CSIRO Sensor and Sensor Networks Research

Progress Report July 2006 to June 2007

www.sensornets.csiro.au

www.csiro.au

Enquiries should be addressed to:
Peter Corke
Peter.corke@csiro.au

Copyright and Disclaimer

Important Disclaimer

Contributors

Peter Corke
Matthew Dunbabin
Tim Wark
Pavan Sikka
Wen Hu
David Abbot
Kegen Yu
Lasse Klingbeil
Shondip Sen
Philip Valencia
Tim Davis
Kerry Taylor
Diet Ostry
Geoff James
Mikhail Prokopenko
Rosemary Hollowell
Cover Image: Mike Trefry

ISBN 07/427

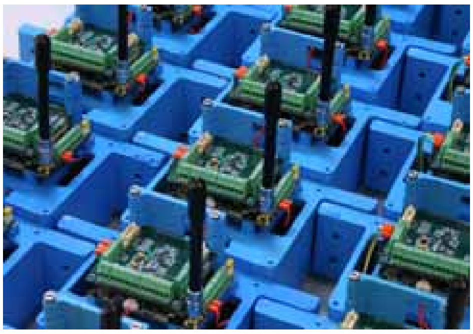
CONTENTS

INTRODUCTION

Measurement is the first step that leads to control and eventually to improvement. If you can't measure something, you can't understand it. If you can't understand it, you can't control it. If you can't control it, you can't improve it.
—H. James Harrington

Management of our natural resources, land, rivers and oceans, is a national priority and increased information is critical to improved outcomes.

Today natural systems are understood by examining a tiny, and hopefully representative patch, perhaps once per year. Shannon's sampling theorem implies that we will completely miss fast dynamic processes or medium-scale spatial variation happening in the environment. Compared to traditional manual methods of data gathering, we believe that wireless sensor networks will provide great improvements in quality, timeliness, spatial resolution and cost. This in turn will lead to benefits to better management of our natural resources.



Current generation wireless sensor nodes during assembly, Fleck3™ base boards with moisture sensor interface boards

The goal of CSIRO's research in this area is:

To create technologies to radically improve the cost and quality of data gathering to enhance the understanding of our natural environments and provide the ability to manage and exploit Australia's resources.

Wireless sensor networks (WSN) are a new technology for collecting data about the natural or built environment. They provide the measurements that we can use to improve outcomes.

This report describes results from the third year of CSIRO's research program in wireless sensor networks. It shows a rich mixture of cutting edge technology and novel applications by a team which now spans multiple CSIRO divisions and laboratories. The program accesses skills in computer science and electrical engineering, as well as physics, chemistry, natural science and biology for sensor development. The program and its technologies have supported the research of four of CSIRO's national priority Flagships.

Our early work was partly supported by the CSIRO Emerging Science program in 2002 and 2003. From that beginning the program has grown to be part of the CSIRO Strategic Plan 2007 – 2011. The Figures show how far we have come, from early outdoor trials to large-scale production of our own hardware running our own developed software, solving real applications. More than 500 nodes have been built and several long-term deployments are now operational.

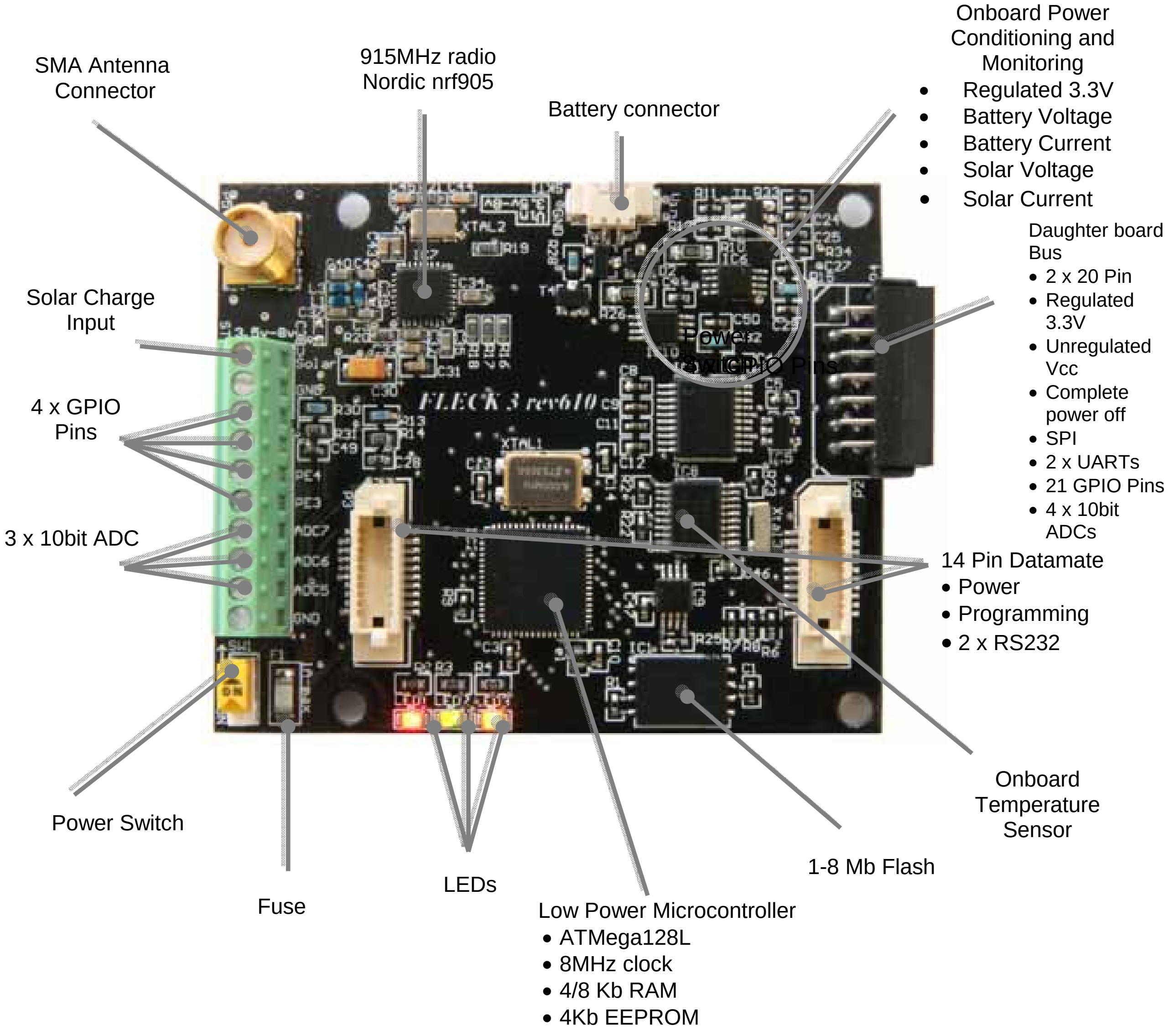
Peter Corke
Theme Leader
Sensors and Sensor Networks
October 2007

Our first large-scale outdoor deployment in early 2003, joint work with Dartmouth College. Using Mica motes in Ziploc bags sitting on upturned plastic flower pots in order to raise the antennas above the ground

OUR HARDWARE

One of key technologies is the Fleck™ series of wireless sensor nodes, the Fleck™ 1, 2 and 3. Our first Fleck™ prototypes became available in December 2003 and since that time over 750 Fleck™s of all types have been built and deployed, and another 300 have been ordered, more than a thousand in total!

The Fleck™ devices incorporate a number of novel design features that set them apart from other devices on the market: superior radio for outdoor applications, superior power supply that is solar-capable, and an extensive range of sensors and sensor interfaces. To get going all you need is a screwdriver to connect batteries, your sensor and a solar cell if you choose.



The Fleck™3 is the current latest generation of our sensor node family. It is a small (50x60mm) device with a long range radio and powerful interfacing capability.

Fleck™3 Specification

- Processor
    - Atmel Atmega 128 processor
    - 512kbyte program flash
    - 4kbyte RAM
    - runs the TinyOS and FOS operating system
    - 3 LED indicators
    - Onboard temperature sensor
    - Onboard real-time clock allows for very deep sleep mode
    - Onboard 1 Megabyte flash memory (upgradeable to 4Mb)
- Radio
    - Nordic 905
    - 433/915MHz with GFSK modulation
    - 50kbps
    - range > 1000m
- Power supply
    - 3.5-8V
    - Standby current, 33uA.
    - Onboard solar cell battery charger with monitoring of solar voltage, solar charge current and battery terminal voltage
    - Power supply that supports:
    - Rechargeable batteries (3xAA) with Overcharge protection
    - Supercapacitors
- Size: 50 x 60mm
- Screw terminals for:
    - 4 digital I/O, interrupt, counters, PWM generator
    - 2 analog inputs
- Expansion board interface
    - 2 x 20 way connectors
    - Robust 4 x hole mounting
    - Signals
        - Most Atmega128 digital I/Os
        - 8 x ADC pins
        - Hardware SPI bus
    - 3.3v power can be switched on/off by the processor
- Datamate connector
    - 2 x RS232
    - Fleck™^{T}rogramming

The use of an onboard real-time clock means that the processor can completely shutdown for minutes to hours at a time since it is freed from the burden of time keeping.

The Fleck™ family has some significant design differences and operational advantages compared to other devices on the market.

- Long-range 433/915MHz radio, with range over 1000m.

- Screw terminals for quick connection to many analog and digital sensors without the need for an expansion board.

- Serial interface connector allows quick connection to a serial device without the need for an expansion board.

- Onboard solar cell battery charger with monitoring of solar voltage, solar charge current and battery terminal voltage

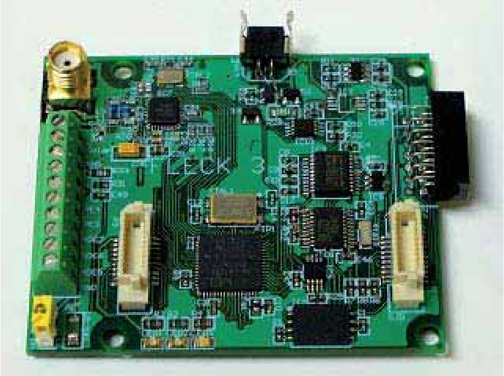
- Improved connectors for sensor interface boards with increased mechanical stability and the option for bolting the boards together.

Programming Support

The Fleck™ nodes can be programmed by means of a cable from the development computer, or “over the air” by radio. Recently we have developed a JTAG debug interface which allows for program loading as well as low-level software debugging.

Latest addition to the family: the Fleck™3 B

We have just received first prototypes of our next generation device – the Fleck™3B. This device is a Fleck™ 3 with an Atmel 1281 processor instead of an Atmel 128. This provides 8kbyte of RAM increased from 4kbyte of RAM and additional power saving modes.



Fleck™ 3B sensor network node.

Expansion and Interface Boards

DSP Board

The DSP board with a Texas Instruments 32bit 150 MHz DSP processor (TMS320F2812) and 1Mbyte of SRAM. Two interfaces have been developed for the DSP: color camera with FPGA-based DMA transfer to memory, and an audio interface with pre-amp, CODEC and VOX circuit. This supports an unprecedented richness in information that can be sensed by a sensor network.

DSP Interface

- Texas Instruments 32bit 150 MHz DSP processor (TMS320F2812M)
- 1Mbyte of SRAM
- FPGA for simple image capture
- Fleck™ can switch power ON/OFF
- Camera and CODEC interface
- 2 x serial and 1 x CAN comms
- 18 x digital I/O with PWM, compare, capture etc
- 8 x 12bit ADCs
- Board can be used as stand alone
- DSP processor interface is SPI
- DSP Audio detect interrupt to the Fleck™

Camera Interface

- Omnivision VGA 640 x 480 colour sensor (OV7640)
- DSP sets parameters by IIC bus
- Windowed and sub-sampled images
- Progressive scan
- Switchable 4 watt LED lighting
- FFC cable to the DSP board

Audio Interface

- Analog Devices 16bit CODEC (AD73311)
- Microphone input
- Aux Output
- FFC cable to the DSP board

Inertial Interface

Measures position and orientation in 3D space, particularly useful for human and animal motion and behaviour studies.

- Accelerometers
  - 3 - axis Analog Devices +/- 2g accelerometers (2 x ADXL202E)
- Gyros
  - 3 - axis Analog Devices +/- 150 deg/s gyros (3 x XRS150)
- 3 x Temperature sensors
- Magnetometers
  - 3 - axis Honeywell 1mV/VGauss magnetic Sensor (1 x HMC1053)
- 3 x microPower instrument amps
- Fleck™ interface
  - 12 x 16bit ADCs with SPI interface to the Fleck™

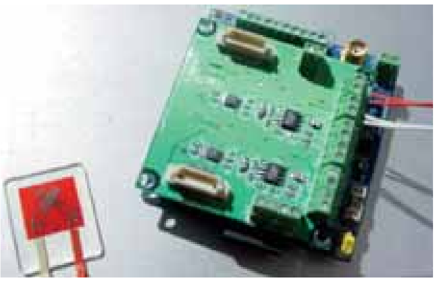
GPS/MMC Interface

Measure position and speed in outdoor environments.

- UBlox GPS engine
  - NMEA or binary format serial output
  - Differential correction input
  - Up to 4 Hz operation
  - Battery backup
  - Low power (new models 50mA)
  - Board can be stand alone with RS232 interface
- MMC socket on flip side
  - Up to 1G of removable storage
- Fleck™ interface
  - GPS interface is RS232 to the Fleck™

Strain Gauge Interface

Measure mechanical strain for machine condition monitoring and stress analysis.



- Strain gauge
    - 4 x strain gauges can be connected
    - 4 x Linear Technology high precision amps (LTC1050)
    - 4 x Linear Technology 20bit digitally filtered ADC (LTC2431)
    - The four ADC conversions can be synchronised by the Fleck™
    - No offset or gain adjustment required
- Fleck™ Interface
    - 4 x 20bit ADCs with SPI interface to the Fleck™

Water Quality Interface

Connect standard water quality sensors to a Fleck™ node.

- Sensors
    - pH (ionode IH20)
    - Redox (ionode IH30)
    - Water Temp
    - Conductivity (TPS)
- Across fresh and salty water ranges
- 16bit ADC sampling on all sensors
- Functionality of popular industry device (TPS WP-81)

Greenhouse Interface

Interface to a set of standard sensors relevant to plant growth: light, temperature, humidity and soil moisture/temperature.

- Photosynethically active radiation (PAR)
    - CSIRO sensor based on Hamamatsu photodiodes (G1118)
    - LI-COR quantum sensor (LI-190)
- Air temperature & humidity
    - Sensirion humidity and temperature sensor (SHT15)
- Soil moisture & temperature
    - MEA gypsum block moisture sensor (GBLite)
    - Analog Devices precision temperature sensor (AD592)
- Fleck™ Interface
    - 5 x 16bit ADCs with SPI interface to the Fleck™
    - Fleck™ digital I/O, output compare

Soil Moisture Interface: Gypsum Block

Interface to standard water tension sensor which measures the ease with which a plant's roots can extract moisture from the soil.

- Gypsum block interface
  - MEA gypsum block moisture sensor (GBLite)
  - Up to 5 x gypsum block sensors
  - Sensor inputs are electrically isolated from each other
- Soil temperature sensor
  - Analog Devices precision temperature sensor (AD592)
- Fleck™ Interface
  - 4 x Fleck™ADCs
  - Fleck™ digital I/O, output compare board and gypsum block

Soil Moisture Interface: Echo Probe

Interface to standard soil moisture sensor which measures the volumetric water content of soil.

