Development of Distributed Sensing Systems of Autonomous Micro-Modules

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Abstract

This paper focuses on the development of miniaturised modular wireless sensor networks that can be used to realise distributed autonomous sensors for future ad-hoc networks. Such modular, mobile networks are key enabling technologies in the field of ubiquitous computing and wearable electronics.

The Ambient Systems team in the NMRC has adopted a phased approach to developing ultra-miniature sensor nodes with a goal of implementation of a 1mm^3 (or less) autonomous sensor module. This paper will detail the progress through phases 1 and 2. The phase 1 modules are 25mm cubes, fabricated as a 3-D stackable modular PCB, which can be mounted on mobile devices or worn on the body; they can measure acceleration, rotation, shock, elevation etc. and have an ultra low-power RF channel-shared link to a base station. There are numerous possible applications in the fields of sports, exercise, entertainment and health. Extra panels, including sensory, memory or computation can be designed and added as needed. This make the phase 1 module a powerful test platform for developing future automous sensor systems.

The phase 2 modules have a much reduced form factor, approximately a 1cm cube; as well as the modularity developed in phase 1, the phase 2 form contains actuators and a PLD platform.

Introduction

Major research efforts are currently targeting the "disappearance" of the computer into the fabric of our environment. In the future, the spaces we live in will be populated by many thousands of objects (often described as "artefacts") with the ability to sense and actuate in their environment, to perform localised computation, and to communicate, even collaborate with each other. Artefacts are playing a large role in research towards intelligent systems and ubiquitous computing[1]. There are two prime drivers: the smaller these objects are the more effective they will be in providing opportunities for integrating the physical and digital worlds, and the greater the number of objects within these systems/networks the more valuable the networks are (Metcalfe's Law). The main properties required to maximise the capabilities of such networks are that it should have high granularity (i.e. high resolution), reconfigurability modularisation and mobility. The system level implementation will be realised through concurrent hardware and software co-design and engineering; innovation in software should be matched by invention in hardware. It is notable in this regard that many issues are comparably reflected in both areas (see figure 1). It is important that novel hardware technology platforms are used for object and system development, incorporating 3-D stacking, multi-chip and micro-sensor integration, thin and flexible substrates, smart materials and ultimately micro-nano-systems. To do this, new form factors for hardware need to be investigated, optimizing performance. In this light, the key initial considerations are interconnection and modularity of the hardware.

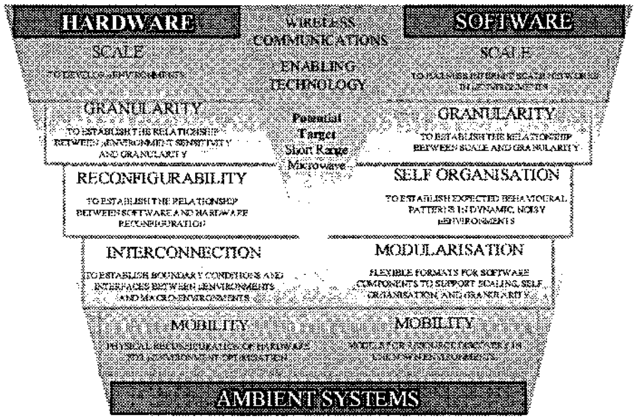


Figure 1: Concurrent development issues for Hardware and Software towards the realisation of Ambient, or Ubiquitous, systems.

Autonomous Sensors

Recent developments in wireless and micro-sensor [2,3] technologies have provided foundation platforms for considering the development of effective modular systems. These systems will increasingly need to take advantage of high density integration techniques to achieve the required levels of miniaturisation, including development of 3-D solutions(see figure 2). Fully realised, they offer the prospect of flexibility in use, and network scalability. Currently, most sensor networks are strongly integrated into the assembly process of their target systems (E.g. the automobile, production line equipment, aircraft, etc). Thus, they carry a high infrastructural overhead. Emerging autonomous formats include wireless units designed to collect data and transmit to central (or distributed) hosts. Interesting examples include passive/active tags, inertial measurement units (IMU), the 1cm^2 wireless integrated micro-sensors at UCLA [4], and the "Smart Dust" project [5,6] at the University of Berkeley.

