5th International Conference from Scientific Computing to Computational Engineering
5th IC-SCCE
Athens, 4-7 July, 2012
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A REVIEW OF WIRELESS SENSOR NETWORK TECHNIQUES FOR STRUCTURAL HEALTH MONITORING

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Keywords: Structural health monitoring, bridge, wireless sensors, sensor networks, SHM, NDT/NDE

Abstract. *This paper presents a review of recent advances of wireless sensor network products for structural health monitoring (SHM) of large structures. The reviewed hardware products are classified based on their characteristics and they are investigated and selected for their efficiency, ease of use, connectivity, energy consumption, and other characteristics. In addition, a collection older and newer implementations is also presented to indicate the applicability of each technique.*

INTRODUCTION

Aging and degradation of transportation infrastructure pose significant safety concerns. They are critical structures such as highway bridges and overpasses, where maintenance and repair are expensive and replacement is usually infeasible. Structural health monitoring (SHM) of these is of great importance in order to ensure public safety and preventing economic losses.

In 2006, the US Federal Highway Administration has classified over 25% of the 599,766 bridges in the United States either as structurally deficient or functionally obsolete, underscoring the importance of SHM. They also name two main reasons for deterioration of the transportation infrastructure: rapid aging of the bridges & significant increase in traffic levels. Half of the bridges in the federal interstate system are over 33 years old and will remain in service for many years, thus requiring monitoring (SHM) and rehabilitation. [1, 2].

The need for structural health monitoring (SHM) of aging infrastructure is well established in the literature [3, 4, 5]. Presently, typical bridge monitoring is performed through periodic visual inspections, but, traditional SHM requires an onsite evaluator, it is prohibitively expensive for all but a small fraction of structures and also suffers from the significant drawback of subjectivity [6]. In the tragic example of the I-35WMississippi River bridge collapse, the bridge passed a visual inspection not long before failure [7].

Autonomous SHM is an increasingly active research area. Several wired SHM systems using networks of sensors for continuous monitoring have been developed, but they suffer from high cost, inadequate design and difficult installation. Their high power consumption constrains their deployment to locations with access to the power. A more important constraint associated with the use of wired SHM systems is the wiring required for power and interconnection [6]. Many recently constructed bridges have such extensive, yet costly, monitoring systems. For example, the total cost of the monitoring system on the Bill Emerson Memorial Bridge in Missouri is approximately $1.3 million for 86 accelerometer channels [8]. This cost is not atypical of today's wired monitoring systems.

The complexity of the wired systems and the recent developments of wireless communications technology led the researchers to new techniques. Today, several existing SHM systems use wireless communication to allow devices to coordinate and collaborate to more effectively measure a structure. These systems often use commercial network devices that greatly reduce hardware design requirements and development time. The ‘motes’ provide basic sensing functionality but they are not always suited for long-term installation on civil structures, as most of these systems use a laptop or base station to aggregate data from the sensor nodes and suffer from high power consumption.

Even under the most stringent power management, these wireless motes have an unattended life of approximately one year. Many networks also lack a mechanism for remotely communicating the measured data without access to the power grid and costly communication hardware. An important drawback when many bridges, especially in rural areas, have no such utilities on-site. Another limitation of wireless sensors is the finite life span of batteries and the high cost & difficulty of battery replacement, which make such systems prohibitively expensive in many cases. [6, 9]

During the last decade many researchers proposed and applied different SHM methods, while many academic and commercial motes appeared with a variety of wireless techniques, sensors, power sources, and data processing support. Several products and prototypes were presented and compared in literature reviews in the last decade. Among the mostly used and referenced are the reviews by Sohn et al., in 2003 [10], by Lynch and Loh in 2006 [11], and by Rice and Spencer in 2009 [12]. In order to complement their work with newer results and products for structural health monitoring (SHM), this paper presents a review of recent advances on wireless sensor techniques, products and applications.

WIRELESS SENSORS FOR SHM

Subsystems Characteristics

The proposed implementations can be divided in two main categories, the academic prototypes and the commercial platforms. In this work we focus on the commercial of-the-shelf platforms that require less HW effort leaving more time for application development.