- Echo probe interface
  - Echo moisture probe (EC-20)
  - Up to 8 x moisture probes
  - Measures permittivity of a medium
  - More accurate than gypsum blocks
- Soil temperature sensor
  - Echo temperature sensor
  - Use same input as Echo moisture probes
- Fleck™ Interface
  - 8 x 16bit ADCs with SPI interface to the Fleck™

MP3 Daughterboard

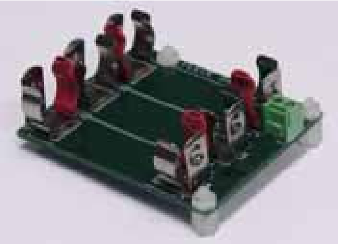
- Atmel AT89C51SND2C chipset
- 2 watt amplified stereo output
- Onboard speaker
- Headphone output

Test Daughterboard

- 3 push buttons
- 10 position rotary switch
- 8 LEDs
- Onboard speaker
- JTAG interface
- Pin headers for all bus signals

Battery Board

- Holds 3 x AA batteries



PROGRAMMING SENSOR NETWORKS

As sensor networks grow in size and complexity, the ability to easily task the network becomes vital. Current software tools such as TinyOS require nodes to be individually programmed, requiring significant effort by specialist developers to program a whole network.

We recognized two problems with software development for sensor networks. Firstly progamming is typically considered at the node level rather than “whole of network level”, and we are developing a new high-level language to address this. Secondly, the dominant event-oriented programming paradigm is limiting for application development, and we have developed a new thread-based operating system.

FOS - The Fleck™ Operating System

General operating system principles apply to wireless sensor networks but severe resource limitations (slow clocks, very little RAM and no hardware memory management) affect the design choices. In some ways they are a return to computer capability of the 1950s but with much smaller physical size and power consumption.

Operating systems are important for WSN. The primary roles of an operating system are to: create an abstraction from the underlying resources, to simplify the functionality exposed to the programmer, to aid in application portability, and to share resources such as CPU time and peripherals. Within the WSN operating system community there are two approaches to this: event based and thread-based.

The event-based paradigm currently dominates but our experience over the last several years indicates problems with this approach as application code size increases This experience mirrors that of others: event-driven code is difficult to write, understand, maintain, and debug [1], and “the problem that the control flow for a single conceptual task and its task specific state are broken across several language procedures, effectively discarding language scoping features. The problem is subtle because it causes the most trouble as software evolves” [2].

FOS Features

FOS provides a priority-based, non-preemptive (cooperative) threading environment with separate stacks for each thread, which has the advantage of providing a simple concurrent programming model which does not require semaphores. The scheduler is also responsible for CPU power management and enters the lowest mode consistent with thread resource requirements. Time-critical operations such as analog data sampling or high-speed timers are handled by callbacks. A virtualized timer is provided for non time-critical delays. FOS currently provides a classical CSMA MAC with optional acknowledgement and low-power listening support. The default multi-hop router implements distance-vector routing.

FOS provides uniform access to underlying resources via a POSIX-like API providing functions for configuring the hardware and sending/receiving data using the hardware, including the SPI-bus, serial ports, non-volatile storage, etc. Support is also provided for a large collection of interface boards including the GPS and inertial measurement sensors used for mobile on-animal nodes. The I/O model is for blocking read and write primitives, with Unix-like semantics, and optional timeout on read.

[1] A. Dunkels and O. Schmidt. Protothreads lightweight, stackless threads in c. Technical Report SICS Technical Report T2005:05, Swedish Institute of Computer Science, Mar. 2005.
[2] A. Adya, J. Howell, M. Theimer, W. Bolosky, and J. Douceur. Cooperative task management without manual stack management. *Proceedings of the 2002 Usenix ATC, June*, 2002.

FOS has been ported to our range of Fleck™s, all of which use the Atmega 128 processor but different radios, the Nordic nRF903 and nRF905 which are significantly different.

Hardware abstraction is always a difficult balance between generality and efficiency, and the philosophy in the development of this OS attempts to take a middle ground where a programmer is expected to be aware of device limitations. With timers, for example, a consistent and powerful interface to timers is presented, however the number of timers, their individual characteristics, and their effect on power management is an issue the programmer must deal with. The code base currently comprises around 25,000 LOC, 90% in C and nearly 10% in Python (backend and data management). A simple program along the lines of count to radio occupies 13,924 bytes of program memory, 361 bytes of RAM and 100 bytes of RAM for the thread stack.

Dynamic reprogramming via serial port and radio has been developed using our lightweight code distribution (LDP) protocol which provides Deluge-like capability. The Light-weight Dissemination protocol (LDP) virally propagates small code modules for the virtual machine. An experimental over-the-air programming protocol for reflashing nodes has also been developed, and dynamic loading and instantiation of compact pre-linked threads has been demonstrated.

Virtual Machines

A Virtual Machine (VM) is a software-based interpreter for an abstract machine instruction set that can be fed a sequence of byte code for execution. Typically a VM has a fixed instruction set much like a real microprocessor, where the aim is to interpret and execute the byte code as fast as possible. An Application Specific Virtual Machine (ASVM) is a type of VM that can be tuned to perform well for a specific class of applications by factoring out the operations which are performed most repetitively and implementing them as discrete operations as part of the abstract instruction set. For example, if the application being deployed was primarily image processing based, then an ASVM might contain an FFT as a discrete instruction. The architecture of our ASVM is presented in Figure 1.

There are a number of advantages to using an ASVM to deploy applications on a sensor network:

- **Reduced code size:** programs compiled to byte code are often much smaller than the equivalent program compiled to a native machine. The primary benefit is that smaller programs require less energy to be transmitted over the radio to each node in the network.
- **Increased performance:** common operations are implemented natively and therefore have a much lower speed penalty than equivalent programs represented purely as abstract arithmetic and logic primitives.
- **Reduced power consumption:** an interpreted byte code instruction typically requires more energy to be executed than its native equivalent operation. However, careful refactoring of programs with common operations implemented natively can significantly remove this overhead.
- **Safety and security:** an ASVM provides a level of safety and security as programs are executed in a sandboxed environment and are unable to directly corrupt the underlying system.

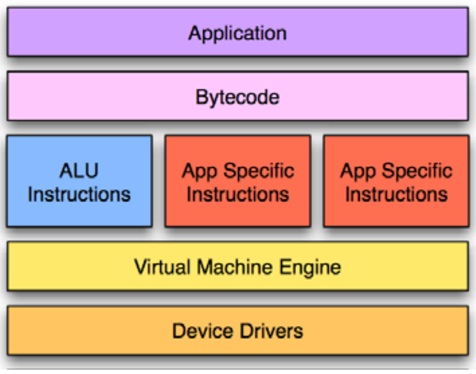


Fig. 1 Architecture of an Application Specific Virtual Machine (ASVM)

Architecture of the ASVM

Our virtual machine has been designed specifically to operate within a constrained memory environment, typically in the order for 4-8 kilobytes of RAM. This makes the VM suitable for operating on the typical class of sensor platforms available today such as the Fleck™, TMotes, Mica and similar devices. The VM is written in strict ANSI C and is very portable between micro-controllers which are supported by the GNU compiler tools.

The VM provides a simple representation of an abstract stack based processor capable of executing a single instruction at a time. The state of the VM consists of a stack, heap, program counter (PC), stack pointer (SP) and a string of byte code which is the program being executed. There are no specific registers or accumulators for arithmetic. An instruction can perform operations to directly manipulate values on the stack.

The VM is designed to allow the instruction set to be reconfigured. By this we mean that new instructions can be defined and include into a particular instance of the VM to provide new logic or arithmetic operations. This allows complex instructions to be called and executed natively on the underlying CPU. These operations can be implemented as single instructions which appear as atomic operations to the bytecode program. The virtual machine also provides a complement of standard arithmetic and logic operations similar to those on a normal processor.

A sensor node is constructed from numerous components such as micro-controllers, radios, transducers and actuators, all of which perform similar functions but can be subtly different from one manufacturer to another. The purpose of the Virtual Machine (VM) is to provide a single clean and well defined machine abstraction layer to conceal the idiosyncrasies of different components. Our VM provides a general purpose 16-bit stack based logic and arithmetic unit which is capable of interpreting a customizable instruction set. The VM is accompanied by a matching reconfigurable assembler which together form a tool chain for generating and executing binaries for the platform.

The VM can be executed in a number of ways:

- As an application within an operating system context
- Directly on bare-metal with supporting device drivers
- As an application on a workstation to support simulation and offline debugging

A simple example of the assembly code to increment a counter and flash the value as a binary bit pattern to the LEDs on a Fleck™.

```
.BEGIN
; initialize the led counter
START:
push0
leds
; increment the led counter
INCR:
ledg
push1
add
leds
pushi 100
sleep
ledg
pushi 7
cmp
blt .INCR
bra .START
.END
```

As a benchmark a simple application was compiled to native code and also to ASVM byte code to demonstrate the reduction in code size. We chose the Fibonacci numbers algorithm as a small and understandable example, shown in Figure 2 as our test program. Two very similar versions of the program were written, one in standard C and the other in our own language.

```
program fib;

int a, b, c, i,
n;
channel out

every (10) {
  (1) -> {
    a = 1;
    b = 1;
    i = 3;
    n = 20;
    while(i <= n)
{
      c = a + b;
      a = b;
      b = c;
      i = i + 1;
      out << (a,
```

```
#include <stdio.h>

int main(void) {
  int a = 1, b = 1, c;
  int i = 3, n = 20;

  while(i <= n) {
      c = a + b;
      a = b;
      b = c;
      i = i + 1;
      printf("%d =
%d\n", a, b);
  }

  return 0;
}
```

Fig 2. Fibonnacci numbers written in our own langauge

MSP430 used in the TMote and the macroprogramming version was hand compiled from an intermediate representation of the parse tree to VM byte code. Results are shown in Table 1.

	Lines of Code	Size (Bytes)
Byte Code	18	~59
MSP430	12	772
AVR128	12	1028

Table 1. Code size

From the results shown in Table 1, we see that there is a significant reduction in code size which has major implications for code distribution in sensor networks.

High-Level Language for Sensor Networks

Recently proposed macroprogramming languages for sensor networks focus on the abstraction problem, with less emphasis on means to compile from a high-level script to an executable program. They assume the availability of reliable transport layer protocols [2], and other library protocols [3,4] to provide support for reliable, point-to-point data-driven connectivity between tasks.

Our work [1] differs because *we provide communication and timing as first class primitives* in order to express applications in a way that explicitly address the following distinguishing properties of physical sensor networks:

1. Sensor network communication is based on unreliable, one to many broadcast communication as opposed to more traditional point to point links.

2. In order to minimize energy use, sensor network nodes need to schedule their local tasks and data transmission tasks separately. A sensor network node should never wait indefinitely for a data message, but should use an agreed schedule for sending and receiving information.

3. Sensor network tasks are sparsely scheduled in time, each with a given, fixed period.

Our macroprogramming abstraction models a sensor network application as a set of periodic tasks communicating over channels. This abstraction defines an abstract task graph that hides the mapping of tasks to particular nodes. The benefits of using well defined channels are that the programmers' attention is shifted from the details of how a message will arrive at its destination to the *significance* of its arrival.

Each task is made up of condition-action rules, see Figure 2 for example, combined with standard programming constructs for sequencing, choice and loops. Boolean conditions may refer to the availability of channel input and capabilities of network nodes. Actions include reading and writing values to channels. Channels available to a task include sensors and actuators used to interact with a node's immediate environment. Tasks that read or write such channels are enabled only on nodes with these capabilities. For example, only a node with a temperature sensor is able to perform tasks that read the temperature channel. In this way, our language provides simple support for role based programming for heterogeneous sensor networks in which individual nodes have different capabilities.

Compilation Procedure

An application is defined as a set of periodic tasks, each using condition-action rules and communication over named channels. The compilation of such programs proceeds as follows:

- Compile a task set with global channels into one in which all global channels are implemented using only single hop communication over the radio channel. The result of this step is a set of prioritized tasks that use only local and single hop comunication. The step adds new tasks and channels to the original task set at a lower priority.

- Use task periods and priorities to determine an explicit schedule for the task set and communication. Nodes and their neighbors communicate during a synchronized interval between local task invocations.

- Distribute tasks and the schedule to nodes in a real network. Each node's capabilities determines whether it performs a particular task or skips to the next.. The network topology determines how abstract global channel links are realized for a particular physical arrangement of nodes.

Task and Communication Schedule

Since each task has a unique priority, tasks can be scheduled using the well known methods of static fixed priority scheduling, with each node's schedule fully determined at compile time. The priority of local tasks is defined by the order in which they are stated in the macroprogram. The schedule length is the lowest common multiple of the periods of all tasks.

The worst case deadline for executing a local task is also calculated at compile time: it is equal to the sum of the worst case execution times of the task plus any higher priority tasks ready at the same time. Since a node can only execute tasks for which it has the capability, the best case deadline may be lower than the worst case.

Sensor network applications are typically characterized by very low duty cycles, and so we expect the compiled schedule will be sparse, with nodes remaining in a sleep state most of the time. However, if a set of tasks can not be scheduled because the frequency of one or more tasks is too high, or a task's worst case execution time is too long, then the programmer can be notified at compile time and the program modified.

Mapping Tasks to Nodes

The compiler maps the task set produced by the last step from an abstract task graph onto a physical network with given topology and capabilities for each node. The full task set and execution schedule is distributed to each node in the network. Whilst executing tasks at each step in the schedule, a node examines its capabilities and the requirements of the task. The node simply skips any tasks for which it does not have the capability.

Global Channels

Channels provide a simple interface for passing messages between rules in a macroprogram. Channels are asynchronous and do not provide any strict guarantees on time of delivery for messages. Periodic execution is a separate construct of the language. A channel can use any underlying transport to carry messages.

---

[1] Sen, S., Cardell-Oliver, R.: A rule-based language for programming wireless sensor actuator networks using frequency and communication. In: Proceedings of the third IEEE Workshop on Embedded Networked Sensors. (2006)

[2] Kumar, R., Wolenetz, M., Agarwalla, B., Shin, J., Hutto, P., Paul, A., Ramachandran, U.: Dfuse: A framework for distributed data fusion. In: Proceedings of the first international conference on Embedded networked sensor systems. (2003)

[3] Bakshi, A., Prasanna, V.K., Reich, J., Larner, D.: The abstract task graph: a methodology for architecture-independent programming of networked sensor systems. In: Proceedings of the 2005 workshop on End-to-end, sense-and-respond systems, applications and services. (2005)

[4] Gummadi, R., Gnawali, O., Govindan, R.: Macro-programming wireless sensor networks using kairos. In: Proceedings of the International Conference on Distributed Computing in Sensor Systems. (2005)

POWER SOURCES

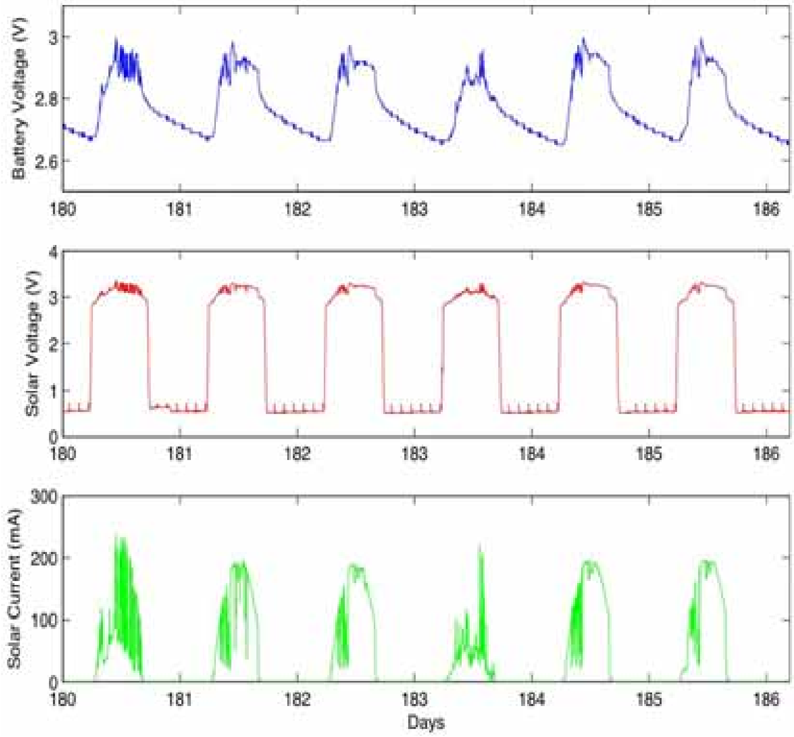
We have deployed Sensor Networks in a variety of situations, and each has its own unique energy requirements, sources and challenges. Every computational cycle, every radio packet, every sensor reading consumes a small amount of energy. If powered from batteries then conservation of energy is paramount and necessitates sophisticated processor and radio scheduling. We are exploring a different approach by powering nodes from energy that can be harvested from the environment allowing perpetual operation.

