



NASA KSC Innovative Partnerships Program Infusion Request Market Opportunity for Wireless Surface Acoustic Wave (SAW) Sensor Arrays

A. Purpose

The purpose of this report is to describe the market opportunity for wireless, Surface Acoustic Wave (SAW) sensor arrays.

B. Request

Fuentek was requested by the NASA Kennedy Space Center's Innovative Partnerships Program (IPP) to provide technology infusion support for a NASA Small Business Technology Transfer (STTR) Phase II contract (Proposal Number 07-2 T6.01-9969). One deliverable within Fuentek's Statement of Work is to provide insight for NASA into the market opportunity for the work resulting from this contract.

C. Technology Summary

The Phase II STTR contract proposes the demonstration of a complete, wireless remote sensing solution using passive SAW Orthogonal Frequency Coded (OFC) sensors and a wireless interrogation system. The Small Business Concern for the contract is Mnemonics, Inc. of Melbourne, Florida. The contract's designated Research Institution is the University of Central Florida (UCF), specifically UCF's Consortium for Applied Acoustoelectronic Technology (CAAT) led by Dr. Donald Malocha.

Surface Acoustic Wave technology is not new. However, using SAW technology as a wireless, passive sensor and integrating multiple SAW sensors into a common communications network is a new, emerging field of use.

SAW sensors offer unique advantages over the current state-of-the-art, semiconductor based monitoring:

- No batteries or local power source are required
- SAW sensors are very small and rugged
- Wireless operation
- 1,000 degree Fahrenheit to cryogenic temperature range of operation

Section E provides an additional, brief background of the technology and the scope of the work being done by Mnemonics and UCF.

D. Market Opportunity Summary

If successfully demonstrated and concluded, the Phase II STTR has the potential to be viewed as a major event in the wireless, sensor network market.



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Today it is difficult to predict future gross revenue for a SAW sensor market. The market is new and cannot yet be classified as even an emerging market.

However, a high-level view for what the market could be like can be established by considering these four areas:

1. SAW electronic devices
2. Wired and wireless sensor networks
3. Radio Frequency ID (RFID) tags
4. Examples of early adopter SAW sensors

SAW electronic devices (Section F) – According to Phonon, Inc., a company that has been designing and manufacturing non-sensor SAW devices and subsystems since 1982, the annual revenue for SAW devices used as electronic components (such as filters, oscillators, and transformers) is \$1+ billion USD. The cost of SAW devices can range from \$20,000 each for specialized military applications to less than \$0.50 each when used in consumer applications (such as cell phones). It is interesting to note that 75% of the SAW electronic device market is outside the US.

Wired and wireless sensor networks (Section G) – In 2008, the business research firm of Frost & Sullivan predicted annual revenue for the global sensor market would be \$44.1 billion. According to Frost & Sullivan, the market is growing at a Compounded Annual Growth Rate (CAGR) of 9.5% and is predicted to reach \$69.2 billion in 2013. The market encompasses a wide range of product and end-user segments. Reviewing the advantages of SAW technology listed in Section C along with the variety of market opportunities and data points discussed in section G, it becomes very obvious that SAW sensors will probably have a major, direct impact on many aspects of the sensor market.

Radio Frequency ID (RFID) tags (Section H) – According to a 2006 IDTechEx report, the RFID tag market was predicted to grow from \$1.9 billion in 2005, to \$24.5 billion by 2015. This market includes both passive and battery powered tags, systems, and services. An RFID tag serves a different function than a SAW sensor. An RFID tag is commonly used to identify an attached object by transmitting a fixed ID number. A SAW sensor measures and transmits a dynamic, changing value such as pressure or torque. However, for the same reasons RFID tags are becoming more common in aviation use (small, light-weight, rugged, wireless, and battery-free), the potential exists to also incorporate SAW sensors to monitor dynamic aviation conditions. An interesting data point – 10,000 RFID tags are used on every Airbus A380 airplane, identifying everything from airline seats to brakes.

Examples of early adopter SAW sensors (Section I) – This section describes some very early adopter examples of SAW sensor applications, such as automotive monitoring, wine discrimination, chemical agent sensing, and torque sensing.



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Quantitatively, if SAW sensor technology could tap 1% of the potential \$2 billion 2015 wireless sensor market in the next five years – that could yield a \$20 million market opportunity. Qualitatively, if one grasps the advantages of SAW sensors, and comprehends the wide range of sensor application opportunities, it becomes obvious that if the approach is proven successful, wireless SAW sensor networks will undoubtedly become an established market segment within the wired and wireless sensor markets.

E. Technology Background

SAW devices have been traditionally used as filters, oscillators, and transformers in electronic circuits. Rayleigh waves, first described by Nobel physicist Lord Rayleigh in 1885, define how an acoustic wave propagates across the surface of a solid. During the 1960's, Bell Telephone Labs applied Rayleigh's theory: by passing a wave across the surface of a piezoelectric material, mechanical energy from the wave (created by the wave's amplitude and velocity) could be transformed into electrical current.