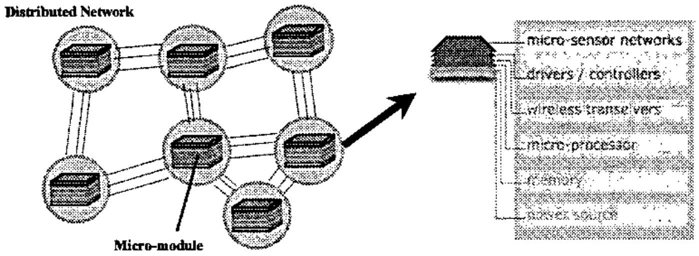


Figure 2: System Format with Modular Nodes.

Sensor System Development

The miniaturised wireless sensor networks presented here are the evolution of a project collaboration between NMRC and MIT Media Lab, performed with the aim of miniaturisation and ruggedisation of the MIT Media Lab "expressive footwear"[7]. Prof. Joe Paradiso and his team at the MIT Media Lab have prototyped a sensor component network of sensors that are integrated with a wireless transmitter and mounted onto a shoe (expressive footwear) [8,9]. The sensors were located either in the insole or on a PCB attached to the shoe. A dancer, equipped with this footwear, has every movement monitored by an off-stage computer. Although currently used to explore applications in interactive dance, this system also has applications in areas like sports training and medicine, interactive exercise, and podiatry diagnosis and therapy.

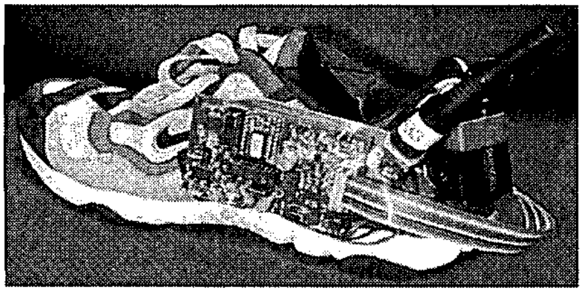


Figure 3: MIT Media Lab "expressive footwear" module

A central objective of the evolution of this sensor platform is increasing its applicability beyond the domain of expressive footwear. Thus, a modular approach, initially for mobile sensor networks, targetting primary functionality as an inertial measurement unit was adopted. The phase 1 module comprises an ensemble of 16 sensors, electronic interfaces, and a wireless transmitter manufactured using a combination of current surface mount techniques and multichip packaging (MCP). The sensors included accelerometers, gyroscope, compass, pressure sensors, bend sensors, electric field sensor and sonar transmission. The module includes; an integrated PIC micro-controller with A/D converter, separate 256K EEPROM memory for local data storage and a 433MHz RF Transceiver with 20kbit/s data rate within a multi-chip module (MCM). Current prototypes consist of miniature sensor packages that can be worn on limbs and torso or mounted within artefacts.

3-D Packaging

In the last several years, new package form factors have offered size reduction in both the length and width of packages (X and Y dimensions). Now, with the popularity of portable devices, along with the expanding communication and computing markets, IC mounted height (Z dimension) reduction is challenged to new extremes. Depending on the specific application requirements, different package level solutions are required. 3D packaging is achieved either by stacking 2 or more die within a single package, or by stacking and connecting completed packages. 3D packaging offers several benefits including:

Smaller, Thinner Packages
Significant size and weight reductions
Reduced Packaging Costs and Components[10]

