical stimulus, i.e. the measurand. By exploiting this effect, semiconductors offer a wide range of possible sensing methodologies, for example:

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Silicon as a magnetic field sensor, via the Hall and magneto-resistance effects. Resonant MEMS structures for measurement of magnetic fields are also available. The technologies cover the range from below the earth’s magnetic field \((10^{-4}\) T\) to fields in an MRI scanner \((10T)\). Integrated devices are now available combining three axis accelerometers with three axis gyroscopes and a three axis magnetometer built in silicon technology.

Silicon as the basis of a photodiode: incident light is absorbed and creates electron hole-pairs which can be detected as photocurrents. Detection at the single photon level is now achievable, e.g. via silicon single photon avalanche diodes (SPADs).

Charge coupled devices (CCD) arrays are also made using silicon technology and can give capture of 2D images at low light levels, especially when the devices are cooled.

Metal oxide semiconductors, e.g. Taguchi sensors based on tin oxide, have a conductivity which varies in the presence of certain volatile compounds.

**Gas sensors**

The detection of gases is a challenge which pervades all market sectors. To address these requirements, many sensor technologies have evolved. These range from a simple humidity sensor with the analyte (i.e. water vapour) present at the percentage level to a sophisticated system to detect illicit substances such as explosives and drugs whose volatile signature may be present at the parts per trillion level.

There are a number of gas sensor techniques used but the main markets for industrial gas sensors are covered by the following four technologies – electrochemical, semiconductor, catalytic and non-dispersive infrared.

- **Electrochemical**: the sensor has catalyst coated electrodes, an electrolyte and a membrane. Gas diffuses through the membrane and reacts at the electrolyte-catalyst interface to create a current. The current produced is calibrated for the gas concentration. Such sensors are typically used to measure oxygen, carbon monoxide, nitrogen dioxide, nitric oxide and hydrogen sulphide.

- **A semiconductor or metal oxide**\(^7\) sensor has semiconducting material applied to a substrate between two electrodes. Heating the substrate causes the semiconducting material to change electrical resistance in the presence of the target gas which is adsorbed onto the metal oxide surface. The measured resistance is related to the gas concentration. The semiconductor is doped and the temperature of operation is chosen to enhance the sensitivity and specificity for the target. Catalysts are also added to the surface of the semiconductor to improve sensitivity and specificity, e.g. a platinum catalyst increases the sensitivity to hydrogen containing compounds.

- **A catalytic or pellistor** sensor works by burning combustible gases on a small heated bead. The released heat of combustion gives an increase in the temperature and thereby the

resistance of the bead. The resulting increase in resistance is measured and correlated to gas concentration – usually percentage of lower explosive limit %LEL. Typically used for flammable gases.

- **Non-dispersive infrared** sensors measure the absorbance of infrared radiation after passing through a short path length of the gas. This is a non-contact method and is typically used for carbon dioxide and increasingly methane and other flammable gases. Unlike catalytic sensors it is fail safe.

Some of the other important technologies available include:

- Chemiresistors\(^8\) are also based on the changing conductivity of a semiconductor, other than metal oxides. The semiconductor is often an organic polymer and may be deposited between interdigitated electrodes. The metallic contacts are varied to optimise sensitivity and specificity. As an example, phthalocyanine is a p-type semiconductor which interacts with compounds such as NO\(_2\), NH\(_3\) and Cl\(_2\).
- Capacitors may also be made with polymers as the dielectric whose properties vary when the target interacts with it. Such sensors are available for humidity sensing. More exotic polymers such as fluoroalcohol poly(siloxane), SXFA, facilitate the detection of some organophosphate targets.

### Electrochemical sensors

Electrochemical approaches offer specificity of detection combined with a method of transducing the signal into the electrical domain. Sensors can be (i) amperometric (current), e.g. the Clark electrode to measure dissolved oxygen\(^9\) (ii) potentiometric (voltage changes), e.g. the pH electrode or (iii) coulombic (charge) in their approach, e.g. to determine the amount of material deposited during an electroplating process.

For detection of a gas, selectivity is achieved by careful selection of the electrolyte and the sensing electrode material. A gas permeable hydrophobic membrane might also be incorporated into the sensing electrode – this allows the gaseous analyte to reach the sensing electrode. One interesting sensor is the micro fuel cell as this does not require an external driving potential. Such devices are available to measure organic vapours such as ethanol for law enforcement of drink / driving regulations.

Measurands, together with typical working ranges, for which electrochemical sensors are available include: ammonia (10ppm), carbon monoxide (300 ppm), hydrogen (2000 ppm), NO (100 ppm), NO\(_2\) (50 ppm), O\(_2\) (1 ppm to 100%), SO\(_2\) (100 ppm).

Recent advances in microfabrication techniques and materials are allowing the volume production of cheap miniaturised sensors. At the same time, advances in electronics are facilitating the production of hand held units which can simultaneously provide the readout from several sensors.

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\(^8\) Chemiresistors based on conducting polymers: a review on measurement techniques, U Lange and V Mirsky, Analytica Chimica Acta, **687**, 105 (2011).

The addition of recognition agents to an electrochemical sensor offers specific detection in a simple format. As an example, in the blood glucose sensor\textsuperscript{10}, the enzyme glucose oxidase specifically catalyses the oxidation of glucose to produce hydrogen peroxide which is then detected electrochemically.

**Fibre optic sensors**

The recent rapid growth of optic fibres as a component in sensors systems is in great part due to the development of the underpinning technology for the telecommunications industry. Thus, components such as single and multimode fibres, fibre coupled lasers and detectors and optical components such as splitters and wavelength demultiplexers are now readily available to a high specification and at an affordable cost.