Over the next decade, funding by the U.S. Department of Defense led to the creation of a strong community of SAW engineers, scientists, and body of technical research. From the mid 1970's through the mid 1980's, SAW research evolved to applications development. Defense contractors such as Hughes Aircraft, Texas Instruments, Westinghouse, Motorola, Raytheon, Eaton, Sperry, and United Technologies implemented SAW technology into military electronic systems. By the late 1980's, domestic suppliers (such as Andersen, Phonon, RF Monolithics, Sawtek, and Vectron) began to dominate the market.

In the last decade, new research has been done in to using SAW devices as sensors. By sending energy to a SAW sensor in the form of a Radio Frequency (RF) signal, converting the signal into a mechanical wave which propagates across the surface of the sensor, then radiating a return RF signal, physical properties such as temperature, pressure, torque, and shear (among many others) can be measured.

The majority of measurement sensors in use today require a dedicated power source and rely on silicon-based electronics. These traditional sensors have restricted use when operating in harsh environmental conditions. In contrast, SAW based sensors have power beamed to them in the form of an RF signal. Since SAW sensors use crystalline-based materials, they can more easily withstand harsh temperature and radiation environments.

Technical challenges have limited SAW sensors from becoming more popular: antennas have been large, sensor masks challenging to produce, and the ability to distinguish unique identities from a collection of multiple, localized sensor responses extremely difficult. The sensor market to date is dominated by silicon-based, DC powered sensors.



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However, Dr. Malocha and the UCF CAAT team are addressing these limitations and now believe they can meet the following goals:

- Produce a variety of sensors using commercial substrate and masking techniques
- Differentiate RF signals using Orthogonal Frequency Coded spread spectrum algorithms
- Reduce antenna size, allowing for operation at 1GHz and distances of up to 50 meters
- Deploy a common network (or networks) for multiple sensor arrays
- Meet application requirements for use in ground, aerospace, and space environments

In a Phase I STTR, Dr. Malocha and his team have demonstrated remote, wireless temperature sensing at several feet and 250 MHz, using OFC sensors and an experimental transceiver test bed.

Now, in a Phase II STTR, working with RF experts at Mnemonics, Inc., Dr. Malocha and the CAAT team intend to demonstrate a commercially feasible system of multiple, wireless sensors operating at tens of feet and 915 MHz. UCF is supplying the SAW sensors and Mnemonics is building the wireless interrogator hardware to implement UCF's OFC algorithms.

Once networks with tens of sensors operating over tens of meters can be demonstrated as commercially feasible, the range of terrestrial and space application could become almost innumerable. Applications proposed by the STTR Phase II are:

- Profiling leading edge wing forces by monitoring temperature, pressure, and acceleration
- Acceleration sensing for monitoring vehicular acceleration and vehicular vibration
- Rotation and directional sensing for vehicular docking, tilt control, and fall detection
- Monitoring structural integrity
- Monitoring in extreme temperature, extreme pressure, toxic or lethal environments
- Automotive performance monitoring
- Civil engineering stress management
- Chemical and biological development (toxic safety monitoring)
- Refinery processing (safety monitoring)
- Flight suit monitoring

The STTR also proposed:

- Wireless SAW sensors could change the future of airframe safety and required/planned maintenance processing. Sensors could be embedded in key structural components of an airframe for persistent monitoring both during flight and for post flight analysis.
- Critical states of air flight could be instrumented less expensively than using heavier fiber optic or wired communication systems.



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- Using wireless SAW devices for remote monitoring in hostile environments may become not only technically feasible but also economically attractive based on the extremely low cost of the sensor device.
- Using passive, wireless SAW sensors along with an active, wireless interrogator facilitates an architecture which could possibly support hundreds of sensors per interrogator.
- In an automobile, a wireless SAW could be deployed as:
 - Pressure sensors in each tire
 - Liquid contaminant sensors in fuel and oil supplies
 - Temperature and pressure sensors within the engine
 - Carbon monoxide sensors within the vehicle
- In-car systems could receive highway safety information from embedded sensors within informational signs or construction areas and alert the driver to a required speed change or other varying conditions.

F. SAW Device Market

According to Phonon, Inc., a company that has been designing and manufacturing non-sensor SAW devices and subsystems since 1982:

- The worldwide SAW market is \$1+ billion
- The US SAW market is \$250+ million. Major segments and uses include:
 - Military radar (\$15M) – Detecting increasingly faster and smaller targets while tolerating increasingly sophisticated jamming and deception techniques.
 - Military Electronic warfare (\$10M) – Disabling hostile electronics and protecting against electronically controlled threats by providing increased sensitivity, selectivity, and identification capability.
 - Military Communications (\$10M) – Processing voice, video, or digital data signals at high rates while providing signal security and resistance to jamming.
 - Commercial Communications (\$100M) – Use in satellites, microwave links, cable TV, fiber optic, mobile digital radio, cellular base-stations, local area networks, and HD TV.
 - Consumer Communications (\$100M) – Use in cellular phones, pagers, ID tags, and wireless controls such as garage door openers and electronic automobile locks.
- The international SAW market is \$750M+. It is dominated by very low cost TV receiver, pager, and cellular telephone consumer applications; both the markets and suppliers are primarily Asian.
- Annual sales for US based SAW device providers:
 - Phonon – \$10M
 - Sawtek – \$100M
 - RF Monolithics – \$50M
 - Vectron – \$25M
 - MicroNetworks – \$20M
- Typical SAW pricing per unit:



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- Military – \$100 to \$20,000
- Commercial – \$10 to \$100
- Consumer – \$.1 to \$10

A report from Frost & Sullivan entitled “Southeast Asian SAW Devices Market for 2007” states:

- SAW devices are also used in MP3 players, wireless LAN for notebooks, RFID, and Their passive operation eliminates the need of battery or power supply and wired-installation in RFID applications (such as transportation, food management, medicine, and others).
- SAW devices are normally priced between \$0.4 and 0.5 for TV and keyless entry applications, \$1 and \$2 for communication devices, and \$1 and \$3 for medical products. For low-cost applications, they are priced normally below \$0.5.