The idea of stacking chips is not new. Sharp Corporation led the way in 1998, when it introduced the first stacked chip scale package (S-CSP) [11,12] of bare- die flash and SRAM for cell phones. Today, Fujitsu, Hitachi, Mitsubishi, NEC, ASE, Toshiba, Dense-Pac Microsystems and Amkor Technology are among the companies producing different kinds of S-CSP's for portable devices. In a typical package of this kind, two or three memory chips are piled on top of each other, separated by a a thin layer of die attach material and connected by wire to die-bond pads on the package substrate. There are a number of companies producing truly innovative 3-D assembly techniques. Tessera Technologies, Inc has a method for attaching memory chips and ASIC's to flexible tape and folding the tape over to create low profile stacks. The μZ family of Multi-Chip packages from Tessera are an extension of their μBGA CSP's[13,14]. Valtronic SA of Switzerland already folds logic and memory components into a single package for hearing aids and other low volume, high value applications[15,16]. On the horizon is a system in a cube based on epoxy molded layers of different chips. Developed primarily for military and space applications by companies such as Irvine Sensors Corporation, USA and 3D Plus, France, these super stacks are now found in micro-cameras for satellites[17,18,19]. NMRC's experience in 3D packaging stems from involvement in the EU funded TRIMOD and BARMINT projects[20,21,22].

Module Evolution

The development of the phase 1 module took place in 2 phases: the development and ruggedisation of the wearable sensor platform and the re-design of the circuits for the miniaturised modularised form factor.

The ruggedisation was necessary to improve the module reliability. This was done in two steps. Firstly, the wearable sensor portion of the circuit was re-designed and fabricated on Copper-clad flex. Sensors incorporated in the flex circuit included bend sensors, dynamic pressure sensors and force sensing resistors. Secondly, these circuits were laminated between protective plastic sheets and reliability tested through a series of non-standard reliability tests with a high yield.

During the design phase of the module, a building block technique for the autonomous wireless sensor network was developed. The formal design of the module PCB was completed with the aim of miniaturising and modularising the circuit to allow it to be unobtrusively worn anywhere on the body. The final design was realised as a 90mm x 30 mm two layer PCB which could be mounted as is or separated into three 30mm x 30mm panels which can be positioned on any portion of the body. Figure 5(a) shows the module before segmentation while 5(b) shows a separated module.

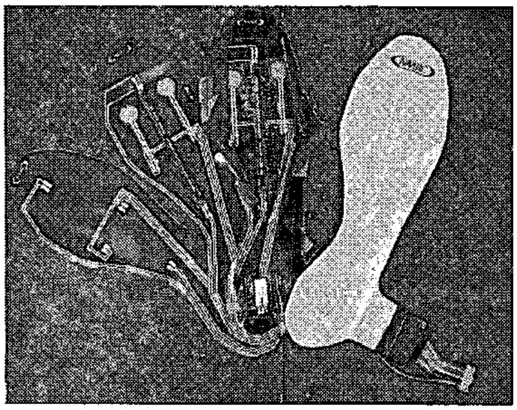


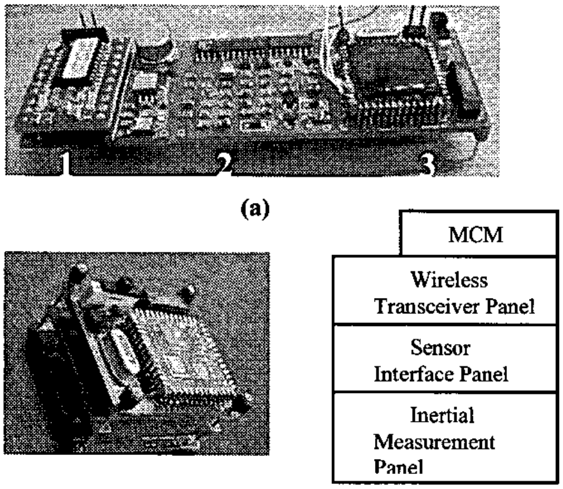
Figure 4: Process flow of Insole development

The 3 panels visible are 1) the inertial measurement panel 2) the force sensors interface panel and 3) the wireless transceiver panel. The sensors found on the inertial measurement panel are given in Table 1:

