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Sensor Technology Roadmapping Efforts at iNEMI

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I. Introduction

The development of advanced sensor technologies offers industry a great many new commercial and technical opportunities. To help empower industry make correct product and technology investment choices, the International Electronics Manufacturing Initiative (iNEMI) has developed a sensors technology roadmap [1] as part of its technology roadmapping effort. The objective of the roadmap is to analyze established technological and manufacturing capabilities and compare these to existing and anticipated sensor applications across multiple market sectors including transportation, health care, consumer electronics, industrial and telecommunications infrastructure, defense, security, and space. This process highlights the gaps which represent obstacles to fully realizing the benefits offered by advanced sensors over the coming decade. In the future, these efforts will also incorporate an analysis of the impact of disruptive technologies (carbon nanotubes, micro-fluidics, distributed sensing, advanced micro-optics) on capabilities for existing as well as new applications.

The iNEMI roadmap compares technology trends with anticipated product needs, and identifies gaps that are potential threats to industry advancements. This roadmap covers the time span from 2005 to 2015. Publication of the biannual roadmaps is followed by in-depth gap discussions to identify areas where common needs can be addressed through research and development, innovation, deployment and standards development.

II. Background and Global Trends

A sensor is a device which detects or measures a physical property and records, signals, or otherwise responds to the information received [2]. A sensor operates as a transducer, wherein a sensing element senses the physical input (the measurand) and a transduction element converts the measurand into an easily measurable quantity like voltage or resistance.

Inputs to sensors can be broadly categorized as physical, chemical, or biological quantities. From the phenomenological point of view, these quantities can be classified for convenience into seven signal domains: thermal (such as temperature, heat flux); mechanical (such as force, pressure, acceleration, position, acoustic); chemical (such as composition, concentration of analytes including biomolecules); magnetic (such as flux density, field intensity); electro-magnetic (such as wavelength, intensity, polarization); electrical (such as voltage, current, charge); and nuclear (ionizing, nonionizing radiation).

Based upon these signal domains, sensors are commonly referred to as pressure sensors, accelerometers, gas sensors, temperature sensors, and so on. More broadly, sensors are often associated with their end-use application, an example of which is automotive sensors. Automotive sensors may be further subdivided into functional groups like engine control, vehicle control, and safety.

A survey was conducted by the Danish Sensor Technology Center A/S (STC) and Risoe National Laboratory, forecasting sensor technology issues and trends up to 2015 [3]. The report was based on responses to a survey by 174 international experts from academia, research institutes and industry. Their results included a ranking of present and future market importance of the principal sensor types and technologies. One of the most noteworthy trends is the importance of micro-electromechanical systems (MEMS) technologies for both present and future markets. The survey also indicates that biological/biochemical sensors and optical sensors will attain greater prominence in the marketplace over the coming 10 years.

The respondents to the survey ranked potential global market volume on a list of topics presented as statements describing specific attributes of various sensor technologies. The top ten topics from this ranking were as follows.

1) MEMS-based miniaturized and low-cost sensor and actuator systems.
2) DNA-sensors for measuring genetic diseases and/or genetically modified food.
3) Sensor communication systems based on advanced mobile communication protocols.
4) Low-cost (less than 5 Euros/unit) silicon MEMS sensors for food and health care applications.
5) Miniaturized energy supplies for integration in self-contained sensors.
6) Lab-on-a-chip sensing in food safety and medical diagnostics (e.g., capillary separation and optical detection).
7) Motion control and collision avoidance systems employing high frequency (>50 GHz) microwave sensors.
8) Ultra-small biosensors and actuators with wireless communication for use with implanted components in medical or other applications.
9) Biosensors for various applications.
10) MEMS devices based on polymer materials.

The Danish study also drew some conclusions regarding the perceived future market volume in relation to the perceived technological feasibility. Some of the key points include: i) the market volume for ultra-small biosensors and self-contained sensors integrating advanced polymer and miniaturized energy technologies is much larger than the technological feasibility, ii) some sensor technologies are perceived to have limited future market potential despite having a high level of technological know-how. These include fiber optic sensors, radio-frequency sensing, eddy-current and ultrasound for use in manufacturing systems, and nuclear based sensors, and iii) biosensors occupy a somewhat ambiguous position, having an overall high perceived market potential hindered in some cases by a low level of technological