Solar Power

Current generation CSIRO node in environmental housing with solar cell on top

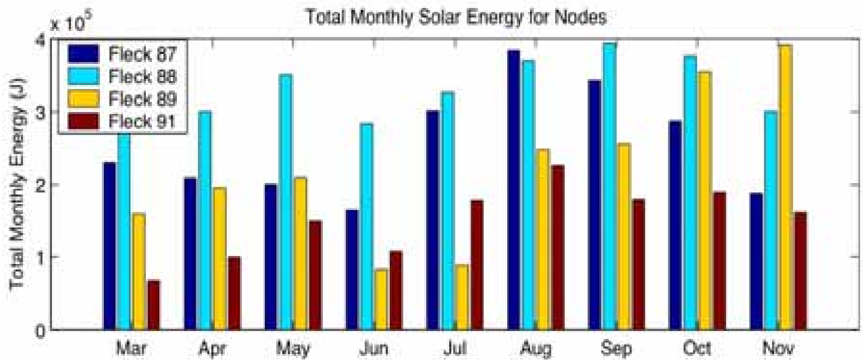
In a sunny environment like Australia, and particularly the outdoors which is our focus, we have led the way in exploiting solar power for sensor networks. The beauty of solar power is exemplified by the following example. Solar generation, at a typical 18% efficiency, is 18 unit(mW/cm^2), with solar insolation of 1000W/m^2. Assuming a device/application with a 1mA continuous average current draw at 3V this is 3mW continuous average power. Further assuming that the device has solar power for 6 hours per day, during that time we need to generate 3 x 24 / 6 = 12mW which can be provided by less than 1cm^2 of solar cell. The challenge is in energy storage to run the node through the night: leakage, efficiency of energy recovery and lifetime. We have also demonstrated 24 hour operation using supercapacitors.

A key feature of the Fleck™ 1 and 3 is an inbuilt solar powered battery charger allowing the Fleck™s to run off the sun with no external components apart from the solar cell. The QCAT test network has operated for more than two years in this fashion.



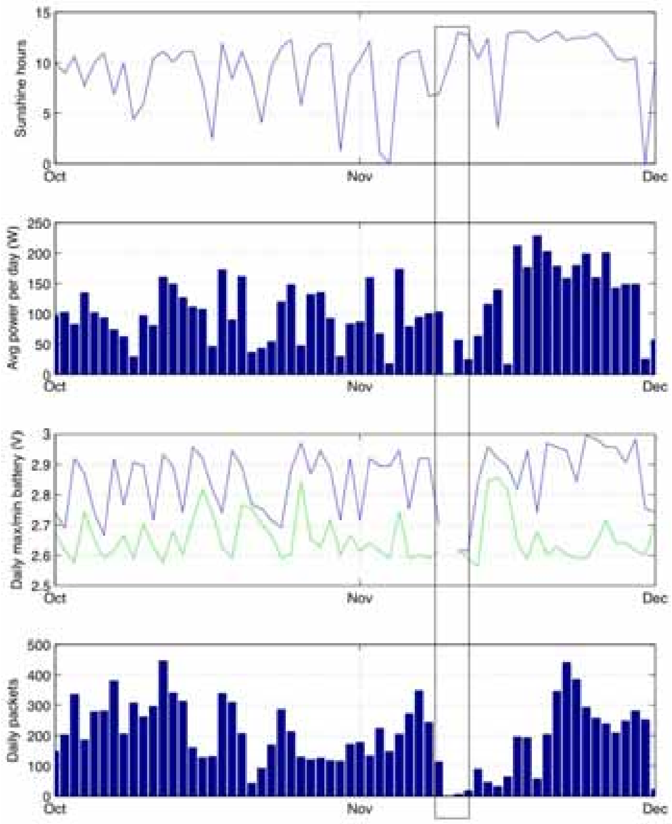
Solar voltage, solar current and battery voltage for a typical a six day period

The daily charge/discharge cycle is clearly shown, where the battery voltage can be seen to slowly drop once the solar power fades away. An interesting observation was that the nightly patrols of security guard cars past the nodes resulted in small peaks in the solar voltage in the nighttime voltage troughs! Current inflow periods vary from 10 hours per day in winter to nearly 12 hours per day in summer.



The solar energy received monthly by each node in the sensor network over nine months (In the southern hemisphere June/July is winter)

By integrating the solar power measurements over time for each month, we are able to estimate the total solar energy yield for each node for each month. This is shown above for four over the period from March to November. While received for each node for each month. This is shown above for four over the period from March to November. While there are clear trends over all nodes in relation to seasonal changes, there is also significant variation between nodes due to location. Nodes such as 88 are far more exposed to the sun and hence show higher energy and far less seasonal variation than nodes such as 91 which are near dense foliage. The monthly energy harvest ranges from 80 to 400kJ which corresponds to a continuous average current of between 17 and 51mA.



Variation for one node over a three-month period which corresponds to unstable local weather conditions. The boxed region was a prolonged server outage

The top curve shows the official sunshine hours for the city , measured 20km away from the deployment, The second curve shows daily average power harvest and we can see some correlation. The third curve shows the daily minimum and maximum battery voltage, which tend to track each other, and the effect of reduced energy harvest can be seen. The bottom graph shows the daily number of packets received which reflects network outages and network software changes.

Our conclusion is that for outdoor application the sun is a great power source.

ANTENNA SYSTEMS

Antennas are a critical part of any communications system, but have not been the focus of much research in the sensor networks community. Leveraging CSIRO's strength in antenna design and wireless technologies we are working to redress this.

Robust Antenna for 915 to 928 MHz

A physically robust antenna covering the 915 MHz to 928 MHz frequency band has been developed that is optimised for mounting on the flanks of cattle. Cattle applications are challenging since the animals work hard to chew off, or rub off, the optimal protruding antenna. The designed antenna provides 3 dBi forward gain and the radiation pattern and input impedance are insensitive to how the antenna is mounted. The antenna is 3.5 millimetres thick and approximately 100 millimetres square. The feed impedance of the antenna is matched to 50 ohms and the radiation impedance is matched to 375 ohms. Manufactured as a single printed circuit board the antenna is inexpensive to manufacture and is extremely robust.

- Antenna gain 3 dBi – Forward gain is insensitive to antenna mounting
- Feed impedance 50 ohms – Impedance is insensitive to antenna mounting
- 3.5 millimetres thick by 100 millimetres square
- Manufactured as a a. cheap and robust single printed circuit board

Spatial Diversity System

A spatial diversity system has been developed for the Fleck™ wireless sensor node. Diversity improves the quality of node-to-node radio communication in a wireless sensor network, overcoming fast fading in a multi-path radio environment, increasing the distance over which communication is reliable, and permitting the use conformal and robust antennas. The spatial diversity system comprises control algorithms and radio-frequency switches that may be used with two or more antenna optimized for the frequency band in use.

The benefits of the diversity system are dependent upon the application. In a cattle sensor network the primary benefit of the diversity system is enabling low-profile antennas to be mounted on the shoulders of cattle in a manner that is resistant to damage. In a fixed network application the primary benefit of the diversity system is doubling the distance over which communication is reliable by enabling high gain antennas to be used.

The diversity system was tested by connecting between one of five antenna and either a Fleck™ sensor node or a power measuring circuit. One of the antennas was optimised for omni-directional short range communication and the other four antennas optimised for high gain, long distance communication. The Fleck™ was used to receive and transmit radio communications and the power measuring circuit was used for carrier detection and for measuring which antenna received the strongest radio signal.

The spatial diversity system is controlled using software running on the Fleck™ node. The software routines select an antenna connection based upon measurements of received-signal-strength or received error rate. The software routines may be incorporated into existing software libraries for the Fleck™ wireless sensor nodes. Forward error correction is implemented using a Reed-Solomon (15, 9, 6) code that is able to measure the error rate when up to 20% of the bits in a radio message are corrupted. The Fleck™ wireless sensor nodes do not support received signal strength measurements in hardware. Received signal strength is measured by using the diversity hardware to connect an antenna to a power measuring circuit.

The analogue signal from the power measuring circuit may be read using the analogue-to-digital converter on the Fleck™ wireless sensor node or may be read from an external analogue-to-digital converter.

The diversity system is a general purpose design that is intended to be optimised upon deployment to meet the requirements of individual applications. The radio-frequency switch connects one of six general purpose radio ports intended for antenna connections to one of two general purpose radio ports intended for Fleck™ sensor node connections. The switch consumes less than 3 microwatts of power and increases the power consumption of a Fleck™ node by less than 0.02%.

DEPLOYMENTS

The QCAT TestBed

The grounds around our laboratories at the Queensland Centre for Advanced Technologies (QCAT) in Brisbane are the location for our longest running outdoor sensor network deployment. The network is the primary engineering testbed and consists of 25 nodes located in and around buildings, amongst trees, creeks, grassy fields and on people and machines. This provides a real-world, medium scale, ad hoc wireless sensor network for identifying the real world challenges to wireless sensor network deployments as well as an experimental test bed for designing and testing wireless sensor network algorithms.

Static nodes in the network harness energy through solar panels in NiMH rechargeable batteries. Through this combination we have had nodes operating since March 2005.

Web display of nodes and their status (www.sensornets.csiro.au)

A typical deployed node.

Each node measures environmental variables such as solar energy and temperature while some also measure soil moisture or water quality. Each measurement sample is then sent back to a base node by wirelessly hopping back through the network to the gateway node.

We built this testbed to understand issues such as scaling, reliability, power and remote management and programming. By being physically deployed outside the network is, deliberately, difficult to reset, unlike many laboratory facilities. This makes software and code dissemination reliability an imperative. The network has been wirelessly reprogrammed over 150 times and physically reset only twice during its lifetime.

Office Deployment

A deployment trial in partnership with an Australian electricity utility used Fleck™s to instrument an agent-based energy management trial at two customer sites: a large cold store and a floor of an office building. The trial was a data gathering exercise, with the aim of Investigating the opportunities for a demand management technology to be rolled out at such sites. We found that both the office and cold-store sites could enjoy potentially significant financial rewards with very little cost to the incumbent business if appropriate demand response technology is used. A total of 25 Fleck™s were deployed, each one monitoring a room in the office building or a sector of the cold store, and data were transported to a secure backend database via two gateway PCs. Key benefits of wireless sensor technology are its ease of retrofit in existing buildings and its flexibility in sensor location.

ADSL, broadband over power line (BPL), and CDMA-EVDO links were used to communicate to the backend system and enable remote administration and management of distant customer sites. The Fleck™s measured temperature, door status, and movement (using PIR sensors), and "Adam" analogue sensing modules measured switching of the heating and cooling plants using clip-on current transducers. Only one Fleck™ failed during the six-month trial and battery-life data obtained during the trial suggests that a single set of batteries should give one year of life in this application. In an office environment, wireless sensor network technology proved to be a reliable and that a single set of batteries should give one year of life in this application. In an office environment, wireless sensor network technology proved to be a reliable and appropriate technique for gathering temperature, humidity, and occupancy data. Inter-node communications in the very densely packed cold-store environment proved to be more of a challenge than in the office environment; we found a large number of Fleck™s was required within a relatively small area to achieve the device density necessary for reliable communications, increasing the cost of deployment.

We conclude that study of and adaptation to the radio propagation environment is an important aspect of wireless sensor deployment in buildings.

James Reserve Experiment

Two Fleck™1 nodes have been installed at the James Jacinto Mountains Reserve, a field station that is part of the University of California system. The reserve is located in a remote wilderness setting, surrounded entirely by the San Bernardino National Forest, east of Los Angeles. These nodes have been installed for more than one year to evaluate their radio performance and solar power performance.

Burdekin Irrigation Network

Installation of salinity and flow sensors

Completed Node

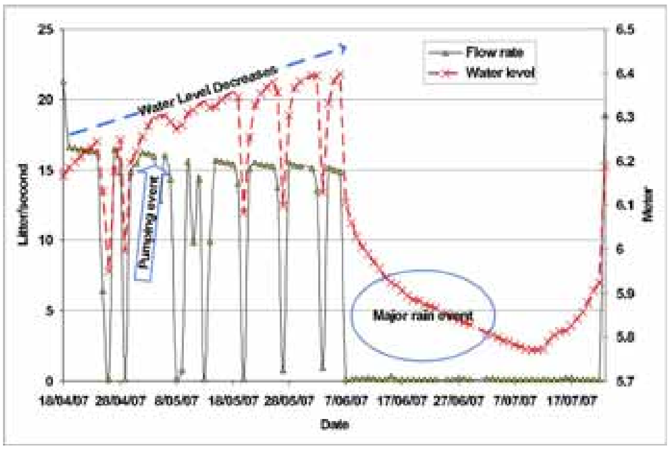
Relay Station

Layout of Network

Saltwater intrusion into coastal aquifers due to poor management has been an ongoing concern for water managers globally. The principle decisions to be made in relation to exploiting these coastal groundwater resources are: where to place the extraction bores, and how much water can be extracted sustainably. Once a coastal aquifer has become infiltrated with saline water it is difficult and very expensive to remediate.

Steadily rising salinity levels have been noticed in a number of production bores adjacent to the coast in the Lower Burdekin. There is concern that the ground water resource in these areas may be degrading, but the extent and the cause of the problem are not well understood.

Similarly, the management options available and the efficacy of particular options are also not well understood.



The Airdmillan Road area which is centrally located within the Burdekin irrigation area (around 10-15km east of Ayr in Northern Queensland) has been an area of concern for the North Burdekin Water Board and subject to a study by CSIRO. One of the recommendations of the CSIRO study was that all the extraction bores in the Airdmillan Road area be metered (including date stamping), as it is unclear how much water is being extracted from the aquifer, and it is suspected that there may be some interplay between aquifer stress and the timing of the extraction.

Bores are within a few kilometres of each other and some have existing power sources. It is envisaged that there will be a mixture of powered and solar Fleck™s. Once the aquifer system is better understood, it may be possible to optimise the extraction in real-time by making decisions about when and where to pump with the objective of minimising saltwater intrusion.

Over a very short period of time, the team designed the hardware and software required to deploy a sensor network in the Burdekin region. Each node measures the volume and rate of water being pumped, the ground-water depth, and the electrical conductivity of the water being pumped. Electrical conductivity is a measure of salinity. The network was deployed in March 2007 and has been providing data on a regular basis since mid-April, achieving overall delivery rates exceeding 60%. The network consists of 5 sensing nodes, 2 relay nodes and a base-station node. The data is being stored in a database and is available from a web-server.

The network has demonstrated the feasibility of the approach and can be used as a testbed for further work in using sensor networks for water management. It also provides a valuable resource to hydro-geologists interested in validating their theories and models of the acquifer structure.

Farm Environment

Agriculture today faces many challenges such as climate change, water shortage, labour shortage due to an ageing urbanized population, and increased societal concern about many issues including animal welfare, food safety and environmental impact. As in other countries where the land has been over-exploited, it has led to problems such as soil erosion, declining water quality, loss of biodiversity and salinity. Importantly these problems are generally inter-linked: over grazing in an inland region may lead to increased erosion, and the increased sediment runoff can harm the distant Great Barrier Reef, or reduced run off can reduce the recharge of underground aquifers. Sensor networks are a critical tool for measuring and understanding the complex coupled dynamics of natural systems.

We are developing a ``Smart Farm'', that applies wireless sensor network (WSN) technology to animal agriculture to address these requirements. We have created a pervasive, self-configuring network of cheap and simple devices that learn about their environment and seek to control it for beneficial purposes.