2-axis accelerometer/tilt sensor – ADXL202E from ADI
3-axis shock sensor- ACH –04-08-05 from MSI
3-axis compass – Honeywell HMC2003
1-axis rate gyro – Murata ENC –
40KR08 40kHz Sonar receiver – Panasonic

Table 1: Inertial Measurement Panel Sensors

The force sensors interface panel contains interface circuitry for all the insole sensors, which are listed in Table 2:



(a)

(b)

(c)

Figure 5: Autonomous Sensor Network Node with Modular Design Format (a) before, and (b) after segmentation. 4(c) is a cross-section describing the stacked module

Height sensor (Electric Field Sensor)
1 Dynamic pressure sensor - PVDF
2 continuous pressure sensors – Force Sensitive Resistors(FSR's)
2 Resistive Bend sensors
1 Flexiforce continuous pressure sensor

Table 2: Insole sensors

The third and final panel of the original design contains a PIC 16F877 8-bit CMOS Microcontroller with A/D converter and a 433MHz RF transceiver packaged in an MCM module.

The modular format of the PCB allows for extra panels to be designed and manufactured as and when required. Though stacked in 3-D in Figure 5(b), miniature flex cable connectors on each panel allow the modules to be connected in a variety of different ways and in an unobtrusive manner. Preliminary versions of this module have been utilised in projects including a wearable network, interactive glove and a localisation system.[9,10]

Module characteristics include:

PIC 16F877 8-bit CMOS Microcontroller with A/D converter
Operating speed: Dc – 20MHz clock input DC – 200ns instruction cycle
8K x 14 words of Program Memory, 388 x 8 bytes of Data Memory (RAM)
Separate 256K EEPROM memory for local data storage
Low Power consumption -< 2mA @5V, 4MHz; 15mA typical @3V, 32kHz < 1mA typical standby current;
433MHz RF True Frequency Shift Keying (FSK) Transceiver
2 channels 20kbit/s data rate – 9600 baud

Results

In order to test the autononomous sensor network node a programming interface circuit board initially had to be constructed. The purpose of this board was to connect the PIC microcontroller In Circuit Debugger (ICD) six pin jack socket to a surface mount socket which allowed a flex connector to relay the programming data into the node. The interface board also contains LEDs and input switches for testing the microcontroller circuit located in the MCM of the node. To test the RF channel a base station containing a PIC-16F877 and Nordic RF-401 transceiver was used. The base station has an RS-232 serial port connector so that data could be displayed on the hyper-terminal of a PC. The node was also connected to the serial port of an iPAQ PDA via the programming interface to allow the data on a Java JTermLite console to be displayed before RF transmission. Figure 6 shows a schematic of the experimental test setup.

Bend and pressure sensors were tested by using the programming interface to connect these sensors into the surface mount flex sockets. The HMC2003 3-axis magnetic compass sensor located on the sensor panel was also tested. Initially the readings from these sensors after analogue to digital conversion were displayed on the iPAQs. The bend and compass sensors were found to give a wide range of readings when actuated. The pressure sensors only gave a narrow range of readings but this should be able to be rectified by adjustment of the resistor values in the conditioning circuitry. Testing of the other sensors is currently in progress. The RF transmission of the sensor data has also been successfully demonstrated. Problems with noise on the RF signal were overcome by stopping the output of data to the serial port on the iPAQ as the serial transmission was found to generate noise on the Nordic's power supply. Grounding of the base-station receiver was also found to help alleviate 50Hz mains hum. After RF transmission the data was successfully displayed on the hyperterminal of the PC.

