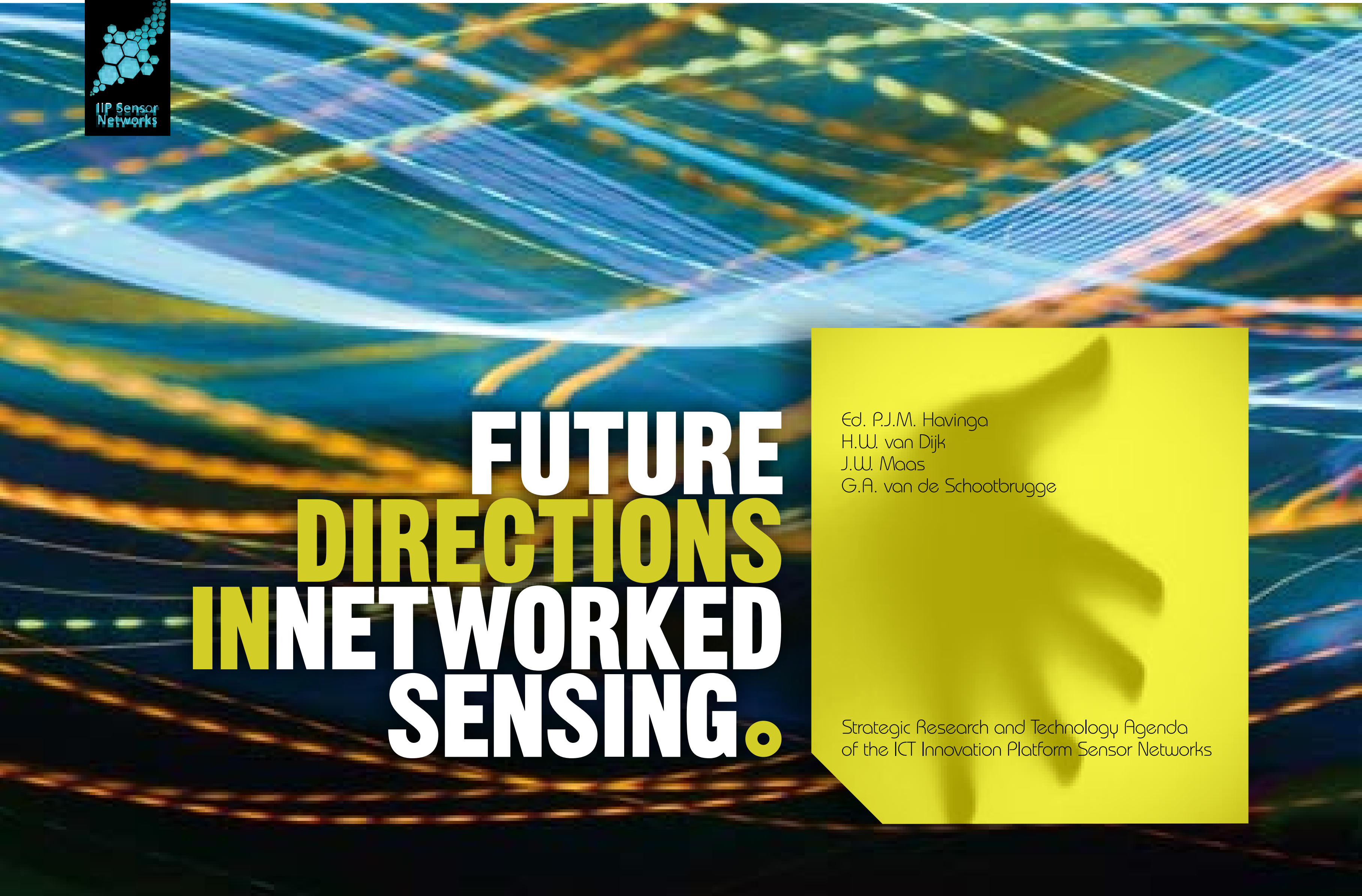
IIP Sensor Networks



FUTURE DIRECTIONS IN NETWORKED SENSING.

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Strategic Research and Technology Agenda of the ICT Innovation Platform Sensor Networks

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PREFACE

SENSOR NETWORKS: FOR THE BENEFIT OF ALL

Sensor network technology is of global importance. Future developments will result from world-wide R&D efforts. Progress and successful implementation will depend on international co-operation. So, Dutch programs in this area should fit into the national and European policies for innovation and economic development.

In March 2010 the European Commission launched the Europe 2020 Strategy to exit the crisis and prepare the EU economy for the challenges of the next decade. The Digital Agenda for Europe is one of the seven flagship initiatives of this strategy, set out to define the key enabling role that the use of Information and Communication Technologies will have to play if Europe wants to succeed in its ambitions for 2020. Major issues of the Digital Agenda are: Sensor Networks, the Internet of Things (IoT) and the Future of Internet. Addressing the key elements, commissioner Kroes stated: "In simple terms it is obviously about chips, wireless networks, readers and sensors, connecting (potentially all) objects to the Internet. These connections allow objects, machines and people to gather, exchange, store and process information" (Brussels, June 1st 2010)

Right. But it is also, and even more important, about values and fundamental democratic choices. These new technologies will be powerful and will strongly influence our life. We face a major challenge: guarding humanitarian values and, at the same time, ensuring progress and competitiveness. Thinking about the future and considering the huge potential of these technologies for creating wealth in a sustainable and fair way, we should always take into account the public image of the proposed solutions. If citizens get the feeling that this new technologies will affect their privacy, control their lives and force them to adapt, public resistance may interfere with a successful deployment of these technologies. I fully agree with commissioner Kroes' call for more R&D and for placing the citizens at the centre - ensuring that the human perspective is safeguarded in all new IT technologies.

R&D communities should make up their mind and update their objectives for the medium term on a regular basis. Important questions are: what is the state of the art, what are the bottlenecks and what is the expected need of potential users? The Netherlands has a relatively strong position in the field of sensor technology. This Strategic Research and Technology Agenda is an important tool for keeping this position.

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CHAPTER 1

INTRODUCTION

Started one decade ago as a wild academic idea, wireless sensor and actuator networks turned into a vibrant research area with a large R&D community dealing with a commercially highly relevant technology. The new paradigm in networked sensing has received significant attention because of the unprecedented benefits it promises in many areas. Seamless integration of computing with the physical world via sensors and actuators will generate higher living standards, greater safety, more comfort and more efficiency in a more sustainable world. Emerging applications include environmental monitoring, health, sport, transport, public and industrial safety, manufacturing plants and ambient assisted living. However, in spite of the significant research efforts that have been spent world-wide since the start, realization of all these great opportunities turned out to be harder than expected.

