



Development of Field Programmable Modular Wireless Sensor Network Nodes for Ambient Systems

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Abstract

The goal of this work is to fabricate robust, miniature, wireless sensor modules. These provide an enabling technology platform to conduct research in creating ambient systems, through implementing wireless sensor network applications. The approach taken is to partition the wireless sensor module into a series of layers with area 25mm x 25mm. This modular approach has resulted in the specification of a series of layers, including a field programmable gate array layer for digital signal processing type operations, forming the initial elements of the 25mm sensor node toolkit that can be programmed for use with different sensors depending on application. This paper highlights the development of the sensor, processing, communication and power layers, and the connection approach used to form a robust modular system. Comparisons are made with other wireless sensor nodes and application examples are given.

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1. Introduction

It is now commonplace to find electronic devices, designed to improve comfort in life and user convenience, in our everyday environments. A lot of these devices have the capacity for some limited computational power. For example ovens have electronic timers to switch themselves on or off and thermostats that control temperature; cars have sensors to tell the driver if everyone is wearing seat belts and mobile phones can act as cameras or game consoles besides providing mobile communication. Although these devices can individually communicate with the user via audio, visual or mechanical mechanisms few devices have the capacity for interoperable communication and the exploration of enhancing artefacts with sensing, processing and communication is still mainly a topic of research [1]. Imagine a world where sensors associated

with artefacts and sensors embedded into the environment could wirelessly communicate their data and interoperate in context with user requirements. For example the oven could detect when the food is burning and send a message to the cook via his/her mobile phone, the cook could then adjust the oven temperature or switch the oven off from the phone. Another scenario sees sensor nodes deployed in agricultural environments. Ambient conditions such as temperature and humidity could be monitored to help improve crop yield by flagging conditions that lead to susceptibility to infectious disease and enabling preventative actions to be taken [2,3]. Wearable computing is another area where wireless sensor nodes are key to successful integration [4,5,6] with several companies already producing goods related to this topic [7,8].

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Mark Weiser saw the above ubiquitous computing concept as an absolute requirement for future systems which can be thought of in many ways as the opposite to virtual reality [9]. In virtual reality the users immerse themselves in a computer generated landscape by donning goggles and sophisticated suits which can sense the state of the person and perhaps provide some feedback. Weiser's vision of ambient computing merges computers massively but seamlessly further into our everyday environments. The creation of ambient systems requires development of sensor, ubiquitous computing and communications hardware technology managed by innovative software solutions. Realization of the ambient vision involves seamless integration of static and mobile wireless sensor nodes that may be able to actuate based on information from the ambient system. These sensor nodes could be powered by batteries or by energy harvested from their environment.

This paper gives an overview of a strategy being employed to design a hardware platform to enable research in massive sensor networks forming ambient systems. A prototype modular sensor node with 25mm form factor is described and compared with other sensor nodes in a similar class. Applications in the field of remote sensing, enhancing everyday artefacts, agriculture and intelligent sensing in remote environments will be given. The modules described can also be viewed as tools for optimizing the design and functionality of wireless sensor nodes to enable research in the miniaturization of wireless sensor node technology.

2. The 25mm Sensor Cube

2.1. Aims and Features

The aim of 25mm sensor cube is to provide a novel 3-D programmable modular system that could be used as a toolkit for ambient systems research (such as robotics, autonomous agents and neural networks, telemetry, transducer networks, etc). The target objectives for the 25mm cube module are to develop:

1. A low volume prototyping and experimentation platform.
2. A platform for sensing and actuating through physical and chemical parameters.
3. A scalable, re-configurable distributed autonomous sensing platform.
4. Intelligent, re-configurable algorithms for scalable Ambient Intelligence (AmI) Systems.

The first and second objectives incorporate the creation of a platform that is robust, available as a low volume prototype, and has the ability to interface to a broad range

of physical and chemical transducers. This will provide a foundation for the third aim, provision of functional low volume prototypes for implementation and evaluation in case study application areas. The fourth objective is a reconfigurable development tool for distributed autonomous transducer networks that are then to be investigated as a building block technology for ambient intelligence. The key properties of the module are

1. *Modularity*: the various sections of the 25mm cube, such as sensing, intelligent processing, communication and power should be modular plug and play in nature so as to allow easy optimisation and configuration for the target application.
2. *Robustness*: The modules should be able to be connected and disconnected from each other multiple times to allow experimentation. They should also be able to withstand harsh conditions such as strong vibration when deployed in mobile sensing applications
3. *Functionality*: A high degree of functionality is required to process sensor information at source to reduce the amount of data that needs to be transmitted to other nodes. This speeds communication by freeing bandwidth over the communication media and saves power to enhance the lifetime of the sensor node.
4. *Compactness*: The modules should be as compact as possible by minimizing the number of external components protruding from the 25mm cube. For example an antenna should be embedded into the RF communication layer module.

2.2. Modularity, Robustness and Connectivity

In order to design the 25mm cube it was first necessary to define the functionality of the system to identify the components that needed to be packed into the cube. Figure 1 shows the modules identified as being critical in the design. The schematic shows that both digital and analogue type sensors are being considered. The signals that they produce are conditioned for interfacing to the processing and communications modules. The conditioning circuitry may contain amplification or analogue filtering to reduce noise for example. For processing there is a field programmable gate array (FPGA) module. This allows intensive digital signal processing (DSP) tasks such as moving average filters, Fast Fourier Transforms (FFTs) to be implemented on the sensor node and this can even support intelligent applications, such as spiking neural nets for miniature robotic control [10]. The communications layer has a micro-controller and RF transceiver. The micro-controller can support less intensive processing tasks, stand-alone or can act as a co-processor to the FPGA section. The micro-controller also handles analogue to digital conversion of sensor data and the communication networking protocols for interfacing with the RF

transceiver. Memory and actuator modules are also included and these will be integrated into the system in the near future. For the present sensing, processing and communication layers are concentrated upon.