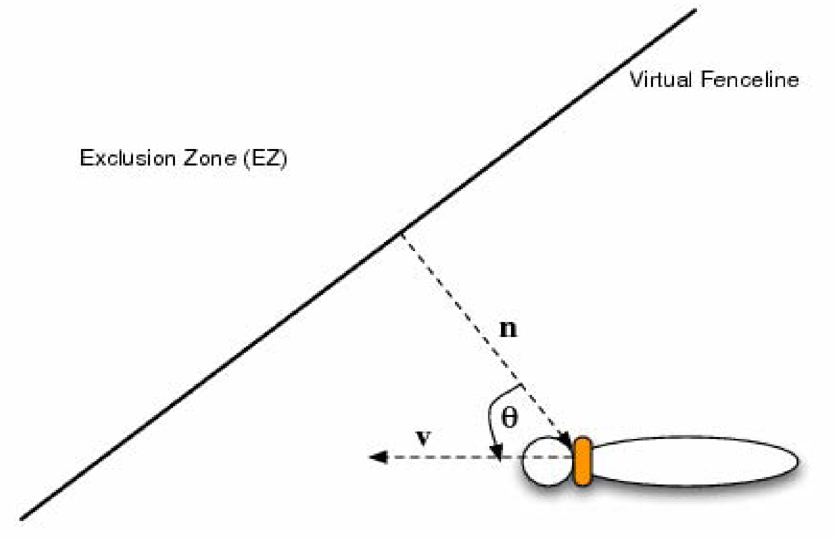
Sensor and Actuator Networks for Virtual Fencing

Cattle control via sensor and actuator networks has been a key part of our research program to date, with initial work focussing on autonomous bull separation to prevent injuries during breeding season.

Our latest work in this area has been undertaken in collaboration with CSIRO Livestock Industries (CLI) as part of the Food Futures National Research Flagship program. The goal of this work has been to develop a methodology for combining scientific knowledge about animal behaviour with computer science techniques to enable autonomous spatial control of cattle via virtual fence lines.

The basic principle behind the research is to present an auditory cue when a fence boundary is reached and mild shock stimuli[1] when the fence is passed. If applied appropriately, cattle can associate the auditory cue with a virtual fence line. In order to allow effective associative learning to occur, cues must be presented to animals in a behaviour-dependent manner. Our research has focussed on the development of state machines which can run on nodes attached to each animal, allowing us to estimate the behaviour state based purely on information derived from onboard GPS sensors.

The Virtual Fencing team



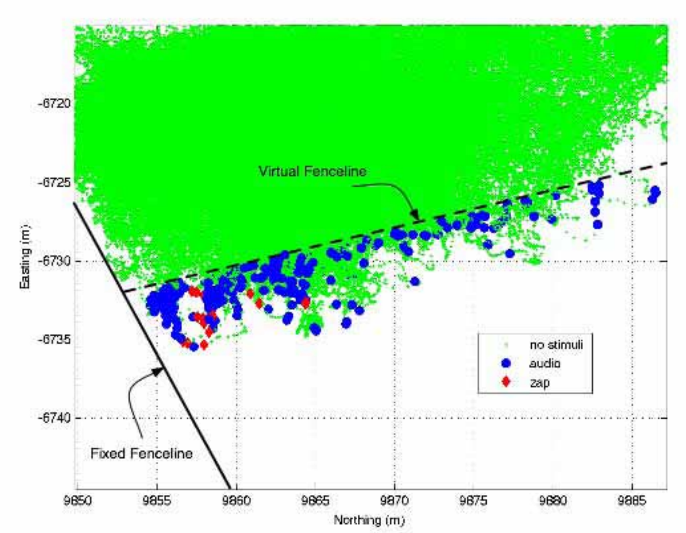
Parameters used in on-board algorithm to determine behaviour in relation to virtual fence boundary: distance from fence, angle of heading to fence and speed

.

Tablet PC used during trial to display real-time cattle information along with the virtual fence

An autonomous trial was successfully completed in April 2007 where a herd of cattle was kept behind a virtual fenceline for 13 hours. Over the period of the day many attempts were made to cross the virtual fenceline, with the maximum distance travelled into the exclusion zone only 5m. In the vast majority of cases, cattle could be controlled using auditory stimuli alone.

Photo of herd during virtual fence trial with virtual fence overlaid in red. Collars can be observed around the necks of each animal which contained all electronics required to make up a node



Trajectories of cattle along virtual fence line along with locations where auditory and electrical stimuli where applied. Maximum distance travelled past VF line was around 5m

Future research in this area is now funded by the Department of Environment and Water Resources (DEWR), with the application focus shifting to protection of environmentally sensitive areas such as river banks or riparian zones. This next phase of work will also seek to address issues in scalability as well as seek to exploit information about the state of the herd, rather than making all decisions at an individual animal level.

Bull Separation

Our work in sensor/actuator networks for animal control has also been applied to the problem of autonomous bull separation for prevention of injuries in herds of breeding bulls. Herds of bulls wearing collars form mobile peer-to-peer networks where sophisticated algorithms running on-board collars predict aggressive intentions between bulls. Virtual fencing techniques are then applied to autonomously keep bulls apart, only when aggressive behaviour occurs. We have successfully completed trials of the technology at Belmont Research Station in collaboration with CSIRO Livestock Industries (CLI) as part of the Food Futures National Research Flagship program, with results reported in [1]

Separated bulls during trial at Belmont Research Station.

[1] The Design and Evaluation of a Mobile Sensor/Actuator Network for Autonomous Animal Control, Wark et.al, IPSN07, pp 206-215.

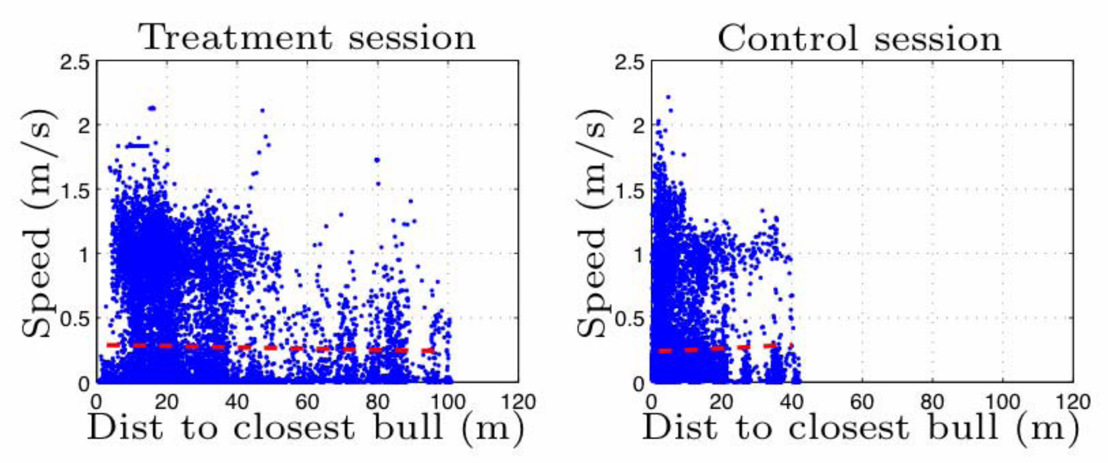


Illustration of speed vs. distance apart for bulls in control group (no collars) and treatment group (wearing collars)

Animals, sensor networks and ethics

It is important to recognise that any scientific study involving animals must conform to strict ethical and legal requirements. CSIRO under-takes to treat animals in research humanely and thoughtfully, and to ensure the best possible standards of health and wellbeing. CSIRO adheres to the standards of the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes, and operates in compliance with all the relevant legislation on animal welfare. Our studies with monitoring and managing animal behaviour are carefully designed, and each experiment has to be approved by an Animal Ethics Committee as a legal requirement. The Animal Ethic Committee comprises a balance of members with scientific, community and animal welfare interests.

As a further surety, the CSIRO animal welfare group in Armidale NSW has monitored animal stress hormone levels during the research and these levels have been found to be well within the limits of normal cattle farming activity.

SENSORS

A Sensor for Detecting Coliform

Sewage pollution of recreational waters is traditionally assessed by the collection of water samples and the enumeration of indicator bacteria such as fecal coliforms and enterococci.

Because current technologies rely on the slow process of bacterial growth to produce identifiable colonies or other visible signs of growth, few methods are capable of providing information on the quality of bathing waters within a few hours. Most culturing techniques take in excess of 24 h before results are obtained.

There exists a detection method based on the uptake of specific marker enzymes by the growing bacteria. Which promises faster detection. The enzymes produce fluorescence that can be detected by eye within about 8 hours.This approach forms the basis of commercially available products such as Colilert^{TM} and Colisure^{TM}. However, using sensitive optical methods enables the detection within about 1 hour and a portable system based on this method has been demonstrated.

The aim of this project was to investigate this method to determine if further improvements in the detection time could be achieved. The experiment was based on the reagents available with the ColilertTM system but the detection was done using a fluorescence plate reader, to achieve high sensitivity to the fluorescence marker.

The main problem with the method is that it requires the bacteria to be in a growth phase to take up the enzymes to initiate the fluorescence. While the fluorescence could be detected at a relatively early stage, this was not consistent between different experiments leading to a large uncertainty in the estimate of the number of bacteria present.

The root of the problem is a time lag between introducing the bacteria to the culture medium and when they start to multiply and consume the fluorescent chemicals. This time lag is variable and depends on the condition of the bacteria at the time of collection and on the conditions associated with the culture medium. The result was that the reliable detection of bacteria concentrations below 150 delu was not possible and that the detection above this to about 300 cfu still required about one hour of incubation time. an alternative approach will be investigated over the next year.

Microbiologist, Dr. Michelle Critchley in the biology lab. at CMSE

Multimedia Sensor Networks

The increasing availability of low-cost CMOS or CCD cameras and digital signal processors (DSP) has meant that more capable multimedia nodes are now starting to emerge in WSN applications. In our applications, we are particularly interested in image processing in low-power, low-bandwidth sensor networks for long-term outdoor deployments. We have created a camera sensor network node using a standard Fleck™ board which is expanded with a Texas Instruments Digital Signal Processor (DSP) board as well a VGA CCD camera board.

With a 640x480 colour CCD sensor, significant local compute power and 1Mbyte of RAM considerable image processing an be performed within the node. Typical operations might be change detection, motion estimation, counting or compression.

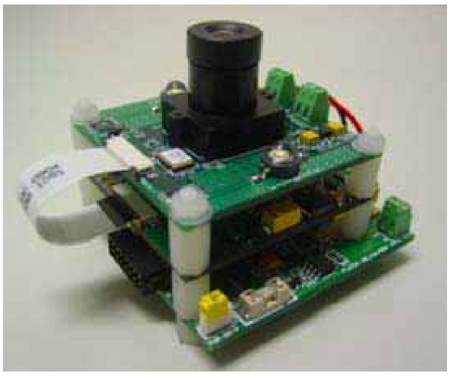
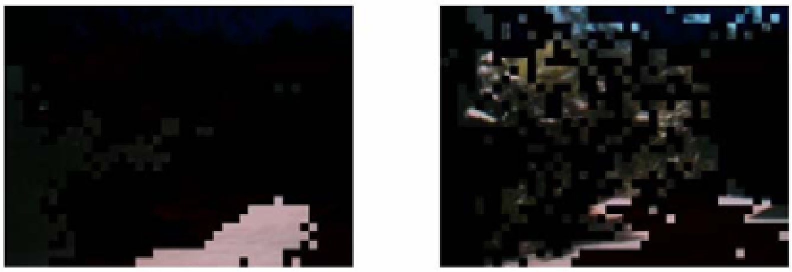


Illustration of camera stack formed by Fleck™ mainboard, DSP board and CCD camera board

One application we have investigated is remote monitoring which requires compressing images at each node to minimise the communication load on the network. The DSP is used to buffer an image taken by the camera and then compress this image. Our compression algorithm is a block-based approach, which encodes blocks differently based on their type. Skip blocks do not need to be encoded as there is little difference between the current and reference frames in this block. Intra and inter-block encoding is performed using techniques similar to JPEG.

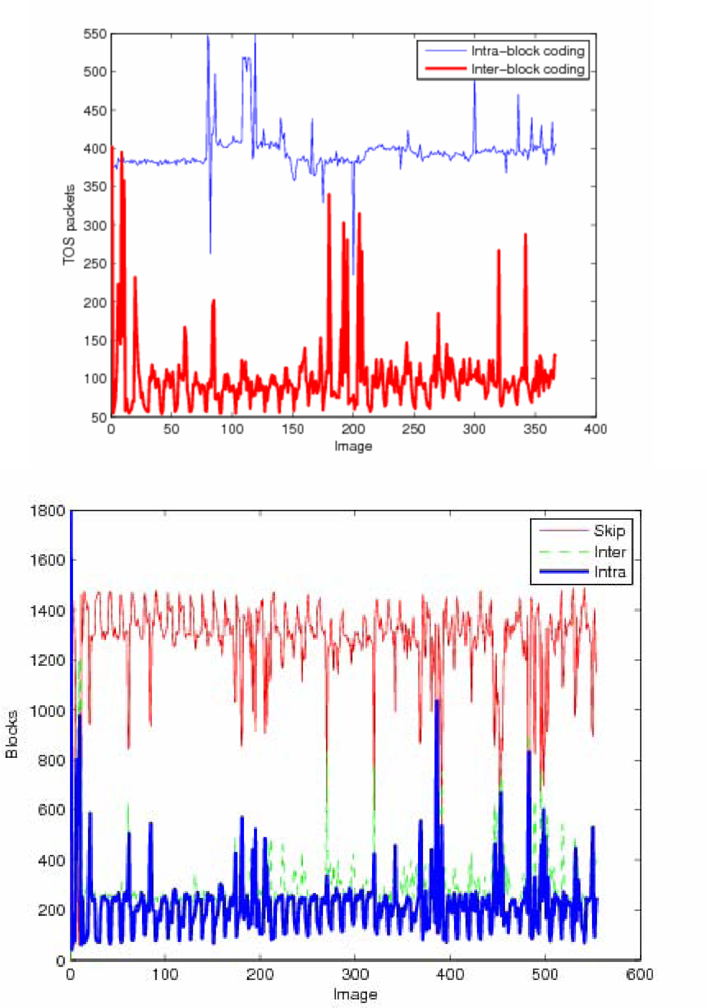


(a) Skip blocks (b) Intra-encode blocks

(c) Inter-encode blocks (d) Output image (base)

Illustration of ways in which blocks are encoded to send data

A camera manager protocol has been developed which detects when new cameras are added to a network. Based on the number of other cameras in the network, the manager program assigns new schedules to the cameras for when to send images. Special focus has been placed on dealing with the situation when packets are lost during transmission in order to maintain image quality.



Number of blocks required to transmit image for varying encoding schemes

The protocol that has been developed to date will typically reduce image sizes by around 97%, greatly reducing the load on the network. Future work will focus on event detection and classification of images at the node to minimise even more the amount of information that needs to be sent over the network.

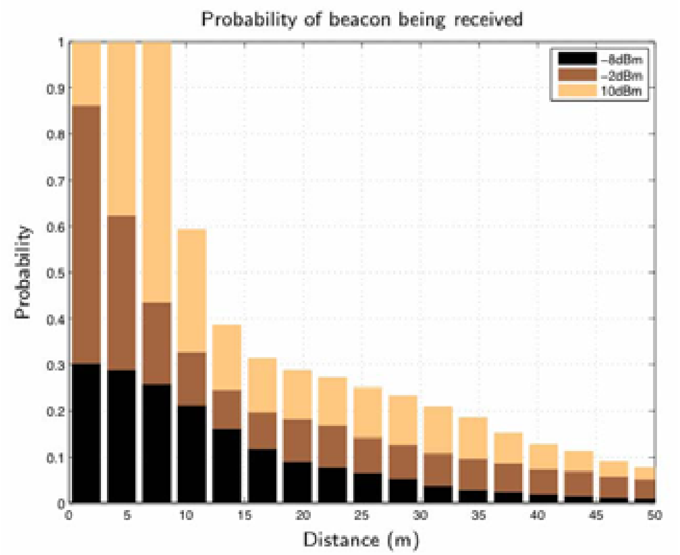
ALGORITHMS

Mobile Delay Tolerant Networks

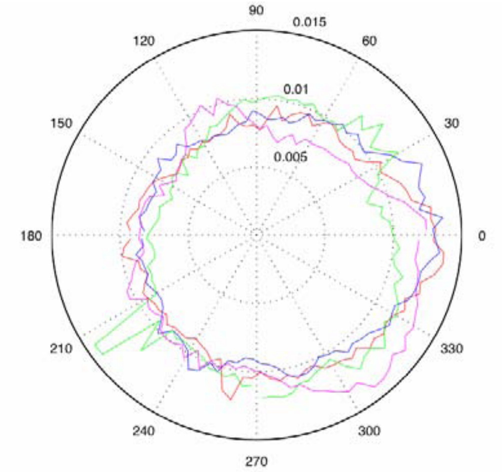
Delay tolerant networks (DTN) are an important subset of ad-hoc sensor networks, where we consider networks with disconnected nodes or nodes with intermittent connectivity. The most common class of solutions for DTN involves nodes buffering data locally until the opportunity arises to upload data to a nearby node.