Following the wireless sensors building blocks presented in [11, 12 & 13], the major functional subsystems of wireless sensors are:

- the sensing interface,
- the computational core,
- the wireless transceiver,
- the power component,

The **sensing interface** provides connection to the sensing transducers and it is responsible for signal conditioning and for converting the analog output of sensors into a digital representation that can be processed by digital electronics. Its main characteristics are the conversion resolution, sample rate, and number of channels available on its analog-to-digital converter (ADC). Another block found only in active sensor systems is the **actuation interface**. It provides the sensor with the capability to act on the physical system. In this work we don’t focus on active sensors, so we considered it as a part of a broader sensing interface, when present.

The **computational core** takes responsibility of the data, i.e., how they are stored, processed, and prepared for transmission. It is consisted of a microprocessor with most critical specifications the bus size, clock speed, memory, and power consumption. A (desirable) larger bus & memory and a faster clock will increase the power consumption. The trade-off depends on the SHM applications requirements for intensive on-board calculations.

The **wireless transceiver** or **radio component** is the component that is be used for both the transmission and reception of data. Most platforms operate on the 900 MHz, 2.4 GHz or the 5 GHz frequencies because they are unlicensed. The radio component should also be selected according to the required communication range and the target power consumption. Another characteristic to investigate is signal degradation due to physical interference, multipath effects, and noise.

The **power component** has a local power source and power saving/harvesting capabilities. Low power consumption is the most desirable characteristic. It depends on radio strength, clock speed, memory types, sensing & processing intensity, and, should be optimized (minimized) in terms of the monitoring needs.

According to [13], to enable Wireless Sensor Network-based SHM applications, the sensor nodes have to provide the following basic functionality (Figure 1):

- signal conditioning and data acquisition for different sensors;
- temporary storage of the acquired data;
- processing of the data;
- analysis of the processed data for diagnosis and, potentially, alert generation;
- self monitoring (e.g., supply voltage);
- scheduling and execution of the measurement tasks;
- management of the sensor node configuration (e.g., changing the sampling rate and reprogramming
- of data processing algorithms);
- reception, transmission, and forwarding of data packets;
- coordination and management of communication and networking.

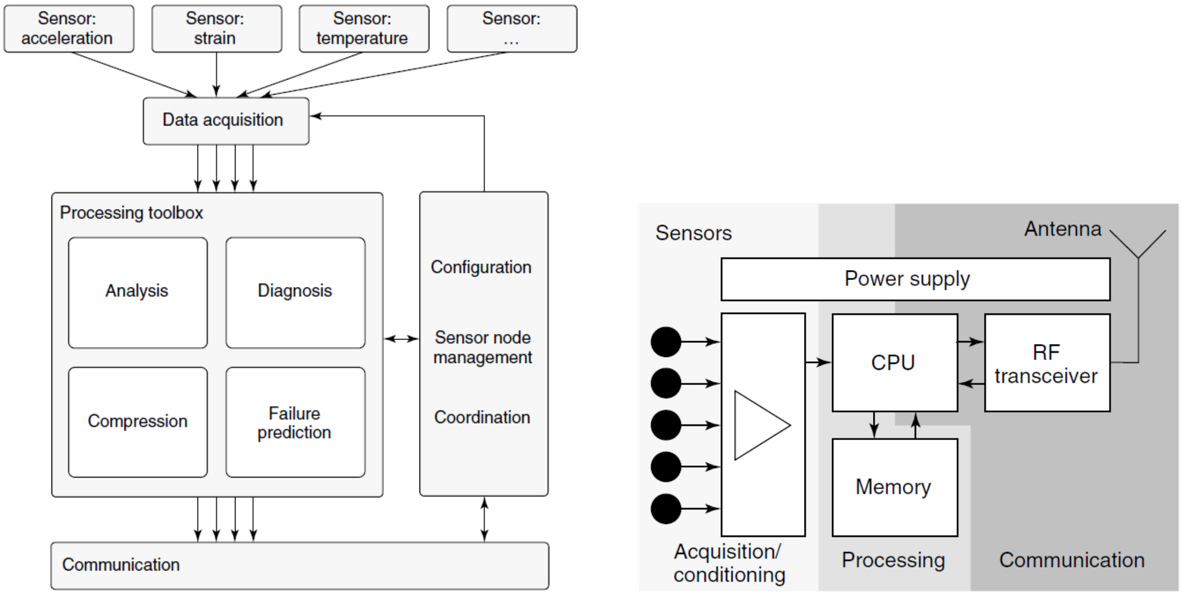


Figure 1. (a) Basic functionality & (b) Hardware structure of a sensor node [13].

