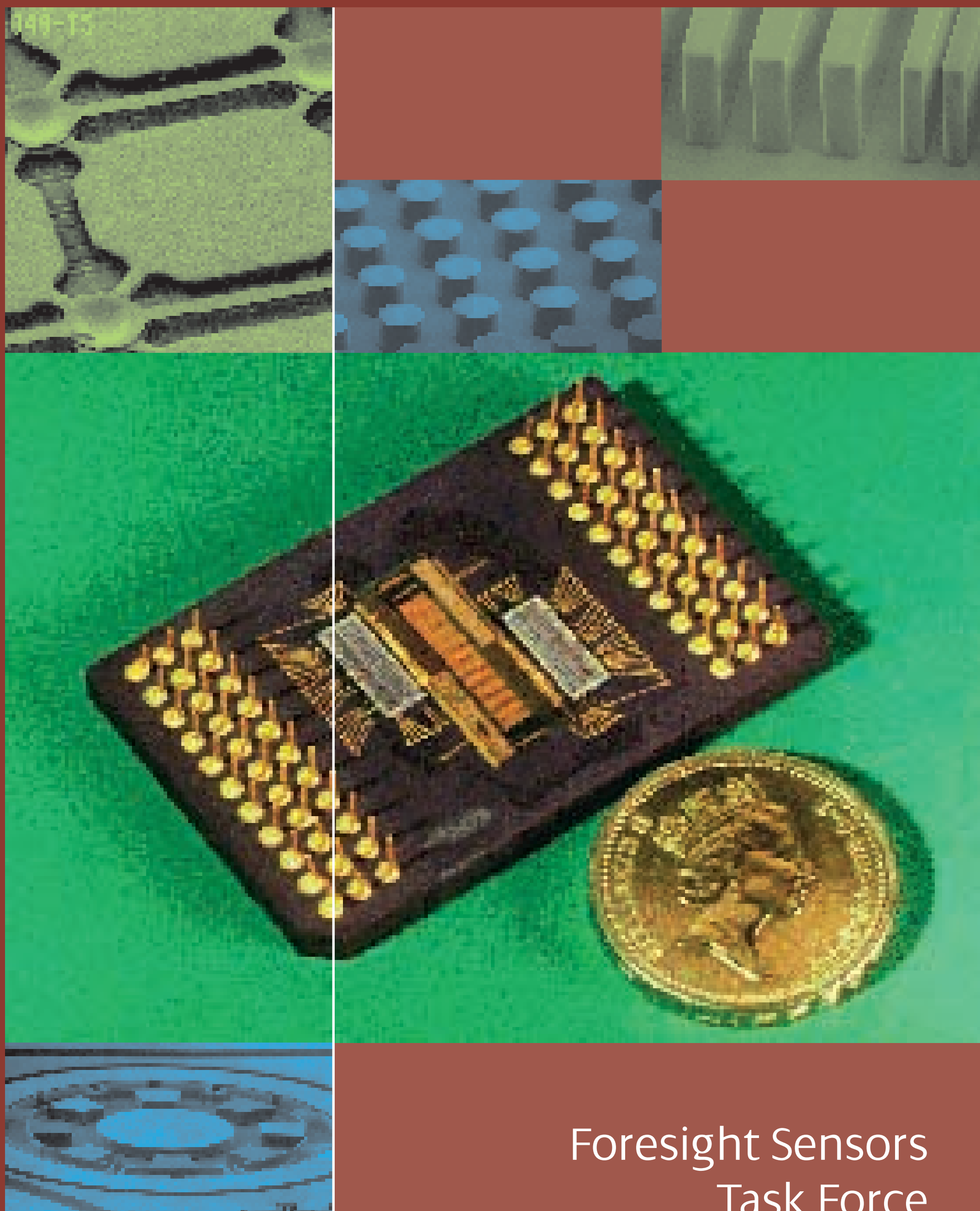
Foresight

Making the future work for you

A Strategic Framework for 2015



Foresight Sensors Task Force

Acknowledgements

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Executive Summary

In the second round of Foresight a number of panels identified the need to set up specialist groups to look at areas in a more informed manner. The need for a contribution from the sensors community was identified by six Thematic or Sectoral Panels.

The Sensors Task Force (STF) has attempted through its membership to represent the diverse interests of the sensors community. This report begins by describing the contemporary scene in macro terms, covering economic and R&D activity. The analysis of the STF begins with an extension of the prompts provided by the various Foresight Panels, based upon the particular expertise of the STF in the measurement and sensing fields. 'Market pull' is anticipated for 2015, defined in terms of major social and demographic trends. The technological attributes to meet these needs are considered before identifying recommendations in the context of a national R&D strategy to meet them.

A holistic approach has been taken, spanning systems incorporating instruments and sensors for research at one extreme, and micro-engineered industrial sub-systems and components at the other. Within this span can be found, for example, instrumentation, control, automation and surveillance together with the many other technologies and applications for sensors. Sensors enable the functionality that is utilized for detection, measurement and control in end-user applications. Sensors are at the beginning of a supply chain with several links, and the value added down the chain could be 1 or 2 orders of magnitude at each stage. Being at the beginning, and thus providing the essential first step in meeting a functional requirement, sensors have high value in both material and intellectual terms. In many respects they often represent the 'difficult bit', in that their combination with electronics requires more common skills (though software, electronics and systems considerations should not be underestimated in some applications).

New sensors are often researched using technologies that are initially investigated for other primary - more economically significant - applications. This process of adaptation typically takes more than a decade. Furthermore, it has historically proved very difficult to displace a particular sensor established in an application (largely because the costs and risks outweigh the benefits), and new technologies are generally slow in becoming established (most likely in new applications that themselves have to be developed). The small degree of displacement makes 'designing in' the key step in establishing a new technology. These two factors combine to create a timescale for progress that is inherently relatively slow, but the results are economically beneficial. Research activity initiated in the next few years will be an important influence on the state of health of the community in 2015.

It is concluded that:

I The UK has historically been quite successful in turning nationally funded research into socially and economically merit-worthy enterprises.

II Within the UK community there are islands of achievement, but also areas judged important for the future where the contribution is sub-critical or over-emphasised, relative to the size of the national economy.

III Overall, the sensors and measurement industry in the UK does not appear to be growing as fast as the global market, and policies are needed in order to try and ensure that the reverse is the case in 2015.

Based on the analysis, the STF recommends that:

A The UK's performance in the planning and execution of sensor-related research and development could be improved by:

- Greater clarification of the social and economic aims of such work;
- A better understanding within the science community of the practical issues associated with the target need, in terms of performance, attributes, cost aspects and potential economic scale; and
- A realistic recognition of issues that potentially disqualify a technology from being suitable for an envisaged need.