Our research in this area has focussed on the use of mobile nodes, or message ferries, present in the network to maximise the throughput of data through disconnected networks in moving data from source to sink nodes. In particular we have considered the use of cattle as message ferries as they represent an important class of mobile nodes with stochastic mobility characteristics. This also presents an attractive solution from an agricultural domain viewpoint, as there are many scenarios involving disconnected nodes on large properties where the need to get data back is not time-critical. Cattle are natural part of the environment who's mobility can be exploited to improve throughout of disconnected networks and move data to sink points located a geographically significant locations.

Extensive work has been undertaken in understanding the communication characteristics between nodes mounted on cattle in order to deploy real DTNs. In particular, experiments have been undertaken to quantify the likelihood of packets being received over varying distances between animals as well as the reception characteristics around the body of each animal.

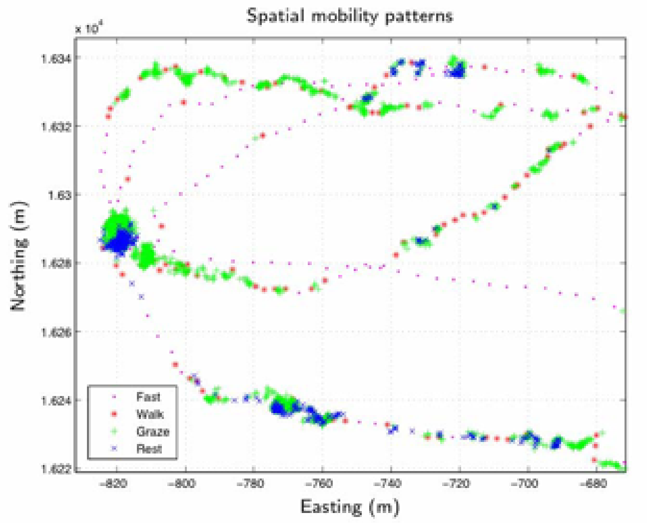


Probability of a single message being received as distance increases



Packet reception performance of antenna mounted horizontally at the top of the collar

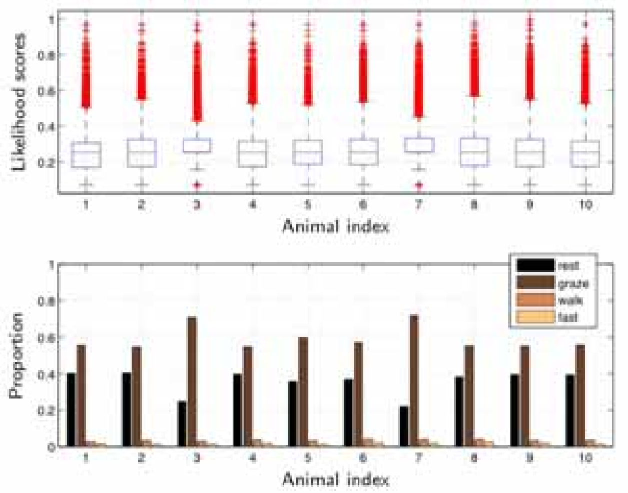
A key aspect of our work in this area has been the development of classifiers for various behaviour states such as grazing, sleeping or walking. The decisions are made from observations derived from accelerometer and GPS measurements and can be calculated in real-time on the device.



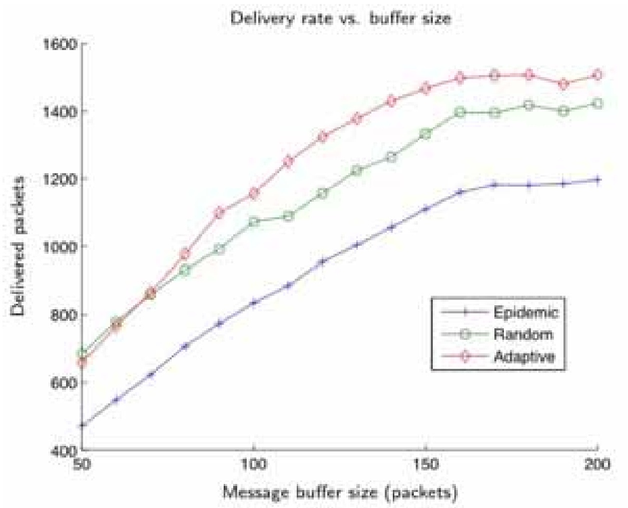
Spatial mobility patterns clearly showing areas of clustering of different types of behaviour

We have chosen to further exploit this information by training statistical models which allow us to characterise the types of behaviour patterns we typically see prior to moving to a sink point (e.g. if located at a water point), as opposed to behaviour during normal periods. Using these types of models we can derive scores for each animal (calculated onboard each device) which indicate how likely it is to be a good candidate for moving data to a sink point.

Simulations and experiments undertaken to date have shown that we can achieve improved network throughput using the additional behavioural information, as opposed to simple schemes such as epidemic routing or randomly choosing ferries.



Box-whisker plot of sink-likelihood scores for various animals along with proportion of time in various behaviour states



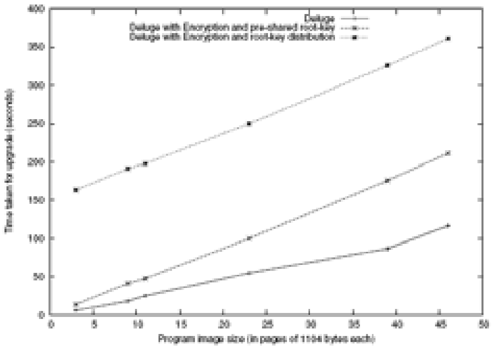
Performance of adaptive protocol when compared to other simpler methodologies

Wireless Sensor Network Security

Information security for wireless sensor networks is a challenging and rich research space as the limited power and physical environment constraints mean that well-developed enterprise security techniques are not suitable. We have focused on the security problems associated with the particular task of over-the-air programming of sensor nodes. As the programming environments for sensor networks mature, we envisage a common program, coded in a high level language, being compiled to a virtual machine language, and then transmitted to all the nodes in a network, relying on a node's local configuration to affect its own interpretation of the program. To support this model, we are particularly interested in ensuring the security of the program that is transmitted, and have focussed on one-hop broadcast transmission, as the most energy-efficient method for this scenario.

Building on a well-known protocol suite for authenticated broadcast, known as SPINS, we have developed a protocol for protecting the *authenticity* but also the *confidentiality* of a large broadcast message. Our new method uses known low-complexity symmetric encryption techniques for confidentiality, while changing the encryption key on a per-packet basis in a verifiable but non-forgeable way to ensure authenticity. We have incorporated our security scheme into Deluge, the de facto network programming protocol for the TinyOS platform.

Our experiments have shown that the cost of the security, in terms of additional communication time, includes a fixed component and a component that varies only linearly with message size making this method suitable for the secure reprogramming task. We have begun to extend these ideas to multi-hop environments, and also to develop methodology for evaluating these and other security protocols with respect to measurable power consumption.



Node Localization

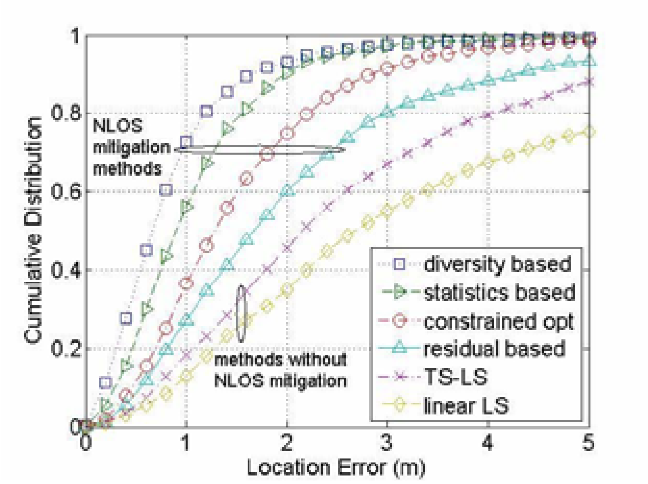
The issue of localization in sensor and communication networks is a key area for a wide range of applications including environmental monitoring, national safety, emergency services, farming, and transportation. Awareness of sensor positions may also greatly improve network efficiency.

We have focused on two important issues in localization. The first is mitigating the non-lineof-sight (NLOS) effect to improve node position information accuracy, and the second is achieving robust localization in GPS/anchor free networks where the nodes are randomly deployed and no *a priori* position information is provided.

Coping with NLOS impact

A major challenge in radio positioning is to achieve desirable location accuracy in an adverse environments such as inside complex buildings and dense urban areas where NLOS propagation usually exists. NLOS conditions, when the direct line-of-sight (LOS) is blocked, results in additional propagation delay for the signal and additional attenuation. So, to obtain accurate node location information, it is crucial to mitigate the NLOS effect.

We studied a variety of NLOS mitigation methods that are seen in the literature, including those using the estimation residual, constrained optimization, error statistics, propagation model, filtering, and database pattern-match. Extensive simulations were conducted to evaluate and compare the performance among the different algorithms. Also we proposed a number of new algorithms to reduce the NLOS effect, including the low complexity Taylor series (TS) expansion based method, sequential quadratic programming based joint position and NLOS bias estimation, and TS linear quadratic programming approach. The effectiveness of the proposed algorithms was demonstrated through simulation. Further, NLOS identification in radio propagation was investigated. We studied identification methods by using either the angle of arrival or the time-of-arrival and radio signal strength measurements in a statistical way.

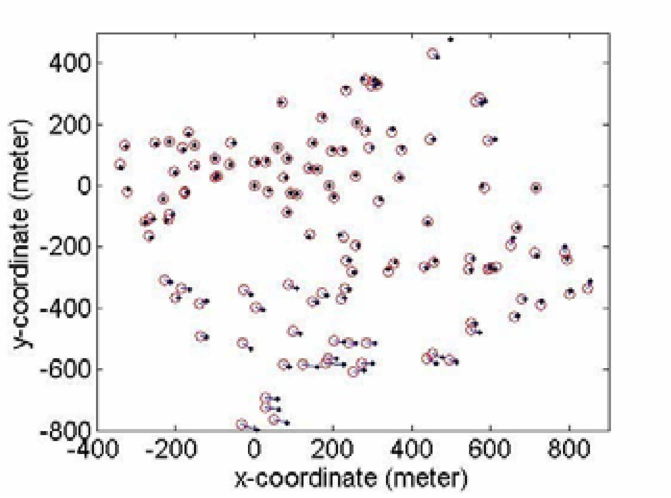


Position estimation error cumulative distribution probability of four NLOS mitigation algorithms and two traditional positioning methods

Robust Localization

One scenario considered in localization is that some nodes are equipped with a GPS receiver so that their global position can be measured, and other nodes can be localized based on the known global position information. Another situation encountered in localization is that there are a large number of nodes randomly deployed in the network, and there is no *a priori* knowledge of any node position information. The second scenario is more challenging and has been our focus.

We proposed and studied a hybrid localization scheme. At first a coordinate system is established by finding a relatively dense group of nodes. Next, the multidimensional scaling (MDS) method is applied to localize the group of selected nodes. Then, the robust quads (RQ) method is employed to localize the other nodes. And then, we make use of the robust triangle and radio range (RTRR) approach to perform the localization task. The RQ and the RTRR methods are used alternately until no more nodes can be localized by the two approaches. The simulation results demonstrated that the proposed hybrid localization algorithm performs well in terms of both accuracy and localization rate.



Typical results of robust hybrid localization in a network of 120 nodes randomly deployed. The node true position is denoted by a dot, while the estimated position is represented by a circle, and the two positions are connected by a solid line.

Spatiotemporal Anomaly Detection in Gas Monitoring Sensor Networks

Since the 1980s, electronic gas monitoring sensor networks have been introduced in the underground coal mining industry. However, no current system can provide site specific anomaly detection. This means monitoring systems often give false alarms, which can be costly to the mining operation. The periodic variation in the gas concentration also increases the number of false alarms in these flat line threshold based systems. Further, current systems ignore the spatial relations between data gathered at different sensor network nodes. These spatial relationships between data could identify anomalies missed by individual sensors.

Conversely, the spatial relationships could explain away the anomalies identified by the individual gas sensors, thus avoiding false alarms.

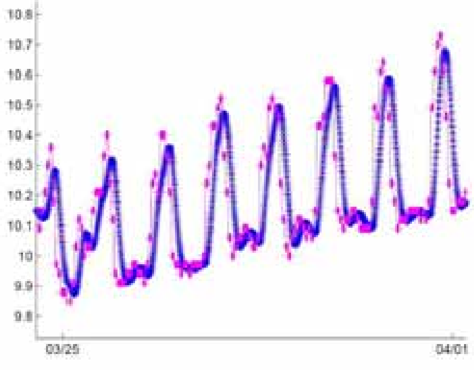
The underground coal mining industry has been struggling with the issues of site-based moving threshold levels for critical gases since the introduction of electronic gas monitoring systems in the 1980s. No satisfactory, scientifically validated methodology is in existence that can provide a mine with its own specific moving threshold levels. Best guess estimates, universal rules-of-thumb and experience-based trigger points are the industry norm.

Typically, existing monitoring systems integrate and interpret incoming data in accordance with a pre-determined set of rules, produces a risk profile, and autonomously initiates a response to a breach of these rules. A problem with this approach is that no clear-cut definition of abnormal situations with respect to the concentration of different gases exist, and it is difficult to produce a good set of rules.

Over the last year, we analysed data gathered from deployed sensor networks in existing Australian coal mines, where each sensor node measures gas concentration, e.g. at 30 seconds interval, of a number of gases, e.g. methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO) and oxygen (O_2), and developed a novel approach to unsupervised learning and anomaly (event) detection.

We used a Bayesian Network model to learn cyclical baselines for gas concentrations thus reducing false alarms usually caused by flatline thresholds. Furthermore, we demonstrated that the system can learn dependencies between changes of concentration in different gases and at multiple locations. In doing so. we defined and identified new types of events that can occur in a sensor network. In particular, we analyse joint events in a group of sensors based on learning the Bayesian model of the system, contrasting these events with merely aggregating single events. Anomalous events in individual gas data were explained when considered jointly with the changes in other gases. Vice versa, a network-wide spatiotemporal anomaly may be detected even when individual sensor readings were within their thresholds.

The presented Bayesian approach to spatiotemporal anomaly detection is applicable to a wide range of sensor networks.