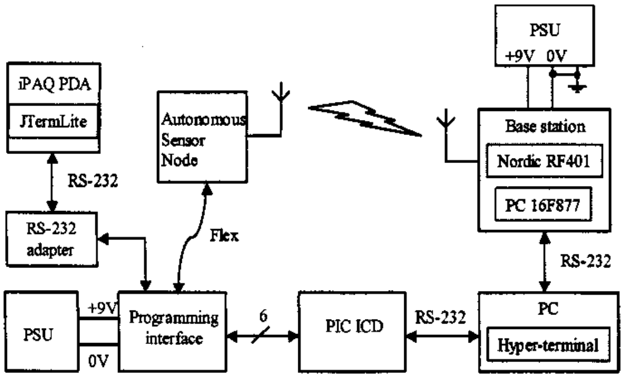


Figure 6: Autonomous Sensor Network

Phase 2 Development

The context for further miniaturisation of the module in this project is provided by a development program, being implemented by NMRC, which targets the implementation of a 1mm cube (or less) autonomous sensor module, a long-term goal which has as its imperative a desire to create modular wireless computational units with integrated sensors and actuators that can be mixed in high volumes into the basic materials from which many everyday objects are made – this could extend from laminate materials, molded plastics through to clothing of various types. Once integrated, the units would form ad-hoc distributed networks that would intelligently analyse the material in which it was embedded and potentially act upon this analysis. Research yielding these results would represent a paradigm shift, and thus faces numerous barriers - physical realisation of the system represents only the beginning of the process - and these barriers will be broken down gradually through an iterative sequence of miniaturisation and scaled distribution of system computation.

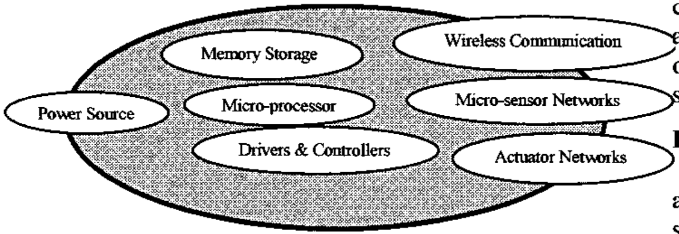


Figure 7: Typical Representation of a Device with Capability for Perception, Action, and Intelligence

The next stage in this program is the development of distributed sensing systems of autonomous micro-modules with a form factor of around 1cm^3 containing both sensing and actuation and using off the shelf components where possible. The application chosen for the demonstrator was that of a die /dice with LED's replacing the dots. When the die stops moving, the processor computes which side of the die is 'up' and communicates this information to all other nodes in range.

This application determined the choice of sensors/actuators while the choice of other components was limited by a) size and b) power restrictions. The final list of components is as follows:

- 1 x PIC18LF4320 – a low-power microcontroller from Microchip in a 8mm x 8mm x 1mm Quad Flat No-Lead(QFN) package with a 13 channel 10-bit ADC
- 1 x Xilinx XCR3064XL – a PLD with 40 available I/O in a 48 pin 0.8mm CSP measuring 7mm x 7mm x 1.8mm
- 1 x Analog Devices ADXL202E – 2-axis accelerometer in a 5mm x 5mm x 2mm LCC package
- 1 x Analog Devices TMP35 – temperature sensor in a 5 lead SOT-23 package measuring 2.9mm x 2.8mm x 1.45mm.
- 6 x Light Dependant Resistors(LDR's) with a diameter of 4.45mm and a thickness of 1.78mm
- 1 x SMD Crystal with dimensions of 7mm x 5mm x 2mm.
- 21 x Different coloured LED's in 0603 packages.

The substrate chosen was a double-sided polyimide flex substrate with dual copper layers of 12µm and a polyimide thickness of 50µm. The NMRC has an internal wet chemistry processing line for flexible printed circuits with larger resolutions than those available from commercial specialist flexible PCB manufacturers. The circuits were designed with a view to prototyping them internally first before transfer to a commercial manufacturer. Thus, track and gap resolutions of 125µm, which is near the limit of the NMRC processing capabilities were chosen. Components were placed on both sides of the flex with the LDR's and LED's and respective passives of necessity placed on the bottom (outside) of the flex. The finished design resembled a pseudo-cross which could be folded up into a cube after component assembly. A complex design was required to fit all components on the flex and still maintain the target form factor of 1cm^3. A schematic of the finished design including both top and bottom layers is shown in Figure 8.