Fibre optic technology is impacting sensor systems in three major ways:

- Optic fibres can be used to collect data from a remote location, e.g. from the bottom of an oil well or from within the structure of an aircraft wing or a bridge. This is particularly useful in electrically noisy environments or where the use of electrical signals might be a safety hazard, e.g. a possible risk of explosion. Power can also be routed to remote sensors via an optical link.
- Optical fibres can be used for distributed sensing in complex and remote locations. For example in the oil and gas industry, the technology is used for distributed temperature sensing. Temperature, strain and sound levels can be measured to metre accuracy.
- The optic fibre is itself part of an optically based sensor. Examples include:
  - Spectroscopic systems which use optical excitation or collection of optical radiation.
  - Systems incorporating materials whose optical properties change in the presence of the analyte; for example the fibre could be coated with a dye material whose fluorescence or absorption spectrum is sensitive to a measurand such as pH.
  - A sensor component can also be built directly into an optical fibre. Examples include fibre Bragg gratings whose optical signature changes when the fibre bends.
  - Bio-receptors, e.g. antibodies, may be grafted to the surface of an optic fibre. The binding of the analyte can then be interrogated via the fibre which provides efficient excitation and collection of fluorescence. Such an approach can be very sensitive\textsuperscript{11} and addresses the challenge of detection of species in optically opaque media.

There is a very wide range of applications and sectors to which fibre optic technology is being applied. Examples include:

- Imaging endoscopes for medical applications; the fibres can then also be used to deliver high powered optical radiation, e.g. to a tumour, for therapeutic applications.
- Sensors for non-destructive evaluation of structures, e.g. the measurement of stresses within cracks.


Sensors can be embedded within an optic fibre which encircles an area to be protected from intruders, for example a runway at an airport. The sensors may be distributed along the fibre to respond to acoustic or seismic stimuli. In addition, the location of the source of the intrusion can also be determined from a central location. There are a number of products on the market which offer perimeter protection and also protection for infrastructure such as oil pipelines and data communications networks.

**Biosensors**

The concept of a biosensor is described in figure 3. The sensor consists of three distinct components:

(i) a receptor which has a sensitive and specific interaction with the target analyte,
(ii) a transducer by which the specific interaction of the target with the receptor is detected and quantified
(iii) an interface layer to attach the receptor to the transducer.

![Figure 3: The key elements of a biosensor: receptor, transducer and linker layer to join the receptors to the transducer.](image)

Some of the receptors which are currently in use and also receptors under development are listed in Table 8, those most commonly in use being antibodies and enzymes. New receptors are now being engineered, e.g. aptamers and molecularly imprinted polymers. Molecularly imprinted polymers incorporate cavities with a shape which matches that of the target analyte. Aptamers are strands of nucleic acids which are selected to form into a molecular structure which interacts strongly with the analyte. Aptamers offer the potential for receptors with a higher stability than the commonly used antibodies.

<table>
<thead>
<tr>
<th>Receptor</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antibodies</td>
<td>Proteins about 7nm in size produced by the immune system to recognise the entity of interest with very high specificity and affinity. Commercially available for a wide range of analytes, e.g. bacteria, viruses, and large molecules.</td>
</tr>
</tbody>
</table>
### Table 8 Principal receptors used in biosensors

<table>
<thead>
<tr>
<th>Receptor Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aptamers</td>
<td>Nucleic acid or peptide molecules developed specifically for the analyte. An emerging technology possibly offering higher stability than antibodies.</td>
</tr>
<tr>
<td>DNA chains of specific sequence</td>
<td>The DNA sequence is engineered to be complimentary to the target sequence. Also available in array format with many microspots corresponding to different DNA sequences.</td>
</tr>
<tr>
<td>Molecularly imprinted polymers</td>
<td>A polymer with small cavities of similar shape to that of the target.</td>
</tr>
<tr>
<td>Enzymes</td>
<td>Enzymes act specifically to enhance rates of reaction. Enzymes are chosen to convert the target to a further material that can then be detected. For example, glucose oxidase catalyses the oxidation of glucose to products which include hydrogen peroxide which can be sensed electrochemically.</td>
</tr>
</tbody>
</table>

The second component of a biosensor is the transducer which converts the specific interaction of the measurand with the receptor into an electrical signal. A very wide range of transduction methods have been reported in the scientific literature and have been converted into commercial products in working biosensors. Some of the principal transduction mechanisms are listed below in table 9:

<table>
<thead>
<tr>
<th>Transduction mechanism</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical changes: surface plasmon resonance</td>
<td>Surface plasmon resonance gives a label free sensor, e.g. Biacore systems.</td>
</tr>
<tr>
<td>Mechanical changes.</td>
<td>Receptors can be attached to MEMS structures, e.g. a micro-cantilever beam whose bending can be read out electrically or optically.</td>
</tr>
<tr>
<td>Optical changes: fluorescence excited on the surface of the biosensor.</td>
<td>Fluorophores become bound to the surface in the presence of the target. These are then detected optically. This is one of the most sensitive transduction approaches.</td>
</tr>
<tr>
<td>Mass changes: directly detect the additional mass of the target analyte binding to the receptor</td>
<td>A shift in the resonant frequency of (i) a quartz crystal microbalance or (ii) a surface acoustic wave device. Arrays of SAW devices produce a ‘nose’.</td>
</tr>
<tr>
<td>Electrochemical, e.g. the detection of products of the reaction between the analyte and receptor</td>
<td>Enzymes are available for some analytes which give products which can be detected electrochemically, e.g. glucose oxidase. Horse radish peroxidase is also widely used in electrochemically based assays.</td>
</tr>
<tr>
<td>Optical changes: analytes on the surface have greatly enhanced optical properties.</td>
<td>Binding to silver or gold nanoparticles can greatly enhance Raman scattering (SERS).</td>
</tr>
<tr>
<td>Electrochemical, change in impedance.</td>
<td>Electrochemical impedance spectroscopy (EIS) measures the frequency dependent impedance of the surface layer. Field effect transistors are also used as transducers, receptors being bound to a floating gate.</td>
</tr>
</tbody>
</table>

Table 9 Examples of transduction mechanisms used in the detection of biological measurands
THE SENSOR VALUE CHAINS

The value chain for physical measurands

Although at the heart of many systems, the actual bare sensor often forms only a small part of the overall product. Figure 4 shows an overall system concept in which a sensor is combined with signal processing electronics to firstly condition the signal and secondly to perform any appropriate signal processing to extract the important information from associated noise.