G. Sensor Market (Wired and Wireless)

A report from Frost & Sullivan entitled “Global Sensors Outlook - 2009: A Review of Key Market Revenue Trends, Technology Snapshots and Growth Perspectives” provides stronger insight into markets that could be impacted by displacing traditional wired and wireless sensors with SAW based sensor arrays. Some highlights are:

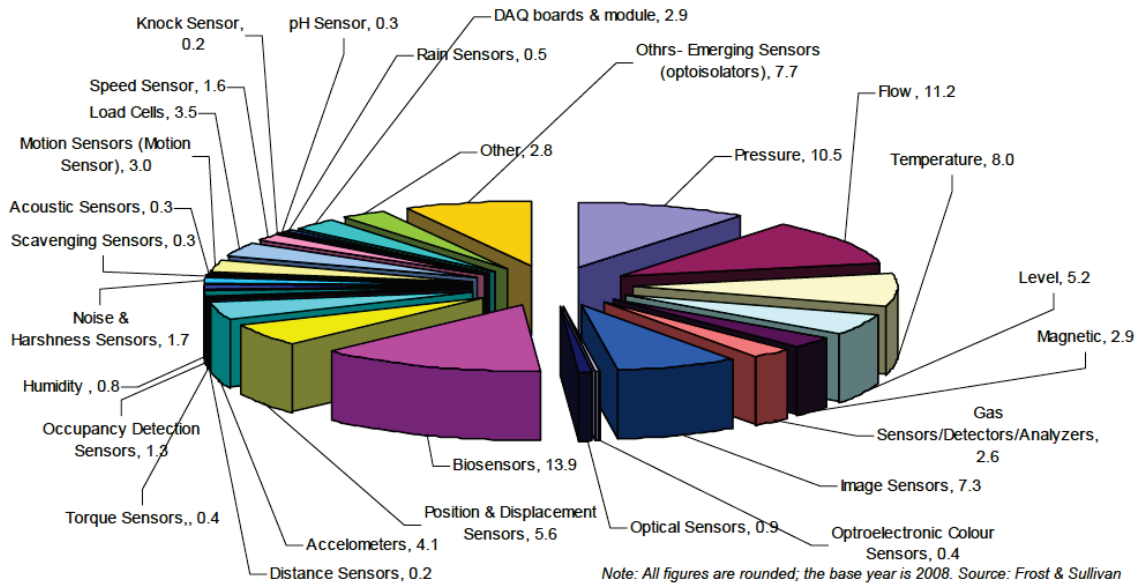
Revenues for the global sensor market in 2009 were predicted to be \$44.1B, growing at a Compounded Annual Growth Rate (CAGR) of 9.5% to a market of \$69.2B in 2013. Frost & Sullivan view two segments as comprising the global sensor market:

| Product segments | End user segments |
|---|---|
| <ul style="list-style-type: none"> • Pressure • Temperature • Flow, Level • Vibration, Velocity • Magnetic • Gas • Image • Optoelectronic • Position, Distance • Torque • Optical • Occupancy • Scavenging • Load Cell • Speed, Knock • Humidity, Rain • pH sensor • Acoustic | <ul style="list-style-type: none"> • Oil and Gas • Food and Beverages • Water and Wastewater • Automotive • Energy and Power • Automation • HVAC • Chemicals • Petrochemicals • Shipping • Paper and Pulp • Semiconductors • Medical and Pharma • Aerospace • Agriculture • Metrology and Meteorology |



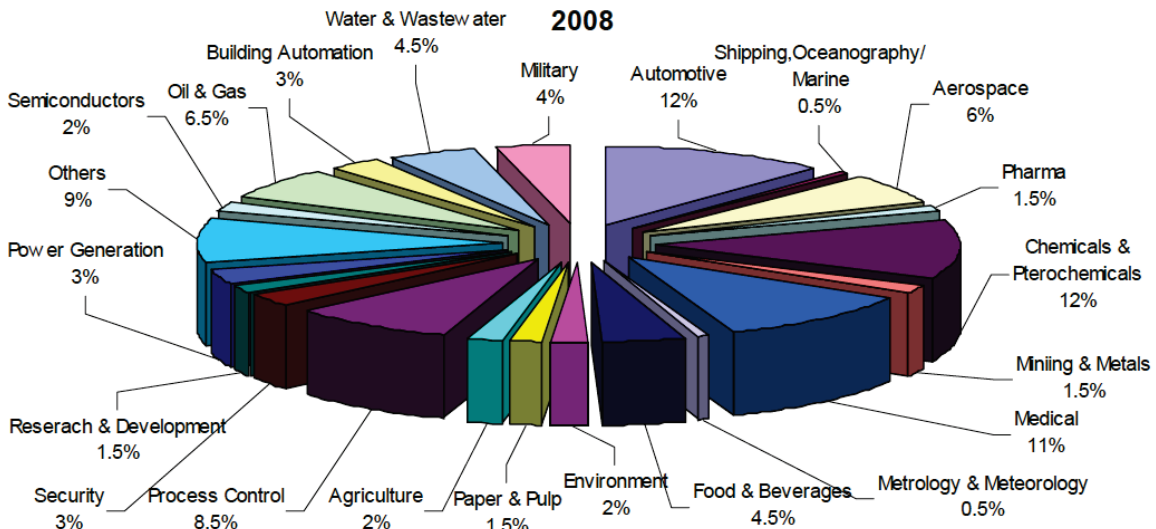
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• Revenue by Major Sensor Types (World), 2008