Retrospective Calibration from Cattle Monitoring Data

One of the applications using Fleck™ devices is the monitoring of cattle. For this purpose a cow is wearing a collar containing a box with a Fleck™2 and some battery packs

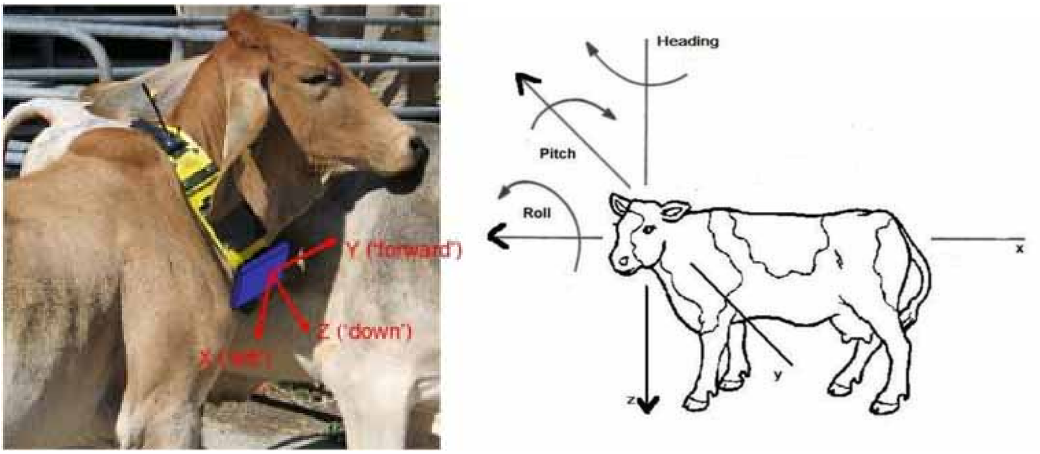


Figure1

Cow wearing a collar, which contains a Fleck™2 device and batteries. The coordinate axes are the ones of the sensor system

GPS, accelerometer and magnetometer data are taken and either stored on a mmc card or sent to a PC using the radio. Depending on the data rate, a few days of data can be recorded without changing the batteries (about 3 days, storing 4 Hz GPS and 10 Hz accelerometer and magnetometer data on the MMC). Future collars will also have solar panels attached to extend this time.

The accelerometers and magnetic field sensors measure the gravitation vector and the Earth's magnetic field in the collars's local coordinate system (Figure 1, left) and therefore allow the calculation of the object's orientation with respect to the global coordinate system (Figure 1, right). A major issue using these sensors is their proper calibration. In common calibration methods, the sensor unit is held in a number of known orientations and the calibration parameters are calculated from the data taken in these orientations. This procedure has to be done beforehand, require additional tools like a compass, and because the sensors are temperature dependant, the calibration is only valid for the specific calibration conditions.

Further problems arise when the device is placed close to ferromagnetic materials after the calibration process. We developed a calibration method for magnetic field and acceleration sensors which is based on the actual data of interest and does not assume certain properties of the environment, since the calibration environment is the same as that of the experiment itself.

Magnetometer Calibration

According to the sensor model, all possible raw ADC readings of the magnetic field sensors lie on the surface of an ellipsoid if the Earth's magnetic field is constant. The basic idea of the calibration method is to record a sufficient number of values while the sensor unit is turned around randomly and fit an ellipsoid to these data. From the ellipsoid parameters the calibration parameters are extracted, which can be used to transform raw ADC values to magnetic field values.

Figure 2 shows raw magnetometer data taken with a Fleck™2, which is mounted on a cow as shown in Figure 1. The data are sampled every 100 ms and stored on a MMC, which is downloaded to a PC afterwards.

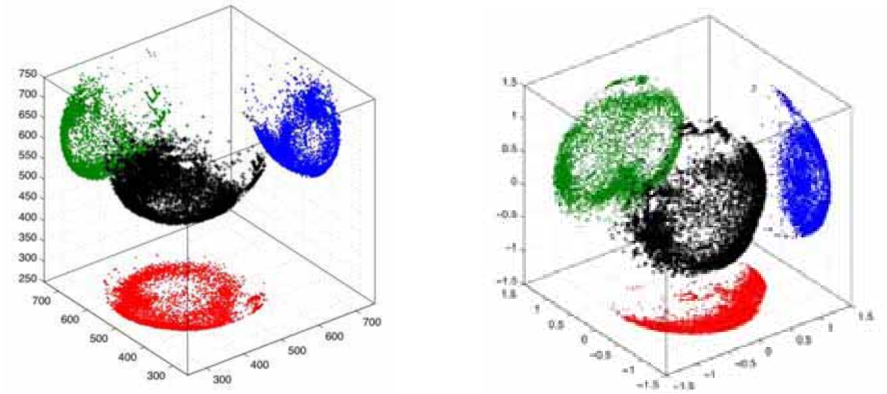
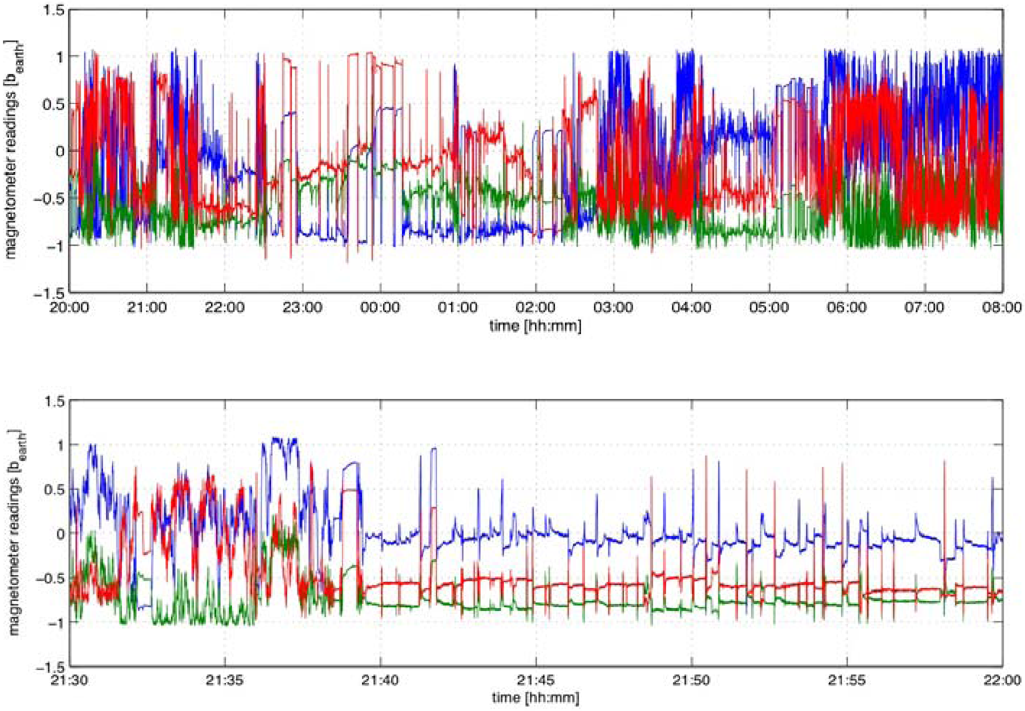


Figure 2

Magnetometers measurements in the sensor coordinate system; left: raw ADC readings, right: values after calibration

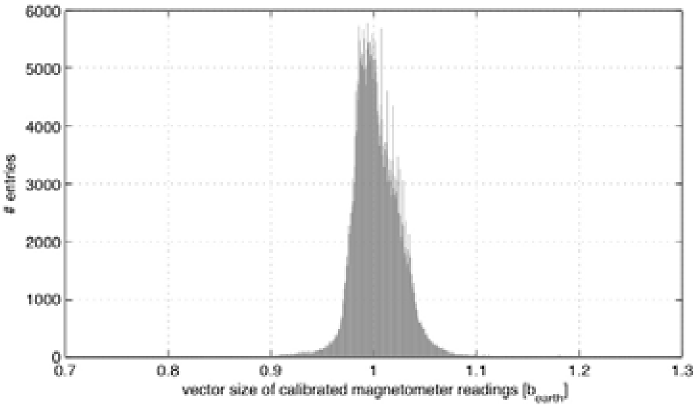
Figure 2 (left) shows the raw measurement vectors in the coordinate system of the sensor device. Since the sensitivity of the different sensors is quite similar, there is no ellipsoid shape observable, but there is a different offset for each axis. Figure 2 (right) shows the corresponding calibrated data. As expected the values are spread over a sphere with radius 1 around the centre of the coordinate system.

When calibrating different datasets it became apparent, that not every calibration was successful in that way. This is probably due to the fact, that some cows are not as agile as others and the data are not spread enough over the whole ellipsoid. In these cases the procedure can be repeated assuming orthogonal sensor axes. So the number of fitting parameters is reduced and a successful fit is more likely. If there are very strong magnetic field disturbances or the single axis magnetometer is twisted, a calibration is not possible, but the data are not usable in that case anyway.



Calibrated magnetometer values; top: 12 hours period, bottom: 30 minutes period

The previous figure shows the calibrated magnetometer over a period of 12 hours (top) and period of 30 minutes (bottom). The quality of the calibration can be checked by looking at the distribution of the vector size of the calibrated data. Since the data should all lie on the surface of the unit sphere, the vector size should be equal to one. Previous figure shows the histogram.



Histogram of Magnetometer readings

Accelerometer Calibration

The same calibration principle can be applied to the accelerometer data. The additional acceleration components which are induced by translational movements have to be minimized. Since this is not obviously easy to tell a cow, a low pass or median filter can be applied to the data first. This is based on the assumption the motion induced acceleration components have a much higher frequency than the orientation based accelerations (gravity).

Figure 4 (left) shows the raw data points (ADC values) in the sensor coordinate system. The figure in the middle shows the raw data after applying a median filter (window size: 20) and the left figure shows the calibrated data.

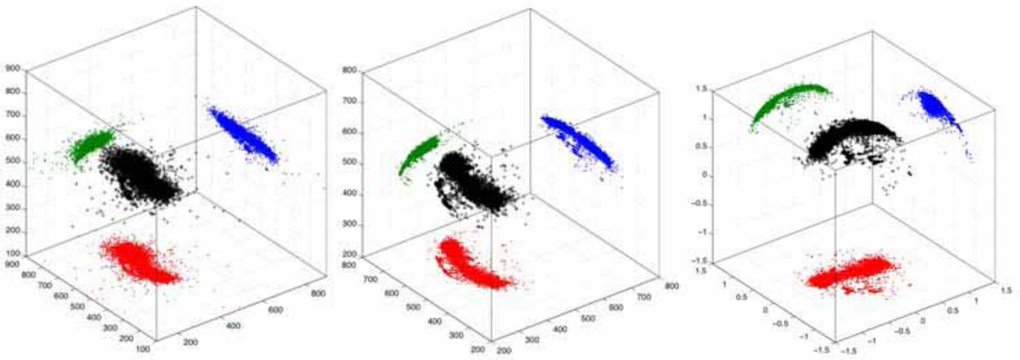


Figure 4

Accelerometer measurements in the sensor coordinate system; left: raw ADC readings, middle: raw ADC readings after a applying a median filter, right: data points after calibration

The biggest problem in calibrating the accelerometers this way can be seen from the figures. A rotation around the gravitational axis does not change the accelerometer readings, but this is probably the most common rotation of a cow in its every day live. As a result there are data points on only small parts of the ellipsoid generated by head-up head-down movements and moderate head shaking. Although the calibration for the shown dataset was successful most of the other datasets couldn't be calibrated that way. In that case the only way to get useful calibration parameters is to determine them using conventional offline calibration methods

APPLICATIONS

Integrated Marine Sensor Networks

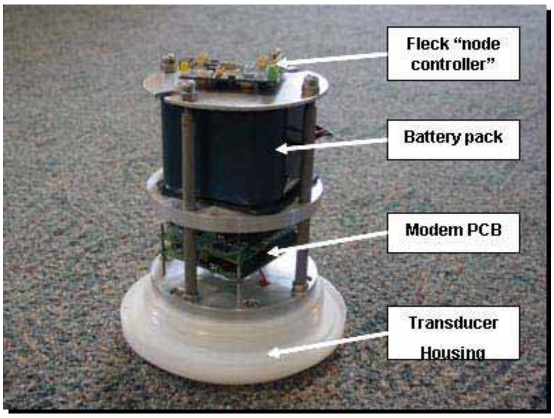
This research is directed towards integrating different marine sensor networks and mobile sensing nodes to improve overall communication connectivity and increased monitoring functionality. The resulting networked system could be capable of detecting broad-scale events and then adaptively guide a mobile robotic survey node to perform fine-scale monitoring capabilities at sites of interest. The work has been focused around developing networked systems for two projects1: Pipeline monitoring system, and Integrated marine observation networks.

These projects explore the development and integration of wireless and wired networks such as acoustic modems and fibre optics in addition to a low-frequency RF pipeline monitoring network. These complementary technologies can be networked together and provide not only sensing, but localisation for robotic systems to interact with the network and perform complex monitoring, inspection and intervention tasks [1].

Acoustic Ad-hoc Networks

Typically designed for reliable point-to-point communications, no commercial underwater acoustic modems currently exist which offer ad-hoc networking capability. This research developed a novel solution to the complex task of acoustic ad-hoc networking through the use a “node controller” to provide the networking layer that commercially available acoustic modems lack.

The Fleck™ was used as the node controller due to its on-board sensing capabilities, multiple serial ports, low-power and microprocessor. Although the radio was not used in this study, it could be used to interface between acoustic and RF sensor networks. The node controller communicates directly with the acoustic modem (link-layer) and provides the necessary networking protocol.



Acoustic ad-hoc network node showing commercial Modem and Fleck™ node controller The system was successfully demonstrated in Brisbane’s Moreton Bay proving the ability to establish ad-hoc multi-hop routes and transfer data within randomly distributed 10 acoustic node acoustic networks. Additionally, the experiments showed that the node controller was capable of determining inter node ranges with accuracies of +/-1.5m [2]

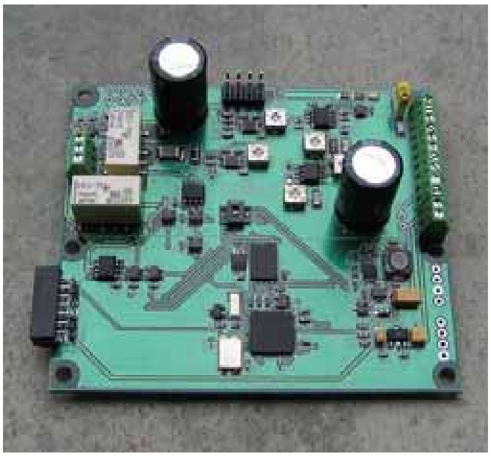
[1] Corke, Detweiler, Dunbabin, Hamilton, Rus and Vasilescu, 2007.
[2] Bengston and Dunbabin, 2007.

10 acoustic nodes ready for deployment in Moreton Bay for ad-hoc networking trials

Low-frequency underwater RF Tag

Off-shore oil and gas pipelines can extend for hundreds of kilometres out to sea and into thousands of meters water depth. The inspection and monitoring of internal flow characteristics within these pipelines is currently expensive with sensors generally sparsely distributed and connected by wires. This makes detailed spatial, and even temporal, monitoring often difficult.

After reviewing the state-of-the-art in wireless pipeline monitoring, we identified an opportunity to improve the spatial sensor resolution and reduce the associated costs of network installation and maintenance through the use of RF data transmission. We developed and patented the Low-Frequency Transmitter (LFT) PipeTag, which has the Fleck™ as its core, along with an integrated subsea monitoring methodology.



LFT PipeTag for subsea pipeline monitoring

The LFT PipeTag is a self-contained surface mounted sensor node that is capable of scavenging and storing energy from the environment, digitising multiple sensor inputs and minimising energy expenditure, as well as relay node data in a daisy chain fashion. All sensing, node control and networking protocol software on the LFT PipeTag including the RF communications is written in FOS.

Autonomous Underwater Vehicle

CSIRO's Starbug robot won two awards this year.
Australian Engineering Excellence Award at the Australian Institute of Engineers Engineering Excellence Awards 2006.

Innovation Award at the Institute of Engineers Queensland Engineering Excellence Awards.

Autonomous underwater and surface vehicles are becoming increasing popular as tools to increase the spatial resolution of remote monitoring programs. Over the last few years CSIRO has been developing an Autonomous Underwater Vehicle (AUV) called Starbug.

This year the Starbug Mk2 was designed and constructed in which a Fleck™, programmed in FOS, was installed to allow wireless communications with a PDA as well as interaction with other fixed and mobile sensor nodes.

Starbug Mk 2 with integrated Fleck™ for sensor network interaction

PDA providing wireless communications and network interface to robots

Autonomous Boat

A further development was an Autonomous Surface Vessel (ASV) called Starship. Starship is a first prototype to evaluate the use a Fleck™ to not only act as a node in within other CSIRO marine and terrestrial networks, but to provide vehicle control capabilities. The system was trialled in Brisbane's Springfield Lake where reliable vehicle control, networked communications and node visitation was demonstrated.