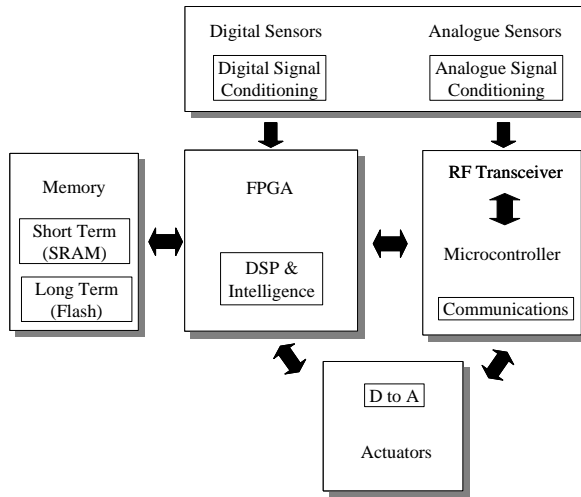


Figure 1: Modules of the 25mm system

In order to achieve a high-density of components it was decided to stack the modules using board-to-board PCB connectors. A previous version of a similar system used flat flexible cables (FFC) and connectors. However, after multiple insertions the reliability of the FFC system was compromised. Also such connecting cables protruded outside the edge of the cube and extra mechanical support was needed to fix the distance between the functional module layers. Several alternative series of connectors were considered. This led to selection of the Hirose 0.5mm pitch board to board connectors [11]. The connectors are available in a range of heights from 5mm to 8mm to allow the board-to-board gap to be tailored to match the height of the components between layers as shown in Figure 2.

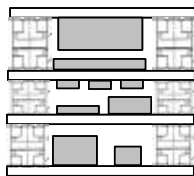


Figure 2: Variable stacking height allows the distance between layers to be minimised depending on the height of components

The connectors have a relatively small footprint in comparison with other options that were considered and are high density; an 80-pin connector will fit across the 25mm PCB. Pin counts of 20, 40 and 80-pins are available and the

high-density gives a firm rugged interconnection between modules without the need for extra mechanical support. Figure 3 shows some examples of possible connector layouts for the 25mm modules. A review of possible components for the primary processing and communication layers revealed that the FPGA device had the largest footprint. The Xilinx Spartan IIE 300K device is available in a BGA 256 pin package has a footprint of 17mm x 17mm which dictates that the 40 pin and 80 pin scheme shown in Figure 3 is the most suitable.

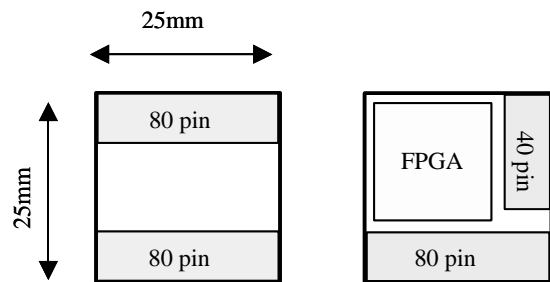


Figure 3: Example layouts for the board-to-board connectors

It was decided to place the board-to-board plugs on the bottom side of the PCBs and receptacles on the topsides of them. Although the individual connectors themselves are non-polarized the orthogonal style of their layout provides the polarization making it impossible to incorrectly interconnect the modules. A bus structure then runs between overlapping connector pins on the top and bottom sides of the PCBs to allow communication throughout the cube and between non-adjacent modules.

2.3. FPGA Module

An FPGA module was included as this provides a re-configurable processing solution in which intensive DSP tasks or in which intelligent functionality can be implemented [10]. The FPGA PCB contains a Xilinx Spartan IIE Field Programmable Gate Array (FPGA) [12]. The Spartan IIE 1.8V FPGA family gives high performance, abundant logic resources, and a rich feature set. The Spartans are seen as the low cost range of FPGAs which is important when considering that potentially thousands of these sensor nodes could be deployed into an environmental application and the nodes could be viewed as being disposable. The device integrated into the 25mm PCB series is the XC2S300E-7FG256. This is a mid-range device with density of up to 300,000 system gates. Features include dedicated block RAM, distributed RAM, programmable I/O and DLLs (Delay-Locked Loops) for minimization of clock skew.

The FPGA avoids the initial cost, lengthy development cycles, and inherent risk of conventional ASICs. Also,

FPGA programmability permits design upgrades in the field with no hardware replacement necessary (impossible with ASICs). The module features an on-board Flash serial EPROM such that the FPGA configuration memory is automatically downloaded on power-up and this configuration memory is in circuit programmable. The module also features an on board 4MHz crystal oscillator chosen to give a moderate processing rate while conserving power. 1.8V & 3.3V low drop out power supply regulators provide the maximum module lifetime from a coin cell battery attachment for the core & LVTTTL input/output (I/O) voltage requirements respectively with a power supply range from 2.7 to 7.0V. A schematic diagram of the module is shown in Figure 4 and the fabricated module is shown in Figure 5.

The 8 layer PCB features blind vias so that components, such as the Flash EPROM, oscillator and 0201 decoupling capacitors could be mounted on the underside of the BGA FPGA package. Due to the number of available connector pins and routing restrictions on this small form factor PCB only 92 of the 182 general purpose I/O pins available on the FPGA were routed to the connectors. Three indicator LEDs and the oscillator enable pin are also controlled from the FPGA.

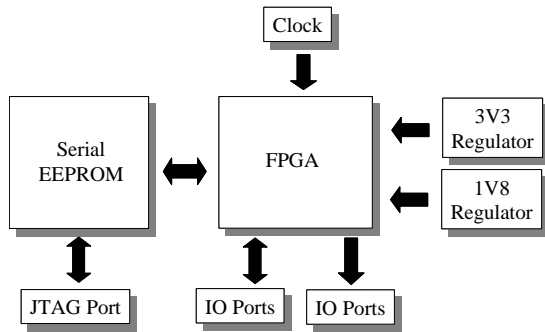


Figure 4: Schematic block diagram of the FPGA processing module

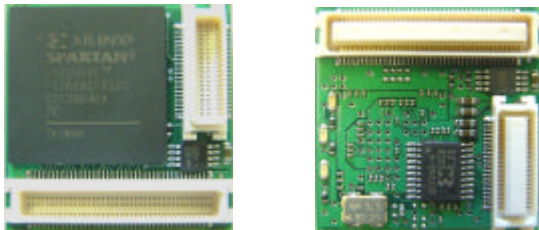


Figure 5: Top and bottom views of the FPGA module

2.4. Communications Module

The communications module consists of a Nordic VLSI nRF2401 2.4GHz RF transceiver [13] driven by an Atmel micro-controller [14].