Lessons learned indicate that the real world in which sensor networks have to operate is hard and continuously confronts researchers and developers with the harsh physical reality. Challenges include the stringent resource constraints of such systems, dynamicity in a real world, heterogeneity of devices, protocols and applications, and complexity when dealing with a large number of autonomous devices. The increasing complexity of such systems can be seen across all these domains. This places strong demands on the needs for advanced new technologies for monitoring and control as well as the underpinning methodologies and theories. The Netherlands have acquired a strong position in the academic and commercial community of wireless sensor networks, and are generally recognized as a leading country in the world.

In this Strategic Research and Technology Agenda (SRA), the Dutch sensor network community presents its vision on the further development of this important technology. The technology is entering a new phase aimed at a more mature profile and pervasive deployment. This implies amongst others the use of standardized tools which are necessary to turn special-purpose solutions into generic network facilities which can be applied for a variety of purposes and in different operating conditions. Efficiency considerations still play an important part in this R&D policy. Part of the future R&D program will be focussed on the know-how that is needed to apply this more generic network technology in the near future. The real potential of sensor networks will become clear when this new phase has passed.

The new networks will not only be deployable in a cost effective way, they will also be complex: large numbers of relatively simple sensor nodes eventually combined with networks of more sophisticated sensor systems like intelligent camera's. In order to profit optimally from the new options, a number of problems have to be solved. Some of them are quite tough! To name a few: networks should be scalable whenever extra sensors are added, which means that they still function and perform better. Future networks will become parts of bigger sensor structures. Other questions that should be answered concern the way information is processed: locally, centrally, combinations. Future networks will be mobile and dynamic. They should be adaptive to new internal and external situations and changing conditions. Last but not least, we will need new concepts for powering the sensor nodes. In many cases, networks of the future will take care of their own energy supply so that the use of batteries can be skipped. These and other technological challenges are described in this SRA.

CHAPTER 2

SMART SYSTEMS FOR SHAPING OUR WORLD.

Sensor Networks belong to the category of Smart Systems. Smart Systems can be described as integrated systems[1] which:

- are able to sense and diagnose a situation and to describe it;
- mutually address and identify each other;
- are predictive and are able to decide and help to decide;
- operate in a discrete, ubiquitous and quasi invisible manner;
- utilize properties of materials, components or processes in an innovative way to achieve more performance and new functionalities;
- are able to interface, interact and communicate with the environment and with other Smart Systems;
- are able to act, perform multiple tasks and assist the user in different activities.

Such systems are networked, autonomous, miniaturized, reliable and in some cases even implantable. New features like ubiquitous connectivity, security, ease-of-use and the integration of mechanical, optical, electronic, biological or other properties through various innovative technologies have yet to be fully realized.

Forecasts show that up to 2020 smart systems applications can reduce 23% of global emissions with an equivalent of 9.2 Gt CO_2(e) by providing smart solutions for energy management and distribution, smart control of electrical drives, and the optimization of logistic or energy-efficient facility management. This figure is equivalent to an impressive market value of 65 to 70 billion EUR world-wide. In the area of e-health, one of Europe's identified lead markets, Europe's market volume is expected to increase until 2020 to an impressive 30 billion EUR. If this materializes, 360,000 new jobs will be created in this sector throughout Europe. Again, smart systems integration will be the all-dominant enabler for smart solutions combining medical devices and IT, for high level systems integration, rapid growth in networked applications and the extension of IT support to healthcare consumers.

Information-technology (IT) firms have identified smart systems as the next big thing. A couple of years ago IBM launched a campaign called "Smarter Planet", touting digital technology that would make energy, transport, cities and many other areas more intelligent. Cisco is promoting its "Smart+Connected Communities". Hewlett-Packard intends to spin a "Central Nervous System for the Earth" with billions of sensors.

Many countries have been investing strongly in smart-infrastructure projects, and some have made smart systems a priority of industrial policy. The "Internet of Things", another label for these systems, is central to the European Union's "Digital Agenda". There is a broad consensus that such systems are really needed. In many countries the physical infrastructure is aging, health-care costs are exploding and money is tight. Using resources more intelligently can make taxpayers' money go further. Monitoring patients remotely can be much cheaper and safer than keeping them in hospital. A bridge equipped with the right sensors can tell engineers when it needs to be serviced.

Most important, smart systems may well be humankind's best hope for dealing with its pressing environmental problems, notably global warming. Today power grids, transport systems and water distribution systems are essentially networks of dumb pipes. If the power grid in America alone were just 5% more efficient, it would save greenhouse emissions equivalent to 53 million cars, calculates IBM. In 2007 its congested roads cost the country 4.2 billion working hours and 10.6 billion liters of wasted petrol, according to the Texas Transportation Institute. And utilities around the world lose between 25% and 50% of treated water to leaks, according to Lux Research, a market-research firm. (The Economist, November 4th 2010)

SOCIETAL RELEVANCE

Sensor networks are important for solving big societal problems. But they also can have quite an impact on the individual life of citizens. Many applications of sensor networks touch upon important human values and even human rights. Fundamental issues like privacy and personal autonomy are at stake. Broad acceptance of these new far-reaching technological tools and infrastructures requires understanding of public resistance caused by emotions and even fear. Informing the public by trusted parties about the pros and cons and taking care of general principles of transparency and human rights are of utmost importance. We can learn from history about the acceptance of new technologies. Why was internet accepted so smoothly and why did European citizens reject genetically modified food?

The recent explosive use of smartphones and their "apps" (small downloadable applications that run on these devices) is now speeding up the convergence of the physical, the digital, and social worlds. Smartphones are packed with sensors, measuring everything from the user's activities to the ambient light. Information that can be shared to enable users, consciously or not, to do a great variety of things, from tracking their friends to controlling appliances in their homes.