![Figure 4](image)

Figure 4 The components of a smart sensor include packaging and signal conditioning electronics. Communications with the sensor and supply of power to the sensor are also essential.

The sensor and electronics must be packaged appropriately to allow the sensor to interact with the measurand whilst at the same time protecting the sensor from the environment. The packaging is an often over-looked activity during the development of a new sensor technology. However, it is often the most expensive and difficult part of the development of a new sensor product. Particularly difficult environments for the package include: corrosive environments, high temperature and pressure, electrically noisy environments and within living systems such as implanted into the human body. The latter is a very complex challenge as the immune system will respond by taking action to reject a foreign body.

Power must be applied to the sensor and electronics and the signal collected for readout or for use in deciding on a course of action to be taken. Communication to remote or noisy environments can be challenging. Emerging wireless and optical communications techniques are now significant enabling technologies as they extend the range of applications of sensor technology into new applications and markets. High energy density batteries, photovoltaics and energy scavenging technologies are also significantly extending areas in which sensors can operate.
Considering the concept of a packaged sensor together with electronics and communications leads to the concept of a hierarchical value chain for sensor products as described in figure 5. This value chain starts with the bare sensor and ends up with a complete system such as a medical device or point of care diagnostic system or with a complete sub-system such as an inertial navigation or guidance unit. The complexity increases as the value chain is accessed (top to bottom in figure 5). In return, the market price of the associated product increases significantly. For example, a MEMS motion sensor will sell for less than £1 while a level sensor or flow rate logging system sells for ~£500.
I. At the heart of the value chain is the bare, unpackaged sensor. For example, an accelerometer, a pressure sensor, a screen printed glucose biosensor or electrodes to measure electrical potential.

II. The sensor must then be packaged for the application. This is a skilled operation and there are companies dedicated to packaging. For example, the pressure sensor might be used in an oil well or the electrodes implanted in the body as part of a pacemaker system. Several sensors could also be combined in one package, e.g. a three axis accelerometer and a magnetometer.

III. The addition of signal conditioning electronics converts the output from the transducer into a useful form, for example converting from the analogue to digital domain or removing noise. Application Specific Integrated Circuits (ASICs) are designed and then manufactured at a foundry.

IV. At this point the readout from the sensor could be displayed for use by an operator in a stand-alone system. Such instruments range from blood glucose and blood pressure monitors to pressure sensors integrated into an automotive tyre.

V. Moving further up the value chain, several sensors may be combined in one package, together with appropriate electronics, and communications interface to produce a complete sub-system which may then itself form a key part of a higher value system. For example, a complete inertial navigation system could then form part of a variety of systems ranging from a transportation vehicle through to guided munitions.
The value chain for chemical and biological measurands

For many chemical and biological measurands, the raw sample often cannot be directly applied to the sensor. For example, a sample of soft cheese cannot be directly applied to a biosensor to look for the presence of listeria. It might also be essential to increase the concentration of a target analyte to bring it into the dynamic range of the sensor (pre-concentration).

The concept of sample preparation and presenting the sample to the sensor in the appropriate form will thus be paramount in the development of many chemical and biological sensor systems. Figure 6 describes schematically a complete integrated detection system which incorporates the elements of sample collection, sample pre-treatment together with the sensor element itself. In addition, physical elements are needed to control the flow of the sample and other reagents e.g. pumps and valves.

In figure 6, the sample pre-treatment unit is here shown removing a contaminant (the solid blue circles) which might otherwise cause a false positive detection event or foul the surface of the sensor. Other sample preparation tasks include dimensional filters to remove large particles, lysis of cells to release DNA for subsequent analysis on a biosensor and pre-concentration of the target measurand.

In developing a product to analyse difficult samples, it is essential to consider all aspects of this integrated system to ensure a competitive product which deals with real world samples. There are now many companies and research groups developing complete Micro Total Analysis Systems (microTAS) or ‘lab on a chip’ systems.
Figure 6 Complete chemical / biological integrated micro total analysis system (μTAS)
PART II – APPLICATIONS AND MARKETS

THE SENSORS MARKET

Sensor technology enables so much of modern life that we take for granted. Cars are crammed with sensors controlling everything from airbag deployment and anti-lock breaking to catalytic converters. Without sensors jet turbine engines would not be able to be tested and flown. Sensor technology underpins much medical diagnosis. Sensing is becoming increasingly important for energy companies working in extreme undersea environments.

Moreover the future will see a move to more ubiquitous sensing as man’s need to better manage resources and optimise processes increases. Sensing and communication by everyday smart devices will enable the so-called Internet of Things. Smart cities will be fully sensored up to maximise the interaction between the infrastructure, the services and the people. Body sensor networks and point of care diagnostic devices have the potential to revolutionise healthcare outside of the acute health trusts. Assisted Living will be enabled by sensing technology embedded in buildings. The possibilities are endless and illustrate just how important sensor technology is to man.

The market for sensors is particularly fragmented and sometimes difficult to bound by definitions. What follows though is a number of market size estimates from a variety of sources. These may vary depending on source and views on future growth but overall are highly indicative of the significant growth markets, regions and technologies.

In some work published in 2009 the Sensors & Instrumentation KTN published the following overall market size data:

<table>
<thead>
<tr>
<th></th>
<th>Sensors Market</th>
<th>Instrumentation Market</th>
<th>Underpinned business</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UK</strong></td>
<td>£3bn</td>
<td>£7.5bn</td>
<td>£120bn</td>
</tr>
<tr>
<td><strong>Europe</strong></td>
<td>£16bn</td>
<td>£43bn</td>
<td>£290bn</td>
</tr>
<tr>
<td><strong>World</strong></td>
<td>£50bn</td>
<td>£124.5bn</td>
<td>£1,500bn</td>
</tr>
</tbody>
</table>

Table 10 Overall market data for sensors, instrumentation and underpinned business

The UK punches significantly above its weight, with a £3bn share of sensors and £7.5bn share of the instrumentation business, despite the fragmented supply chains and foreign ownership of larger companies. This 6-7% of world sensors market is confirmed in a range of other studies.