Source: Frost & Sullivan "Global Sensors Outlook - 2009: A Review of Key Market Revenue Trends, Technology Snapshots and Growth Perspectives"

• Percent of Revenue by End Users (World), 2008



Source: Frost & Sullivan "Global Sensors Outlook - 2009: A Review of Key Market Revenue Trends, Technology Snapshots and Growth Perspectives"



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- Key Classifications and Percent Revenues (World), 2008:

| Classification | Revenue (B) | % Total |
|----------------|-------------|---------|
| Application | • \$24.0 | 54% |
| Base | \$16.7 | 38% |
| Emerging | \$3.4 | 8% |

- Percent Revenues by Geographic Region (World), 2009

| Region | % Total |
|---------------|---------|
| Asia Pacific | 40.9% |
| North America | 29.4% |
| Europe | 23.5% |
| Rest of world | 6.2% |

- High Growth Markets (World), 2008-2013

| Market | CAGR | Trend |
|----------------|---------|------------|
| Torque | 25.4% | Flat |
| Humidity | 20.5% | Increasing |
| Distance | • 19.2% | Increasing |
| Scavenging | 19.2% | Increasing |
| Acoustic | 19.2% | Increasing |
| pH | 16.2% | Increasing |
| Rain | 16.3% | Flat |
| Other emerging | 16.3% | Increasing |



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- High Growth Technologies (World), 2008-2013

| Technology | CAGR | Trend |
|---------------|---------|------------|
| Wireless | • 48.5% | Increasing |
| Semiconductor | 16.7% | Flat |

- Emerging Technology Trends (World), 2008-2013

- The use of sensors is growing in most end-user applications. With the increased level of accuracy, the reliance on sensors is on the rise as never observed before.
- Wireless sensors are likely to continue to exhibit strong growth at the instrument and system levels.
- Wireless sensor networks are the future of the electronic world and are likely to depend on the success of two new breakthrough technologies: ultra-wideband and WiMax (IEEE 802.16).
- Energy Harvesting (Energy harvesting involves capturing and converting one form of energy into other, such as solar into electrical energy, which can then be used to power devices in sensor networks. By replacing batteries, these sensors can provide better return on investment in the long run. By eliminating batteries, these sensors also provide the perfect environmental solution by removing the toxic waste that is generated by the usage of batteries.)
- ... security, environmental, power, and energy are likely to experience growth in revenues and be least impacted by the current economic slowdown.

- Automotive End-user Application Trends (Europe), 2008-2020

- Safety systems are moving from independent to integrated systems. Global safety systems are growing at 7 percent and are expected to reach \$13.4 billion in 2013.
- Tire pressure monitoring sensors are expected to penetrate into both European Union and Asia. The national highway and safety authority ruling in the U.S. has led to mandatory adoption of tire pressure sensors in the country.
- Electronic stability control systems are expected to be a key driver of MEMS inertial sensors (accelerometers and gyroscopes) and magnetic sensors.
- Accelerometer market is expected to grow due to increase in adoption of airbags in new markets such as India, China, and Eastern Europe.
- Environment regulations and consumer preference for fuel-efficient vehicles are expected to aid the growth of pressure sensors in the engine train and fuel management systems. Pressure sensors segment are expected to witness double digit growth rates.



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- Process Industry Trends by Technology Type (World), 2008-2013

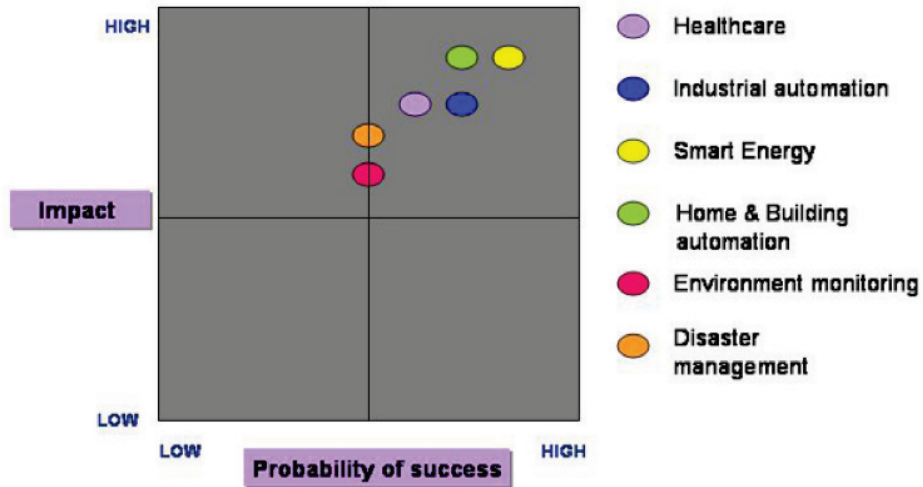
| Era | Trend |
|-----------|----------------------|
| 1960's | Pneumatic |
| 1970's | Digital |
| 1990's | Intelligent |
| 2008-2013 | Network and wireless |