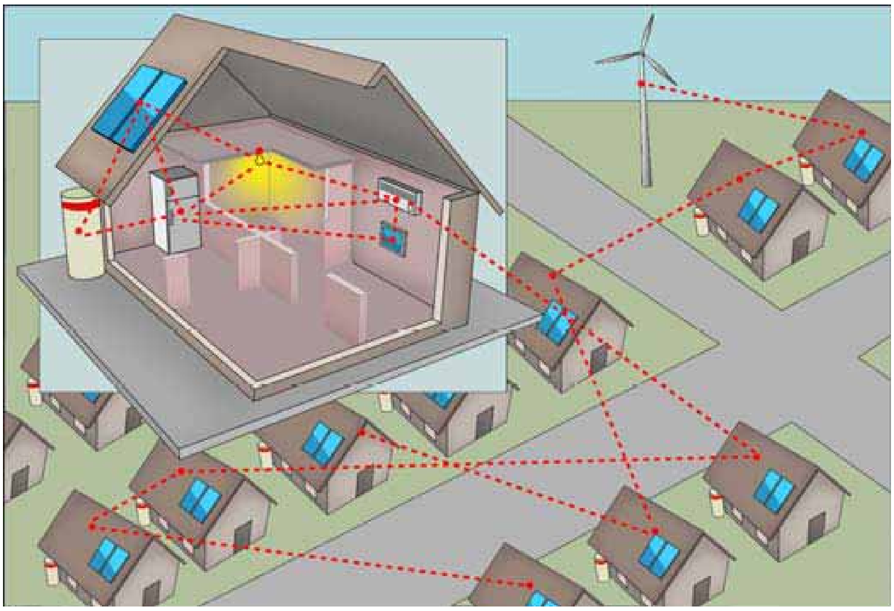
Starship Autonomous Surface Vessel with on-board Fleck™ for communications and control

Hot Metal Carrier

The Hot Metal Carrier(HMC) is a 20 tonne forklift-lift vehicle used in Aluminum Smelters for transporting molten aluminum. The Autonomous Ground Vehicles (AGV) group at QCAT is autonomating an HMC that operates around our site and needs access through a roller door entrance to one of the sites sheds. This project was to automate the opening and closing of the shed door such that the HMC could open the door, and know that the door is open before exiting or entering the shed, and then close the door behind it, sounding a warning to people near the door. We developed an interface board that interfaces the door control signals to the standard I/O interface on the Fleck™. The signals include sensors such as limit switches and exclusion lasers as well as control of Siren, Flashing lights Door Up Door Down and Door Stop. One Fleck™ was mounted on the door with the interface circuitry described above, and the second mounted on the HMC with a serial interface to the HMCs onboard computer. The Fleck™ mounted on the door broadcasts the state of the door at 1 second time periods, listens continuously for commands from the HMC and activates the door and warning system when requested. The HMC Fleck™ continuously listens for the door and sends state information down the serial line when in range or an out of range message when not in range.

Distributed Energy Management and Control

This year we concluded our 4-year project to reduce Australia's greenhouse emissions by enabling the widespread adoption of "distributed energy" (DE) technology: using customer loads and local generators to manage overall electricity demand and assist the wholesale market and distribution network. By establishing CSIRO as the hub of Australian activity in DE we have formed the foundation for a new project targeted at particular applications in this field: energy management in buildings and the refrigerated food chain, zero-emission home energy management (Fig. 1), virtual power stations, and mini-grid technology for export to growing economies.



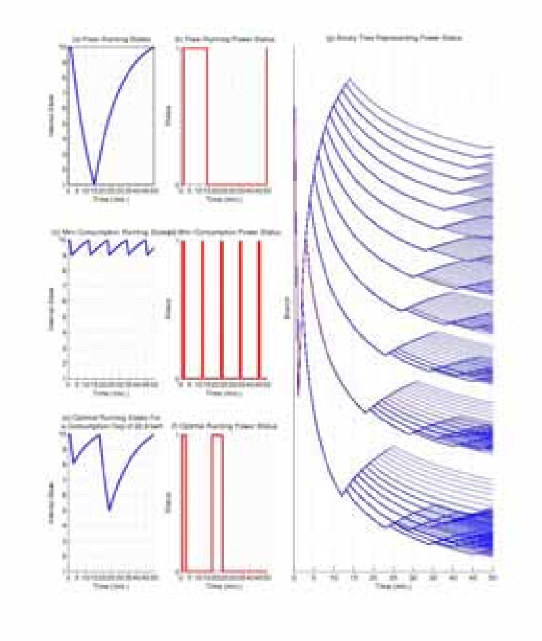
A network of zero-emission homes

Introducing control of customer loads and generators together with communications and some distributed management technology creates DE in the form of large-scale sensor/actuator networks. They have nodes embedded in a variety of city and urban environments, ranging from retrofit interfaces for building management systems to home energy managers linked with new metering technology to air-conditioners and other appliances with built-in processing and communications hardware. Some nodes may be wireless sensor nodes, as we reported last year, but a range of communications media and protocols may be used for effective demand management.

This is future technology but very near future: electricity utilities, appliance manufacturers, meter providers, and control-system providers all have hardware under development and undergoing customer trials. Missing so far is local modelling and intelligence to manage energy so the customer is not disadvantaged by joining a distributed energy network. Also missing is aggregation technology to quantify the system responses that may be obtained by coordinating a network of customers and to enact these responses in a timely and reliable fashion to meet market and network requirements. CSIRO is now positioned to provide intelligent agents and aggregation technology in the Australian and international DE marketplace.

We have developed a new simulation environment to validate algorithms to coordinate customer loads. It uses two-layer hierarchical control that allows low bandwidths typical of existing power-line carrier communications. Simulation runs with over 10,000 customer loads have been achieved on ordinary laptops.

To manage appliances in up to 20-30 houses, the typical fan-out from a distribution network transformer, we have developed an optimisation algorithm based on trees expressing the possible future states of each appliance. It includes appliance models that permit forward planning.



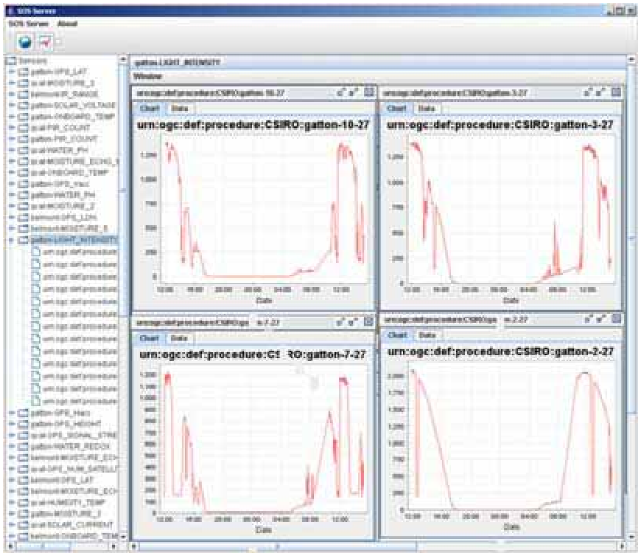
Some alternative forward plans for an appliance (left) and their tree representation (right) Our hardware demonstration mini grid at the Newcastle Energy Centre now includes an intelligent agent integrated with the building management system and forward-planning cool rooms that adapt to their changing contents.

The staff canteen at the Newcastle Energy Centre with adaptive agent

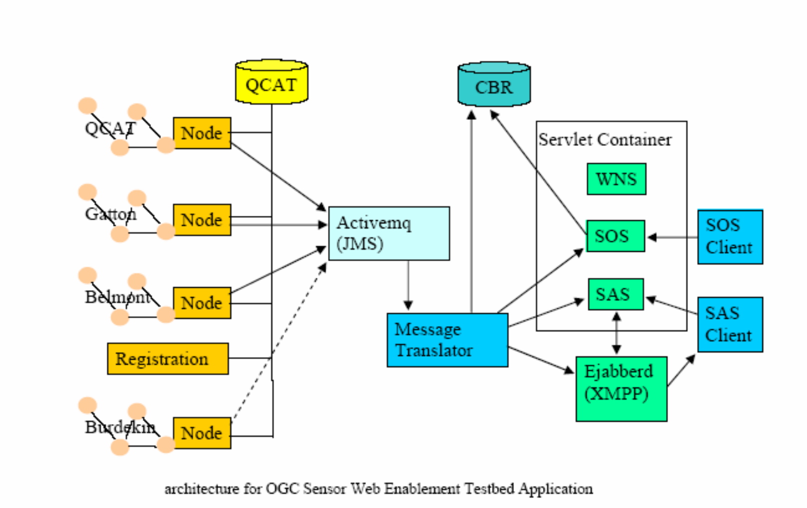
The Open GIS Sensor Web Enablement Testbed

We participated in an international program aimed at developing standards for enabling access to sensor networks through Web protocols, the “Sensor Web Enablement” testbed program of the Open GIS Consortium. We implemented, applied and evaluated a suite of linked standards proposals some of which are in a very early stage of development. These included the Sensor Observation Service, Sensor Alert Service, Sensor Planning Service, Web Notification Service, Observation and Measurement (O&M) and SensorML.

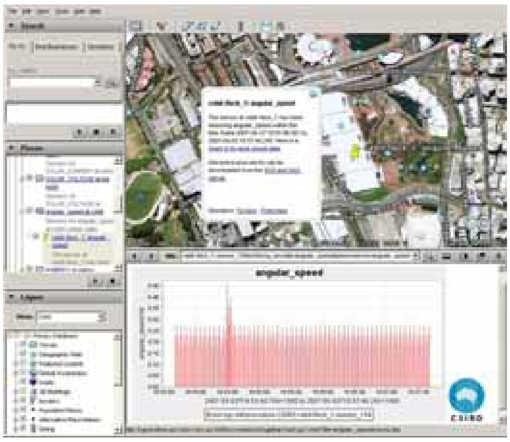
Our work formed part of a large international demonstration of the standards being deployed in an emergency response scenario. Our evaluation has fed into a review of the standards, and some of our recommendations have been implemented by software vendors. It will also influence our development of CSIRO’s Reference Model for Water Information management.



Web clients for Sensor Observation and Sensor Alert services reporting real time data acquired by CSIRO’s Fleck™ sensor nodes.



Architecture for OGC Sensor Web enablement Testbed Application



Google Maps client demonstrating the standards-based serving of real-time sensor data collected from a water wheel installed at the CeBIT exhibition in Sydney, 2007.

PUBLICATIONS 2006/2007

Journal papers accepted/published:

- Kerry Taylor, Tim Austin, and Mark Cameron (2006). A web service architecture for revenue-earning information products. *International Journal of Cases on Electronic Commerce*, 2:76-93, 2006.

- Quan Z. Michael Sheng, Boualem Benatallah, and Zakaria Maamar, User-Centric Services Provisioning in Wireless Environments, to appear in the *Communications of the ACM*.

- Laurent Lefort, Kerry Taylor and David Ratcliffe, "An Empirical Comparison of Scalable Part-Whole Ontology Engineering Patterns" in Expert Systems: *The Journal of Knowledge Engineering., SpecialIssue on Advances in Ontologies,* to appear.

- D. Swain, T. Wark and G. Bishop-Hurley, "Using high fix rate GPS data to determine the relationships between fix rate, prediction errors and patch selection", *Ecological Modelling*, (under review), 2007.

- Jiaming Li, Geoff Poulton, Geoff James, Astrid Zeman, Peter Wang, Matthew Chadwick, Mahendra Rajah Piraveenan, "Performance of multi-agent coordination of distributed energy resources", *WSEAS Transactions on Systems and Control*, vol. 2, no. 1, pp. 52-58, January 2007

Journal papers submitted:

- T.Wark, W.Hu, P.Sikka, L.Klingbeil, P.Corke, G. Bishop-Hurley, "The Design and Evaluation of a Model-based Routing Protocol for a Mobile Delay-Tolerant Network", *IEEE Transactions on Mobile Computing*, 2007.

Conference papers accepted/published:

- T. Wark, C. Crossman, W. Hu, Y. Guo, P. Valencia, P. Sikka, P. Corke, C. Lee, J. Henshall, J. O'Grady, M. Reed and A. Fisher, "The Design and Evaluation of a Mobile Sensor/Actuator Network for Autonomous Animal Control", *ACM/IEEE International Conference on Information Processingin Sensor Networks (IPSN)* – SPOTS Track, Boston, April 2007.

- J. Karlsson, T. Wark, P. Valencia, M. Ung and P. Corke, "Demonstration of Image Compression in a Low-Bandwidth, Wireless Camera Network", *ACM/IEEE International Conference on InformationProcessing in Sensor Networks (IPSN)*, Boston, April 2007.

- P. Corke, P. Valencia, P. Sikka, T. Wark and L. Overs, "Long-Duration Solar-powered Wireless Sensor Networks", *Workshop on Embedded Networked Sensors (EmNet**s)***, Cork, June 2007.

- Y. Guo, P. Corke, G. Poulton and T. Wark, Animal Behaviour Understanding using Wireless Sensor Networks**,** *IEEE SenseApp Workshop*, Tampa, November 2006.

- T. Wark, C. Crossman, P. Valencia, L. Klingbeil, G. Bishop-Hurley and D. Swain, "Wireless Sensor Networks for Farming", *Horizons in Livestock Sciences: Research for the Farm of the Future*, Gold Coast, October 2006.

- K. Yu and Y. J. Guo, “NLOS error mitigation for mobile location estimation in wireless networks,” in *Proc. IEEE Vehicular Technology Conf. (VTC)*, Apr. 2007.

- K. Yu and J. Y. Guo, “Efficient positioning algorithms in non-line-of-sight environments,” to appear in *Proc. IEEE Int. Symp. Personal, Indoor and Mobile Radio Communications (PIMRC),* Sept. 2007

- K. Yu and J. Y. Guo, “Improved positioning algorithms for non-line-of-sight environments,” Submitted *to IEEE Transactions on Vehicular Technology*.

- K. Bengston and M. Dunbabin, “Design & performance of networked ad-hoc acoustic communications systems using inexpensive commercial CDMA modems”, *Proc of IEEE Oceans* 2007, Aberdeen, June 2007.

- P. Corke, C. Detweiler, M. Dunbabin, M. Hamilton, D. Rus and I. Vasilescu, “Experiments with underwater localisation and tracking”. Proc. *International Conference on Robotics & Automation*(ICRA), Rome, 2007, pp.4556-4561.

- Glenn Platt, Geoff James, Joshua Wall, and Sam West, “The intelligent control of distributed energy networks”, *Proceedings, International Symposium on Energy, Informatics and Cybernetic*s (EIC 2006), Orlando, Florida, July 2006

- Ariel Liebman, Geoff James, and Glenn Platt, “Risk management in an intelligent grid: agent based demand side management”, *Energy Trading and Risk Management,* Sydney, October 2006

- Astrid Zeman and Mikhail Prokopenko, “Predicting Cluster Formation in Decentralized Sensor Grids”, *10th International Conference on Knowledge-Based & Intelligent Information & EngineeringSystems* (KES2006), Bournemouth UK, October 2006

- Bhavna Orgun, Mark Dras, Abaya Nayak, and Geoff James, “Approaches for semantic interoperability between domain ontologies”, *The Australasian Ontology Workshop* (AOW 2006), Hobart, Australia, December 2006

- Glenn Platt, Josh Wall, Geoff James, and Phil Valencia, “Wireless Sensor Networks as Agents for Intelligent Control of Distributed Energy Resources”, *Proceedings, IEEE International Symposiumon Wireless Pervasive Computing* (ISWPC 2007), Puerto Rico, February 2007

- Elth Ogston, Astrid Zeman, Mikhail Prokopenko, and Geoffrey James, “Clustering distributed energy resources for large-scale demand management”, accepted for publication, *First IEEE International Conference on Self-Adaptive and Self-Organizing Systems,* Boston, July 2007

- Kerry Taylor, Christine M. O'Keefe, John Colton, Rohan Baxter, Ross Sparks, Mark Cameron, Laurent Lefort, and Uma Srinivasan (2006). A data network for health e-research. *In Proceedings of the European Conference on eHealth (ECEH06), volume 91 of Lecture Notes in Informatics, Proceedings*, pages 215-226, Fribourg, Switzerland, October 12–-13 2006.