B New communities should be stimulated within areas of common sensor need and technology in order to ensure effective transfer of excellence and focus of work on areas with market potential. Examples of such communities that have added value in this way were the Optical Sensors Collaborative Organisation (OSCA), Gas Analysis and Sensing Group (GASG), SWIG (Sensors in Water Group) and the Faraday Partnerships. However it is important that such new communities:

- Focus on big themes and/or important market pullers;
- Ensure greater involvement of academic and industrial researchers (the latter involving representatives from 'manufacturers' and 'users');
- Are multidisciplinary and achieve a critical mass of activity;
- Are formed around participants in existing relevant nationally funded research and development activity; and
- Are conscious of 'entrepreneurship' as a means of advancing sensor technologies to the market.

C The STF highlighted that this is a very dynamic and significant market. So, it is essential that progress is monitored against these targets and that there are regular reviews of the developing challenges and opportunities in these markets. It is thought that the DTI is the ideal body to take on this role.

D The EPSRC (in liaison with the other Research Councils) should consider setting up a body to ensure that research in this area is potentially of economic value. This should include:

- Strengthening the requirements for justification of sensors related research in proposals;
- Organising bi-annual themed workshops through which the research, manufacturing, and user communities can exchange views (the process that gave rise to the INTERsECT Faraday Partnership "Announcement of Opportunity" being a useful model for implementing this recommendation).

The secret of successful sensor research is realistic boldness in both technical and applications terms, and in the latter sense, from a national economic perspective, to address potentially significant future needs.

1 Introduction

In the second round of Foresight a number of panels identified the need to set up specialist groups to look at areas in a more informed manner. The need for a contribution from the sensors community was identified by the following Thematic or Sectorial Panels:

- Ageing Population
- Crime Prevention
- Manufacturing 2020
- Healthcare
- Materials
- Defence, Aerospace and Systems.

The Sensors Task Force (STF) has attempted to represent the diverse interests of the sensors community 'writ large'. The experience of members of the STF listed below serves to illustrate the breadth of the community (even so the STF does not fully represent it):

- Automotive industry (physical variables)
- Physical variables transducer manufacturer (with systems experience)
- Process industry instrumentation and control
- Scientific/research instruments
- Micro-engineering/Gas sensors
- Data processing and data fusion/defence
- Biochemical/biomedical sensing and instrumentation
- Optical, physical and chemical sensors; exploitation.

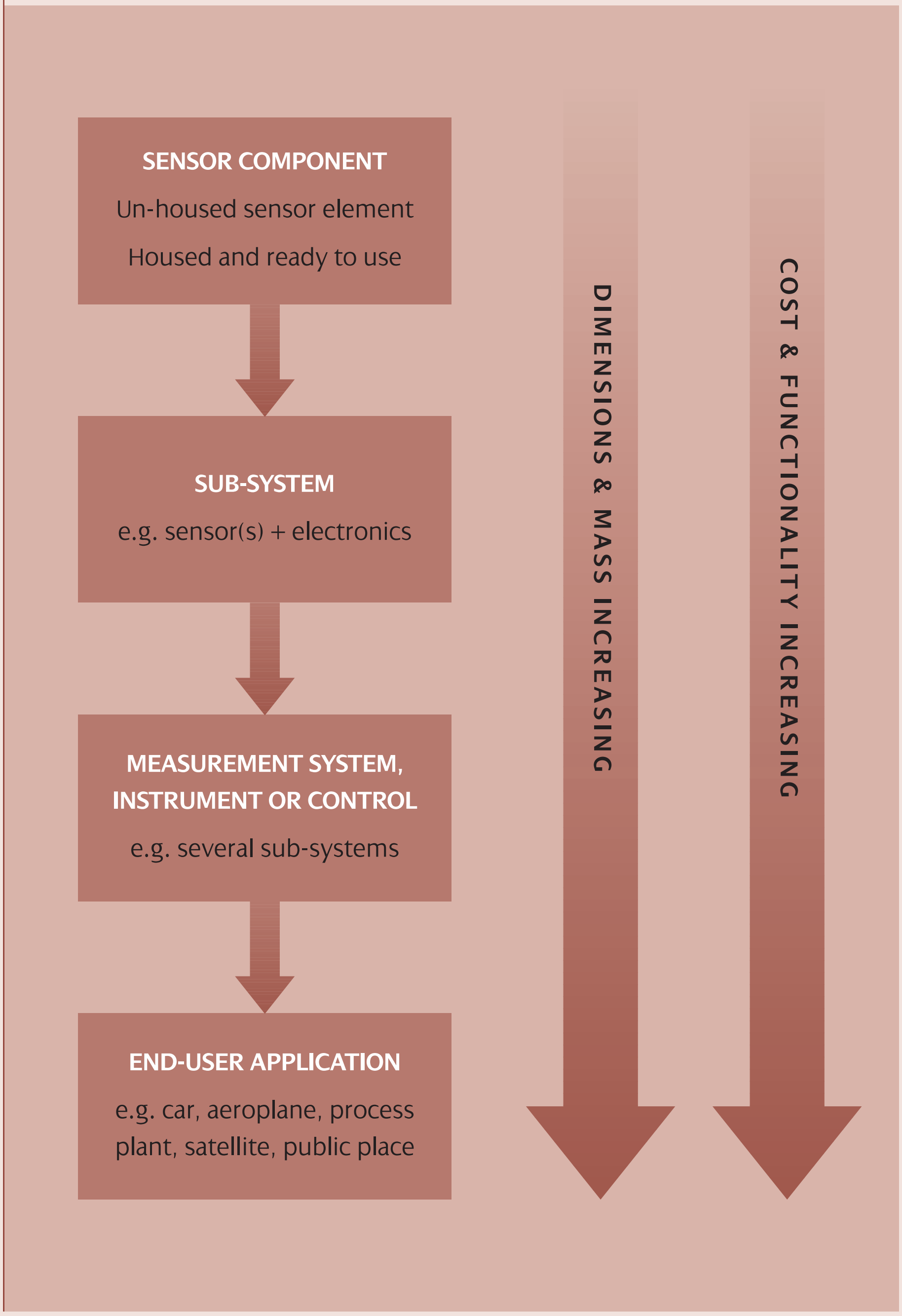
Section 2 of this report describes the contemporary scene in macro terms

Sections 3 and 4 provide an account of the approach adopted by the STF. This analysis begins with an extension of the prompts provided by the various Foresight Panels described above, based upon the particular expertise of the STF in the measurement and sensing fields. 'Market pull' is anticipated for 2015, defined in terms of major social and demographic trends. The technological attributes to meet these needs are considered before identifying recommendations in the context of a national R&D strategy to meet them.

A holistic approach has been taken, spanning systems incorporating instruments and sensors for research at one extreme, and micro-engineered industrial sub-systems and components at the other. Within this span can be found, for example, instrumentation, control and automation and the many other technologies and applications for sensors. Figure 1 illustrates how sensors enable the functionality that is utilised for detection, measurement and control in end-user applications. Sensors are at the beginning of a supply chain, the value added down the chain could be 1 or 2 orders of magnitude at each stage. Being at the beginning, and thus providing the essential first step in meeting a functional requirement, sensors have high value in both material and intellectual terms. In many respects they often represent the 'difficult bit', in that their combination with electronics requires more common skills (though software, electronics and systems considerations should not be underestimated in some applications).