A December 2008 report from Frost & Sullivan entitled “Wireless Sensor Networks” highlighted the following:

- Disaster management is also arriving on the scene with applications ranging from first responders to systems assisting firefighters and other rescue teams. It won't be long before sensor networks become an integral part of such systems given the fact that a lot of work has been and is being conducted on coming up with solutions for monitoring the environment and early warning systems.
- Several researchers are developing sensor networks to predict the onset of floods and fires to aid preventive measures. In the case of body sensor networks, several wireless sensors on a person could monitor parameters such as heart beat and temperature in hospitals or for athletes during sports training.
- ... so with a slow start, a sharp increase in deployments can be expected in the next five to 10 years time frame. Companies like Intel are investing a considerable amount in R&D for wireless sensor networks based healthcare applications.
- Emerson's Smart Wireless solution and Honeywell's One Wireless are examples of application of WSNs in the field of industrial automation.
- Online monitoring also helps in industrial applications in areas such as condition monitoring of critical equipment. Assessing the working conditions of machines such as pumps, turbines and so on that may be critical to a process, several times a day helps determine if the equipment is working in proper condition. Any variation in performance would warn the operator in advance to schedule maintenance operations. Hence, unplanned downtimes can be avoided.



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Opportunity analysis of WSN applications
Source Frost & Sullivan

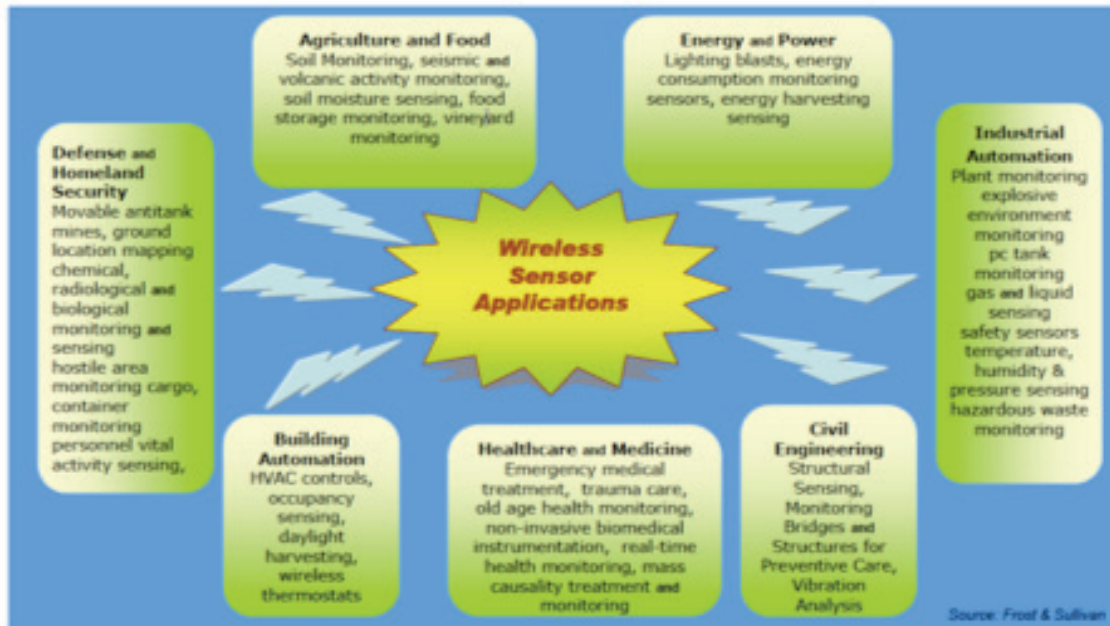
A June 2006 report entitled “Wireless Sensor Networks” by Frost & Sullivan highlighted the following:

- The wireless sensor market is in its early stages.
- The wireless sensors and transmitters are not used widely and therefore have a small market. Nevertheless, it is very promising because there are enormous growth opportunities.
- The following chart predicts market revenue and growth for wireless sensors and transmitters (temperature, pressure, level, flow, acceleration, vibration, velocity, humidity, gas, biosensors, photoelectric, security monitoring, position, proximity, and others):

| Year | Revenue (M) | Growth rate |
|--------|-------------|-------------|
| 2002 | \$94.4 | - |
| 2003 | \$108.7 | 15.1% |
| • 2004 | • \$127.9 | 17.7% |
| 2005 | \$159.9 | 25.0% |
| 2006 | \$206.1 | 28.9% |
| 2007 | \$273.7 | 32.8% |