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12 Research carried out by the old Sensors and Instrumentation KTN in 2009 and based on a variety of sources, including the UK Statistics Authority and the German / Continental Association for Sensors Technology (AMA).
According to research by Frost & Sullivan\textsuperscript{13}, the worldwide sensors component market is estimated to grow from a 2009 global value of $44bn to $69.2bn by 2013. For sensor systems, the market is estimated to be seven times that of sensor components\textsuperscript{14} and therefore looks likely to be around $490bn by 2013. The proliferation of sensors is largely driven by four key technology trends – lower cost, lower power, chip-level integration and wireless connectivity. Overall growth in the sensors market has been unaffected by the worldwide recession, with the market growing around 9% per year between 2008 and 2010, rising to 10.6% per year in 2013.

BCC\textsuperscript{15} have estimated the global market for sensors at $56.3 billion in 2010. It is expected to increase to $62.8 billion in 2011 and then to nearly $91.5 billion by 2016, at a compound annual growth rate (CAGR) of 7.8%.

Clearly, despite some variation in estimates, the sensors market is significant in its own right, enables much other industry and is growing at a healthy rate.

Information from a range of market research reports would suggest the following as the most important markets by sensor type: biosensors, flow sensors, pressure sensors, temperature sensors, imaging sensors, position & displacement sensors, level sensors, accelerometers, motion sensors, magnetic sensors and gas sensors.

In terms of growth in the markets for specific sensor types the following are experiencing growth in the 15-20% (CAGR) range: humidity sensors, torque sensors, distance sensors, acoustic sensors, pH sensors. Healthy growth rates (>10%) for biosensors and gas sensors are also noted by various analysts. Many other markets such as speed, level, motion and knock sensors are only experiencing low single figure CAGR’s.

The most important end user sectors for sensors include: automotive, chemicals & petrochemicals, medical, process control, oil & gas, aerospace, water & wastewater, food & beverages, defence, power generation, security and building automation.

The Asia Pacific region is now the world’s largest regional market (>40%) and fastest growing. The USA (approx. 30%) and Europe (approx. 25%) are only experiencing modest levels of growth.

One of the most dynamic sensor markets is that for wireless sensors. These are projected to show a Compound Annual Growth Rate of 48.5% between 2008 and 2013, although previous predictions have significantly underestimated wireless adoption rates due to large installed bases of legacy equipment and the proliferation of wireless standards\textsuperscript{16}. IDTechEx find that the market for wireless sensor networks will reach $2 billion in 2021. These figures refer to WSN defined as wireless mesh networks, i.e. self-healing and self-organising. This growth in wireless sensing is also driving predictions of explosive growth in energy harvesting technologies. IDTechEx\textsuperscript{17} are predicting a $4.4bn market (including non-WSN applications) by 2021 however ABI Research\textsuperscript{18} are only

\begin{itemize}
  \item[Frost and Sullivan, Global Sensors Outlook-2009, March 2009]
  \item[multiple estimated by Scottish Enterprise based on analogous MEMS sensor components \& systems published data and an industry validation exercise]
  \item[Sensors: Technologies and Global Markets, BCC, March 2011]
  \item[Sensing a Brighter Future, Scottish Enterprise, 2010]
  \item[Energy Harvesting and Storage for Electronic Devices 2011-2021, IDTechEx, April 2011]
  \item[Energy Harvesting for M2M Devices, ABI Research, March 2011]
\end{itemize}
predicting a $480m market by 2016.

The market for biosensors and chemical sensors\(^{19}\) is expected good growth, at a compound annual growth rate (CAGR) of 9.6% during the 5-year period from 2011 to 2016. This sector is expected to be worth $13 billion in 2011 and $21 billion in 2016.

MEMS technology has opened up many opportunities for growth in sensor markets. The MEMS sensor industry as a whole is currently very healthy, experiencing a compound annual growth rate (CAGR) of 10% in 2011 with an expected 10.5% CAGR to 2015, according to Jérémie Bouchaud of IHS iSuppli. The majority of this growth is coming from MEMS pressure sensors, accelerometers, and gyroscopes. The two top areas of growth are due to mobile & consumer electronics and automotive applications.

Medical sensing is often pointed to as an opportunity to future growth particularly if obstacles such as clinician access, clinical trials and regulatory approvals can be overcome. Frost & Sullivan\(^{20}\) finds medical sensor market revenues of $6bn in 2009 and estimate a market of $12.5bn by 2016. Berg Insight claim that the global market for home health monitoring grew to approximately €7.6 billion in 2010, driven mostly by chronic diseases such as diabetes, asthma, and cardiac arrhythmia.

Probably the biggest driver of sensor development and deployment is the automotive industry. Strategy Analytics\(^{21}\) predicts that the market for automotive sensors will rise from $12.9 billion in 2010 to $13.8 billion in 2011, a year-on year growth of 7%. The global economic recovery has triggered demand rebound for vehicles, especially in emerging markets. Additionally, planned vehicle safety, emission, and fuel economy enhancements will drive automotive sensor shipments to over 5 billion units, worth $21.9 billion in 2018. Over the period 2010 to 2015, Strategy Analytics expects automotive sensor revenues over the same period to grow by 8.4% CAGR, as carmakers respond to tightening environmental, fuel mileage, and safety legislation, as well as consumer expectations.

Gas sensing in the automotive sector looks set of growth. Strategy Analytics\(^{22}\) predicts emission and fuel economy mandates will drive deployment of a growing number of sensors, including oxygen, nitrogen oxide, cabin air quality, ammonia, and hydrogen sensing devices. They forecast that tightening emission and fuel economy mandates, including legislation in the emerging markets, could result in the annual deployment of 177 million gas sensors in the market by 2017.