Internal Packaging Diagnostic Sensors

Figure 9 shows a simplified sensor architecture for autonomous modules. Each module has an application layer, sensor, actuator or both which is usually it's primary function. The module must be aware of it's location relative to itself and other nodes of the network. Thus, it requires an orientation layer e.g an accelerometer or IMU. The module must also be aware of it's own ability to function properly, thus a module integrity sensing layer is required which will add diagnostic capability to the module.

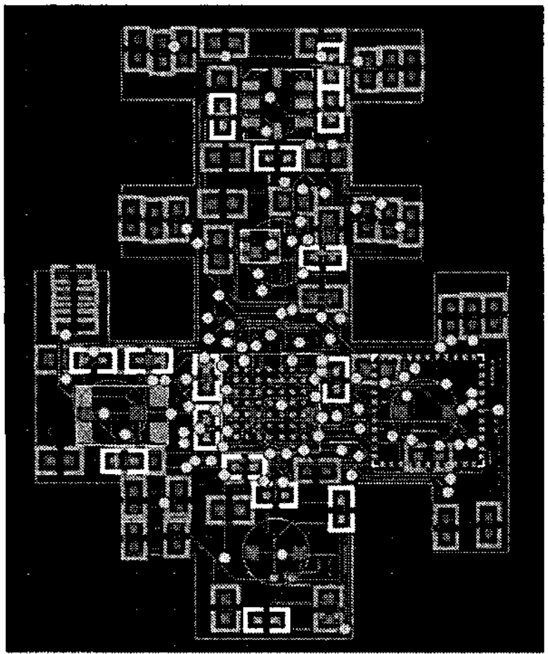


Figure 8: Schematic design of cube

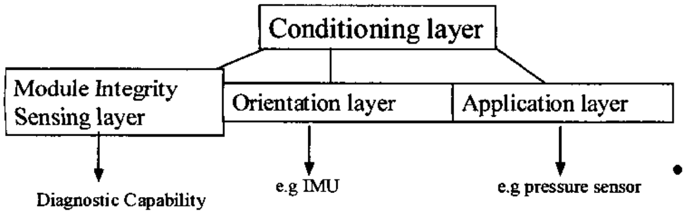


Figure 9: Sensor architecture for autonomous modules

The usage of embedded sensors for real-time failure analysis is becoming more widespread in the aviation, aeronautical and construction industries and for military applications. MEMS sensors have been developed for structural health monitoring including strain sensors, adhesive bond sensors, corrosion sensor, humidity sensors, acoustic sensors and optic fibre sensors. Companies such as Analatom Inc[25,26], Oceana Sensors[27], Physical Acoustics Corporation[28], Sarnoff Corporation, and researchers such as those in the Damage Tolerance Group at Cranfield University[29] are designing and implementing such sensors and moving towards creation of ad-hoc networks of such smart sensors for diagnostic purposes. However, the practise is not widespread in the microelectronics packaging field. It was decided to implement some diagnostic sensors into the $1cm^3$ cube for the creation of a smarter sensor node which could provide information about its' internal packaging stresses and strains and communicate this to the processor. The sensor chip we chose was a MESMERIC test chip mechanically thinned down to 150μm.

MESMERIC Test Chip

MESMERIC is an EU funded project whose primary objective chip is to produce an advanced mechanical & thermal stress test chip, which can be used to:

- Characterise current/future microelectronics/optoelectronics packages
- Validate thermal/mechanical models of packages.

A key goal of the design and layout of the MESMERIC chip was to ensure a modular/flexible die size, with each diced option having the primary thermo-mechanical measurement capability. The MESMERIC test chip is an 18 x 18mm chip consisting of three primary tiles arranged in a 5x5 array[ ].