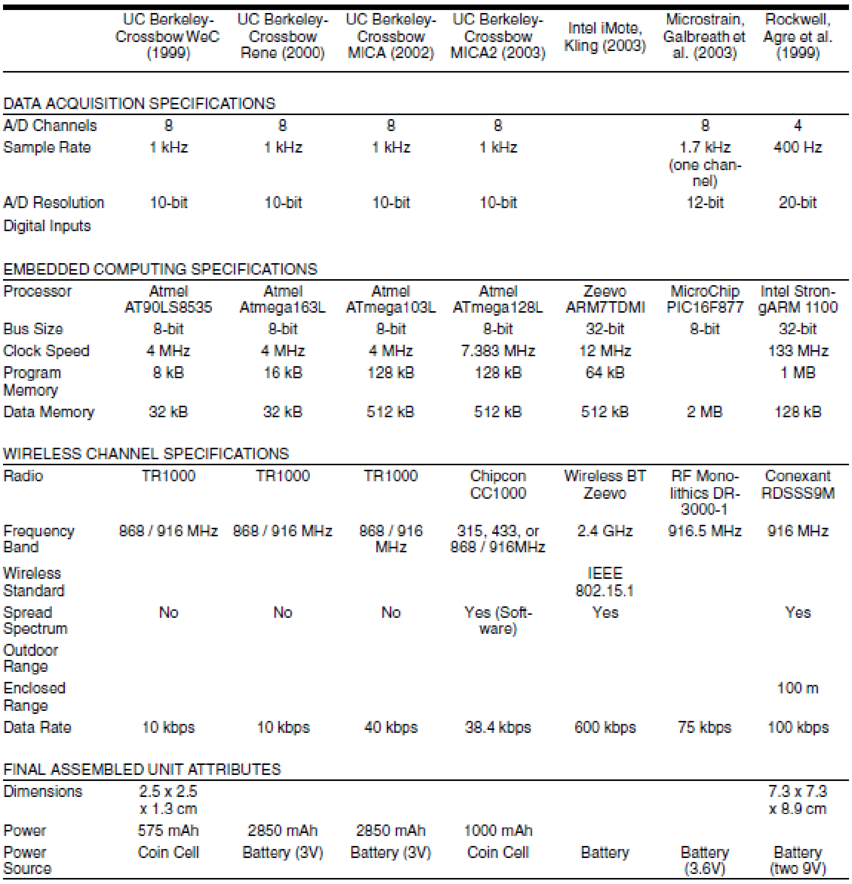
Classic Wireless Sensor Platforms

Starting from the existing reviews [11, 12, 13] we present in Tables 1 - 3 the commercial platforms for wireless sensors and their characteristics as they were reported by the corresponding researchers.

Many prototypes and products were based on the Berkeley family of Motes, such as: Mica2 (Crossbow 2007a), MicaZ (Mainwaring, et al., 2002), Telos (Polastre, 2005), iMote (Kling, 2003), and Imote2 (Kling et al., 2005; Adler et al. 2005). These are open source hardware and software platforms with generic sensing interface, and allow users to customize the sensors and the software to their application.

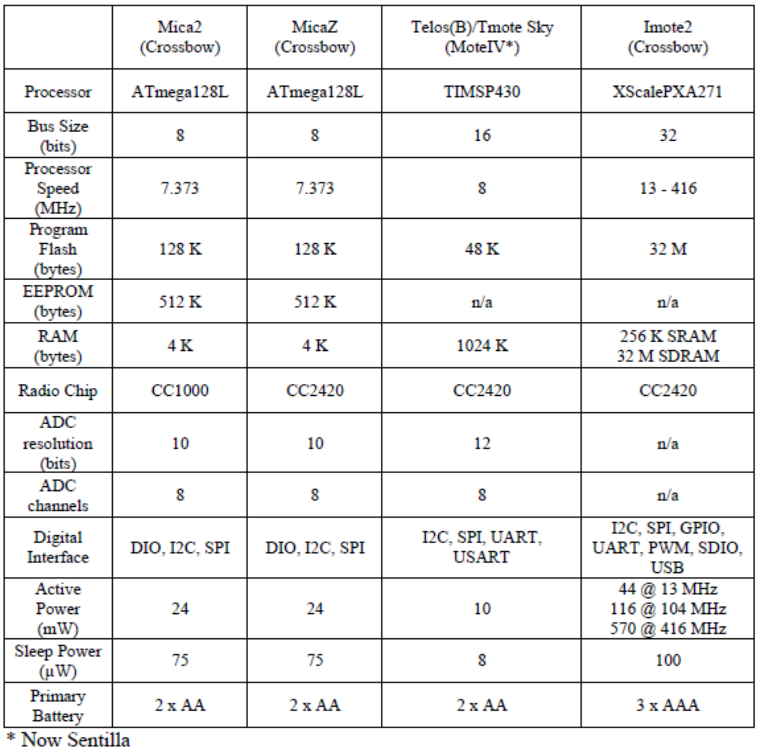
After the development of the Berkeley family Motes, many proprietary wireless sensor platforms have been also proposed. Some of commercially available microprocessor platforms have been proprietary, emulating wired sensors in the sense that the users cannot embed onboard processing algorithms. Others, like Imote2, became more popular as they allow embedding on-board processing algorithms while providing high processor speed and large RAM size.