Sensor networks potentially can answer to the big societal issues. In the domain of health support[2], sensor systems support remote monitoring and tele-treatment of care consumers. This prolongs the stay and treatment of people in their own environment; intramural care can be replaced by less costly extramural care. Sensor networks play a role in systems for Home Care Services, Decision Support, Tele-treatment, and Ambulatory Medical Imaging. In the domain of mobility[3], sensor network systems will be able to warn for dangerous or aberrant situations on the road. In case of traffic jams, emergencies, or special traffic lanes, sensor networks facilitate the car to take over control. In addition, sensor systems are essential to improve road utilization. In the domain of safety and security[4] for the citizen, sensor technology provides important information, while the absence of sensor data enlarges the risk of calamities and inadequate decisions. Current operational warning systems are often unreliable, generate too much false alarms, and often too late. Sensor systems can realize early warning systems to support crowd management, crowd control, management of terrorist threats, dike guarding, fire safety, monitoring of processes in the chemical industries and other high-risk processes. Other domains where sensor networks can make the difference, socially speaking, include sports, sustainability and critical infrastructures.

THE INTERNET OF THINGS

Miniaturization will lead to a massive use of sensorized products and items. These sensorized items will communicate with persons and with each other using internet technology. This Internet of Things concept was introduced by Kevin Ashton of Proctor&Gamble in 1999. It will be a part of the Internet of the Future, as recently articulated by Gérald Santucci, chair of the EU initiative on Internet of Things and Future Internet Enterprise Systems.[5]
These and other services are bound to grow together into what Jan Rabaey, a computer scientist at the University of California at Berkeley, grandly calls “societal information-technology systems”, or SIS. Technological progress is sure to supply the necessary components. Moore’s law, which holds that the processing power of a single computer chip roughly doubles every 18 months, applies to sensors, too.

More processing power and better connectivity also allow the construction of computing systems capable of storing and crunching the huge amounts of data that will be produced by these sensors and other devices. All over the world companies are putting together networks of data centers packed with thousands of servers, known as “computing clouds”. These centers not only store data but sift through them, for instance to allow a smart system to react instantly to changes in its environment.

Is the Internet of Things 'the next big thing? According to the believers, it will help solve some of the biggest problems facing the world such as energy supply and health care. Buildings currently waste more energy than they use effectively. We will be able to cut this waste down to almost nothing. Health care is currently delivered in lumps: we visit the doctor a couple of times a year at most, and get our blood pressure checked every now and again. The IoT will allow us to monitor our bodily functioning all the time. A few sensors discreetly attached to the body will keep us constantly informed about how our vital functions are doing. It will also help us to keep ourselves healthy. Pill bottles will tell us when to take our medicines; wine glasses will be able to tell us when we have had enough to drink; sugar bowls will warn us about our sugar intake.

DUTCH INNOVATION POLICY

ICT has been identified by the Dutch government as an innovation area of major strategic importance. R&D-programs in this area are co-ordinated and supervised by ICTRegie. This agency mobilizes supply and demand in ICT knowledge around challenging themes. For this purpose so-called ICT Innovation Platforms or IIPs have been established. An IIP is an interest group of stakeholders sharing a common interest in a particular subject. Sensor network technology is one of the special interest issues in the Dutch innovation policy, and the IIP Sensor Networks (IIP-SN) is one of the established platforms. IIP-SN is an open platform aimed at strengthening, connecting and continuing activities in the field of sensor networks through development of a technology base that is ready to meet important challenges in industry and society. Current interest concerns areas like health, safety & security, mobility and sustainability.

IIP-SN structures its activities in domain-oriented themes. These themes follow closely the set of other IIPs, in particular related to mobility, health, security and sustainability. Many of the established IIPs explicitly stress the need to further develop smart sensor systems, distributed intelligence, and complex models. This underlines the important enabling character of sensor network technology.

IIP-SN stimulates research and development at all levels of the value chain through projects with concrete objectives. Universities and knowledge generating organizations are encouraged to share their R&D results with private parties through partnerships with industry (including SMEs) and users. The Universities for Applied Sciences (vocational training) play an important role in the education of engineers and in the transfer of know-how to industry through applied research programs.

CHAPTER 4

SENSOR NETWORKS.

The first decade of the century, the interest in wireless sensor and actuator networks (WSN) has grown dramatically. This interest is the result of new technological opportunities offered by the ongoing miniaturization of electronic building blocks. The result of Moore's Law: more functionality, smaller dimensions, cheaper, lower energy consumption. IC-technology, MEMS-technology (Micro-Electro-Mechanical System) and NEMS (Nano-Electro-Mechanical-System) cause a true paradigm change in the world of sensor network technology.

Sensor networks show a great diversity. Some are cabled, others are wireless. Revolutionary developments are expected in the wireless domain. In some cases, networks consist of sophisticated nodes, for instance heterogeneous networks combining intelligent cameras with other sensing devices for security purposes like boarder protection. In most cases however, the future networks will consist of a large number of relatively cheap nodes with some memory, some processing capacity, some wireless communication facilities and some power. These networks differ as to the architecture, the way intelligence and processing is distributed over the network, the energy conservation mechanisms of the nodes, the powering (batteries, harvesting), etc.

Sensor network technology promises automatically monitoring and responding to all kinds of trouble in nature (forest fires, environmental pollution, gletscher status, etc.), on the road (safety issues, transport efficiency, etc.), in the hospital (patient monitoring, drugs logistics, etc.), and in industry (monitoring and control, logistics, asset management, etc.). In many cases these networks cover wide areas with hundreds or even thousands of sensors. Networks with millions or even billions of tiny and very cheap sensors are expected within ten to twenty years from now.

WSNs are wireless mesh networks that link devices that contain a wireless transceiver, a communication protocol handler, an application specific processor with appropriate storage, an onboard power source, and at least one sensor and/or actuator. In a WSN mesh network, any node can electronically talk to any other node that is in range. WSN nodes are self-forming - put them in the range of the network and they automatically join - and the network is self-healing - it finds a way to signal around any failed nodes because the mesh of communicating nodes allows multipath hopping of the signals in and out of the network. To that extent a WSN is comparable with the internet, but whereas the internet has TCP/IP as the standard transport protocol, WSNs lack a common stack on which all applications are implemented.

WSNs are easy to install and exceptionally scalable - deployment of more and more nodes in a system is relatively easy - and they are responsive to their environment. They are designed to provide information of great integrity and usefulness from large numbers of imperfect, low cost nodes infrequently sending and receiving modest amounts of information to each other over modest distances, many short ranges adding up to long range[6].

Although currently various sensor and actuator node platforms are commercially available, no operational large-scale network of cheap, energy-efficient and small sensor and actuator node platforms exists. Therefore, it is time to identify what it takes to go beyond small-scale prototypes.