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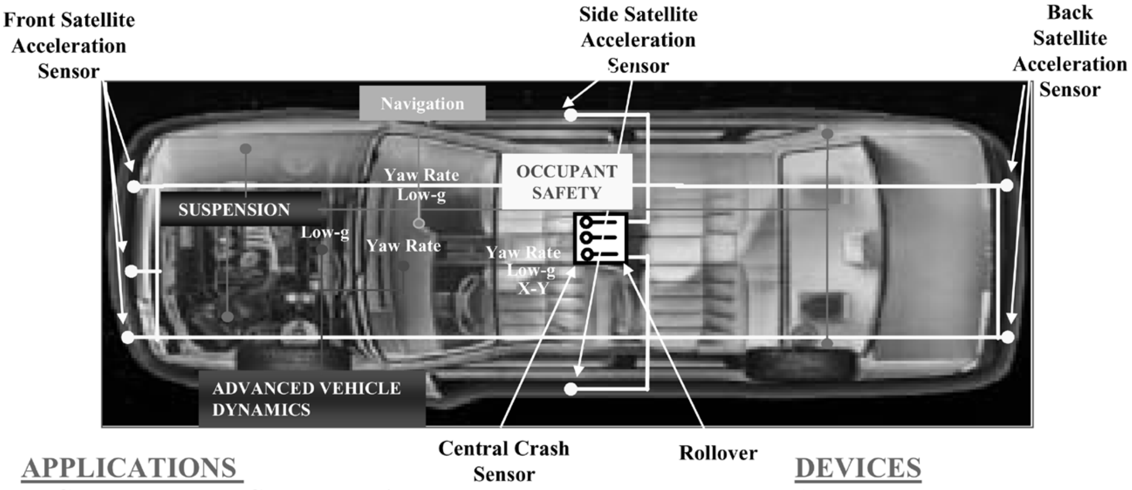

APPLICATIONS	**DEVICES**
• **Central Module - Crash Detection, Rollover**	**Accelerometers, yaw rate sensors**
• **Occupant Detection & Positioning**	**Accelerometers**
• **Side Modules - Side Crash Detection**	**Accelerometers plus processing, com.**
• **Remote modules - Crash Severity**	**Accelerometers**
• **Advanced Vehicle Dynamics**	**Low g Accel., yaw rate sensors**
• **Ride Control**	**Low g Accelerometers**
• **Navigation**	**Yaw rate sensors**

Fig. 1. Major automotive applications for inertial sensors.

know-how. Specifically highlighted in this context were implantable biosensors, those which substitute for human sensing functions, and those employing living organisms.

The rapid evolution of sensor technologies over the preceding twenty years has been enabled by the commensurate evolution of integrated circuits, MEMS technology, improved passive components, software, communication protocols, and miniature power sources. Key features of sensor technologies which drive widespread implementation across all sensor types are low price, small size, robustness, dispensability, the ability to be self-calibrating, and a high level of integration.

Sensor technology is projected to have significant impact on the health care, food processing, chemical processing, transportation, agriculture, and environmental market sectors. The 2004 iNEMI sensor technology report focuses on a roadmap for automotive systems, with additional sectors to be included in future roadmaps.

III. SENSORS FOR AUTOMOTIVE APPLICATIONS

The global market for sensors in the automotive market is expected to be $12.4 Billion in 2000 according to Strategy Analyties [5]. Sensors play a central role in enabling the higher level of integration of intelligent electronics into automotive systems. Subsystems in automobiles relying on advanced sensors include engine control, safety systems, vehicle control, collision avoidance, passenger comfort, and vehicle security. Sensors for powertrain applications account for over 50% of the total sensor value in automobiles. The cost of implementing advanced electronic functions continues to be driven downward by innovations in sensor technology. Additional growth of sensor use in automobiles will result from legislation governing tire safety for passenger vehicles, which is expected to drive growth in pressure monitoring systems over the coming several years. The major automotive applications for inertial sensors are illustrated in Fig. 1.

The iNEMI sensor technology report presents roadmaps of five key sensor application areas in the automotive industry. One of the highest growth areas, in terms of rate of growth as well as total revenue, is expected for automotive vehicle application of pressure sensors. Automobile manufacturers and their subsystem suppliers are incorporating pressure sensing in a wide range of new applications. The report examines pressure sensors used for engine control, tire pressure monitoring, and side airbags. Roadmaps are also presented for accelerometers used for airbags and for antilock braking systems and vehicle dynamic control systems. The status of the technology is shown for 2004, and any changes from the current state of a certain attribute are indicated by a new entry at a later time. If the attribute remains unchanged then no further entries appear for that attribute.

The key attributes covered in the roadmap include sensor characteristics (such as accuracy, sensitivity and range), transducer technology (such as piezoresistive, capacitive), packaging, manufacturing methods (such as bulk or surface micromachining), integration platform and levels (for example system in package or SiP, system on chip or SoC, integrated memory or signal conditioning), power supply source, and communication methods.

IV. SENSOR TECHNOLOGY ROADMAP FOR TIRE PRESSURE MONITORS

The roadmap developed for tire pressure monitors is presented in Table I. As a result of the adoption of the 2000 Transportation Recall Enhancement, Accountability, and Documentation Act (TREAD), 65% of all new vehicles were mandated to have a tire pressure monitoring system by the fall of 2006. A tire pressure monitoring system notifies drivers of low tire pressure. These legislative requirements have made this one of the fastest growing sensor application areas.