Another significant driver of sensor markets is the move to smart metering. ABI Research expects advanced metering infrastructure rollouts to boost the wireless sensor networking chip market to 300% growth in 2011. Pike Research\(^{23}\) have claimed that cumulative global investment in smart water meters will total $4.2 billion during the years from 2010 to 2016, with annual market revenues reaching $856 million by the end of the period, a 110% increase over 2010 levels. By 2016 the worldwide installed base of smart water meters will reach 31.8 million units, up from 8.0 million in

\(^{19}\) Sensors: Technologies and Global Markets, BCC, March 2011
\(^{20}\) Sensors Market in Medical Applications, Frost & Sullivan, 2010
\(^{21}\) Automotive Sensor Demand Forecast 2009 to 2018: BRIC Regions Drive Deman, Strategy Analytics, 2011
\(^{22}\) Emission Sensor Mandates Boost Automotive Gas Sensors, Strategy Analytics, Dec 2010
\(^{23}\) Pike Research, Feb & Aug 2011
2010. Global installed base of all types of smart meters will reach 535 million units by 2015 and continue its robust growth reaching 963 million units by 2020.

ABI Research predict worldwide shipments of IEEE 802.15.4 wireless sensor network (WSN) chipsets into the home are forecast to exceed 242 million a year by 2015, up from just 8.5 million in 2010. With a CAGR of 74% during the same period, standardized chipsets are quickly replacing proprietary wireless offerings by driving down costs and simplifying the inclusion of short-range wireless connectivity in home devices. ON World’s recent research finds that Smart Home sensor network chipset shipments will approach 100 million worldwide in 2015, enabling nearly $6 billion in cloud services for energy and home service providers.

So overall, despite some discrepancies in reported market sizes the clear picture is one of sizeable markets with many very rapidly growing market segments and technology areas.

OPPORTUNITY AREAS FOR SENSOR TECHNOLOGIES

“If you can not measure it, you can not improve it” ...Lord Kelvin

Sensor technology is already applied across almost all sectors of the economy and is likely to become increasingly important as an enabling technology in the future. The following is a brief account of some of the most important sensing needs of a range of applications areas or sectors.

Aerospace:

- Sensors & instrumentation for on-board and test rig engine health monitoring (extreme environment, high temperature and vibration sensing)
- Airframe structural monitoring.
- Pilot information systems
- Wireless meshed sensor networks to support control of energy consumption

Healthcare:

- Point of Care tests for diagnosis of infectious diseases
- Low cost tests for long-term chronic disease management
- Monitoring for personalised healthcare
- Telehealthcare – combining diagnostics with communications
- Activity sensors for monitoring well-being in assisted living
- Body worn sensors, implantable sensors and smart pills
- High throughput systems including label-free sensing technology for drug discovery
- Sensors for pharmaceutical production process monitoring e.g. particle analysis, multiphase fluid flow monitoring

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24 Wireless Sensor Networks and Home Control, ABI Research, Q4 2010
Energy:

- Smart metering
- Sensors for control of the Smart Grid e.g. voltage, current and partial discharge sensors
- Control systems for off-shore renewable energy installations
- Embedded sensors for predictive condition monitoring of remote infrastructure often in extreme environments e.g. high temperature, pressure, undersea
- Sensors for underwater autonomous vehicles
- Corrosion monitoring
- Next generation nuclear systems require sensors for control technologies

Environment and safety:

- Gas sensing for emissions monitoring
- Water quality monitoring
- Marine spill monitoring and response
- Sensors for on-site detection and quantification of contaminated land

Automotive:

- In-vehicle safety systems e.g. pre-impact sensors, driver awareness monitoring, tyre pressure monitoring
- Driver assistance
- Vehicle to vehicle or vehicle to infrastructure systems using sensors
- Fuel mixture analysis
- Vehicle detection
- Traffic network management
- Navigation aids and collision avoidance systems
- Hydrogen safety sensors for fuel cell powered vehicles and refuelling infrastructure

Built environment:

- Structural integrity monitoring of buildings, bridges, tunnels, pipelines etc
- Smart buildings for energy efficiency – e.g. presence detection and triggering lighting, heating and ventilation

Security and Defence:

- Intruder and perimeter monitoring
- Chemical, biological, radiological, nuclear and explosives detection (especially rapid, portable and rugged for field deployment)
- Explosives detection
- Wearable sensors for monitoring vital signs of soldiers and firemen
- Biometrics
Leisure and Entertainment:

- Smart clothing
- Gaming
- Greater functionality on smart phones
- Sports performance monitoring

Agriculture and food:

- Fertiliser utilisation and land run-off monitoring
- Ripeness monitoring
- Infield detection of plant diseases – virus and fungal detection
- Early detection of pest infestation
- Sensing for post-harvest supply chain management & waste reduction e.g. in perishable goods
- Sensing to manage agricultural water usage

TRENDS IN SENSOR REQUIREMENTS

As industry moves to greater levels of sensing and control, as medical use of sensors becomes more established and as the impact on our environment demands more sensing, the specification of sensor technology becomes more demanding. This does however provide many opportunities for product differentiation and the basis of new areas of business. Some specific industry needs that are driving sensor developments include:

- Significant reductions in the size of sensors and their associated electronics and supporting hardware. As well as size there are strong drivers for weight reduction, particularly by the aerospace industry. This is at least partially being achieved through chip level integration of sensors and miniaturisation.
- Providing more functionality in a sensor. This may be through combination of sensors and sensors combined with actuators in MEMS technology. It may also be through adding data processing and intelligence at the sensor to allow diagnosis and verification.
- Reductions in sensor costs and improved overall system costs. This is aided by sensor developments utilising technologies developed for other purposes e.g. fibre sensors from telecommunications technology.
- Wireless sensors that communicate with a control system and wireless sensor networks which enable lower cost retro-fitting of monitoring systems. This is also driving an increased interest in power management techniques and energy harvesting technologies as the limitation of batteries is the biggest constraint on extensive deployment of wireless sensor networks. In addition, there is a need for a new generation of specifically ultra-low power sensors capable of exploiting the advances in energy harvesting. Wireless communications standards have begun to coalesce and standards in energy harvesting are starting to emerge.
- Distributed or multi-point sensing in a single device e.g. fibre optical sensors or distributed temperature, pressure and vibration monitoring.
• Increasingly packaged for deployment in challenging environments e.g. extremes of temperature, pressure, corrosive environments. Preferably intrinsically safe and EMC resistant.
• There is greater demand for low voltage (<1.8V) in order to support the market for handheld devices.
• The medical market is driving a trend to low-cost and non-invasive point of care tests
• Demand for high accuracy and ultra-high reliability over long lifetimes. This is driven by a desire for much reduced levels of user maintenance of sensor systems.
• Increased focus on systems level solutions often using standard COTS components. Increasingly systems are sold with a significant on-going service element as the user expects to take less responsibility for operation and maintenance.

EMERGING AND DISRUPTIVE TECHNOLOGIES

Emerging and potentially disruptive technologies fall into two categories: (i) new sensor technologies, e.g. silicon carbide, nanotechnology and carbon based technologies and (ii) enabling technologies, e.g. wireless communications and plastic electronics.

Silicon carbide

Silicon carbide\(^\text{25}\) is a semiconductor which can, in the same way as silicon, be used as the basis of a wide range of sensors and electronic devices. However, in contrast to silicon, silicon carbide can function at high temperatures, e.g. up to 600°C, high power and in conditions of high radiation. Sensors can thus be made for a range of applications in aggressive environments, e.g. monitoring pollution in hot exhaust gases. Silicon carbide based electronics also functions at high temperature offering the prospect of integrated sensors and signal conditioning electronics.

Nanotechnology

Nanotechnology exploits the nanoscale (critical features of order a few nanometres, i.e. dimensions of order \(10^{-9}\) of the width a human hair). Frost and Sullivan estimate that the nanobiotechnology\(^\text{26}\) market is $21b in 2011 increasing to $36.2b in 2017. Nanotechnology offers:

• Structures with a high surface to volume ratio which can offer very high sensitivity sensors.
• Quantum effects which offer new material properties, e.g. the wavelength of emission of quantum dots can be tuned across the visible spectrum.
• Enhancements of transduction mechanisms, e.g. the Raman spectrum of molecules absorbed on nanoparticles of silver can be enhanced by factors as large as 10\(^3\), offering the prospect of signal molecule detection.

\(^{26}\) http://www.frost.com/prod/servlet/market-insight-top.pag?docid=220558740
Carbon based nano-technologies

Carbon based nano-technologies such as carbon nanotubes (CNT) and graphene have very high surface to volume ratios and very novel thermal, electrical and mechanical properties that can be exploited in the construction and transduction mechanisms of sensors. It will probably be necessary to functionalise these novel materials to make them sensitive to particular chemical and biological measurands.

Wireless Sensor Networks

One of the biggest trends in recent years has been to wireless sensors and wireless sensor networks. The addition of communications and on-board processing has enabled a raft of new applications and improvements to existing ones. Wireless enables spatially distributed sensing over much wider areas. It allows significant weight reduction, e.g. in aircraft, by reducing cable usage. Using wireless sensing in building automation has resulted in significant cable cost reductions. Wireless sensor networks enable rapid and relatively non-disruptive retrofitting of systems. The main constraint on wider uptake of wireless sensing is the issue of power, in particular the need to periodically change batteries. It is claimed by some that up to 90% of envisaged wireless sensor network applications are just not possible with batteries. There are many applications where batteries are just not reliable enough or are unable to cope with the sensing duty cycle for sufficiently long periods of time. Currently most networks are therefore limited in size and are nowhere near the thousands of nodes networks required. The so-called ‘Internet of Things’ implies a future where there is a higher level of ambient intelligence largely built upon device to device communication of sensed data. For this to become reality the scenario of billions of battery changes is unworkable. Energy harvesting technologies are emerging as a potential solution.

Plastic Electronics & Printed Sensors

Innovation in plastic electronics promises to revolutionise low cost sensor manufacture. Printing in its various forms offers a means of manufacturing sensors on a mass production scale reducing costs to pennies. This will enable the vision of ubiquitous sensing. Some of the main technical barriers have already been overcome e.g. conductivity, robustness, low cost deposition and simple formulation and processing. Examples such as printed RF position sensors are already a reality and are suitable for highly accurate operation in extreme conditions e.g. aerospace.
CERTIFICATION AND REGULATION

In order to deploy sensors and instrumentation in specific applications / industries there is a need to address compliance with a range of, often sector specific, regulations, certifications and standards. Many products must meet a range of requirements set out in EU directives before they can be sold. This knowledge is best applied at the beginning of the design process so as to avoid costly alterations to ensure the compliance required to sell into your target industries.

CE Marking is required to verify that the product meets EU safety, health or environmental requirements. The standards required depend upon the equipment and the environments in which they are to be operated. In areas such as medical devices meeting the certification requirements is a lengthy process and involves various levels of clinical trials. The US equivalent is FDA regulation.

Some examples of certification relevant to achieving CE Marking for sensors include:

- **Electromagnetic Compatibility (EMC) testing:** This is required to demonstrate that the equipment has the necessary level of "immunity" to the electromagnetic interference present in the environment in which it operates. In addition it must be demonstrated not to introduce electromagnetic interference at a level likely to affect other equipment in its vicinity. Relevant standards bodies include CEN, CENELEC and BSI.
- **Laser Class Evaluation:** In various jurisdictions, standards bodies, legislation, and government regulations define classes of laser according to the risks associated with them, and define required safety features which must be incorporated.
- **ATEX product certification** (or EC Type Examination): This is the check on the design specification of a product in relation to a series of standards laid out under the equipment directive. Other related certifications include IECex and DSEAR. It involves a detailed process of examination, testing and assessment of equipment intended for use in potentially explosive atmospheres. Employers are required to specify workplace zones according to a classification system that depends on the likelihood of an explosive atmosphere occurring.
- **Ingress Protection Rating or IP Code:** This classifies and rates the degrees of protection provided against the intrusion of solid objects (including body parts like hands and fingers), dust, accidental contact, and water in mechanical casings and with electrical enclosures.