EVOLUTION

Networked sensing technology can be broken down into a) a technology that interacts with the physical world, further specified in sensing, analysis, synthesis, and actuation, b) in a technology that facilitates communication and cooperation among interacting nodes, and c) a technology that manages the thus formed system[7].

The evolution of sensor networks has been driven by research and development, which can be attributed to dedicated regions in the technology space. In Figure 1 we have indicated the current main fields of interest. Basically, research has been focused on developing efficient sensors, efficient radios for internodal communication, efficient routing and media access protocols. Research has started to work on management, business logic, and programming of sensor networks. Yet many systems still take a centralized position by transferring sensor data to a backbone for further processing and actuation. As indicated in Figure 1, emerging research and development interests include now management, in-network reasoning and control, and actuation. In addition, dependable networking and communication receive their fair share of attention.

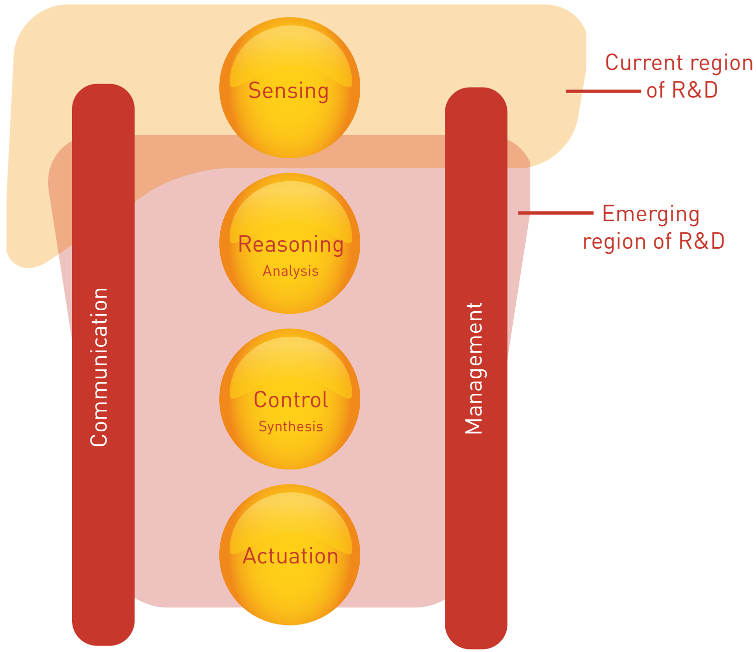


Figure 1. Sensor Network Evolution.

The field of sensor networking is very diverse. Dependability, scaling, trustworthiness, time to market, business alignment, and integration are all potential show stoppers for successful facilitation. Yet there is a universal consent that it can be done. The way to proceed is to develop models for many of the identified issues and their expected solutions. Proper models will guarantee seamless interaction. In addition, validation and exploration is important to keep in touch with the market. In parallel, innovative business models must be explored.

This SRA follows the proposed structural approach by identifying four core themes in sensor network technology. A fifth theme comprises the driving application domains, see Figure 2.

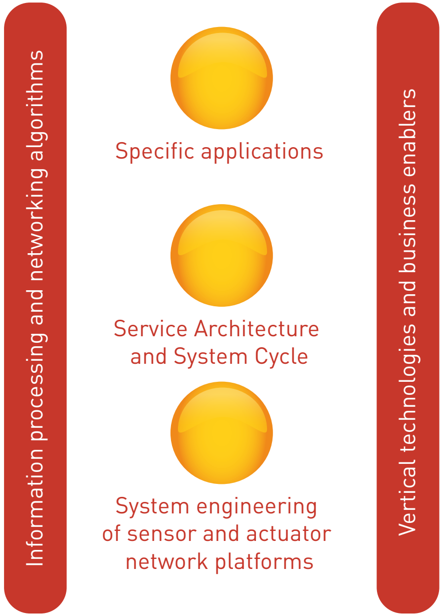


Figure 2. Sensor Networking Themes

CHAPTER 5

STRATEGIC RESEARCH AND TECHNOLOGY AGENDA.

This Strategic Research and Technology Agenda Sensor Networks (SRA) identifies inhibitors of successful developments and proposes solutions to mitigate potential barriers. It is meant to inform the general public, politicians and decision makers, and funding organizations about the importance of networked sensing, the state-of-the-art and the steps needed to create and strengthen a strong and profitable knowledge and technology base.

The SRA is based on a large number of position papers and on the outcomes of a two-days workshop (August 2010), in which a group of leading Dutch experts participated. In addition, a condensed version of the list of identified inhibitors and solutions has been subjected to an on-line survey. The respondents helped to prioritize identified issues, which are organized around four themes:

1. Data: system engineering and platforms
2. Information: processing and networking
3. Control: service architecture and system cycle
4. Business and Society: vertical issues

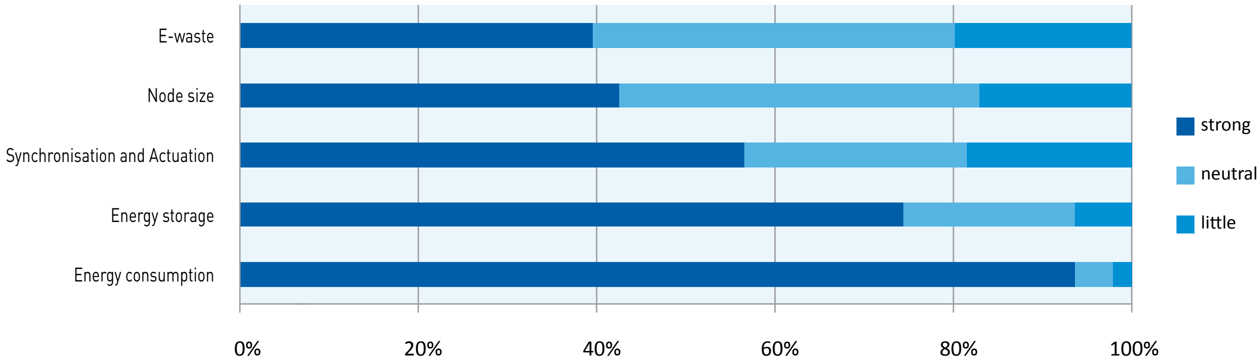
For each theme we have identified inhibitors, roadblocks that hinder the pervasive application of sensor networks in the domain we sketched before. In an on-line survey, experts in the field ranked the significance of the inhibitors. The process of identifying and ranking inhibitors yields a set of research and development directions that potentially enable solutions to the enumerated inhibitors. These enabling topics too have been ranked given their urgency. They will be presented in a separate section.