The transceiver consists of a fully integrated frequency synthesizer, a power amplifier, a crystal oscillator and a modulator. It is an intelligent GFSK transceiver in a small 25mm² package footprint operating in the 2.4GHz ISM band. Output power and its 125 frequency channels are programmable. Current consumption is very low with transmit and receive currents typically 30-40mA peak @ -5dBm output power, and built-in power down modes make power saving easily realizable. ShockBurst mode, where data is transmitted at a high rate (up to 1Mbps) over a short time window, provides ultra-low power operation. The module also features an on board embedded TCA10F antenna from TriCome [15] that eliminates the need for an external antenna to keep the mote compact.

The micro-controller is the ATmega128L, an AVR 8-bit advanced RISC Architecture with 128 kbytes in-system programmable flash [14]. The module can be programmed with custom or standard protocols to achieve networking and communication with other nodes or for general product development. The micro-controller device has the same core as that used on the Mica Motes. Currently work is underway to port TinyOS onto the 25mm mote, an optimised operating system that allows fast configuration of the sensor nodes, and so far libraries have been developed to support the Nordic nRF2401 transceiver in energy efficient operation [16]. This programmable transceiver has been designed to connect with a separate battery module and FPGA layer depending on the configuration required by the end user or mobility/portability requirements. The module also features an extra 4 channel analogue sensor input connector, which is separated from the 40 and 80 pin connectors in order to reduce noise. Use can then be made of the micro-controllers embedded analogue to digital converters in order to convert the sensor data into digital format. Similar to the FPGA module, on board low dropout regulators take input voltages from 2.7 to 7V allowing power supply from a battery of two 3V coin cells to prolong node lifetime. In Figure 6 a schematic block diagram shows the interconnection of the main components of the communications module and the top/bottom views of the PCB are shown in Figure 7.

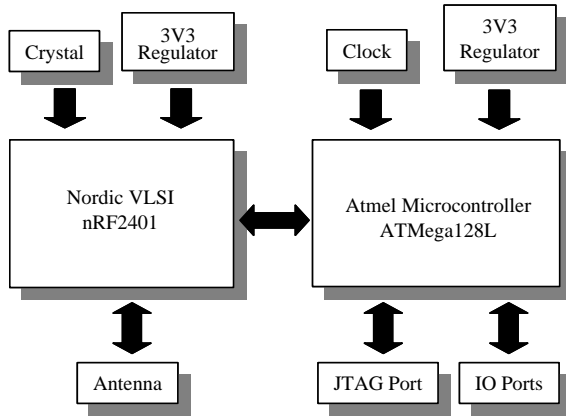


Figure 6: Schematic block diagram of the communications module

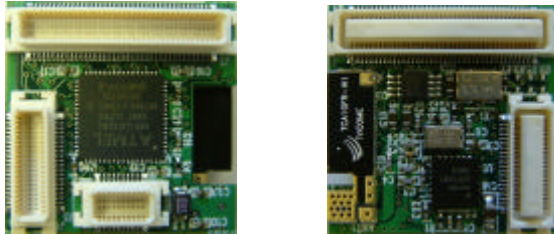


Figure 7: Top and bottom views of the communications module

2.5. Sensor & RS232 Interface Module

This PCB is a wired communication and sensor interface to the FPGA module. It contains a dual channel RS232 transceiver, the Maxim MAX3224ECAB in a small SSOP20 package enabling wired serial communication with a PC or a PDA for example [17]. The transceiver supports data rate to a maximum of 250kbps and has ESD protection for the RS232 I/O pins. Just 1 μ A standby current and an auto shutdown plus power mode make the device power efficient.

The module also contains two TLC549CD Analogue to Digital (A to D) converters from Texas Instruments [18] for interfacing analogue sensors to the FPGA module. The A to D converters work serially and require just two serial control signals, a clock and enable. This means that just three FPGA I/O pins are required per converter. The converters have 8 bits resolution and a 17 μ s maximum conversion time. They have a controllable sample and hold function and are accurate up to ± 0.5 LSB maximum error.

The module allows interfacing to seven external sensors of the type that change their resistance according to the parameter being measured (e.g. thermistors or light dependent resistors - LDRs). External sensors can be

plugged into the board using a crimp connector system. Figure 8 shows top and bottom views of the 25mm sensor and serial port interface module.

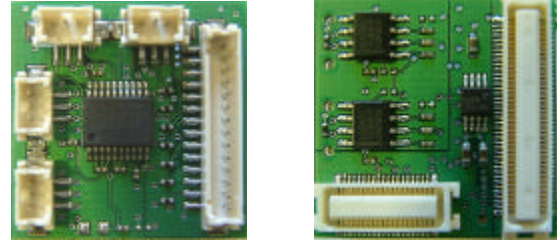


Figure 8: Top and bottom views of the sensor & RS232 interface PCB

2.6. Coin Cell Power Module

Power can be supplied to the motes using a simple coin cell interface that has been developed. Coin cells may be used to provide power to the 25mm system by running power line buses through the 40 and 80-pin connectors. A PCB has been designed to directly interface coin cells using the stackable connector system. There are several options for the choice of coin cell including support for 20mm and 24.5mm cells. Table 1 shows a range of options with capacities from 130mAh hours for configurations that draw little power to 560mAh for the more demanding applications. Single and double coin cell holders are also available.

Table 1
Options for coin cells in the power module

Capacity (mAh)	Height (mm)	Diameter (mm)	Voltage (V)
130	2.5	20	3
180	3.2	20	3
260	3	24.5	3
560	5	24.5	3

2.7. Programming interfaces

The FPGA and micro-controller modules are in circuit programmable. Programming can be achieved using the programming cables and pods from Xilinx and Atmel that are interfaced to the modules using specially designed programming and test PCBs. The deluxe programming interface shown in Figure 9 shows how a FPGA can be programmed. This version of the interface PCB brings all of the I/O from the 40 and 80-pin headers out to headers which can easily be probed when testing. The PCB has an

on board regulator to allow powering from 3.3 to 9 volts. Two RS232 9 pin serial ports also facilitate test from a PC or laptop.