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| Year | Revenue (M) | Growth rate |
|------|-------------|-------------|
| 2008 | \$373.5 | 36.4% |
| 2009 | \$526.7 | 41.0% |
| 2010 | \$772.8 | 46.7% |
| 2011 | \$1,176.8 | 52.3% |
| 2012 | \$1,853.9 | 57.5% |



Other trends and data points of interest regarding wireless sensors:

- In their Top 10 Information Technology Predictions for 2009 report, the Gartner Group predicts that by year end 2012, physical sensors will create 20 percent of non-video Internet traffic. Real-time environmental sensing is growing rapidly as our ability to capture and analyze valuable information increases.
- In a January 2009 article entitled “Wireless Sensor Networks: Maintenance Free or Battery-Free” in the Magazine of Record for the Embedded Computing Industry, the following ideas were discussed:
 - Two recent major technology waves were the cell phone and wireless Internet (Wi-Fi). Now there is a third wireless wave coming: wireless sense and control networks that



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can connect and control all kinds of equipment in our buildings, homes and businesses.

- Today, we are entering this third wireless wave. Also known as “The Internet of Things,” the third wave utilizes wireless sense and control technology to bridge the gap between the physical world of humans and the virtual world of electronics. Sense and control networks do not enhance human communication. Instead, they allow sensors to interact with actuators, creating a more dynamic world and avoiding error-prone, monotonous and costly human intervention. However, the strength of wireless sensor networks can only be fully achieved when the wiring for both the data communication and the power supply is eliminated.
 - For example, a network of 4,000 nodes and a battery life of 10 years, means that on average 1 battery per day needs to be changed.
 - Because the true cost of wireless sensor networks has shifted into the area of the maintenance cost, wireless sensor networks that gather industrial or machine data have yet to become a cost-effective solution. The majority of the sensors used are still battery powered; these batteries require regular changing and or recharging. In addition, reintegrating the downed nodes after battery maintenance, further adds to this onerous labor expense.
 - There are many different types of applications that will be able to benefit from ultra-low-power wireless sensor networks. These include monitoring of temperature, vibrations, humidity, position, tank levels, etc. in industrial plants and manufacturing. They can also be linked to the control and actuation of HVAC systems, storage, robot movements, temperature control, etc. But there are many others that are not so obvious. For example, agricultural applications now benefit from the use of wireless sensor networks when temperature sensors or soil moisture sensors are used for remote monitoring of test fields, vineyards or green houses and to control irrigation and fertilization.
- In recent articles written by the Powercast company (Powercast’s technology delivers wireless power for providing power-over-distance to individual sensors or wireless sensor networks), the following points are made:
 - Hard-to-service locations can add significant cost to battery replacement in wireless sensors. Costs for changing batteries in wireless sensors have been estimated to range from \$10 per node for easily accessible nodes up to \$100 per node.
 - ON World estimates the labor cost for changing batteries in wireless sensors will be greater than \$1 billion during the next several years. The undesired maintenance task of battery replacement is a significant force acting against the growth of wireless sensor networks. In large-scale commercial deployments, users may want sensors to be located above ceilings, behind walls, inside sensitive or hazardous environments, and on the exterior of structures. Replacing batteries is simply not a practical or cost-effective solution for these applications.



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- Component suppliers and wireless sensor companies often estimate a battery lifetime of 5-10 years for their devices. Using disposable, primary batteries for wireless sensors involves two major challenges: maintaining sensors in hard-to-service locations and scaling a sensor network to hundreds or thousands of nodes. Hard-to-service locations can add significant cost to battery replacement in wireless sensors. Costs for changing batteries in wireless sensors have been estimated to range from \$10 per node for easily accessible nodes up to \$100 per node.
 - In large-scale commercial deployments, users may want sensors to be located above ceilings, behind walls, inside sensitive or hazardous environments, and on the exterior of structures.
 - In one recent application, wireless power technology based on RF energy harvesting was used to recharge batteries for a wireless sensor operating in a perpetually cold environment – the penguin exhibit at the Pittsburgh Zoo. The batteries in existing sensors needed to be replaced every 3-4 months, an unacceptably short time frame.
- Several references have described the use of wireless sensor networks in the context of developing third-world countries:
 - Volcanic studies and eruption warning systems
 - Meteorological observation
 - Fire detection
 - Earthquake studies and warning systems
 - Water quality monitoring
 - Flood, cyclone and tsunami warning systems
 - Environmental observation and forecasting
 - Disaster prevention
 - Agricultural management
 - Structure health monitoring
 - Habitat monitoring
 - Oil pipeline monitoring
 - A 2004 article by the Gale group entitled “Wireless Sensor Networking: \$7 billion market by 2010”, reports that, according to ON World, by 2010 wireless sensors will also be widespread for consumer markets such as monitoring and controlling heating, lighting, venting, and appliances. They also predicted an end-user market worth \$7 billion by 2010.
 - A November 2008 article entitled “Wireless Sensor Networks 2009-2019” on the website “RFID Solutions Online”, highlighted the following from an IDTechEx "Wireless Sensor Networks 2009-2019" report:



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- WSN can assist with many of the big issues of this century including security, safety, protecting the environment, animal and plant conservation, healthcare and efficient food production for example.
- 99% of sensors installed in the world are still wired and, over the next ten years, WSN will constitute no more than ten percent of the wireless sensors that are sold, mainly because of technical challenges.
- Starting with humble applications such as meter reading in buildings (the first killer application earning profits for several participants and strong growth), WSN will grow rapidly to become a \$1.75 billion market in 2019. That will make them a significant part of what will then be an RFID business of over \$25 billion, more than one quarter of that expenditure relating to active RFID where the tag has a power source.