DATA: SYSTEM ENGINEERING AND PLATFORMS

System engineering and platforms concern the capturing of data, the actuation, and the interface to support efficient, flexible, and accurate control over the fundamental processes of sensor networks. From this theme's perspective it is imperative to design and develop energy efficient and miniaturized hardware, for integrated and multi-functional sensing, for analogue and digital signal processing, and for effective actuation. Flexibility is ensured through the use of energy harvesting and energy storage mechanisms. Special attention is required for packaging for deployment in harsh environments. Ease of deployment and accurate control will be provided through the design and development of energy efficient communication, synchronization, collaboration, and co-location techniques. Radio technology for existing and new media are covered, think of ultrasound underwater and ultrasound through-the-wall communication.
Inhibitors for system engineering and platforms include:

Energy consumption. Many sensors and actuators have limited access to energy, which makes it the single most scarce resource in sensor networks. Power hungry designs may increase the functionality of devices, but will considerably reduce their lifetime.

Inhibitors for Data



Energy storage. Energy is generally not ubiquitously available. It is either limited in capacity by the battery, or only available at specific times in case of energy harvesting. Large batteries contradict miniaturization and frequent replacement of batteries is uneconomical.

Synchronization and Actuation. Current actuator nodes generally support a limited number of modalities. In order to increase control and response capabilities more complex actuators nodes are necessary. Nodes require efficient means for synchronization, in time and in space. Inability to synchronize various modalities reduces the accuracy of measurements and control considerably.

Node size. Sensor and actuator nodes are deployed close to an object under observation or control. As an example, biosensors will be unobtrusively attached to people or integrated within their cloths to enable creative and comfortable applications. Big integrated nodes generally require too much energy, too much space, and too much maintenance to be merged in the environment and to be economical.

E-waste. Nodes are deployed in harsh or aesthetically appealing environments. This requires appropriate packaging. At the end of their lifetime, nodes become electronic-waste. Just leaving them behind is a high burden on the environment and a potential destruction of assets.

INFORMATION: PROCESSING AND NETWORKING

Information processing concerns all necessary steps from the sensing of data through the information as presented to applications for further processing and interpretation. The loop is closed, information processing involves compound sensors (sensor of sensors) as well as compound actuators. Networking concerns the process of propagating data through a network that is in a constant state of flux.
Inhibitors for processing and networking include:

Scalability. Many engineered sensor networks suffer from performance loss, or even breakdown, when deployed at a large scale. Ideally, adding more nodes to a network should improve the performance rather than attenuate it. Currently, proving scalability is an academic exercise.

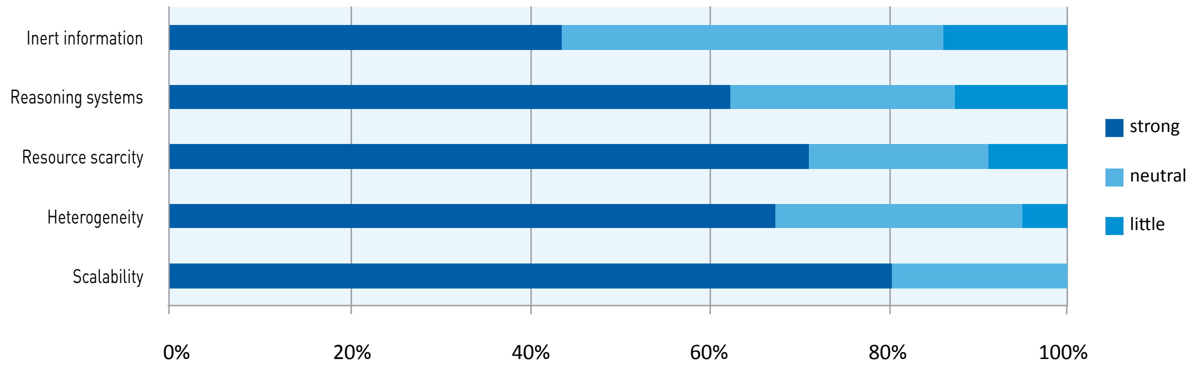
Heterogeneity. Sensor networks are built by using a large body of experience from many application domains. Consequently, the variety in existing sensor and network technologies is large. An enabling, universal, technology must be able to cope with these nodes that differ in time scale, in semantics, in size, and in distortion. Current systems lack effective provisions to deal with this heterogeneity.

Resource scarcity. Sensor networks suffer constantly from a lack of resources. When energy consumption, bandwidth, processing power, and storage capacity are wrongly managed, the lifetime of a system is affected in a negative way. Real-time behavior is a crucial factor enabling efficient resource usage and is also essential for quite a range of applications: prompt response to observations and immediate action.

Reasoning systems. Future sensor systems must be flexible and functional. Without the ability to support multiple applications, to maintain concurrent modes of operation, and to reconfigure seamlessly, the acceptance in the value chain is confined to niche markets. For that reason, a proper system support for an in-network reasoning system is essential.

Inert information. Networks that dynamically scale in size and density must handle data streams that vary in detail and breach over time. Since both too much and too little data renders the network useless, the network must be able to handle the dynamics in the data supply. An additional problem is that system-wide objectives, if articulated, may not comply with individual objectives. Interference takes place at all levels: media use, processing, and storage.