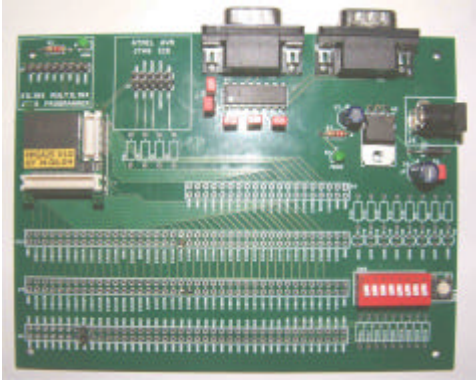


Figure 9: Deluxe programming interface, programming of FPGA module shown

A compact version of the PCB has also been designed and is shown in Figure 10 with one of the communications modules inserted for programming.

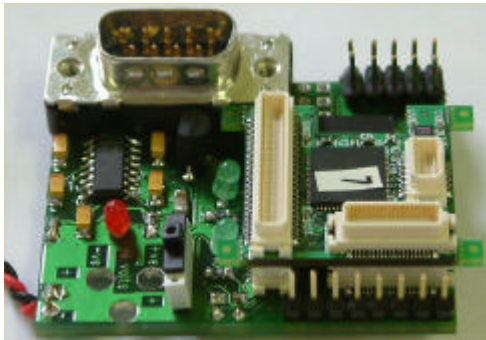


Figure 10: Compact programming interface, programming of the communications module shown

2.8. Module Stack

The stacking of the modules is shown in Figure 11. This demonstrates how the sensor/RS232 interface, FPGA, RF communication and power module can all be

interconnected to form a compact wireless sensor node. Due to the flexibility of this programmable sensor node different configurations may be considered. For example the sensor interface, FPGA and power modules could solely be used without the RF communication system to form a wired sensor node. Alternatively the FPGA layer can be omitted if there is not a requirement for DSP or intelligent application.

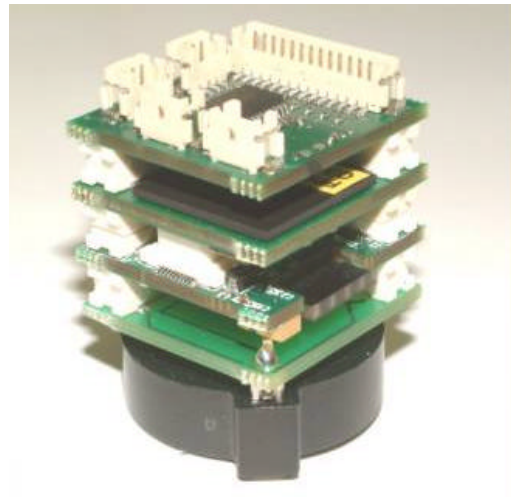


Figure 11: Stacking of the sensor interface, FPGA, communication and power modules

3. Comparison between Mica Mote, Intel Mote and NMRC 25mm Modules

This section evaluates the NMRC sensor nodes by comparing with other motes that are similarly classified. Issues such as robustness, construction, communication, input/output and processing power are discussed.

The NMRC nodes contain a series of miniaturized modules for sensing, computation, communication and power, built using standard surface mount and printed circuit board (PCB) technology. These sensor nodes are robust and highly functional due to their capacity for digital signal processing type computation on field programmable technology. They form a compact system as the design methodology strives to embed components of all layers within the 25mm x 25mm target area. Researchers at Berkeley developed the MicaMote platforms [19,20], a series of programmable sensor motes commercially available from Crossbow Technology [21]. Intel also have recently publicised the aptly called iMote [22]. Comparisons are made between the 25mm wireless sensor nodes presented here with Mica and Intel iMotes in this section. An overall comparison of electrical and mechanical specification is given in Table 2.

3.1. Construction

For deployment reliability and robustness are key concerns; imagine how much faith a user would have in a system when for example, due to a faulty sensor, a car is warning its driver that the boot is not shut when it actually is. In this case the ambient system can overcome this limitation to by taking data from many sensors and using ambient intelligence to decide upon the open or shut state of the boot.

The stackable connector system and form factor used in the NMRC modules draws immediate comparison with the Intel Mote arrangement. The NMRC modules are comparable in size to the Mica2Dots. They are slightly smaller at 25mm side length compared to 30mm for the Intel iMote and considerably smaller than the Mica2 Mote.

The connector density on the NMRC modules also is much higher at 0.5mm pitch allowing many more interconnections between the layers and into the

Table 2 Comparison between NMRC 25mm sensor node and Mica2/Mica2Dot/Intel motes

	NMRC 25mm Sensor Node	Mica2 Mote	Mica2Dot	Intel® iMote
PCB Area (mm ²)	25 x 25	58 x 32	25 (diameter)	30 x 30
Clock Speed (MHz)	4	7.3827	4	12
FPGA	Spartan IIE 300E	No	No	No
Microcontroller	ATMega128L(MLF)	ATMega128L	ATMega128L	ZEEVO TC2001P
ADC channels	8	8	6	Planned for future motes
ADC resolution (bits)	10	10	10	
Power supply	Coin Cell 3V	2 x AA	Coin Cell 3V	Coin or AA
Hardware UART	2 (Microcontroller) + Multiple (FPGA)	2	1	1
USB	no	no	no	Slave
Expansion Connector	80 + 40 + (20 ?C)	51	18	21 + 9
Flash (kB)	128 + 524 (FPGA)	128	128 + 512	512
SRAM (kB)	4 (Microcontroller) + 20 (FPGA) + Expansion Module planned	4	4	64
EEPROM (kB)	4	4	4	4
Current draw (mA)	5.5 (Microcontroller) + 20-50 (FPGA)	5.5	8	65 (TC2000)
RF	Nordic nRF2401 (GFSK)	CC1000 (FSK)	CC1000 (FSK)	Bluetooth
RF Data Rate (bps)	1M	38.4k	38.4k	723.2 k
Radio Freq. (Hz)	2.4G	916M/433M	433/868/916M	2.4G
RF Tx. current (mA)	10.5	25	27	37.5 (TC2000)
RF Rx. current (mA)	18	8	10	34.0 (TC2000)
?C RF Sleep current (?A)	1	1	1	1.49 (TC2000)
Radio range (m)	10 (Low power mode)	300	200	30

processor(s). This may be useful in several different configurations such as interfacing to multiple sensors or creating memory expansion modules (Flash, SRAM etc.).