A complication of this rather simplistic picture, which does not affect these observations, is that what looks like a subsystem in one market sector can be put into a moulded case and become a finished product in another. The most important point is that a functional requirement is met in terms of the required performance and price.

Figure 1
Supply chain concept for sensor exploitation



New sensors are often researched using technologies that are initially investigated for other primary - more economically significant - applications. Examples include fibre optics (primary stimulus communications), silicon as a sensing material (primary stimulus electronic circuits), thick film processes (printed circuit boards) and new magnetic materials (information storage). This process of adaptation typically takes more than a decade. Furthermore, it has historically proved very difficult to displace a particular sensor established in an application (largely because the costs and risks outweigh the benefits), and new technologies are generally slow in becoming established (most likely in new applications that themselves have to be developed). The small degree of displacement makes 'designing in' the key step in establishing a new technology. These two factors combine to create a timescale for progress that is inherently relatively slow. Research activity initiated in the next few years will be an important influence on the state of health of the community in 2015.

Sections 5 and 6 of the report contain the STF's conclusions and recommendations.

2 Market evolution and the UK within it

2.1 The global market

The need for measurement and control, largely to operate and protect expensive capital plant and equipment, began seriously in the second half of the 20th century. It was however not until the middle of this period that the words 'sensor' and 'transducer' came into wider usage in the technological community. This evolution has been subsequently reflected in the global market, as it has grown. There has been a gradual shift in the centre of gravity away from large systems incorporating relatively few and expensive transducers towards the utilisation of more and more sensors, as components or in sub-systems. The price of the components has fallen as volumes have increased. The philosophy of 'protection' has been partly displaced by one of 'user friendliness' as this change has come about. With the concomitant increase in the cost effectiveness of electronics for use in association with sensors, it has been possible to develop systems capable of performing automatically, complex tasks such as those that would otherwise require human attention.

The global sensors market (itself a slightly amorphous concept to define) is valued in the range between €15 billion[1] and €30 billion[2]. Surveys currently emphasise the higher rate of growth of 'modern sensor technologies' (at ~10% per annum) as against 'traditional technologies (~4% p.a. growth). The Intechno study[2] (which has a component 'bias') identifies housed, ready to use sensors as representing 90% of the market, followed by un-housed components (5%), sub-systems (2%), and measurement systems and instruments (3%). Scientific or research instruments were not included in either study.

There are more than 10 variables that are commonly measured (flow, pressure, temperature, chemical composition etc.), and approaching 10 different ways of measuring each one (e.g. for flow we could use differential pressure, vortex shedding, Coriolis effect, ultrasonics, etc.). Aside from a few large international firms (none of them British), most participating firms are specialists in terms of technology and the markets that they serve (and there are at least 10 well defined market sectors that are served in, say, 10 territories). We see immediately from this macroeconomic analysis that the 'sensors market' is, and will most likely continue to be, dominated by the activities of smaller firms including SMEs. Furthermore, if the UK sensors community is prospering, new firms will be created (from the science base, industrial spin-offs and spin-outs) as well as established ones growing.

1 InTech Magazine, Instrument Society of America, June 1999, p.40

2 "Sensor Markets 2008", Intechno Consulting, Basle, Switzerland, May 1998. This study does not include the defence sector, an omission that affects the conclusions by ~15%.

2.2 The UK contribution

2.2.1 ECONOMIC ACTIVITY AND TRADE

GAMBICA (the UK Association for Instrumentation, Control & Automation) has assessed the contribution of the industry to the UK economy in the period 1993-1999[3] using national trade statistics. Key words for the data categories are 'instrumentation', 'instruments', 'measuring, navigation, and surveying equipment', and 'automotive instrumentation', rather than sensors or transducers. The latter - often components allowing these higher value products to be assembled - are generally accounted for separately in the detail underpinning these broad product headings. Grossed up, the defined product groups represent sales of ~£5 billion, not rising significantly above inflation but with exports accounting for ~60% of the total and with a positive balance of trade running at 10-20% of annual sales. Internationally the UK is probably fourth in rank with ~7% of production behind the USA, Japan and Germany[4]. 3000 enterprises were involved in the UK, employing ~80,000 people (in 1994).

When defined narrowly, the 'measurements and sensing' industry makes a good contribution to UK GDP, though the positive input to the balance of trade is perhaps more significant. The value of the sector arises through the gearing effect previously considered, but it also goes beyond superficial economics, however, when the protection of plant, equipment, human health and safety is considered. Some industries cannot operate without sensors; the trend to automation requires more sensors.

An inference can be made that the UK industry is not expanding significantly; as a nation we appear not to be participating in the growth being enjoyed elsewhere. This suggests that internally funded industrial R&D may be at best holding its own.

2.2.2 RESEARCH

Research supported with public funds is carried out under various schemes, including LINK, Faraday Partnerships and the research councils (including NERC but principally EPSRC). Research on the application of a technology to sensing is appealing to some students and it introduces them, in principle, to the practical interactions of their chosen technology with the real world.

The EPSRC supports[5] ~250 projects to the value of ~£40M mentioning sensors and instruments (identified by a key word search) across all programmes, but largely through the Engineering, Information Technology/Computer Science and Materials activities.

3 Data collected by the Office of National Statistics (ONS) using PRODCOM and 1992 SIC classifications and extracted by consultants working for GAMBICA.

4 This suggest a global market of ~$100 million that is indicative of a wider market definition used by GAMBICA compared with those employed to generate the data referred to in notes 1 and 2 above. Reconciliation of the various surveys suggests a roughly equal split between components and instruments, with the former growing faster in both volume and monetary terms.