Inhibitors for Information

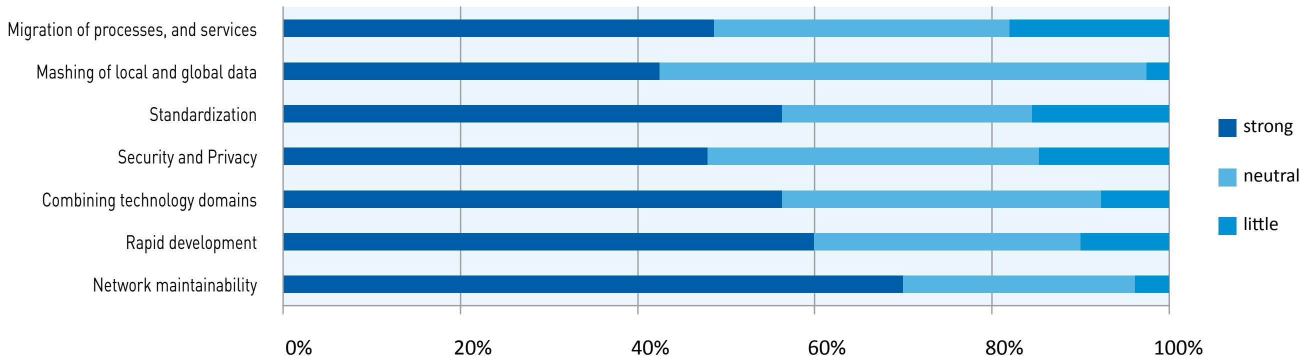


CONTROL: SERVICE ARCHITECTURE AND SYSTEM CYCLE

An operational networked sensing and actuation system is the result of a development and deployment process. In a fairly standardized approach, the following steps are involved: analysis, design, implementation, testing and maintenance. We call this the system cycle. A platform approach aims at a service architecture, tooling and middleware that is independent from the hardware platform, supporting a wide range of information processing and networking paradigms and applications. Thus creating a service architecture.
Inhibitors to the service architecture and system cycle include:

Network maintainability. Networks must be reliable and easy to maintain. Ideally, systems are self-healing and optimally redundant. A careful trade-off between abstraction and transparency is necessary to handle heterogeneous and large-scale networks. Proper tools for in-system diagnosis, debugging, control and general management support are invaluable.

Inhibitors for Control



Rapid development. The universal acceptance of sensor systems is hindered by long development times. Without proper programming models that handle heterogeneity and provide debugging aids, this situation will remain to exist. In order to prove the value of models, large testbeds are required.

Combining technology domains. In addition to the inability to combine data from various sources, often the various technology domains are ill connected. A generic platform that semantically supports combinations of multi-layered technology domains would be a true asset.

Security and Privacy. Societal acceptance of sensor networks requires trustworthy methods for selective disclosure of data and revocation of data if expedient. In order to generate value by a sensor network, inherent support for authentication, authorization, and accounting is crucial.

Standardization. Without proper alignment of design principles and standardization of sensor and actuator configurations and their data, system composition will remain a tedious and labor intensive process.

Mashing of local and global data. The effective combination of locally sensed and globally accumulated data gives a performance boost to services of sensor networks. However, currently the technology does not enable semantically supported combinations of multi-layered data, which makes it virtually impossible to create a platform that supports heterogeneous data sets.

Migration of processes and services. System flexibility is a requirement for many announced applications of sensor networks. Proper mechanisms to support migration of processing and services, as well as reconfiguration after node failures, currently prevent universal application of sensor networks.

BUSINESS AND SOCIETY: VERTICAL ISSUES

The value chain of sensor networks contains integral aspects that cannot be confined to specific layers of technology, design, processing or networking. These aspects constrain the whole system, its concepts, its fundamental principles, and the effectiveness of business processes. Important issues include encouragement for innovative application of sensor networks, fostering cross-sector partnerships built around the value chain of sensor networks, and leveraging sensor networks as user-based open innovation schemes. In addition, the regulatory and policy issues must be addressed to create interoperability, openness, lawful interception, and privacy to name but a few. All aforementioned issues originate from business enablers, business opportunities, and political and societal concerns. Inhibitors for vertical issues include:

Dependable systems. Social and business acceptance requires reliable and trustworthy systems. Failing systems are a cause of frustration for consumers, which has its effects on business opportunities. Even more sincere is the dependability on accurate observation systems for monitoring of critical infrastructures.

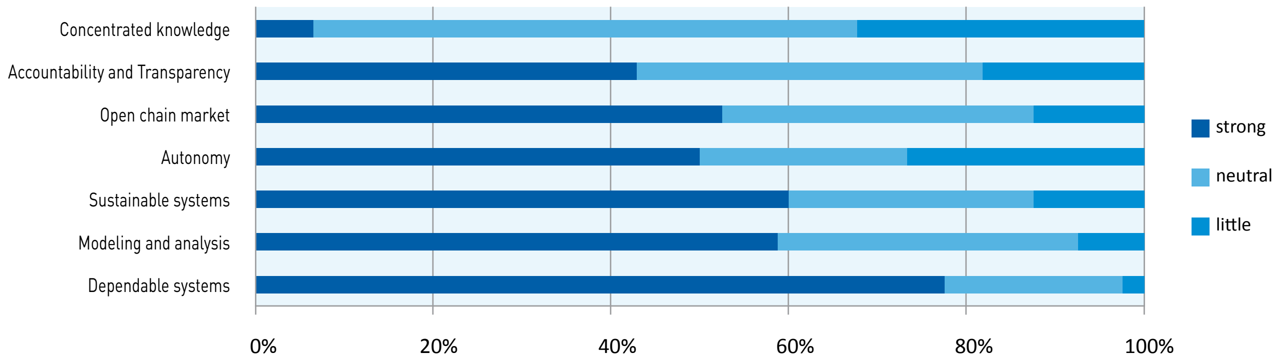
Modeling and analysis. Large-scale and highly dynamic sensor networks show emergent behavior. Effective application methods and tools are required for the assessment of the impact and efficacy of these systems. Evaluation of installed systems as well as performance prediction of systems under development is important. In every business model reasoning about quality is an essential asset. If we cannot publish a quantitative quality measure of data procurement, proper reasoning becomes impossible.

Sustainable systems. Social and political acceptance of sensor systems demands efficient use of resources and of the public space. The main resource is energy, which concerns the energy used by the system itself as well as the energy used by the system under observation. Green buildings and green technology will be accepted if and only if it can stand its promise to save energy.

Autonomy. For the ubiquitous application of sensor networks autonomy of nodes and the network is an absolute must. Typical characteristics such as self-supporting, self-configuring, and maintenance-free must be achieved.

Open chain market. Until now, sensor networks have been treated as a technology for niche markets. In order to conquer the world, viable innovative business models are crucial.

Inhibitors for Business



Accountability and transparency. Users are accountable for their actions while they should rely on being in control. The system must accommodate both properties for successful business deployment and public acceptance. Large-scale networks may have different hardware owners and different service providers. The lack of clear models of ownership and management of data and infrastructure hinders the acceptance and use of these systems.