The Mica2 and Mica2Dot motes appear to be a bit more fragile when the sensor and power sections are connected to the micro-controller and RF sections. The long 51-pin connector of the Mica does not give too much support when pressure is applied on the far edge of the PCB relative to this connector between the sensor and main mote PCBs. The battery section of the Mica2 Mote is also loosely supported with a double-sided sticky tab underneath the mote PCB. The 18 pins mounted on its circumference interconnect the Mica2Dot with its sensor layers. Care must be taken to interconnect its modules otherwise the pins could easily be damaged. The Intel iMote looks robust as they use two connectors, on opposite edges of the iMote to improve stability, an arrangement more similar to that of the 25mm sensor node.

3.2. Communications and Interoperability

Intersystem communication to actuate based on collection of data from many different systems designed to various standards is also a major challenge that needs to be overcome to navigate the ambient data highway. The ambient vision implies that a huge sensor/actuator network infrastructure will be developed integrating existing technologies with new advances as they become available. The radio frequency communication schemes developed in recent years have use in the development of ambient systems. It is now common to have a communications standard such as Bluetooth [23] embedded into a mobile telephone so that data can be wirelessly streamed in through the phone to or from a gadget in a local environment and Zigbee [24] is emerging as an attractive low power alternative and new versions of the MICA and NMRC nodes will support this standard.

For communications the Nordic transceiver [13] used in the NMRC module boasts the highest data rate. The Nordic transmit current is lower than the MICA2 Mote. Although the Nordic receive current is higher, it should be noted that advantage can be taken of the Shockburst mode [13] where data is received or transmitted over a very short time period. The power consumption figures given in Table 2 for the iMote are based on the Zeevo TC2000 chip used [25]. The iMote uses the next generation of this IC, the TC2001 for which no datasheet was available. The TC2001 boasts lower power but the figures in the table serve as a guideline that is likely to be improved upon with the newer device. For the TC2000 the power consumption figures for the wireless transmission and reception are considerably higher. This is perhaps due to the use of a Bluetooth scheme designed for applications such as streaming audio as compared with sending intermittent packets of sensor data.

The embedded antenna of the NMRC communication module gives a compact and robust design but range is low due to this and the higher operating frequency of 2.4GHz. This is also somewhat similar to the Intel design that uses Bluetooth at 2.4GHz and the embedded antenna option to achieve a slightly greater range of 30m. The whip antenna attachment of the Mica2 and Mica2Dot adds to the overall size of the Motes but has the advantage of extending the range. To summarize the 25mm sensor node and the Intel motes are compact but short range while the Mica2 and Mica2dot Motes are less compact but have a much greater transmission range. In the realization of ambient systems it is likely that sensor nodes will be available from a variety of manufacturers. One can therefore foresee a world in which Mica, Intel and NMRC motes all have their place. The compact short range Intel and NMRC 25mm sensor nodes would perhaps be more suited to indoor application such as home automation while the slightly bigger long range Mica Motes might be better deployed outdoors for agricultural application.

3.3. DSP & Intelligence Capability

The main point to differentiate between the NMRC 25mm modules and the others is the inclusion of the FPGA. FPGAs are useful when computationally intensive signal or image processing tasks are required and are also useful for implementation of intelligent neural network type computations. Another feature of the FPGA is that it has a relatively high number of user programmable input and output pins that conceivably could allow a large number of sensors to be connected to the node. The main drawback with this technology is its power consumption. FPGA technology is SRAM based and therefore has relatively high power consumption in comparison to micro-controller technology. However, in the near future one can expect the power supply issues of FPGAs to be addressed by the major corporations involved in the manufacture of these devices. Low power was notably a major focus of the FPGA 2004 symposium [26,27,28,29]. Due to the modular nature of the 25mm sensor platform it should be noted that the sensor could be assembled without the FPGA layer if DSP or neural network implementation is not required. Power consumption and battery lifetime would then be comparable with the other motes mentioned. The Intel iMote also has some capability for higher power processing the ARM7TDMI CPU core provides a 32-bit execution engine and runs at 12 MHz to give 4 times performance improvement over the MICA. However the drawback with the increased computational capability is also reflected in the increased power consumption. The power consumption quoted for the Zeevo TC2000 is 65mA although it should be noted that the next generation device, the TC2001, used in the Intel mote is likely to have improved on this specification. The ARM7TDMI architecture is vastly