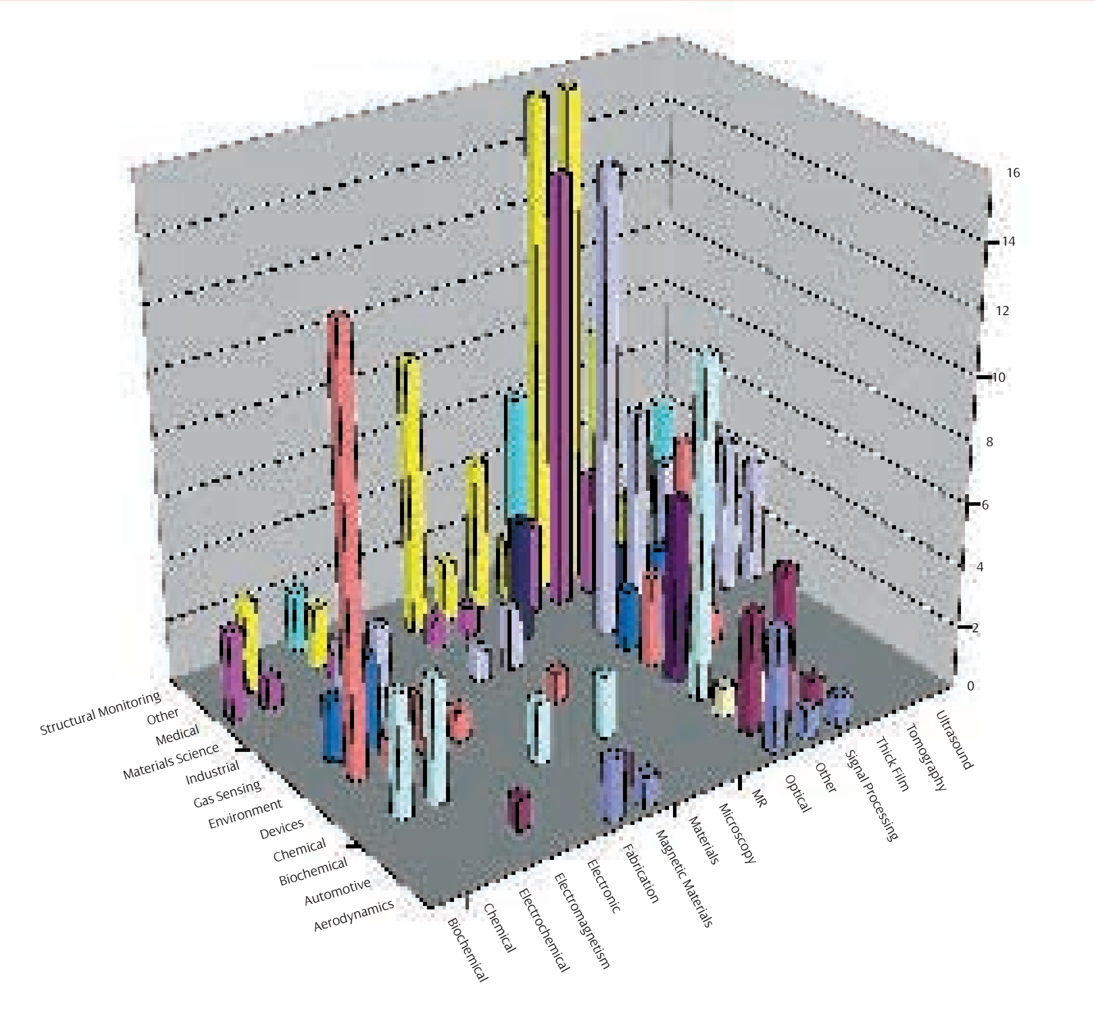
5 Information from EPSRC provided to the Sensors Brainstorming Panel, 24th October 2001.

With an average project length of 3 years this equates to a spend of ~£13M a year. Figure 2 gives a matrix of number of grants against applications and technologies. The source data is tabulated in Annex 1. 12 application areas and 16 technologies are involved; 9 programme areas participate. 11% of the grants address components, 50% sub-systems, 26% measurement systems or instruments, and 13% target scientific or research instruments. About a third of the support relates to optical sensors and instruments (a field in which exploitation has been disappointing after the excitement of the 1980's).

There is some evidence that UK researchers are not proportionately engaged in the conferences following contemporary 'big themes', such as the SENSOR (Nuremburg), TRANSDUCERS (international) & EUROSENSORS events. Attendance and quality at national meetings is declining. The UK is presently considered to be weak in the sensors micro-engineering field[6].

Figure 2

Number of EPSRC current grants against applications and technologies



6 Microsystems Manufacturing Association (MMA).

2.2.3 CREATION OF NEW SENSOR FIRMS

The table below lists some of the new sensor firms and their products that have been created in the last few decades, these being mainly entrepreneurial spin-outs from universities, national laboratories or other firms (as indicated). Where it is judged that defence funding has contributed significantly to the technology development, this is identified. As enterprises, these firms are valued at more than £2 billion; if the level of EPSRC funding has been consistent since the 1980s (when sensing became fashionable), and it supported just the establishment of these growing firms, the rate of return on this national investment is more than 15% in real terms. The life of firms is not exhaustive.

Table 1
Some recently formed and/or successful UK sensor firms

COMPANY	GROWTH PERIOD	TECHNOLOGY SOURCE	PRODUCTS
Druck	1970's on	Industry & National laboratory	Pressure sensors
Malvern Instruments	1970's on	MoD	Photon counting
Lion Laboratories	*Late 1970's on*	*University*	*Breathalyser*
Apollo Fire Detectors	*Late 1970's on*	Industry spin-out	Fire detectors
EEV	*Late 1970's on*	*National laboratory*	*Gas sensor*
Renishaw	1980's	Industry	Metrology
*City Technology**	*1980's*	*University (MoD)*	*Gas sensor*
Medisense	*1980's on*	*University*	*Blood glucose*
Inverness Medical	*1990s*	*Known (from Medisense)*	*Medical diagnostic strips*
*Capteur**	*1990s*	*National laboratory & university*	*Gas sensor*
IRISYS	Current	Industry (MoD)	IR sensor arrays
Spectraprobe	*Current*	*Industry spin-out*	*Spectrometry*
Sensox	*Early stage*	*University*	*Gas sensor*

*Capteur has merged with City Technology - both are now part of First Technology plc

Gas and chemical (medical) sensing firms - in italics - are particularly represented in this list and as a nation we have done well in this area of application.

3 Market Pull for 2015

The STF decided to build upon the requests for guidance framed by the other Foresight Panels, and felt that it would be useful to identify, from a sensing perspective, themes of 'market pull'. The forces creating these themes - market pullers - are both societal and economic, and the main test in creating the list below (ordered alphabetically) was the judgement that these forces would remain in effect and grow in significance through the period from now until 2015:

- Ageing population
- Crime prevention
- Defence and terrorism
- Domestic electronics and smart homes
- Monitoring the Environment
- Food and Agriculture
- Healthcare
- Increasing population
- Increased product functionality
- Industrial health and safety
- Leisure industry and toys
- Manufacturing processes
- Mobility and transportation
- Telecoms and media

We note immediately a difficulty of this approach. Firstly it could be argued that the list is not comprehensive. For example 'sustainability' or 'sustainable development' does not appear explicitly; neither do the 'energy industries'. These apparent omissions can be seen, on reflection, as likely to be covered by one or several of the above. Secondly, and paradoxically, a sensor is generally a very specific device, in terms of its attributes, field of application, scale of manufacture etc. Somehow, we need for the purposes of national planning, to generalise realistically and constructively.

3.1 Opportunities and challenges

The STF set about examining each of these pulling forces, in detail, from a sensing perspective. The two steps in this process were to:

1. Identify the possibilities for sensors that the force represents, and
2. From the perspective of the quantities or qualities that need to be measured, consider the technical challenges, limitation and needs.

The results of this exercise are given in full in Annex 2. Annex 2 contains a considerable amount of detail, each entry combining the thinking of the most expert STF member(s), modified by a discussion amongst the members as a group.

Without prejudicing detailed points made in each entry, the STF felt able to draw out some general points - truisms - by way of anticipated needs, trends and observations that will stand the test of time through to 2015. In doing this it is useful to differentiate between "performance" (how well the sensing device performs its stated task), from "attributes" (aspects of the device outside the headline performance category), and economic factors. Thus, for clarity, a high performance pressure sensor that has an attribute of being susceptible to vibration might not be suited to a propulsion application but could be deployed in a borehole (provided other attributes such as reliability, size and mass) are appropriate as well as cost. Sometimes, attributes and cost can be more important than performance.