Concentrated knowledge. For the successful and promptly deployment of sensor networks, access to the appropriate knowledge and experience is crucial. Without a fully equipped knowledge center it will be difficult for new entrants to find their way, which hinders business acceptance of sensor networks as an enabling technology. In addition, the lack of methods and tools for (large scale) validation and feasibility studies limits successful business applications. Experience is crucial.

ENABLERS AND DIRECTIONS FOR RESEARCH AND DEVELOPMENT

In the previous sections, we have presented a range of inhibitors for each of the themes. A number of them include an obvious solution, while others will benefit from a more general approach. The non-exhaustive list of solution directions in each of the four identified domains is as follows:

Data

1. Auto calibration. Maintenance-free nodes are enablers for many business models. Unmanned calibration of measurements is generally a hard problem, which becomes even more problematic when nodes are inaccessible and when the number of nodes is large.

2. Sensor/Actuator platform. For the flexible deployment of sensor networks, a standardized platform is essential. A platform allows for efficient reuse, effective resource sharing, and easy configuration and deployment.

3. Ultra-low power. Flexibility, accuracy, and response time come with a requirement on the processing bandwidth of sensor and actuator nodes. Development of high-precision, high-speed, yet low-power digital signal processing units is crucial. Sensors and actuators operate in the physical, thus analogue, domain, while data management and control processing are generally in the digital domain. Conversions from one domain to the other are loss-free only at the cost of a significant amount of energy. Better and scalable conversions will help to exploit opportunities to reduce energy costs.

4. Energy harvesting. Tiny nodes use little energy and, what is more, tiny nodes are often surrounded by energy sources. However, most of the time the energy is not in the right form to be used by the node directly. New means are needed to harvest these energy sources. The ultimately goal is a generation of self-supporting nodes.

5. Reconfigurable radio design. Reconfigurable radios yield highly sensitive, flexible, and energy efficient radio components. Special attention is required to make them context aware, which enables efficient use of resources. Examples include quality-aware MAC, time synchronization and localization.

6. Recycling. The ecological footprint of large-scale sensor networks is quite significant. Careful design to minimize the waste, during production, operation, and at the end of their lifetime is required to guarantee societal acceptance. Solutions are sought to structurally develop systems that enable reuse and repurpose end-of-life equipment, and that annihilate worn-out infrastructures.

Information

7.Dynamic clustering and linking. Application should address nodes and clusters of nodes by their properties, rather than by their physical address. Naming, identifying, and profiling of logically structured nodes and clusters will greatly simplify the composition of complex, dynamically changing applications.

8. Adaptive distribution. Processing and storage nodes can be scattered over the network or can be concentrated in a central area. An adaptive arrangement of processing and storage sites configures and reconfigures the networks of these resources depending on the actual state of the network and the nature of the application. Applications benefit from the appropriate organization of a network. Sometimes a centralized approach is adequate, while at other times application infer data in a distributed way.

9. Incomplete data. Suppose that we can build a decision making hierarchy, based on the amount and accuracy of the available data. At some point in the decision tree the outcome is not likely to change. This decision can be used, irrespective of the fact that the data is complete or not.

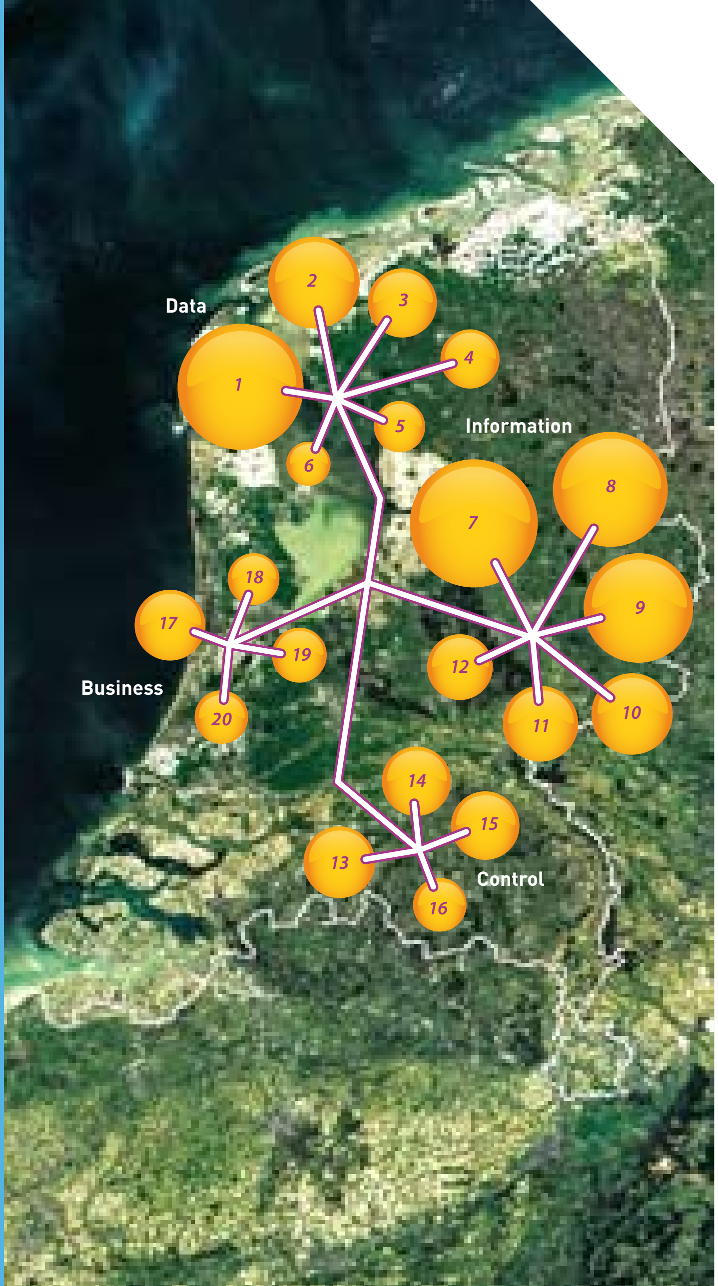
10. Adaptive sampling and censoring. By exploring the networked capabilities of sensors, it is possible to reduce energy consumption while still being effective. Adaptive sampling methods, that is scheduling and assignment of nodes, in time, in space, and in information, potentially improves efficiency.

11. Semantic data aggregation. Data that comes from different sources is difficult to combine. In case of a semantic annotation, data can be transferred automatically to a common domain, which simplifies complex applications. Semantic aligning and standardized tagging of information across heterogeneous node sets is a solution to self-calibration, automatic mashing of data, and business integration.