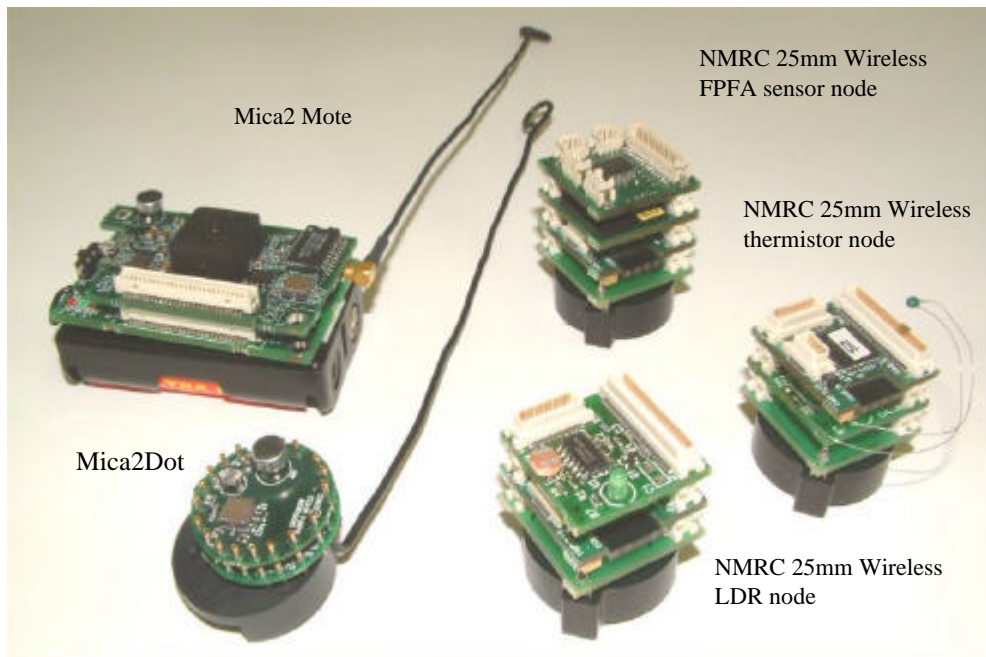


Figure 12: Comparison of 25mm sensor nodes and Mica2 Motes

different from that of the FPGA and it is difficult to make a direct comparison of performance. One advantage of the FPGA is that it may be programmed with a language such as VHDL. From a prototyping perspective this is very attractive and gives a basis for ASIC design when miniaturisation below 25mm is to be considered.

Figure 12 shows the 25mm sensor node photographed with the Mica2 and Mica2Dot Motes so that the relative sizes and construction can be overviewed. Note the external whip antennas on the Mica2 Motes.

4. Applications

The field of application for wireless sensor nodes is very wide ranging. Applications include sensing in remote environments, home automation and enhancement of everyday tangible artefacts, wearable computing, agriculture and remote sensing of environments inaccessible to humans. Some examples of where the 25mm platforms are currently being deployed are described below.

4.1. Remote Sensing

The project SOCIAL (Self Organised Societies of Connectionist Intelligent Agents Capable of Learning - IST-2001-38911) aims to use the 25mm module and in particular the FPGA module in a sensing application for

remote and hazardous environments [10]. The project aims to build a collaborative autonomous agent that can be deployed in oil pipelines and work in conjunction with other agents to detect corrosive damage. The agents will use pH sensing to detect the damage and indirect wireless communication mechanisms to relay the information to other agents in the vicinity. Spiking neural networks will be used to control the behaviour of the agents so that they can navigate towards the damaged section of pipeline and possibly collaborate to repair it. The 25mm FPGA module will host digital implementations of the neural networks that interpret the data from pH sensors to move along pH gradients towards the fault by controlling actuators such as miniature propellers and pumps. The processing power of the FPGA becomes an advantage here as look up tables can be exploited to store the spike response kernels and a number of neurons can independently process information in parallel. A 25mm pH sensor interface layer and a Zigbee version of the communications module will be used in conjunction with the FPGA module. During development stages it is also proposed to use an inertial measurement unit containing accelerometers, gyroscopes and magnetometers to track the location of the agents. A schematic of the proposed agent architecture is shown in Figure 13.

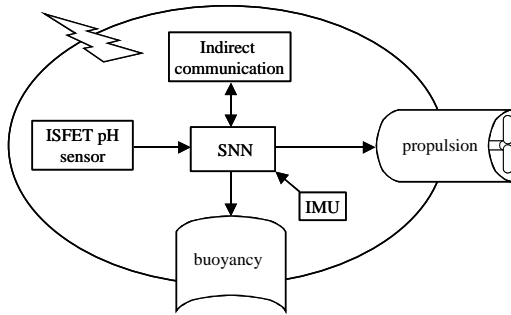


Figure 13: Architecture of the SOCIAL agent

4.2. Distributed and Scalable System Application

Notable development work for distributed collaborative systems is taking place in the research area of the “Disappearing Computer” Initiative (EU IST Future and Emerging Technology Programme) [30]. In the “Disappearing Computer” initiative, scaling and power aware computation techniques are being applied to development of solutions for distributed artefacts, which are everyday objects with embedded electronics. The nature of the individual artefacts is based upon mobile computational units, such as the mobile phone, PDA, etc, and thus intelligent use of power and bandwidth are major issues. The process of scaling is also a major issue, in particular where dynamic and mobile services and functions are required of the distributed system of artefacts. The use of component software forms, applied to units with both a tangible physical and digital presence, is one method under development to address this challenge. In the E-Gadgets Disappearing Computer project [1,31] sensor networks were integrated into everyday objects such as tables and chairs using the FPGA technology [12] to interface sensor data to PDAs with WLAN cards. The PDAs were running a Java based operating system called GAS-OS (Gadget Architecture Style) that allowed artefacts to be dynamically interconnected over the WLAN so that users could configure their own automated environment. For example in a study scenario if the chair is occupied, near the table and the table detects that a book is open upon it then the light could be synapsed to turn on.

The following figures demonstrate how the electronics in the enhanced desk artefact the e-desk could be miniaturised using the FPGA and sensor interface modules of the 25mm system. The desk has sensors embedded into its surface to detect if an object is placed in a certain location. Figure 14 shows a view from underneath the surface where 30 sensors were deployed. The vision would be to expand the number of sensors further so that a much

more detailed view of the state of the surface could be extracted. Transfer of all the sensor data to the computational device could be achieved with a novel bus system or by using a device such as an FPGA with a large number of data inputs. The electronics used in the eGadgets project consists of, two 50mm x 50mm signal conditioning boards to interface to the weight sensors (light dependent resistors) in the seat of the chair, a 100mm x 100mm standard FPGA development module and a 30mm x 30mm RS232 converter to interface the digital data to the PDA. Figure 15 shows the 100mm FPGA module used and compares with the 25mm FPGA. Stacked with the sensor interface layer the 25mm FPGA could be used to drastically reduce the size of the electronics to make integration into the artefact much simpler.