The observations of the STF are:

A General

- i The future holds the promise of vast quantities of sensed data and information that needs to managed, transmitted, processed and acted upon.
- ii Better sensors help minimise both the quantity of data that needs to be transmitted and the information processing resources that are required to analyse it.
- iii Similarly, better information processing can reduce the need for improved sensors.
- iv Social need might enhance the value of a sensing opportunity, but many social applications only become viable at low cost; otherwise pricing will be flexible to suit the application.
- v In research, there is an on-going need for well-judged correlation between an envisaged sensor and its application (in terms of manufacturability, price, performance, and attributes).
- vi There will continue to be downward pressure on cost, and sensor volumes will increase; sensors will continue to be 'designed down' for applications.
- vii It is likely that there will be further strengthening of the contemporary market emphasis on sensors as components, in a system.
- viii Complex tasks currently requiring human discrimination will be increasingly automated.

B **More specific and technological**

ix Sensors will need to continue to be well adapted to their applications environment.

x Current performance and attribute trends will continue to give emphasis to:

- Lower power
- Smaller size
- Lower mass
- More sensitivity
- Improved selectivity
- Enhanced reliability.

xi Sensing needs can be satisfied by a system that is derived from an economic trade-off between various types of possible sensors and the processing that makes sense of the data to satisfy the application.

xii Sensors with a dormancy mode (that 'wake themselves up') and that are perhaps self-powered will be useful.

xiii The qualities of 'plug and play' - simple and seamless embedding of sensors into systems - will become of increasing importance; ease of calibration is one relevant attribute.

xiv Non-invasive and remote (non-contacting) sensing methods will increase.

xv Effect sensors that indicate when deleterious effects of a known character are occurring but give no direct information as to the cause will become a more useful 'first line' of monitoring.

xvi Sensing qualities or derived variables of human character rather than classical measurands will increase (though this might be achieved by combination of sensors responding to classical parameters).

xvii Positional information integrated within sensors using GPS will become a useful feature.

3.2 Ranking of the market pull factors

The market pull listing in Annex 2 is ordered differently from the above alphabetic one, as a result of a ranking exercise carried out by the STF subsequent to the detailed discussions. This was done independently, at arms length, electronically. Members were invited to rank each 'puller' on the basis of "their importance for sensors in the UK, in 2015". Three groups were identified: high importance, medium and low importance, and there could be no more than five votes allocated by each member into any of the respective groups. Other than 'importance' the criterion for ranking was not defined, but in most cases a test involving economics and 'capability' was applied. The result of the voting is given in Table 2 below ("X" representing an individual members' vote):

Table 2

2015 Ranking of "Market Pullers"

RANK	MARKET PULLER	HIGH	MEDIUM	LOW
1	Healthcare	XXXXXXX	X	
2	Crime Prevention	XXXXXX	X	XX
3	Defence/Terror	XXXXX	XX	X
4	Manufacturing Processes	XXX	XXXX	X
5	Monitoring the Environment	XXX	XXX	XX
6	Increased Product Functionality	XXX	XXX	XX
7	Industrial Health & Safety (Environment)	XXX	XXX	XX
8	Leisure Industry	XXX	XX	XXX
9	Mobility/Transportation	XX	XXXXX	X
10	"Domotics" - Domestic Electronics & Smart Homes	XX	XXXXX	X
11	Ageing Population	X	XX	XXXXX
12	Food & Agriculture		XXXX	XXXX
13	Increasing Population		XXX	XXXXX
14	Telecoms & Media		XXX	XXXXX

Quantification of the votes gives confidence to the visual perception that these market forces fall into three distinct groups: the top three are of "high importance", the lower four are of "low importance", and then there is a middle ground (with little to separate the seven representatives).

3.3 Diffusion of science and technology

Mention has been made of the parasitic nature of sensor science and technology, adapting advances made for apparently bigger and more important reasons. This process is central to the development and application of sensors, and it clearly opens up the possibility of the wrong science being done, when viewed from a sensing perspective.

The process of diffusion of knowledge and experience between sectors - perhaps from the more R&D intensive to the less so - will continue, and it is to be welcomed in that it opens up the prospect of facilitating more radical - and hopefully more valuable - advances. Similarly, there are stages to the development of a technology in the market. Critical is the entry-level combination of price, performance and attributes. Subsequently both prices fall and, often, performance improves. Value added is more critical than price on its own. New applications can be created through such developments.

4 Winning technologies?

The portfolio of EPSRC projects referred to above and tabulated in Annex 1 covers the following technologies and applications:

Application Area: Aerodynamics, Automotive, Biochemical, Chemical, Devices, Environmental, Gas Sensing, Industrial, Materials Science, Medical, Other, Structural Monitoring

Technology: Biochemical, Chemical, Electrochemical, Electromagnetic, Electronic, Fabrication, Magnetic Materials, Materials, Microscopy, Magnetic Resonance, Optical, Other, Signal Processing, Thick Film, Tomography, Ultrasound.

The rather heavily populated technology category 'other' (see Figure 2 adjacent to the more numerous 'optical' row) can be further broken down in headline terms as shown in Table 3 below. The picture here presented is not untypical of that to be expected from a 'responsive mode' approach, and where much of the research captured by the search alludes to sensing and instruments rather than being directly focussed on these activities.

The sensing field is very broad in both technical and applications terms. It is not felt appropriate for the STF to try and identify what technologies amongst all these, and others that could be identified, will be winners in the future[7]. Other Foresight activities (e.g. in Denmark[8]) have attempted to do this, but the SFT has preferred to employ a market pull approach. The STF believes that a better appreciation of future sensing needs will help to strengthen the link with the research portfolio, as it develops in the coming years.

The secret of successful sensor research is realistic boldness in both technical and applications terms, and in the latter sense, from a national economic perspective, to address potentially significant future needs.

7 The STF does however recognise that the UK is in danger of becoming sub-critical in the important technology of microengineering and it supports the initiative of the Microsystems Manufacturing Association (MMA) in stimulating the establishment of a conveniently located development and prototype manufacturing facility.

8 The report is available for download from www.sensortec.dk. It is the result of a 12 month nationally funded collaboration between Risø National Laboratory and Sensor Technology Center A/S, employing a detailed questionnaire circulated internationally. The work of the STF is uninfluenced by this study. There are interesting similarities, and differences, between the respective conclusions.

5 Conclusions

I The UK has historically been quite successful in turning nationally funded research into socially and economically merit-worthy enterprises.

II Within the UK community there are islands of achievement, but also areas judged important for the future where the contribution is sub-critical or over-emphasised, relative to the size of the national economy.

III Overall, the sensors and measurement industry in the UK does not appear to be growing as fast as the global market, and policies are needed in order to try and ensure that the reverse is the case in 2015.