Table 1. Summary of commercial wireless units by Lynch and Loh, 2006 [11]



	UC Berkeley-Crossbow WeC (1999)	UC Berkeley-Crossbow Rene (2000)	UC Berkeley-Crossbow MICA (2002)	UC Berkeley-Crossbow MICA2 (2003)	Intel iMote, Kling (2003)	Microstrain, Galbreath et al. (2003)	Rockwell, Agre et al. (1999)
DATA ACQUISITION SPECIFICATIONS							
A/D Channels	8	8	8	8		8	4
Sample Rate	1 kHz	1 kHz	1 kHz	1 kHz		1.7 kHz (one channel)	400 Hz
A/D Resolution	10-bit	10-bit	10-bit	10-bit		12-bit	20-bit
Digital Inputs							
EMBEDDED COMPUTING SPECIFICATIONS							
Processor	Atmel AT90LS8535	Atmel Atmega163L	Atmel ATmega103L	Atmel ATmega128L	Zeevo ARM7TDMI	MicroChip PIC16F877	Intel StrongARM 1100
Bus Size	8-bit	8-bit	8-bit	8-bit	32-bit	8-bit	32-bit
Clock Speed	4 MHz	4 MHz	4 MHz	7.383 MHz	12 MHz		133 MHz
Program Memory	8 kB	16 kB	128 kB	128 kB	64 kB		1 MB
Data Memory	32 kB	32 kB	512 kB	512 kB	512 kB	2 MB	128 kB
WIRELESS CHANNEL SPECIFICATIONS							
Radio	TR1000	TR1000	TR1000	Chipcon CC1000	Wireless BT Zeevo	RF Monolithics DR-3000-1	Conexant RDSSS9M
Frequency Band	868 / 916 MHz	868 / 916 MHz	868 / 916 MHz	315, 433, or 868 / 916MHz	2.4 GHz	916.5 MHz	916 MHz
Wireless Standard					IEEE 802.15.1		
Spread Spectrum	No	No	No	Yes (Software)	Yes		Yes
Outdoor Range							
Enclosed Range							100 m
Data Rate	10 kbps	10 kbps	40 kbps	38.4 kbps	600 kbps	75 kbps	100 kbps
FINAL ASSEMBLED UNIT ATTRIBUTES							
Dimensions	2.5 x 2.5 x 1.3 cm						7.3 x 7.3 x 8.9 cm
Power	575 mAh	2850 mAh	2850 mAh	1000 mAh			
Power Source	Coin Cell	Battery (3V)	Battery (3V)	Coin Cell	Battery	Battery (3.6V)	Battery (two 9V)