- Jaleel Shaheen, Diethelm Ostry, Vijay Sivaraman, and Sanjay Jha "Confidential and Secure Broadcast in Wireless Sensor Networks“ Proc. 18th *annual IEEE Symposium on Personal, Indoor, and Mobile Radio Communications*, Athens, Greece, Sep 2007.

- S. Li, V. Sivaraman, A. Krumm-Heller, C. Russell, "A Dynamic Stateful Multicast Firewall", IEEE *International Conference on Communications* (ICC), Glasgow, Scotland, Jun 2007.

Unlisted conferences and workshops:

- Kerry Taylor, Paul Brebner, Michael Kearney, Dana Zhang, Kelly Lam and Vladimir Tosic, “Towards Declarative Monitoring of Declarative Service Compositions”, 2nd International Workshop on Services Engineering (SEIW 2007) in conjunction with *The 23rd International Conference onData Engineering* (ICDE 2007) April 16, 2007, Istanbul, Turkey

- Laurent Lefort, Kerry Taylor and David Ratcliffe (2006). Towards scalable ontology engineering patterns: Lessons learned from an experiment based on W3C's part-whole guidelines. In Advances in Ontologies 2006, *Proceedings of the Second Australasian Ontology Workshop* (AOW 2006), volume 72 of Conferences in Research and Practice in Information Technology, pages 31-40, Hobart, Australia, 5 December 2006. Australian Computer Society. http://crpit.com/Vol72.html

- Ian Naumann, Emma Lumb, Kerry Taylor, Robert Power, David Ratcliffe, and Michael Kearney (2006). The Australian Plant Pest Database: a national resource for an expert community. In Andrew Treloar, editor, *Proceedings of The Twelfth Australasian World Wide Web Conference*, (AusWeb06), Noosa, Australia, 30th June to 4th July 2006. http://ausweb.scu.edu.au/aw06/index.html

- Xiaobing Wu, XML Document Classification with Co-training. In *Work in Progress Proc of Inductive Logic Programming Conference* Oregon USA , June 2007.

- Xiaobing.Wu, An Inductive Learning System for XML Documents. In Proceedings of *Inductive Logic Programming Conference* Oregon USA , June 2007.

Conference papers under preparation:

Books & Proceedings

- Quan Z. Sheng, Kerry L. Taylor, Zakaria Maamar, and Paul Brebner, "Research in RFID Data: Issues, Solutions, and Directions",in Yan Lu , Yan Zhang, Laurence T. Yang, Huansheng Ning, in *"The Internet of Things: from RFID to Pervasive Networked Systems*” to be published Feb 2008

- Quan Z. Sheng, Zakaria Maamar, Mark Cameron (Eds*.). The First International Workshop on RFID Technology: Concepts, Applications, Challenges* (IWRT 2007). June 12 2007, Funchal, Madeira, Portugal.

Other (abstracts):

- Kerry Taylor (2006). The semantics of water. Abstract of Keynote address in A. Orgun Mehmet and Meyer Thomas, editors, Advances in Ontologies 2006, *Proceedings of the Second Australasian Ontology Workshop* (AOW 2006), volume 72 of Conferences in Research and Practice in Information Technology, page 3, Hobart, Australia, 5 December 2006. ACS.

- Kerry Taylor and Arun Ayyagari (2006), Research topics in semantic sensor networks: Preface to the proceedings of the semantic sensor networks workshop. *In 5th International Semantic WebConference* (ISWC2006): Supplemental Proceedings, Athens, Georgia, USA, November 2006. Springer. http://www.ict.csiro.au/ssn06/

PATENTS

Remote Monitoring of Underwater Objects AU2007901245 (Jiaming Li, Geoff Poulton, and Geoff James, “Distributed Energy Management”, Australian provisional patent, filed 3rd August 2006, proceeded to PCT 27th July 2007.

OTHER ACTIVITIES

Partners

Wealth from Oceans Flagship
Water for a Healthy Country Flagship
Energy Transformed Flagship
Food Futures Flagship

Visits

Prof Daniela Rus, MIT, January 2007

Visitors/Students

Cameron Tarbotton
Phillip Sitbon, Portland State University
Jon Binney, University of Southern California
Johannes Karlsson, Umeå University

Honors Project Students:

Brenton Lang, Griffith
Brett Wood, Griffith

PhD Students

Chong An (UQ), supervisor Peter Corke
Tuan Dinh Le (UNSW), supervisor Wen Hu
Stephen Tansing DET
Dhirendra Singh
Matt McKay

Visits and Seminars

- “Towards the Digital Farm'', ICT Outlook Forum, Melbourne, 23 October 2006, Peter Corke
- Visit and presentation at USDA ,New Mexico, November 2006, Tim Wark,
- “Outdoor Robots and Sensor Networks'', Autonomous Systems Lab, ETH, Zurich, 19 December 2006, Peter Corke.
- Visit to James San Jacinto Mountain Reserve, UC Riverside, April 2007, Tim Wark
- The Instituto Superiore Mario Boella, TORINO, April 16 2007, Peter Corke
- Politechbnico di Milano, April 17 2007, Peter Corke.
- Visit to James Reserve / CENS, April 2007, Tim Wark
- “Wireless Sensor Networks for Environmental Monitoring”, Distributed Systems Group, ETH, Zurich, April 18, Peter Corke.

- "Wireless Sensor Networks for Environmental Monitoring", Parallel and Distributed Systems group, TU DELFT, April 20, Peter Corke
- "Long-Duration Solar-powered Wireless Sensor Networks", Fourth Workshop on Embedded Networked Sensors, 25-26 June, 2007 Cork, Ireland. Pavan Sikka

Technical Committees

- IPSN 2007, Peter Corke
- IEEE Vehicular Technologies Conference, Ad Hoc and Sensor Networks track, Peter Corke
- Sensys 2007, Peter Corke
- Emnets IV, 2007, Peter Corke

We also presented the work at the ICT Centre stall at the CeBIT exhibition (http://www.cebit.com.au, it's the biggest annual IT exhibition in Australia) in Sydney.

Media

2006
21 July - Smart Agent Technology Exhibited at CeBIT 2006 - Energy Transformed Update - Smart Agents at CeBIT 2006
21 July - Meters go the extra mile for energy smarts - Science by Email - Development of Smart Meters
15 September - Our big backyard - 2GZ (Orange) - Tim Wark discusses WSN in farms
18 September - Sensor Network set to revolutionise farming - Tim Wark on WSN and the Smart Farms project
19 September - 7.30 News - 4BU (Bundaberg) - Tim Wark on smart farms
19 September - CSIRO aims to shrink solar collar cow trackers - Australian - Smart farms project
20 September - Smarter farms aim of CSIRO - Kiama Independant - Tim Wark on WSN for farms.
20 September - Smart Farm on the way - Beaudesert Times - Report on smart farms project
22 September - CSIRO builds smart farm - Border News - Tim Wark on smart farms project
27 September - CSIRO builds smart farms of the future - Casterton News - Tim Wark on Smart Farm project
28 September - Technology Bytes - Murray Valley Standard - Smart Farm project
29 September - Smart farm of the future - Bega District News - Tim Wark on Smart Farm project
3 October - Morning Show - ABC South East SA (Mt Gambier) - Tim Wark discussing Smart Farms project
5 October - Sensor networks sign of the times - North West Farmer - Smart farms project
11 October - Wireless farm - Australian R&D review - Tim Wark on Smart Farm project
11 October - CSIRO builds smart farm - Clifton Courier - Tim Wark on Smart Farm project
30 October - Channel 10 (Adelaide) - Ten News - Alex Zelinsky on water crisis
1 November - CSIRO wireless sensor network - Food Australia - 1st anniversary of wireless sensor network
1 November - CSIRO builds smart farm - Australian Sugarcane - WSN research
14 November - Race for better dipstick in the dry - Australian - Wireless sensor networks in WRON
1 December - CSIRO builds farm of the future - National Grape Growers - Tim Wark on WSNs for farming
8 December - Rural Report - ABC Western Plains (NSW) - Tim Wark on Smart Farms project
12 December - Rural Report - ABC Upper Hunter - Tim Wark on smart farms

2007
25 January - Working towards 'smart farm' of future - Farming Ahead - Tim Wark on Smart Farms project
1 February - The Rural Report - ABC Central Australia - Tim Wark on Smart Farms project
1 February - Technology on tap to measure shrinking water supplies - Computerworld - WSNs as part of WRON project
1 February - CSIRO leads water information initiative - Supercomputing online - WSNs as part of WRON project
5 February - CSIRO leads water initiative - Monday Mail - WSN involvement in WRON
6 February - Technology on tap to measure shrinking water supplies - Infoworld - WRON project
7 February - Technology on tap - Computerworld - WRON project
13 March - Fixing leaks - The Australian - Ross Ackland on WRON
22 March - 2NM (Muswellbrook) - Sky Rural News - Ross Ackland discusses WRON
22 March - Curtin FM (Perth) - News - Ross Ackland on wireless sensor networks and water use
22 March - Sensors to get the measure of water, Australian, Page: 32
22 March - ICT for World Water Day 2007 - IDM.net.au - Wireless sensor networks and WRON
22 March - ICT for World Water Day 2007, Angela Priestley, 2007, http://www.idm.net.au/story.asp?id=8186
26 March - World Water Day 2007 - Monday Mail - Ross Ackland on WRON
26 March - 4BU (Bundaberg) - News - Report on WRON
26 March - News briefs - Slattery's Watch - Sensor networks and WRON

27 March - Sensors to get the measure of water - Australian - Wireless sensor networks and WRON
27 March - Private sector wants toe in water - Australian - Ross Ackland on WRON
27 March - Sensors to get the measure of water, Australian, Page: 32
28 March - Technology to help monitor water - Beaudesert Times - WRON and North Burdekin Water Board
28 March - Technology to help monitor water, Beaudesert Times, Page: 26
29 March - Pooling knowledge for water reform - Image and Data Management - WRON's involvement in Federal water plan
April - New Technology aids Australia's Water Resources, Pace - Process & Control Engineering, Page: 14
26 April - ABC Channel 2 (National) - News - Virtual fencing system
1 May - New water sensor advances control - Grapegrowers and Vignerons - Flecks used in water monitoring
May - New water sensor advances control, Grapegrowers & Vignerons, Page: 36
3 May - Not a fence in sight - The Land - Virtual fencing trial
3 May - Virtual containment with a collar - The Land (Northern Edition) - Virtual fencing
7 May - Burdekin salt water battle in high-tech mode, Australian Canegrower, Page: 20
25 May - Virtual fencing progress slow but sure - Australian Farm Journal - Virtual fencing trial
9 June - Fenceless grazing - Warrnambool Standard - Virtual fences 12 June - Data deluge coming – The Australian - Peter Corke on online analytics
13 June - CSIRO developing virtual fences for livestock - Australian Food News - Report on virtual fencing trial
June - Remote sensor data for water management, Engineers Australia, Page: 58
14 June - Morning Show - 2DU (Dubbo) - Virtual fencing
14 June - Statewide Drive - ABC Gippsland - Virtual fencing
14 June - Drive - ABC 774 (Melbourne) - Virtual fencing
14 June - Don't fence me in: GPS cows - The Age - Virtual fencing for cows
14 June - Fencing the future - Stock & Land - Virtual fencing for cows
14 June - Don't fence me in: clever collar keeps cows in virtual paddock - SMH - Virtual fencing for cows
14 June - CSIRO works on invisible fence project - Queensland Times - Virtual fencing for cows
14 June - Breakfast - ABC 702 (Sydney) - Virtual fencing for cows
14 June - Breakfast - 2CC (Canberra) - Virtual fencing for cows 14 June - Rural Report - ABC Northern Tasmania - Virtual fencing for cows
14 June - Breakfast - 2LM (Lismore) - Virtual fencing for cows
14 June - Breakfast - Radio National (Canberra) - Virtual fencing for cows
14 June - Bovines without borders - Guardian Unlimited - Virtual fencing
15 June - Australian scientists invent virtual fence for cows - iTNews.com.au - Virtual fencing
15 June - Virtual fence for livestock from CSIRO - Bega District News - Virtual fencing
15 June - Heard of cows wearing collars? - The Press - Virtual fencing
15 June - Don't fence me in - Shepparton News - Virtual fencing
15 June - New fence virtually brilliant - South Burnett Times - Virtual fencing
15 June - Breakfast - 6PR (Perth) - Virtual fencing for cows
16 June - Virtual fencing not far off - Hamilton Spectator - Virtual fencing
18 June - Livestock being the virtual fence - Geraldton Guardian - Virtual fencing 18 June - Bovines could be zapped instead of fenced in - Ashburton Guardian - Virtual fencing
18 June - Virtual fencing viable - Bairnsdale Advertiser - Virtual fencing
18 June - Livestock virtually fenced in - Medical News Today - Virtual fencing
19 June - SKY Rural News - 2NM (Muswellbrook) - Virtual fencing 19 June - Livestock virtually fenced in - Great Southern Star - Virtual Fencing
19 June - Livestock virtually fenced in - Science Daily - Virtual fencing
19 June - Livestock virtually fenced in paddocks - Murray Valley Standard - Virtual fencing
19 June - Country Today - 3WM (Horsham) - Virtual fencing
20 June - Rural Report - ABC Western Plains - Virtual fencing
20 June - Rural report - ABC New England North West - Virtual fencing
20 June - Livestock virtually fenced in - West Wimmera Advocate - Virtual fencing
20 June - Virtual fencing viable - Snowy River Mail - Virtual fencing

20 June - Livestock virtually fenced in - Quirindi Advocate - Virtual fencing
20 June - Virtual fence - Cairns Post - Virtual fencing
20 June - Fenced in by technology - Weekly Times - Virtual fencing
20 June - Virtual fencing foe real livestock? - The Poultry Site.com - Virtual fencing
20 June - CSIRO makes cattle fences obsolete - Cobden Times - Virtual fencing
20 June - Corral cows with a virtual fence - Dairy Herd Management Magazine - Virtual fencing
21 June - Fenced virtually - Queensland Country Life - Virtual fencing
21 June - Fencing without posts or wire - Stock & Land - Virtual fencing
21 June - Fencing the future - Countryman - Virtual fencing
22 June - Bush Telegraph - Radio National (Canberra) - Virtual fencing
22 June - Invisible fences allow better use of pasture - Esperance Express - Virtual fencing
22 June - Future farms without fences - Tasmanian Country - Virtual fencing
22 June - Fence-free farms in the future: CSIRO - Longreach Leader - Virtual fencing
22 June - New sensor technology advances Australia's water management - WfHC Flagship – Sensor networks
25 June - Virtual-livestock fence: replacing wire with wireless - Gizmag - Virtual fencing
25 June - GPS heralds era of virtual livestock fence - Main Report's Profitable Agri-Business – Virtual fencing
27 June - Rural Report - ABC Gippsland (Sale) - Virtual fencing
26 June - WIN News - WIN Gippsland (Sale) - Virtual fencing
26 June - Remote sensor data for water management - Engineers Australia - WSN and WRON
27 June - Livestock virtually fenced in - Casterton News - Virtual fencing
28 June - Line on computer maps boundaries - Stock Journal - Virtual fencing
28 June - Virtual farming: a new reality - Stock Journal - Virtual fencing
28 June - Plans for fencing - Western Plains Advertiser - Virtual fencing
28 June - Watch out! Martian technology is now here - Monitor Roxby Downs - Virtual fencing
28 June - Plans for fencing - Mortlake Dispatch – Virtual fencingThe project also features in a CSIRO DVD titled 'Creating Impact for Industry' and shown by Geoff Garrett recently at a roadshow in Queensland.

Contact Us

Phone: 1300 363 400
+61 3 9545 2176

Email: enquiries@csiro.au

Web: www.csiro.au

Your CSIRO

Australia is founding its future on science and innovation. Its national science agency, CSIRO, is a powerhouse of ideas, technologies and skills for building prosperity, growth, health and sustainability. It serves governments, industries, business and communities across the nation.