Table 3
Breakdown of 'other' category in EPSRC technologies portfolio

ACTIVITY	NO OF GRANTS	ACTIVITY	NO OF GRANTS
Microscopy	9	Acoustic sensing	2
Tomography	6	Automotive roll sensing	2
Ultrasonic condition monitoring	6	Sheet manufacturing	1
Basic materials science	5	Body heat	1
Semiconductor materials	5	Self powered sensors	1
Gas sensors	5	Electronic nose	1
MRI	5	Signal processing	1
Structures	4	Pressure sensing	1
X ray instruments	3	Mass spectroscopy	1
Composites manufacture	3	Robot control	1
Micro-TAS	3	Control	1
MEMS sensors/actuators	3	Radiometry	1
Medical instruments	3	Pipeline fluid loss	1
Gyroscope/rate sensing	2	Photovoltaic systems	1
Environmental sensing	2	CVD diamond	1

6 Recommendations

Based on this analysis, the STF recommends that:

A The UK's performance in the planning and execution of sensor-related research and development could be improved by:

- Greater clarification of the social and economic aims of such work;
- A better understanding within the science community of the practical issues associated with the target need, in terms of performance, attributes, cost aspects and potential economic scale; and,
- A realistic recognition of issues that potentially disqualify a technology from being suitable for an envisaged need.

B New communities should be stimulated within areas of common sensor need and technology in order to ensure effective transfer of excellence and focus of work on areas with market potential. Examples of such communities that have added value in this way have been the Optical Sensors Collaborative Organisation (OSCA), Gas Analysis and Sensing Group (GASG), SWIG (Sensors in Water Group) and the Faraday Partnerships. However it is important that such new communities:

- Focus on big themes and/or important market pullers;
- Ensure greater involvement of academic and industrial researchers (the latter involving representatives from 'manufacturers' and 'users');
- Are multidisciplinary and achieve a critical mass of activity;
- Are formed around participants in existing relevant nationally funded research and development activity, and
- Are conscious of 'entrepreneurship' as a means of advancing sensor technologies to the market.

C The STF highlighted that this is a very dynamic and significant market. So, it is essential that progress is monitored against these targets and that there are regular reviews of the developing challenges and opportunities in these markets. It is thought that the DTI is the ideal body to take on this role.

D The EPSRC (in liaison with the other Research Councils) should consider setting up a body to ensure that research in this area is potentially of economic value. This should include:

- Strengthening the requirements for justification of sensors related research in proposals.
- Organising bi-annual themed workshops through which the research, manufacturing, and user communities can exchange views (the process that gave rise to the INTERsECT Faraday Partnership "Announcement of Opportunity" being a useful model for implementing this recommendation).

Annex 1

EPSRC Grants: Number by application area and technology

	BIO-CHEMICAL	CHEMICAL	ELECTRO-CHEMICAL	ELECTRO-MAGNETIC	ELECTRONIC	FABRICATION	MAGNETIC MATERIALS	MATERIALS	MICROSCOPY	MAG. RES	OPTICAL	OTHER	SIGNAL PROC	THICK FILM	TOMOGRAPHY	ULTRA-SOUND
Aerodynamics						2	1				4	1	1			
Automotive			1				1				4	5	1			
Biochemical											1	1				
Chemical		4	4			2		2			11		1			
Devices											6					
Environmental		14	1	2	1			1			3	7	1			
Gas sensing		2	3								2	3				
Industrial			3	3			1	2			15	7	5		5	4
Materials science									4			2				
Medical	3	1		1			1	1		3	14	4	1		2	1
Other		3		2			9	2	5	2	16	16	8	2		2
Structural monitoring				2							6	7		1		4

Annex 2

Identification of Future Sensor needs

POSSIBILITIES FOR SENSORS

MEASURANDS
Challenges Limitations Needs

1 Healthcare

Possibilities for sensors

- Rapid screening for diseases
- Chemical assay chips
- Biological (protein sequencing) chips
- DNA chips/pharmaco-genomics
- Glucose, cholesterol, etc biosensors
- Non-invasive clinical sensors
- Drug-delivery systems
- Smart medicine/telemedicine
- Sensors for minimal invasion surgery, such as pressure, temperature, location, force
- Robotic surgery
- Tissue engineering (drug development & organ replacement)
- Drug design and testing
- Intelligent toilets
- Intelligent beds (ulcers)

Measurands – Challenges Limitations Needs

1. Cost variable (diagnostic - low cost, pharmaceutical - higher cost)
2. Typically high volume objectives
3. Highly complex manufacture (combination of device + bioreagents)
4. Highly regulated creates an entry threshold
5. Funding available for development & value creation in “start-up” technology (ie early stage)
6. Market large & evolving (so there are new opportunities)
7. Data is quality critical
8. There are specialist technical requirements - biocompatible, bio-reagents etc.
9. Lab on chip for diagnosis (in surgery) and screening
10. Technical complexity and diversity (from low cost to expensive)
11. Sensitivity and selectivity important
12. Market is effectively regulated for product approval

2 Crime Prevention

Possibilities for sensors

- Detect/analyse activity (home, work, locality) - physical and electronic
- Mark objects of value - physical and electronic
- Detect stolen goods - physical and electronic
- Locate/track stolen goods - physical and electronic
- Computer/network intrusion - physical and electronic
- Tagging and control of offenders
- Collect evidence
- Intelligent objects that know when they are being stolen (used unusually)
- Link to defence/terror for bigger crimes and for smuggling etc.
- Personal identification/access control (Iris, fingerprint, retina, voice)
- Intelligent surveillance for higher integrity intruder alarms (more reliable)

Measurands – Challenges Limitations Needs

1. Detect/analyse activity (home, work, locality) - physical and electronic
   a. Price of sensors with sufficient resolution
   b. Passive infra-red (IR) seems just about affordable (burglar alarms, welcome lights) but is not able to distinguish people and activities and so spot abnormalities
   c. Could a crude imaging (visual or IR) be made cheap enough and accurate enough?
2. Mark objects of value physical and electronic - exemplified by mobile phones
3. Detect stolen goods - physical and electronic
4. Locate/track stolen goods - physical and electronic
   a. Ultra-violet pens are cheap and easy to obtain but not many scanners - some used for bank notes. What about automatic scanning?
   b. Could electronic tagging work? Perhaps a small, MEMS device(s) that had a unique identity programmed in - perhaps transpond to a signal or regularly neutralised by contact with owner or key (alarm when this doesn’t happen) or give warning on abnormal use - might need a constantly learning/adapting chip

5 Computer/network intrusion - physical and electronic: can usually collect data - challenge is to detect hostile attacks and distinguish from accidents or normal use (this needs analysis/processing)
6 Tagging and control of offenders: smarter
7 Collect evidence by electronic recording
8 Intelligent objects of value that know when they are being stolen (e.g. used unusually)
9 Anti-counterfeiting/smart money
10 Link to defence/terror for bigger crimes and for smuggling etc.
11 Personal identification /access control (Iris, fingerprint, retina, voice) seem to be just about there - possible improvements required for higher confidence applications
12 Intelligent surveillance for higher integrity intruder alarms (more reliability)
   a Similar to detect in the home
   b Networks of sensors