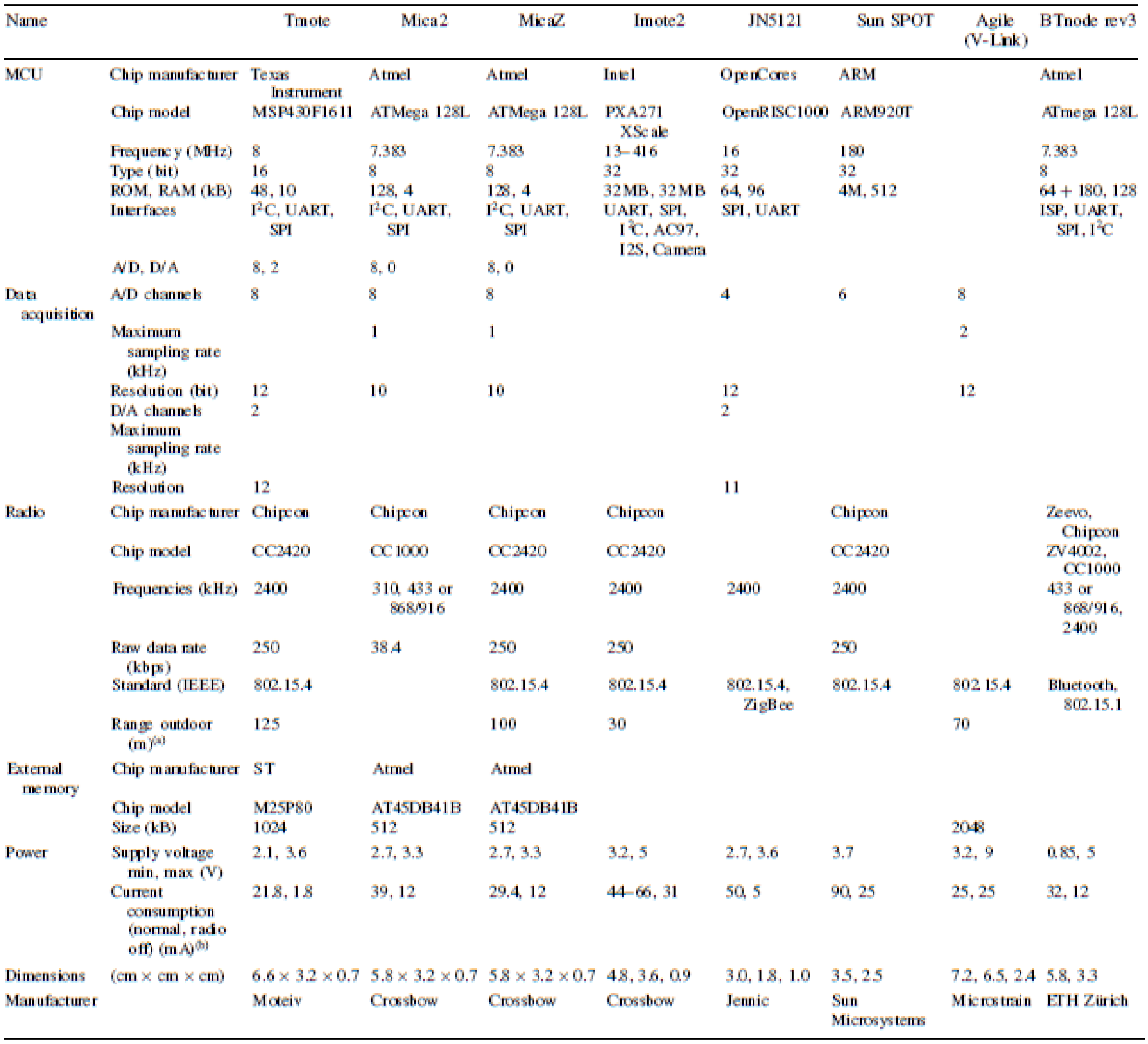
Table 2. Commercially available smart sensor platforms studied by Rice and Spencer, 2009 [12]



	Mica2 (Crossbow)	MicaZ (Crossbow)	Telos(B)/Tmote Sky (MoteIV*)	Imote2 (Crossbow)
Processor	ATmega128L	ATmega128L	TIMSP430	XScalePXA271
Bus Size (bits)	8	8	16	32
Processor Speed (MHz)	7.373	7.373	8	13 - 416
Program Flash (bytes)	128 K	128 K	48 K	32 M
EEPROM (bytes)	512 K	512 K	n/a	n/a
RAM (bytes)	4 K	4 K	1024 K	256 K SRAM 32 M SDRAM
Radio Chip	CC1000	CC2420	CC2420	CC2420
ADC resolution (bits)	10	10	12	n/a
ADC channels	8	8	8	n/a
Digital Interface	DIO, I2C, SPI	DIO, I2C, SPI	I2C, SPI, UART, USART	I2C, SPI, GPIO, UART, PWM, SDIO, USB
Active Power (mW)	24	24	10	44 @ 13 MHz 116 @ 104 MHz 570 @ 416 MHz
Sleep Power (µW)	75	75	8	100
Primary Battery	2 x AA	2 x AA	2 x AA	3 x AAA