These primary tiles are:

1. *Tile 'Control'*

This is the minimum fully functional die size available (3.6mm x 3.6 mm). This contents all the bondpads and interface logic circuitry to communication to the PC measurement system. Structures in this tile are:

- Humidity Sensor
- Strain gauge rosettes: The n and p type diffused resistors consists of five diffusion interconnected with metal links, to achieve the target resistance value of 8,500 ohms. The temperature sensing p.n. diode was embedded in the center of the rosette. This rosette layout fits into a 330um sq. area.
- Polysilicon resistor, which will act as a heater, targeted at 50 ohms. These are in a 'U' shape to achieve die area coverage. Each polysilicon resistor has double force pads and a local sense connection. This bondpad arrangement also can be used to characterise bond wire degradation under high current situations.
- P.n. diode for sensing temperature in a themo-mechanical measurement set-up.

2. *Tile 'Repeats'*

This tile is repeated 23 times and communicates to the Control logic tile via vertical and horizontal address bus. This bus transmits the required decoding information and the resistors four wire force and sense measurements. The structures are.

- Strain gauge rosettes, three located on the tile corner, mid edge and centre, with the appropriate decoding logic.
- Humidity sensor, same circuitry as in Control tile
- Polysilicon heater and p.n. diode

In four tiles located along the centre diagonal of the 18 mm^2. die,.there are stand-alone p.n. diodes, which are connected directly to bondpads. These stand-alone diodes will allow thermal characterisation, with out powering up the logic circuitry. Two tiles contain stand alone 'NMRC' strain gauge rosettes. These rosettes are exactly the same as the other rosettes, with the exception that they are connected directly to the bondpads. Figure 10 shows the layout of the completed MESMERIC test chip. It was not feasible to use the control tile with any other tile as this would increase the size of the sensor chip to over 7mm x 7mm so the choice was down to the stand alone strain gauge tiles with p.n. diodes. It was decided to utilise the larger strain gauge tile as this would sense stress over a larger area while taking up the same number of I/O as the smaller, 600µm SOT-23 sub-tiles. Since I/O limitation was now a factor, after analysing the resistance measurements of the rosettes, 2 p type and 2 n type rosettes were bonded out along with the diode for a total of 7 I/O. A close –up of the strain gauge characterisation rosette is shown in Figure 11

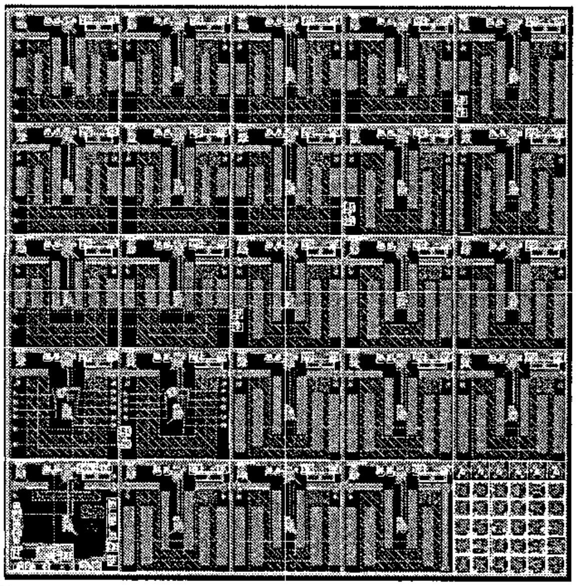


Figure 10: Complete MESMERIC test chip layout

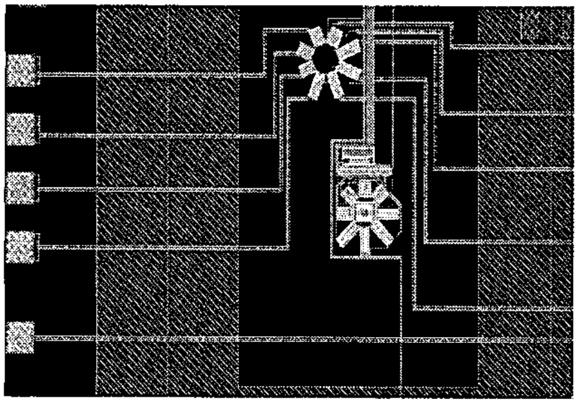


Figure 11: Close-up of layout of MESMERIC strain gauge characterisation rosette.