3 Defence/Terror

- Detect, track, recognise targets
- Identify threats
- Control weapons and defence assets
- Secure communications
- Decision aids (responsive to user - both preferences and stress/tired/overload)
- Locating and identifying faces (in video)
- Detection of explosives, chemical/bio agents & nuclear activity (high sensitivity, portable, remote)
- Biological particle detection/classification
- Early warning devices (electromagnetic or acoustic sensors for vehicle, pre-release of explosive/chemical/biological material)
- Remote sensing of vehicles, explosive/ chem./bio material

1 Robust and advanced technical solutions sought
2 Development costs can be funded, but UK competes against high US funding
3 Rapid uptake of new technology/product possible
4 Subsequent extension into broader markets often possible and will continue
5 Costs are initially flexible, low in longer term
6 Possibility that civil work on medical diagnostics and drug delivery will be adapted for detecting biological threats

4 Manufacturing Processes

- Material selection
- Rapid prototyping of devices
- Better instrumentation for process control
- Raw material screening
- Product evaluation
- Micro-assembly
- Mass production of micro-parts
- Need for improved efficiency and lower costs
- Robotic manufacture (e.g. automotive industry)

1 Intrinsic safety or other hazardous area protection
2 Robust, preferably non-invasive monitoring
3 Selectivity, without the need for sample extraction and pre-treatment
4 Little manual maintenance, self-cleaning or anti-fouling sensors
5 Data deconvolution methods (esp. for low cost spectroscopy, eg NIR, quadrupole MS, low power NMR, high speed LC/GC)
6 Real-time monitoring

- Better understanding of processes in the development phases using instrumentation that may be directly translated to production (streamlining of R&D phase into manufacture & supply)
- Telescoping of manufacturing stages by using instrumentation to give real time indication of production progress (removal of intermediate storages and stock - release of dead capital)
- Enabling of continuous processing and/or agile manufacturing plant which is responsive to fluctuations in market volume
- Creation of flexible, multi-product, production using generic instrumentation capable of operating with a wide range of conditions / products (rapid response to change in demands from market)

7 Low cost/mass produced versions of existing proven techniques
8 Multi-disciplinary integration of sensors/control with mechanical/process engineering for revolutionary, not evolutionary, new manufacturing
9 Low-level (ppm to ppt) selective contamination monitoring
10 Cost more important than novelty
11 Facilitating the converting of batch to continuous processes and scale up of small scale (micro- 'factory on a chip') to large scale
12 Automation
13 Metrology (validation etc)

5 Monitoring the environment

- Air Quality (Terrestrial & Ozone Layer)
- Water Quality
- Materials and species (e.g. NO, SO, pollen, ozone)
- Toxics / Particulates
- Radiation
- Biohazards
- "Leaks" (e.g. water, pollutants)
- Remote Sensing vs Local
- Meteorological measurements (RH, pressure, temperature, wind velocity)
- Noise
- Understanding the Data

1 Low power optical, infra-red, radar (inc' synthetic aperture), bio- and chemical sensors
2 Operate in extreme environment (hot/cold, radiation, biohazard, remote distance)
3 Data transmission rates, data volume, data compression
4 Signal-to-noise
5 Autonomy (smart systems, AI, neural nets)
6 Low cost
7 Security and integrity of system
8 Miniaturisation (micro/nano)
9 Better (more local) weather monitoring
10 Traffic management
11 Biological issues adapted from defence?
12 Dormancy/self powering

6 Increased Product Functionality

- Lighter
- Smaller
- Automatic operation
- Easier to use (if manual or semi-automatic)
- Increased safety
- Lower power consumption devices (lower operating temperature, smarter stand-by)
- Reduced energy consumption (processes)
- Better accuracy and stability
- Reduced cost
- Data processing and control
- Products created by the availability of (new) sensors e.g. using micro-engineering

1 Can be very low cost
2 Simple
3 Easy to integrate into equipment or systems (plug and play)
4 Small
5 Light
6 Low power consumption
7 Not always regulated markets; higher cost if regulated

7 Industrial Health & Safety (Environment)

- Robust on-line monitoring, preferably non-invasive, to reduce the need for occupational exposure by manual sampling
- Environmental compliance monitoring (air, water & solid phases) for specific species by fixed point and remote/satellite monitoring
- Protection of personnel from environmental hazards in the workplace through 'wearable' monitors (e.g. asphyxiation, radiation, hazardous chemical, adverse physical conditions)
- Earlier and more reliable warning of toxic gas releases
- Protection of property (esp. against explosion hazard)
- Protection of people from machinery
- Safe operation of remote or un-manned machines
- Earlier and more reliable warning of fire

1. Market spans high value to low cost
2. Methods for reliable low level gas detection (environmental releases)
3. Water monitoring (solids/chemical)
4. Low power methods for remote and portable use
5. Improved gas sensors (for heath and safety)
6. Integrated physical/chemical fire sensors
7. Smart proximity sensing
8. Unobtrusive monitoring of employees, crowds etc (drugs, alcohol, 'competence', stress, physiological indicators)
9. Legislation likely to follow technology availability (duty of care etc).

8 Leisure Industry

- Electronic toys, such as Tamaguchi, Robot dogs, Gameboy, Playstation consoles
- Virtual Reality (more sensors and actuators)
- Smart sports equipment such as smart shoes, skis, clothes
- Smart balls (for accurate location)
- Electronic line calls and net calls in tennis
- Electronic gadgets for executives (see Innovations catalogue)
- More elderly and hence more leisure time
- Interactive televisions

1. Very low cost, especially the toy industry
2. RF comms to link to TVs, PCs, Play Stations
3. Dynamic market, with short product lifetime very untypical of traditional sensor markets
4. Physiological performance monitoring
5. Microphones and speech recognition
6. Robotic toys - object recognition and avoidance has synergy with defence and security applications
7. Smart apparel (shoes ...)
8. Emphasis on simple and reliable components
9. Chemical/heath measurands are relevant

9 Mobility/Transportation

- Means of propulsion will evolve e.g. electric vehicles (EVs), hybrid vehicles, use of fuel cells etc. and all will require sensors adapted for conventional measurands
- Driver-less control
- "Shared" commuter transportation
- Location/Motion (Congestion)
- Proximity/Navigation
- Intelligent Traffic Systems
- Environment/Pollution
- Inter- Modal Transportation
- Safety & Security

1. Low cost sensors (emphasis also for aerospace)
2. Design for hostile environment e.g. on engine or on-brake caliper mounted sensors (higher temperature, higher vibration, higher EMC, etc.)
3. Lower emissions, alternative fuels, all-electric/hybrids - all require new sensors
4. Advanced electronic control systems (continued increased in addition of electronics for a range of different features)
5. Mechatronic design/multi-disciplinary design for electronics/sensor/actuator modules