* Now Sentilla

Table 3. Wireless sensor platform selection by Bischoff et al, 2009 [13]



Name		Tmote	Mica2	MicaZ	Imote2	JN5121	Sun SPOT	Agile (V-Link)	BTnode rev3
MCU	Chip manufacturer	Texas Instrument	Atmel	Atmel	Intel	OpenCores	ARM		Atmel
	Chip model	MSP430F1611	ATMega 128L	ATMega 128L	PXA271 XScale	OpenRISC1000	ARM920T		ATmega 128L
	Frequency (MHz)	8	7.383	7.383	13–416	16	180		7.383
	Type (bit)	16	8	8	32	32	32		8
	ROM, RAM (kB)	48, 10	128, 4	128, 4	32 MB, 32 MB	64, 96	4M, 512		64 + 180, 128
	Interfaces	I^{2}C, UART, SPI	I^{2}C, UART, SPI	I^{2}C, UART, SPI	UART, SPI, I^{2}C, AC97, I2S, Camera	SPI, UART			ISP, UART, SPI, I^{2}C
	A/D, D/A	8, 2	8, 0	8, 0					
Data acquisition	A/D channels	8	8	8		4	6	8	
	Maximum sampling rate (kHz)		1	1				2	
	Resolution (bit)	12	10	10		12		12	
	D/A channels	2				2			
	Maximum sampling rate (kHz)								
	Resolution	12				11			
Radio	Chip manufacturer	Chipcon	Chipcon	Chipcon	Chipcon		Chipcon		Zeevo, Chipcon
	Chip model	CC2420	CC1000	CC2420	CC2420		CC2420		ZV4002, CC1000
	Frequencies (kHz)	2400	310, 433 or 868/916	2400	2400	2400	2400		433 or 868/916, 2400
	Raw data rate (kbps)	250	38.4	250	250		250		
	Standard (IEEE)	802.15.4		802.15.4	802.15.4	802.15.4, ZigBee	802.15.4	802 15.4	Bluetooth, 802.15.1
	Range outdoor (m)(a)	125		100	30			70	
External memory	Chip manufacturer	ST	Atmel	Atmel					
	Chip model	M25P80	AT45DB41B	AT45DB41B					
	Size (kB)	1024	512	512				2048	
Power	Supply voltage min, max (V)	2.1, 3.6	2.7, 3.3	2.7, 3.3	3.2, 5	2.7, 3.6	3.7	3.2, 9	0.85, 5
	Current consumption (normal, radio off) (mA)(b)	21.8, 1.8	39, 12	29.4, 12	44–66, 31	50, 5	90, 25	25, 25	32, 12
Dimensions	(cm × cm × cm)	6.6 × 3.2 × 0.7	5.8 × 3.2 × 0.7	5.8 × 3.2 × 0.7	4.8, 3.6, 0.9	3.0, 1.8, 1.0	3.5, 2.5	7.2, 6.5, 2.4	5.8, 3.3
Manufacturer		Moteiv	Crossbow	Crossbow	Crossbow	Jennic	Sun Microsystems	Microstrain	ETH Zürich

Tables 1-3, contain a selection of platforms at the time when each review was conducted. More products were present and continue to appear, either commercial or research prototypes, but most of them are based on the same principles and architecture. Some product lists in the Internet can be found at [15 - 18].

Overview of Recent Products

TmoteSky originally from Moteiv and later from Sentilla [19] is presented as an example of a popular WSN platform. Many platforms with similar hardware setups exist today, based on the Texas Instruments microcontroller family MSP430 and the Chipcon radio CC2420. TmoteSky is the next-generation mote platform for extremely low power, high data-rate, sensor network applications designed with the dual goal of fault tolerance and development ease..

Figure 2. TmoteSky board

Advanticsys [20] provides a large variety of wireless sensor network based devices. The XM1000 is the new generation of mote modules, based on "TelosB" technical specifications, with upgraded 116Kb-EEPROM and 8Kb-RAM and integrated Temperature, Humidity and Light sensors. They are all fully compatible with TelosB hardware platform and its related commercial products such as TmoteSky, also ensuring TinyOS and ContikiOS support**.**

Figure 3. Advanticsys boards

Memsic [21] provides a portfolio of wireless sensor network products such as eKo, MICAz, TelosB, and IRIS Wireless Development Kits that allows choosing the optimal solution for each application. MEMSIC develops on WSN technology and recently acquired Crossbow Technology that produced the wireless sensor board for Imote2.