Some other certification of relevance includes:

- **MCERTS:** This is the UK Environment Agency's (EA) Monitoring Certification Scheme. It provides the framework for businesses to meet quality requirements for both equipment and competence of individuals to use it. Compliance with MCERTS gives the EA confidence in the monitoring of emissions to the environment. In the USA the Environmental Protection Agency (EPA) defines a number of accepted 'Standard Methods' for environmental measurements. Any new measurement approaches will need to demonstrate equivalence to these before they will be accepted.
- **Kitemark:** The Kitemark is a UK product and service quality certification mark which is owned and operated by The British Standards Institution (BSI Group). The Kitemark is most frequently used to identify products where safety is paramount. It is not a legal requirement, but is often used as a point of differentiation in competitive markets and is widely trusted. To obtain Kitemark certification, products and services are assessed by BSI Product Services.
Finally, it is worth considering whether you will be required by your customers to demonstrate compliance with specific Quality Management Systems e.g. ISO 9001 & 14001. This is a common requirement in many industries.

There are a limited number of third party certification bodies i.e. organisations accredited to carry out assessment and certification. These can advise companies on the requirements for the industries into which they wish to sell. The certification organisations most commonly used in the UK are:

- ERA Technology
- TUV NEL
- Sira Test & Certification
- Baseefa

**FUNDING OPPORTUNITIES FOR SENSOR DEVELOPMENT**

There are several public sector funding sources of relevance to sensor technology. Whilst it is rare to see a funding call specifically targeted at developing sensor technology it is common for challenge or applications focused calls to lend themselves to sensing solutions. Opportunities range from small-scale single company projects through to large-scale multi-year multiple partner collaborative projects.

**Grants for R&D:**

The objective of Grant for Research & Development is to assist small and medium sized businesses, including pre-start-ups and start-ups, to engage in Research & Development projects in the strategically important areas of science, engineering and technology, from which successful new products, processes and services can emerge. It is possible to sub-contract some of the work where internal skills are missing.

The Technology Strategy Board runs a continuous application process for Grant for Research and Development – ‘responsive mode’. You may enter the process at any time, and decisions will be made at the end of two-monthly cycles.

There are 3 types of grants within this scheme. At the research end of the spectrum they fund work to explore the technical feasibility and commercial potential of a new technology, product or process through:

*Proof of Market* - an assessment of commercial viability through market research, market testing and competitor analysis, Intellectual Property position, initial planning to take the project to commercialisation including an assessment of costs, timescales and funding requirements. Projects up to 9 months; maximum grant of £25k to cover up to 60% of project costs.
Proof of Concept - initial feasibility studies, basic prototyping, specialist testing and or demonstration to provide basic proof of technical feasibility, IP protection, investigation of production and assembly options, pre-clinical research studies for healthcare technologies and medicines including target identification and validation. Projects up to 18 months; maximum grant of £100k to cover up to 60% of project costs.

At the development end of the spectrum they fund prototype development where proof of concept and market has already been addressed.

Development of prototype - a pre-production prototype of a technologically innovative product, service or industrial process, including small demonstrators, IP protection, trials and testing (including clinical), market testing, marketing strategies, identifying routes to market, product design work and Phase 0 pre-clinical studies for medicines. Projects up to 2 years; maximum grant of £250k to cover up to 35% of project costs for medium sized companies and 45% for small and micro businesses.

More detail can be found at: http://www.innovateuk.org/deliveringinnovation/grant-for-research-and-development.ashx

SBRI:

The SBRI programme uses the power of government procurement to drive innovation. It provides opportunities for innovative companies to engage with the public sector to solve specific problems.

Competitions for new technologies and ideas are run in specific areas and aim to engage a broad range of companies using short-term development contracts.
SBRI enables the public sector to engage with industry during the early stages of development, supporting projects through the stages of feasibility and prototyping.
Companies with potentially interesting technologies and ideas submit an application, either through the Technology Strategy Board or direct to the department, depending on the competition. All submitted ideas are assessed, and those judged to be the most promising are awarded development contracts. These tend to be single company applications. This first feasibility phase lasts generally 2 to 6 months, with contracts typically being up to a maximum of £100k.

Following a second assessment stage, a subset of these ideas may be awarded a second phase contract which can be for up to 2 years and a maximum of £1M. These contract values and durations are dependent on the challenge being addressed. This second phase will generally be for the development of a prototype or demonstrator.

After completion of the second phase, companies are expected to commercialise the resulting product or service which is taken to market and open to competitive procurement.
The need for sensor related solutions has featured very clearly in a significant number of SBRI calls in recent years. The most likely government departments backing such calls are:

- Ministry of Defence
- Department of Health
- Home Office
- NHS and NHS Innovation Centres
- Food Standards Agency & DEFRA

For further details and to see current as well as previous opportunities please go to:
http://www.innovateuk.org/deliveringinnovation/smallbusinessresearchinitiative.ashx

**Technology Strategy Board Collaborative R&D:**

Collaborative research and development (R&D) is designed to assist the industrial and research communities to work together on R&D projects in strategically important areas of science, engineering and technology - from which successful new products, processes and services can emerge.