	6 High reliability, high integrity, fault tolerant systems (comms and power for x-by-light systems) 7 Fly by wire systems compatibility 8 Vehicle to vehicle and vehicle to traffic infrastructure communications 9 High volume manufacturing capabilities (for automotive); high performance (aerospace) 10 Increasing reliance on sensors, including for newer concepts such as EVs with fuel cells 11 Smart public transport - matched to demand and environmental factors 12 GPS systems also open up other possibilities
10 "Domotics" - Domestic Electronics/Smart Homes ■ Energy management (including smart lighting) ■ Robotic cooking ■ Smart air conditioning systems (air quality and ventilation management) ■ Remote management (incl. security) ■ Intelligent cleaning robots ■ Fully integrated home/networked ■ Smart "re-configurable" décor ■ Alternate cooking technology ■ People sensors, people tracker/security systems ■ Earlier and more reliable warning of fire	1 Low cost market 2 Integrated, low cost CO_2, RH and temperature sensors (for air conditioning) 3 Low cost communications (wireless?) 4 Sensors to recognise specifically gas mixtures: a Products of cooking at higher temperature b Products of combustion/fire at ambient temperature 5 Object location (source or detector in motion) 6 Light level sensors (for smart lighting systems) 7 Integrated physical/chemical fire sensors 8 Auto-restocking of fridges etc.(stock sensing & control) 9 Evolution from switches to sensors and control
11 Ageing population ■ Local environment monitored ■ Movement in Home ■ Body Signs ■ Physiological Measurements ■ Information Understanding ■ Sense Augmentation & Replacement ■ Mobility Intelligent Home	1 Reliable Gas Sensors 2 Drug Delivery 3 Data Crunching 4 Sensors & systems integration 5 Remote, non-contacting monitors (physical, chemical, presence) 6 Information management
12 Food & Agriculture ■ Precision Agriculture - Sensors for controlling targeted application of agrochemicals and measuring actual amounts of crop-protection chemicals required (economic and environmental drivers). Heavy use of GPS and visible/IR satellites at present - other remote sensors in the future?	1 Non-destructive testing (eg, Ultrasound /UV/ Electrical impedance) 2 Interfacing of sensors into the real-world environment (eg, monitoring on irregular surfaces such as leaves or soil) 3 Biosensors for generic toxicology (eg, Nitrifying bacteria Tox, Activated sludge Tox, Fish Tox, Algae Tox, Invertebrate Tox)

- Biotechnology, growth in genomics and proteomics in future to aid intensive agriculture in developing world. Sensors to assist with characterising beneficial effects and environmental impact
- High throughput screening of bio-active species - methods of detection
- Combinatorial chemistry - screening and separation of required species
- Toxicological testing of new products - especially based on toxico-genomics
- Deskilling/simplification of intensive agricultural techniques so that they may be adopted in developing world - instrumentation to provide assistance with decision making for farmers
- Sustainable agriculture - measures of key parameters in soil, water courses, etc, so that they may be maintained from season to season
- Weather forecasting - more accurate monitoring of conditions to allow successful planting and sowing of appropriate crops
- Healthy food monitoring - measures of parameters in food which will indicate their general benefit to the consumer
- Distribution network monitoring - ensuring rapid transfer of goods from the farmer to the consumer taking into account contingency needs
- Early disease monitoring and tracking (e.g. BSE, F&M, others)
- Legislative demands on the industry - environmental drivers

4 ‘Effect’ sensors incorporating the desired bio-activity
5 Low cost (micro?) sensors for physical parameters, inc. remote communication & self powered (solar?)
6 Data-interpretation technology for yield mapping/prediction
7 Low cost GPS sensors with cellular network communication for tracking
8 Simple biosensors for detection of virus, and other disease transmission modes
9 Low-level contamination sensors
10 Low/self powered devices
11 Adaptability for applications

13 Increasing population

- Environmental Conditions
- Mobility
- Food/Water Supply
- Energy
- Housing
- Fire/Safety Risk
- Education
- Healthcare
- Crime/Security

1 Low-cost application
2 Data transmission to central systems, e.g. fire stations, police stations, transportation systems has infrastructure implications
3 Reliable, low maintenance, graceful failure to limp-along mode
4 Automatic fault diagnostics and signalling
5 ‘Rate sensors’: where are people, where are they going, what doing, how fast

14 Telecoms & Media

- Communications interference
- Communications speed and bandwidth
- More convenient than carrying telephones, pagers etc (Star-Trek badge or woven into clothes)
- Inter-link types of communication and media
- Personalised information suppliers that know my interests
- Paperless newspapers
- Lots of remote video sensors that can be selected to provide live feeds

1. Communications interference: need to detect EM interference (probably achievable) - and processing to compensate sensibly
2. Communications speed and bandwidth heading in the right direction and should be ok provided national infrastructure appears
3. More convenient communications than carrying telephones, pagers:
   a. Reduce size (heading in right direction)
   b. Build into garments (need to be cheaper, washable, more rugged, flexible) or attach as a badge
4. Inter-link types of communication and media
   a. Higher bandwidths
   b. Intelligent links between different types
5. Personalised information that know individual interests needs intelligence to train an "agent" to individual tastes with processing to act on it
6. Paperless newspapers: electronic paper - re-writable, large enough, lightweight, clear enough to read, adapting in dim and bright conditions; colour
7. More remote video sensor that can be selected to provide live feeds
8. Improved local communications - optical; RF

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The Sensors Task Force met for the first time in November 2002 and held three further meetings prior to the Public Consultation Meeting

The Foresight Programme

The Foresight Programme brings together the voices of business, Government, science and others to look at what might happen in the future and what we need to do now to secure long-term competitive advantage and enhanced quality of life for all.

It was launched in 1993 following the Government White Paper on science, engineering and technology, Realising Our Potential. It has a panel-based structure and operates on a five-year cycle. The current round of Foresight began in April 1999 - the most ambitious programme of future thinking ever undertaken in the UK. It moved beyond the technology focus of the first round, which reported in 1995, to examine the opportunities that arise from the interaction of innovations in science and technology with wider social and market trends.

Each Foresight panel - from the three thematic and ten sectoral panels - have looked at the future for a particular area, identifying the challenges and opportunities that the country is likely to face over the next 10 to 20 years and beyond. During the current round, the panels and their Task Forces (over 500 individuals in all), have engaged in a wide public debate, with 190 conferences and seminars and 33 consultation papers published on the Foresight website and have developed and strengthened networks in the process.

The panel reports - available on the Foresight Website or by contacting the Foresight Directorate - provide the basis from which panels and others are working to help turn the recommendations into action - at national, regional and sectoral level.

Panels that have been set up as part of the current round:

- Ageing Population*
- Crime Prevention
- Manufacturing 2020*
- Built Environment & Transport
- Chemicals
- Defence, Aerospace & Systems
- Energy & Natural Environment
- Financial Services
- Food Chain & Crops for Industry
- Healthcare
- Information, Communications & Media
- Materials
- Retail & Consumer Services*

A further industry-led panel is looking at Marine issues and there is a task force addressing the impact of e-commerce on business processes and supply chains.

The Foresight programme is currently being reviewed, to build on the success that it has had and to ensure that it focuses on the challenges that lie ahead. The first phase of the review - led by a board chaired by the Government Chief Scientific Adviser, Professor David King FRS - has been completed and consultation about the way forward is being undertaken, largely via the Foresight website.

* Panels that have now stood down

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