H. Radio Frequency Identification (RFID) Tag Market

A Radio Frequency Identification (RFID) tag does not provide the same functionality as a SAW based sensor. An RFID tag conveys static, pre-programmed information – usually for identification or tracking use. The purpose of a sensor is to measure a physical property which changes with respect to time and then report state values back to a collection or analysis device. RFID tags are normally read from only a few meters distance. In contrast, SAW sensor networking is anticipated to be effective over tens of meters distance (or greater).

However, RFID tags share some common attributes with SAW sensors: both can operate passively (without batteries), are small and lightweight with a low profile, are relatively low cost, and transmit their information wirelessly. As a result, when SAW sensor networks become commercially available; they may share some of the same application environments with RFID tags.

For example, a 2004 CNET News article entitled “Wireless sensors ready to go global?” describes how 10,000 RFID tags are used on every Airbus A380 airplane, identifying everything from airline seats to brakes. The tags will contain serial numbers, codes, and maintenance history that should make it easier to track, fix, and replace parts.

According to a 2006 IDTechEx report, the market was predicted to grow from \$1.9 billion in 2005, to \$7.2 billion in 2008, and to \$24.5 billion by 2015 (including tags, systems, and services). 1.8 billion RFID tags were sold in 2005: 410 million of those were active tags (such as used in car clickers) and 1.39 billion were passive tags (such as used in plastic cards). It was expected that 3.1 billion tags will be used for pallets and cases in 2006. By 2008, item level tagging (especially by pharmaceuticals) and tagging of baggage, animals, books, tickets and other non retail markets would account for about 6.8 billion tags, and 15.3 billion tags for pallets/cases. Forecasts by territorial region show that by 2010, 48% of RFID tags by numbers will be sold in East Asia, followed by 32% to North America.



I. SAW Sensor Market Examples

Multiple markets – Sengenuity (<http://www.sengenuity.com/technology.html>) is a company that is currently in the market of producing SAW based sensors. Some examples of applications for SAW sensor technology given by SenGenuity are:

- Industrial and environmental
 - Fluid condition based monitoring
 - Process control using temperature, pressure and fluid sensors
 - Work place safety monitoring
- On and off highway automotive
 - Fluid condition based monitoring
 - Engine performance control
 - Tire pressure monitoring
- BioMedical
 - Point-of-care Diagnostics
 - Emergency Room Diagnostics
 - Drug Discovery and Development
- Homeland Security
 - Chemical agent detectors
 - First responder identification
- High volume manufacture
- Measuring the surface temperature of rotating turbine blades
- Measuring the surface temperature of rotation machine tools like turrets
- Vacuum chambers
- Process Ovens
- HVAC Systems
- Patient temperature monitoring
- Construction: Thermal profile of poured concrete
- Indicators of oil quality:
 - Viscosity
 - Conductivity (water & contaminants)
 - Dielectric Constant (water & contaminants)
 - Water Content
 - Soot Content
 - Base Number
 - Acid Number
 - Particulate Count

Torque sensing – The Sensing and Control group of Honeywell’s Automation and Control Solutions Division has developed a SAW sensor for measuring torque in automotive,



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transportation, and rail powertrain applications. The following table lists features and benefits of the innovation as described by Honeywell:

| Features | Benefits |
|--|--|
| <ul style="list-style-type: none"> • Battery-free, wireless operation • Nominal resonant frequency 433MHz • High measurement bandwidth upto1kHz • Small, light weight design • High accuracy and resolution • Immunity to electromagnetic interference • High temperature operation up to 150°C • Robust packaging, durable design • Operates in harsh environments • Long term stability • Established manufacturing processes | <ul style="list-style-type: none"> • Flexible package design allows for easy integration with current systems • Varied sensor mounting locations and applications: <ul style="list-style-type: none"> - Input and output shafts (transmission) - Transmission components - Clutch pack monitoring - Crankshaft and engine components - Driveline (4WD and AWD) - Steering and chassis systems • Improved vehicle performance and economy • Improved vehicle safety (driveline management) • Optimization of powertrain management • Capability to incorporate speed sensing (Torque x Speed = “Power Modules”) • Compatible with Honeywell tire pressure sensors for integrated chassis systems • Honeywell system uses patent protected methodology for sensing and reading/interrogation. |

Chemical agent sensing – The MSA Safety Company of North America is marketing a SAW MiniCAD mk II™ Miniature Chemical Agent Detector:

- **Description** – The SAW MiniCAD mk II Detector is a personal, lightweight, solid-state chemical agent detector for simultaneous detection of trace levels of nerve and blister agents. The MiniCAD Detector is highly selective to these agents and is extremely resistant to false alarms. It operates from either standard off-the-shelf lithium batteries or a rechargeable battery pack using proven SAW (Surface Acoustic Wave) sensor technology.
- **Operation** – The SAW MiniCAD mk II Detector uses a pair of Surface Acoustic Wave (SAW) microsensors. SAW sensors are piezoelectric crystals that detect the mass of chemical vapors absorbed into chemically selective coatings on the sensor surface. This absorption causes a change in the resonant frequency of the sensor. The internal microcomputer measures these changes and uses them to determine the presence and concentration of chemical agents. The SAW sensor coatings have unique physical properties which allow reversible adsorption of chemical vapors.