Since this sensor application is so recent and the tire is isolated from the vehicle electronic system, the technologies deployed in tire pressure monitors are among the most advanced in automotive use today. Current sensors employing capacitive transducers are manufactured using a surface micromachining process and are the smallest in size. These incorporate on-chip integration that includes memory and signal conditioning and is enabled by CMOS technology, which will continue with finer feature sizes. Nevertheless, today's level of on-chip integration does not include all the functionality required for tire pressure monitoring systems. These functions also include wireless communications, energy source, motion sensing, and microprocessing. Hence, current systems employ a multi-package module platform to integrate all

TABLE I
ROADMAP FOR TIRE PRESSURE MONITORS

Attribute	**2004**	**2006**	**2008**	**2010**
Accuracy	+/- 1.5%			
Sensitivity	2 psia/V/bit			
Measurement Attribute	Tire Pressure			Tire ID
Transducer technology	Capacitive, piezoresistive			
Environmental Conditions	-40C to + 125C			
Lifetime	15 Years			
Measurement Range	0 - 85 psia			
Packaging:				
Size	TBD			
Package	SOIC - 18 Pin		QFP	
Frequency Response	N/A			
Temperature Compensation	On Chip			
Response Time	2 mS			
Electrical Supply Requirement	3V +/- 10%		3.3V	
CMOS Feature Size	0.8 microns		0.25 microns	
Memory	Flash/ROM			
Processing	Surface Micromachining			
Signal Conditioning	On Chip			
Communication	Wireless		wireless, on chip	
Communication Protocol	Digital			
Energy source	Battery			Batteryless (inductive?)
Integration Platform	Multi package Module	System in Package	System on Chip	

necessary functions. Substantial opportunity exists for greater miniaturization and cost reduction through integration of all functions in a system-in-package and/or system-on-chip platform.

Because tire pressure monitors are isolated from the vehicle's electrical system, they require wireless communication capability as wellas an independent energy source. To enable further miniaturization and reduce costs, a great need exists for new energy source technologies which would eliminate batteries altogether. RF inductive power sources may have a promising future in this application.

V. CONCLUSION

MEMS technologies have had tremendous impact on sensors for automotive applications. The automotive market value for MEMS sensors in 2002, including accelerometers, gyroscopes and pressure sensors, was over $1 billion, and is projected to increase to $1.5 billion by 2007 []. The shifting emphasis of MEMS processing from bulk to surface micro-machining is expected to enable further miniaturization and reduced cost of MEMS sensors, opening new application areas. Bulk micromachining involves the selective removal of the wafer's substrate material to form a MEMS structure (e.g., cantilevers, holes, grooves, membranes). Surface micromachining involves the deposition of thin structural and sacrificial layers, and the sacrificial layers are subsequently removed to form raised structures (e.g., gears, comb fingers, cantilevers, or membranes). Surface micromachining is conducive to fabricating MEMS sensors (e.g., accelerometers) with on-chip signal conditioning and self-test circuitry, can facilitate the creation of smaller, intricate, and precisely patterned structures, and can accommodate high-volume IC processes. Small embedded sensor technologies represent a major new development for the 21st century, and will eventually become ubiquitous in electronic and mechanical equipment. These devices will radically alter our approach to activities as diverse as industrial process engineering, equipment maintenance, military combat, and surveillance.

Realization of the potential for embedded sensors will require continued development of miniaturized sensor elements, integrated control systems, and micro-actuators which can all be interconnected in a single package with a small form factor. We recommend aggressive development and deployment of surface micromachining technologies for sensor components. Sensor and/or actuator systems with high aspect ratio structures will require deployment of technologies such as deep reactive ion etching (DRIE), wafer-level sealing, or LIGA, lithography, galvanoformung (German for electroforming), and abformung (German for molding). LIGA is a process which involves forming structures in a polymer mold photolithographically, and then electroplating into these cavities. Advances in microelectronic fabrication technologies combined with system-on-chip design will lead to rapid development of the control systems needed for smart embedded sensors. These needs especially affect the automotive industry, which currently utilizes a multi-package module for many sensor applications which require integration of sensors, microprocessors, signal conditioning, communications, power source, and memory functions. Packaging technology must evolve toward higher levels of integration using system-in-package solutions, sometimes as an intermediate step toward eventual system-on-chip implementation.

A number of important disruptive technologies (nanotechnology, micro-fluidics, distributed sensing, advanced micro-optics) are poised to have substantial impact on the commercial marketplace for sensors as we enter the next decade. Technology gaps hindering the full realization of market opportunity exist for ultra-small and implantable biosensors and self-contained sensors integrating miniaturized energy technologies. The need exists for a wider selection of biocompatible materials for packaging of biosensors backed by long-term reliability and safety data. Miniaturization is especially critical for implantable devices, and one of the keys to achieving this is the availability of ultra-small, stand-alone power sources which have long life. Although continued research is required into miniaturized fuel cells, this area may benefit from breakthrough developments in nanotechnology for energy storage devices.

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