Figure 4. Memsic boards

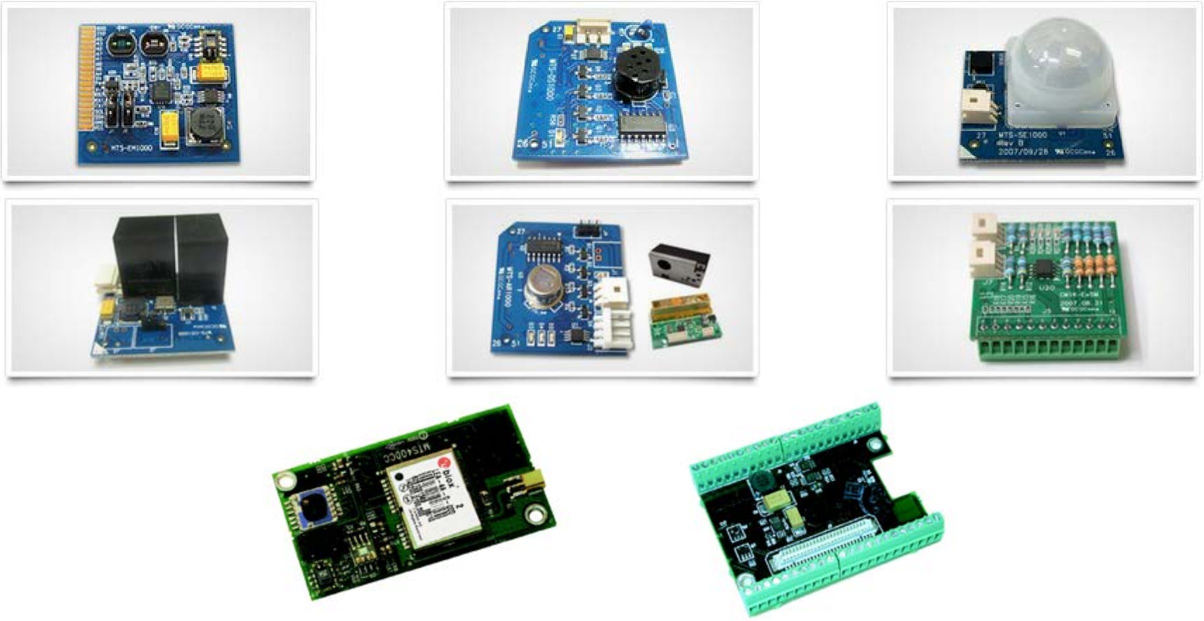
MicroStrain [22] provides a line of wireless sensor nodes, such as V-Link, offering a range of measurement options including strain, acceleration, displacement, pressure, load, torque, temperature, etc. They operate as part of a sensor network - LXRS, and they use a base station and special software tools for data collection and processing.

Figure 5. MicroStrain boards

Unicomp Informatics [23] provides the UCMote DRD mote, a Dual RaDio platform (second radio optional), based on the Atmel ATmega128RFA1 and Silicon Labs SI4432 RF Transceiver, as well as, the UCMote mini mote designed for Universities, R&D companies and for everyone who wants to get a small all-in-one WSN device that has ultra low power consumption.

Figure 6. Unicomp boards

A large variety of sensor boards is available for these products that include sensors for: voltage, strain, acceleration, displacement, pressure, load, torque, temperature, inertial sensing systems for orientation, attitude, heading, position and velocity estimations, dual-axis accelerometer, dual-axis magnetometer, light, , acoustic and sounder, barometric pressure, relative humidity, GPS, etc.



. Figure 6. Advanticsys and Memsic Sensors

A leading OS for these implementations is the TinyOS [24]. It is an open source, BSD-licensed operating system designed for low-power wireless devices, such as those used in sensor networks, ubiquitous computing, personal area networks, smart buildings, and smart meters. It is also supported by a worldwide community from academia and industry.

SUMMARY

The applications of wireless sensor networks in SHM continue to expand. Wireless sensor networks are the key for more reliable systems and have the potential to increase safety by providing early warning of impending structural hazards. There is a high mobility in the commercial area and commercial sensor nodes demonstrate both improved performance and lower power consumption. The increased performance and cost reduction achieved by newer systems is expected to expand the practice of SHM to a significantly higher number of civil infrastructures.

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