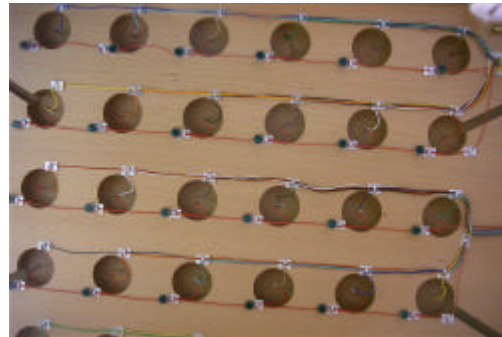


Figure 14: Underneath view of the e-desk showing embedded sensors

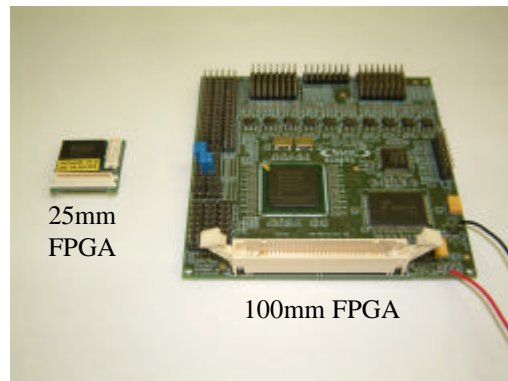


Figure 15: Comparison of the 100mm FPGA used in the E-Gadgets project with the 25mm module proposed as a replacement

4.3. Agricultural Applications

The GoodFood project [3] is an Integrated Project presented within the IST thematic area of EC VI FP and aims at developing the new generation of analytical

methods based on Micro and Nanotechnology solutions for the safety and quality assurance along the food chain in the agrofood industry. The project aims to sense the quality and environment surrounding agricultural produce through the food-chain to address current and future concerns about the safety of foodstuff. Sensor node and mote technology is being applied in the GoodFood project to replace the technology used nowadays to assess food safety and quality. Conventional testing relies on lab solutions that are bulky, costly, punctual and time consuming. In the initial case scenarios the safety of wine is researched by employing wireless sensor networks in the vineyard and the wine cellar. The Mica2Mote has been proposed as the sensor node to be deployed in the vineyard and will be interfaced with sensors such as air/soil humidity and temperature, light, leaf temperature. The use of the 25mm sensor node has been proposed for the indoor wine cellar application where shorter range communication is more suitable. Data from these stages, and further product lifetime stages including transportation, storage and sale will be collected using an ambient intelligence approach and this data will be analysed in order to improve food quality.

In a similar vein the project PLANTS (IST-2001-38900) has a goal to develop (bio)sensor and (bio)actuator networks that enable artefacts to induce complex responses from plant-life and perceive their environment in a plant-like way [2]. This project takes an approach similar to e-Gadgets where wireless sensor nodes around plants form e-Plants to enable automatic actuation of e-Gadgetised irrigation systems, light, temperature controllers etc. and better human plant interaction.

4.4. Wearable Computing

Research, which uses the 25mm sensor nodes in the wearable computing area, is currently underway. The project involves the wireless transmission of sensor information from a glove to see the position and track the motion of the hand and fingers. Extending the system to two hands the system has useful application for example as a sign language translator. Wearable computing poses major challenges for miniaturisation of motes and sensor nodes. Although good progress has been made on the miniaturisation of the sensor nodes described in this paper. Further miniaturisation effort is required to comfortably and seamlessly embed wireless sensor networks into clothing and parallel research tracks are considering new technologies, packaging and interconnect techniques to achieve this [32,33].

5. Conclusions and Future Work

This paper has described the development of the NMRC's 25mm wireless sensor node system. This is a robust, miniature and modular technology that is currently being used to conduct research in creating systems of ambient intelligence through implementing wireless networks of sensor nodes. The design of a series of platforms for sensing, processing, communication and power has been described.

Comparisons with other similar sensing nodes in this class, namely the Mica2, Mica2Dot and Intel motes, revealed advantages and disadvantages of each. The inclusion of a FPGA layer in the NMRC 25mm sensor node lends this system well to sensors in which digital signal processing can be performed or intelligent decisions can be made locally in the sensor node to reduce the amount of data that would need to be wirelessly transmitted. With advances in low power FPGA technology this could ultimately save on overall power consumption and reduce traffic on the radio frequency band.

The strategy employed to confine layers to 25mm x 25mm has resulted in a compact sensor node design which, due to its modularity, has the potential to be highly extensible. For example for intense DSP tasks several FPGA layers could be stacked into a single node. The compactness comes with a limitation in that wireless range is more limited. The compact nature and short wireless range of the 25mm node makes this module perhaps more suited to indoor usage whereas the larger, long range Mica2 Mote is better suited to outdoor usage, the larger batteries giving it longer lifetime. Due to the suitability of different sensor nodes and motes to various environments and applications one can envisage a world with all of these working and contributing data towards ambient intelligence (AmI).

This research platform represents NMRC's first step towards the development of miniaturized sensor nodes, the design emphasis being on robustness, high functionality, flexibility for use with many sensors and applications in miniature layers of target area 25mm x 25mm. Future work on this platform will extend the library set of layers and apply the nodes in various scenarios. With further research in technology, interconnect and packaging, sensor nodes could eventually be miniaturised to a level where they could be woven into fabrics for wearable applications, deployed as particles from a spray can or sprinkled like dust. The team behind the development of the 25mm sensor node is also involved in the development of sensor node solutions at smaller scales of 10mm, 5mm and 1mm side length cubes. The next goal is to provide functionality at a scale of a 10mm cube using flexible PCB substrates to obtain high functionality per unit volume using commercial-off-the-shelf components. Thin flexible substrates and bare die assembly techniques are then being considered at a 5mm form factor cube level whilst novel

techniques for stacking thin silicon die are being developed to reach the ultimate goal of a 1mm cube. The 1mm cube specification for future autonomous transducer nodes aims to provide ubiquitous computational sensor networks that will drive the vision of AmI.