12. Joined network and information coding. Keeping a strict separation between communication layers is known to result in suboptimal use of the available channel capacity. Cross-layer optimization of information and communication may increase the information capacity of a network considerably.

Control

13. Sensor experience testbed. In order to enable the proposed fundamental, creative, and technology-rich solutions, alignment of efforts is an absolute must. To validate methods individually as well as in cooperation with each other, large-scale experience field laboratories must be developed. These laboratories can be part of a one-stop entry point for knowledge dissemination.



14. Programming models. Generic application rules, with accompanying programming primitives, and proxies provide the basis for compiler-founded techniques in the programming and configuration of sensor networks. The application rules include technical aspects as well as political aspects. Dissemination of these rules and their acceptance are important assets.

The plotted radius of each enabling solution corresponds with the identified urgency. A big circle calls for immediate action.

Data

1 *Auto calibration*
2 *Sensor/Actuator platform*
3 *Ultra power DSP*
4 *Energy harvesting*
5 *Reconfigurable radio design*
6 *Recycling*

Control

13 *Sensor experience testbed*
14 *Programming models*
15 *Platform models for nodes and networks*
16 *System wide resource management*

Information

7 *Dynamic clustering and linking*
8 *Adaptive distribution*
9 *Incomplete data*
10 *Adaptive sampling and censoring*
11 *Semantic data aggregation*
12 *Joined network and information coding*

Business

17 *Application driven development*
18 *Business model development*
19 *Future Internet*
20 *Personalisation and differentiation*

15. Platform models for nodes and networks. Uniform abstractions and transparencies are absolute prerequisites to develop model-based composition methods and tools. Given these models, networks of sensors can be deployed of the shelve.

16. System wide resource management. The setting of individual nodes and the overall objective of the system may no be in line. Aligning methods may help to mitigate interference and scaling problems.

Business

17. Application driven development. Before true multidisciplinary development in sensor networks can be effective, interdisciplinary projects that accelerate public acceptance and business in this field have to be initiated. Identified application domains include Smart Farming, Mobility and Transportation, Safety and Security, Sustainability, Care and Health, and Society Participation. Although production and logistics are situated in the tail of value chain, it is essential to prepare for efficient activities. Interestingly, sensor networks can help to realize these activities.

18. Business model development. For the broad acceptance of sensor network technology properly aligned business models must be developed. From past experience expedient business models include: Monopoly, Open source, Service Oriented Architecture, and Participatory. The latter uses the public to gather and distribute data in the public space. A particular challenge is the development of a really large-scale network, with more than 100,000 cheap and redundant nodes. Research and development activities for these markets are notoriously difficult.

19. Future Internet. International programs on Future Internet and the Internet of Things have overlapping objectives with the current agenda for sensor networks. Activities in that context and results from that program are relevant for sensor network technology. A second aspect involves the integration of sensor networks and the Internet. Technological challenges concern the use of proxies and firewalls.

20. Personalization and differentiation. The human factor is important for the acceptance of sensor networks. Bringing synergy to the value chain, e.g., uniting consumers and farmers, production methods and life stock, will open new opportunities. Personalization and differentiation are two aspects that contribute to the synergy, however unobtrusive implementation is a strict requirement.

CHAPTER 6

CONCLUDING REMARKS AND POINTS OF ACTION.

In this Strategic Research and Technology Agenda we have structured the field of sensor networks. We have spotted a trend that sensor network technology moves from pure sensing and communication towards the inclusion of reasoning, control and management. In other words, sensor network technology is maturing. The same trend is observed in the way the field is approached nowadays. Initially, the development was interdisciplinary with distinct applications and experiences. Now the time has come to move over to a more multidisciplinary approach with more generic results.

The structuring of the field of sensor networks gives us a platform to identify the hard problems, the challenges, and the conceivable solutions. Our enumeration is far from complete. The last step in a visionary SRA is to qualify the significance of potential show stoppers (inhibitors) and to elucidate the urgency of starting work on proposed solutions. Hereto we organized a survey among two stakeholder groups: the contributing experts and the interested potential users. Highlights of the survey with respect to clearly identified inhibitors and solutions that require immediate attention, are the following:

- Energy consumption and energy storage are show stoppers for sensor networks. Work should start immediately to realize auto-calibration.
- Scalability, heterogeneity and resource scarcity are clear inhibitors. Potential solutions that require immediate attention are adaptive sampling and censoring, and naming and forming of dynamic topologies.
- Rapid development, network maintainability, and proper methods for process and service migration are an absolute must. Work on platforms and programming models should start immediately, supported by sensor experience testbeds and field labs.
- For the vertical issues, the inability to build proven dependable systems is an absolute show stopper. Urgent actions are necessary on shared infrastructures, business models, and an overall efficiency gain of the value chain.

The responses from experts in the field and the potential users were strikingly similar. The differences lie in the vertical issues and the system engineering. According to the potential users, recycling, security, privacy, and personalization require immediate attention whereas, experts strongly suggest to start working on various aspects of system engineering and platforms, including ultra-low-power DSP, reconfigurable radios, A/D-conversion and sustainability through design for recycling and energy harvesting.

Final recommendations:

- Experience in the field should be exploited to create viable business models. It is absolute indispensable to keep building an active community through networking, joined projects and tangible products.
- Sensor networks will become mainstream commodities, thus entering the human ecosystems. The sensor network community should be aware of ethical issues that will come along with its success.

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NOTES

1 *See SRA EpoSS, The European Technology Platform on Smart Systems, Integration, 2009; http://www.smart-systems-integration.org/public/documents/publications*

2 *From the SRA IIP Health Support, Vision and Research Agenda (May 2008)*

3 *From the SRA IIP Mobility as ICT System, Strategic Research Agenda (March 2009)*

4 *From the SRA Sub-Arena Integrated Systems (March 2009)*

5 *Gérald Santucci, The Internet of Things; Between the Revolution of the Internet and the Metamorphosis of Objects (2010) http://cordis.europa.eu/fp7/ict/enet/documents/publications/iot-between-the-internet-revolution.pdf*

6 *source IDTechEx.*

7 *See Meratnia et.al. "Sensor networks in the Low Lands" in Sensor vol 10, (2010); http://www.mdpi.com/journal/sensors/sections/state-of-the-art-sensors/*

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