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Wine discrimination – A 2004 paper from the Laboratorio de Sensores in Madrid, Spain describes using SAW sensor technology to differentiate wine:

- A surface acoustic wave (SAW) sensor array has been developed in order to discriminate Spanish wine coming from different grape varieties and elaboration processes. Sensors were coated with diverse thicknesses of polyepichlorohydrin (PECH), polyetherurethane (PEUT) and polydimethylsiloxane (PDMS). Linear techniques as principal component analysis (PCA) and linear discriminant analysis (LDA) and non-linear ones as probabilistic neural networks (PNN) have been used for pattern recognition. A classification success rate of 86% has been achieved.

Automotive monitoring – In a May 2007 press release, Texas Instruments describes the “First Automotive Surface Acoustic Wave (SAW) Sensor Coupled With TI Controller Enhances Fuel Efficiency and Safety”. The following press release...

DALLAS (May 14, 2007) -- As automotive tire pressure monitoring system (TPMS) mandates come into effect and torque sensing applications like electronic power steering (EPS) become standard on even low- to mid-range cars, Texas Instruments Incorporated (TI) (NYSE:TXN) today announced that Transense Technologies plc is using their TMS320F28x digital signal controllers as a key component in the automotive industry's first targeted piezoelectric surface acoustic wave (SAW) sensor based systems. Operating in environmentally harsh or remote automotive and industrial applications, the Transense sensor units operate wirelessly, require no power source and are typically 11 mm by 3 mm and less than 2 grams in weight. By using the F28x-enabled SAW TPMS, braking distances and the risk of accidents due to tire under inflation or failure are reduced. Fuel efficiency is also enhanced by up to ten percent through properly inflated tires and engine drag reduction through the elimination of the hydraulic pump in EPS systems.

SAW Sensor Uses Acoustic Wave for Measurement

SAW sensors utilize a radio frequency electric field to generate an acoustic wave which spreads over the piezoelectric substrate surface, transforming back to an electric field and re-transmitting for measurement. 32-bit DSP performance and high integration of the F28x digital signal controllers perform essential real time data handling, calculation and reporting functions. The F28x device calculates the spectrum of the SAW impulse response, finds the frequency of natural oscillations of the SAW sensor and can handle additional tasks such as system communication via the on-chip CAN BUS for instance. A radio frequency (RF) application specific IC (ASIC) dual channel controls RF transmission and reception.

SAW Sensors Answer US Mandated Tire Pressure Monitoring Requirements

According to the US Department of Transportation (DOT), up to 27 percent of passenger cars and 33 percent of light trucks operate with under inflated tires, resulting in an estimated 23,000 crashes and 535 fatalities each year. As part of the November 2000 enacted Transportation, Recall Enhancement, Accountability and Documentation (TREAD) Act - which affects all light



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motor vehicles registered after September 1, 2007 - TPMS technology must alert drivers of significant under-inflation of their tires.

Most existing TPMS are direct active systems utilizing a silicon micro-electro-mechanical system (MEMS)-based sensor inside each tire powered by a battery. Pressure and temperature information is transmitted by radio from each of the wheels to an electronic control unit (ECU) and displayed as either a number or a warning indicator. Batteries inside tires add weight, have limited life and cannot be replaced. With 1.2 billion tires sold annually, this waste represents an increasing environmental hazard. The passive Transense SAW sensor incorporates a three element die within a small gas tight capsule. Pressure is transmitted via a diaphragm to deform the die and mechanically strain one of the elements, while all three elements see thermal strains. The sensor is interrogated by an RF signal – no battery is required – first exciting, then transmitting the three resonant SAW frequencies from which independent pressure and temperature are subsequently determined.

Electronic Power Steering Becoming Standard on Many Cars

By 2010 half of all the cars sold in Europe are projected to be equipped with electronic power steering (EPS) systems that reduce both installation and production time for manufacturers and save fuel and maintenance costs for consumers. A vital part of the EPS control system is a torque sensor that measures the driver steering input. Existing EPS systems typically employ potentiometers or optical transducers mounted on a length of steering shaft with reduced section to increase local twist and hence measurement sensitivity. This approach tends to reduce driver feel and increases the sensor production cost.

Transense SAW based sensors, positioned at +/-45 degrees to the shaft axis, provide direct measurement of torque rather than position, without the need to make expensive modifications to the steering column. When torque is applied to the shaft, one of the SAW resonators compresses while the other extends, leading to a combined frequency shift proportional to the applied torque. The RF signal transmits between rotating and stationary parts of the assembly via a non-contact coupled transmission line. With the exception of the SAW sensor, no electronic components are mounted on the shaft, maintaining driver feel and keeping costs low.

Switching from a hydraulic steering system to an electromechanical model eliminates the constant drag on the engine while the reduced weight contributes to overall fuel economy; estimates indicate that EPS leads to a fuel economy improvement of approximately three to four percent. ...