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7. References

- [1] A. Kameas, S. Bellis, I. Mavrommati, K. Delaney, A. Pounds-Cornish and M. Colley, An Architecture that Treats Everyday Objects as Communicating Tangible Components, Proceedings of the First IEEE International Conference on Pervasive Computing and Communications, PerCom'03, March 23 - 26, 2003 Fort Worth, Texas, pp. 115 -124.
- [2] C. Goumopoulos, E. Christopoulou, N. Drossos and A. Kameas, The PLANTS System: Enabling Mixed Societies of Communicating Plants and Artefacts, P. Markopoulos et al. (Eds.): EUSAI 2004, LNCS 3295, pp. 184-195, 2004.
- [3] K. M. Razeeb, S. Bellis, B. O'Flynn, J. Barton, K. Delaney and C. O'Mathuna, A Hybrid Network of Autonomous Sensor Nodes, ACM International Conference Proceeding Series, Proceedings of the 2nd European Union symposium on Ambient Intelligence, 8-10 November 2004, Eindhoven, The Netherlands, pp. 69-70.
- [4] R. DeVaul, M. Sung, J. Gips, A. Pentland, MIThril 2003: Applications and Architecture, Proceedings of Seventh IEEE International Symposium on Wearable Computers, 21 - 23 October 2003, pp: 4- 11.
- [5] U. Anliker, J. Beutel, M. Dyer, R. Enzler, P. Lukowicz, L. Thiele, G. Troster, A systematic approach to the design of distributed wearable systems, IEEE Transactions on Computers 53 (8): Aug 2004, pp. 1017-1033.
- [6] G. J. Kim, S. H. Han, H. Yang, C. Cho, Body-based interfaces, Applied Ergonomics 35 (3), May 2004, pp. 263-274.
- [7] E. Vogt, Always on, always with me [wearable computing], R&D, Xybernaut Corp., Fairfax, VA, USA, MST News, n 2, April 2002, p 11-13.
- [8] Infineon Technologies: Wearable Electronics Portal: <http://www.wearable-electronics.de/>
- [9] M. Weiser, The Computer for the Twenty-First Century, Scientific American., September 1991, 265(3), pp.94-104.
- [10] S. Bellis, K. Mahmood, C. Saha, K. Delaney, C. O'Mathuna, A. Pounds-Cornish, G. de Souza, M. Colley, H. Hagraas, G. Clarke, V. Callaghan, C. Argyropoulos, C. Karistianos, G. Nikiforidis, FPGA Implementation of Spiking Neural Networks - an Initial Step towards Building Tangible Collaborative Autonomous Agents, Proceedings of 2004 International Conference on Field Programmable Technology, ICFPT'04, The University of Queensland, St Lucia Campus, Brisbane, Australia, 6-8 December, 2004
- [11] HRS Hirose UK website: <http://www.hirose.co.uk/>
- [12] DS001-2, Spartan-IIIE 1.8V FPGA Family: Functional Description Version 2.0 11/18/02 <http://www.xilinx.com>
- [13] Nordic VLSI nRF2401 Single Chip 2.4GHz Radio Transceiver Datasheet nRF2401rev1_1: <http://www.nvlsi.com/>
- [14] Atmel ATmega128/ATmega128L Data Sheet Rev. 2467L-AVR-05/04: <http://www.atmel.com>
- [15] TriCOME website: <http://www.tricome.com>
- [16] A. Barroso, J. Benson, T. Murphy, U. Roedig, C. Sreenan, J. Barton, S. Bellis, B. O'Flynn, and K. Delaney, The DSYS25 Sensor Platform, Proceedings of the Fourth IT&T Conference, Limerick, Ireland, October 20-21, 2004
- [17] Maxim MAX3224-MAX3227/MAX3244/MAX3245 Data Sheet 19-1289; Rev 2; 10/03: <http://www.maxim-ic.com/>
- [18] Texas Instruments TLC548C, TLC548I, TLC549C, TLC549IData Sheet SLAS067C - Rev. 09/96: <http://focus.ti.com/>
- [19] Wireless Measurement System Mica2 Data Sheet, Document Part Number: 6020-0042-05 Rev A
- [20] Wireless Microsensor Mote Mica2Dot Data Sheet, Document Part Number: 6020-0043-04 Rev A
- [21] Crossbow Technology Inc. Website: <http://www.xbow.com/>
- [22] Intel Mote overview webpage <http://www.intel.com/research/exploratory/motes.htm>
- [23] The official Bluetooth wireless info site: <http://www.bluetooth.com/>
- [24] Zigbee Alliance: <http://www.zigbee.org/>
- [25] TC2000 Single Chip Bluetooth Solution Pre-Production Data Sheet, MK-0004 Version 2.9006v16, October 2002
- [26] Jason H. Anderson, Farid N. Najm, Tim Tuan, Active leakage power optimization for FPGAs, Twelfth ACM International Symposium on Field-Programmable Gate Arrays, FPGA 2004, Monterey, California, February 22-24, 2004, pp. 33 - 41.
- [27] F. Li, Y. Lin, L. He, J. Cong, Low-power FPGA using pre-defined dual-Vdd/dual-Vt fabrics, Twelfth ACM International Symposium on Field-Programmable Gate Arrays, FPGA 2004, Monterey, California, February 22-24, 2004, pp. 42-50.
- [28] A. Gayasen, Y. Tsai, N. Vijaykrishnan, M. Kandemir, M. J. Irwin, T. Tuan, Reducing leakage energy in FPGAs using region-constrained placement, Twelfth ACM International Symposium on Field-Programmable Gate Arrays, FPGA 2004, Monterey, California, February 22-24, 2004, pp. 51 - 58.
- [29] Deming Chen, Jason Cong, Fei Li, Lei He, Low-power technology mapping for FPGA architectures with dual supply voltages, Twelfth ACM International Symposium on Field-Programmable Gate Arrays, FPGA 2004, Monterey, California, February 22-24, 2004, pp. 109 - 117.
- [30] The Disappearing Computer Initiative website: <http://www.disappearing-computer.net/>

- [31] e-Gadgets project website:
<http://www.extrovert-gadgets.net>
- [32] T. Healy, J. Donnelly, B. O'Neill, K. Delaney, K. Dwane, J. Barton, J. Alderman , Innovative Packaging Techniques for Wearable Applications using Flexible Silicon Fibres, Proceedings of 54th Electronic Components and Technology Conference ECTC 2004, Las Vegas, USA, June 1-4 2004.
- [33] J. Barton, B. Majeed, K. Dwane, K. Delaney, S. Bellis, Development and Characterisation of Ultra Thin Autonomous Modules for Ambient System Applications Using 3D Packaging Techniques, 54th Electronic Components and Technology Conference, ECTC 2004, Las Vegas, USA, June 1-4, 2004.