A quarter segment of an 8 inch MESMERIC wafer was partially diced to 150µm. This segment was then carefully mechanically thinned using back-grinding with the result that individually thinned die were available. One of these die was then adhered to the top of the processor package using an adhesive with a high melting point. The 7 I/O were then wirebonded, using standard 25µm Aluminium wire to bond pads on the flex surface. To ensure good bonding to the flex surface, it was necessary to bond the flex to a rigid surface. This was done by sticking the flex to a ceramic substrate using wafer 'blue film' which was later dissolved in a solvent.

Assembly Procedure

The components on the top layer of flex (inside of the cube) were assembled first. A standard SMT alloy solder, Sn62Pb36Ag2, MP of 179-189°C, was dispensed on to the pads using a CAM/LOT liquid dispensing system. The components were placed with a manual pick and place unit and reflowed. The MESMERIC chip was then glued to the top of the processor and wirebonded to the flex as described above. This can be seen in Figure 10.

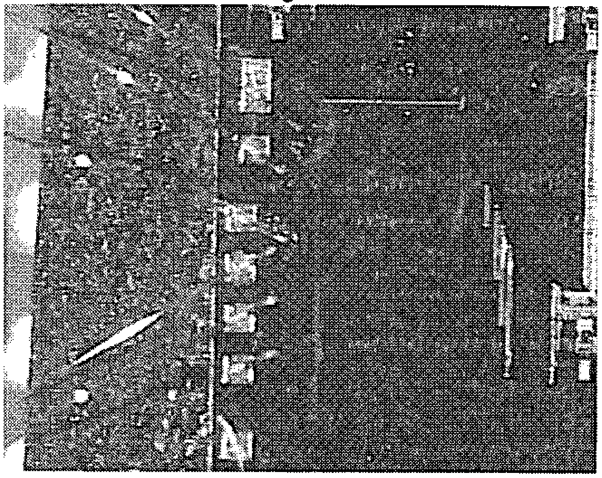


Figure 12: Stress test chip bonded to microprocessor and wirebonded to flex substrate

The components for the bottom layer (outside of the cube) were then assembled. This involved the dispensing of a low temperature solder alloy, Sn43Pb43Bi14, MP 144-163°C, placement of the components and reflow. The cube was then carefully folded into a cube and glued together. Figure 13 shows a block diagram of the phase 2 module assembly procedure.

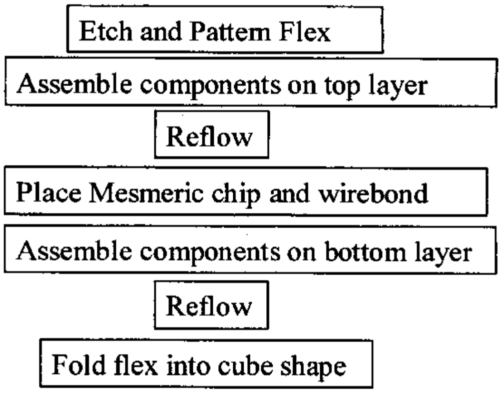


Figure 13: Assembly procedure for phase 2 module

Conclusion And Future Work

This paper has presented the work done in evolving a module for a miniaturised wireless sensor network through two phases of it's development. The implementation of the phase 1 module form factor, in a stacked PCB, is useful in numerous applications, including for sports, exercise, entertainment, and health; in addition, the imaginative use of flex circuitry may provide for further form factors to be evaluated (for example, connected panels could be wrapped around the wrist). The current size is too large to expand the application potential of the form beyond niche level; the realistic number of stackable panels is currently four. To expand the viability of the format, it is appropriate to look at the potential for further miniaturisation of this module with an initial target volume of 1 cm^3. The design, development and assembly of the phase 2 module containing both sensors and actuators and some capability for module integrity sensing was also presented.

Acknowledgments

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