The scope of the collaborative R&D competitions has recently been expanded to support large collaborative R&D projects and smaller projects approved within faster timescales. These may vary with specific competitions and funding limits are specified by individual competitions but generally include:

- **Feasibility studies** – small projects lasting for a maximum of one year and often less than £100k; up to 75% funding
- **Fast-track projects** - projects lasting no longer than 18 months and having a maximum total cost of up to around £200k; up to 50% funding
- **Larger Collaborative R&D projects** – projects of around a few £100k to £m’s to last up to five years; funding mainly for applied R&D; up to 50% funding

Project opportunities for sensors R&D can be either challenge-led innovation or technology inspired innovation. Challenge-led opportunities for sensors have cropped up in a wide range of competitions. In the past these have included future nuclear energy, detection and identification of infectious diseases, maximising recovery of UK’s oil and gas Resources, informed logistics, high value manufacturing and many others. It is well worth reading the detail of each call’s scope if you believe that your sensor technology may be part of the solution to challenges highlighted. Technology inspired competition opportunities support core expertise and leading edge and next generation technologies that will help underpin UK business growth. These are more likely to specify sensors and related technologies within the call and are likely to be less prescriptive about the applications for which they are developed.

The collaborative R&D projects must be industry led and other than some feasibility studies must include partners. Academics may be partners but are not necessarily required to form a consortium.
The Competition Brief and the Guidance for Applicants will state the levels of funding available for a competition. This is the Technology Strategy Board’s flagship funding mechanism so there is extensive detail and announcement of periodic funding calls at:

http://www.innovateuk.org/deliveringinnovation/collaborativeresearchanddevelopment.ashx

Knowledge Transfer Partnerships (KTP):

KTPs enable companies to obtain knowledge, technology or skills which they consider to be of strategic competitive importance, from the further/higher education sector or from a research and technology organisation. The knowledge sought is embedded into the company through a project or projects undertaken by a good quality individual recruited for the purpose to work in the company but employed by the research partner and seconded to work in the company.

Two types of KTP are available – Classic KTPs and Shorter KTPs. Classical KTPs last between 1 and 3 years and are designed to help organisations address strategic needs. Shorter KTPs last between 10 and 40 weeks and are designed to address more short-term tactical issues. Government contributes towards the knowledge base partners’ cost of participation, whilst the company makes up the balance of the project cost.

The application for funding is made through the KTP website to the KTP Programme Office. Applications are approved by the Technology Strategy Board on behalf of the organisations funding Knowledge Transfer Partnerships. Visit the KTP website for more information or details of an adviser in your area: http://www.ktponline.org.uk

Research Councils:

These are not generally viewed as a funding source for companies. However, much early-stage sensor related research is funded by the various Research Councils. By their nature they only fund academic research although there are still opportunities for company involvement.

Some projects are larger-scale collaborative R&D where companies fund their own involvement (in-kind or actual cash) but leverage research council investment in the academic partners’ work.

Most research councils (including EPSRC, MRC, BBSRC) also offer Industrial CASE (Collaborative Awards in Science and Engineering) studentship opportunities whereby they part fund the cost of a PhD student working on a company focused research project. Awards are allocated via competition.

For some researchers seeking to exploit their research possibly though a spin-out company there are opportunities for funding to bridge the gap between traditional research grants and more commercial funding. These include schemes like ‘Follow-on Funds, Business Plan Competitions and
in some cases Knowledge Transfer Accounts.

More detail on the various forms of industry engagement and research exploitation support is available at the individual research council websites accessible from: http://www.rcuk.ac.uk

**National Institute for Health Research i4i Programme:**

i4i is an NIHR research programme that provides investment in, and improved identification of, promising healthcare technologies in order to accelerate the development of new healthcare products for the 21st century. It also funds translational research, extending between basic research and pre-clinical trials or health technology assessments.

There are 4 funding streams in the i4i programme (these were previously known as Future Product Development or FPD themes). *Streams 1 and 2* are open to all research providers in the English academic and NHS communities. For streams 3 and 4, teams must be based in England and/or Scotland, and contain at least one industrial collaborator and one academic or NHS-based collaborator. Streams 3 and 4 are the most relevant for companies developing sensor technology for the medical applications.

*Stream 3* - i4i commercial viability study (formerly i4i FPD3a) Investigations lasting up to one year involving collaboration between at least one industry and one research (academic or clinical) partner aimed at determining whether an innovative use of an existing or emerging product or technology can be used to meet a healthcare need and identifying the barriers that would need to be overcome. Funded projects serve primarily as the first stage of a full collaborative applied research project. Project costs can be no more than £100k in total and 75% funding is available.

*Stream 4* - i4i collaborative applied research project (formerly i4i FPD3b) A detailed investigation of up to 3 years involving collaboration between at least one industry and one research partner (academic or clinical) that builds on the results of a completed assessment of feasibility. This will provide further evidence of the capability to deliver improved healthcare outcomes and commercial opportunity, delivering an advanced prototype along with plans for commercial and intellectual property exploitation. Funding is to a maximum of 50% of the total project costs, and £100k- £300k per year is available.
For more details go to: http://www.ccf.nihr.ac.uk/i4i/Pages/Home.aspx

**National Physical Laboratory’s Technology Innovation Fund:**

This is not a grant source but does offer heavily subsidised access to extensive facilities and expertise of direct relevance to most areas of sensors and measurement.
NPL will work with you on any technological issue from anywhere up to 10 days at a set, subsidised rate.
For full details and contacts to discuss your specific needs please go to: http://www.npl.co.uk/technology-innovation-fund
European Union Framework Programme Funding:

The Seventh Framework Programme (FP7) of the EU presents a number of opportunities for sensor related R&D. These are very large scale, multi-year projects with multiple partners from across the EU. Accessing this funding therefore requires considerable effort and coordination and timescales to success are relatively long. As a funding opportunity this is best suited to strategic research agendas particularly where developing relationships with other partners is a key motivation. European funding provides a number of routes and mechanisms and covers many different themes. A comprehensive description is beyond the scope of this document.

The best source of information on the opportunities and the applications process is the various National Contact Points for each theme area. These can be found at: [http://www.innovateuk.org/deliveringinnovation/internationalprogramme.ashx](http://www.innovateuk.org/deliveringinnovation/internationalprogramme.ashx)

Sensor technology opportunities are found across most themes but are most clearly identified in the ICT programme and the NMP programme. Applications focused programmes where sensor related themes have cropped up previously include Health, Transport (including Aeronautics), Environment, Space, Security and Energy.