Considerations in Establishing Environmental Sensor Networks

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ABSTRACT
Collecting real-time data at appropriate temporal and spatial scales is critical to understanding complex environmental processes. The emerging generation of ‘smart’ sensors opens up a range of opportunities for automated intelligent monitoring of natural systems. Scientific research and engineering development, requiring extensive cross disciplinary collaboration, is extending the existing monitoring in areas as diverse as marine, rainforest, riparian, lakes, agricultural environments. However the deployment of small energy efficient computers into a dynamic and often hostile situations requires careful planning, redundancy and robust designs. The data itself will contain more noise from an organic environment than an anthropogenic environment and be difficult to interpret statistically but the benefits are likely to alter the method that managers and researchers will interact with the environment. This paper explores the development status and directions of sensor networks designed specifically for environmental monitoring.

1. INTRODUCTION
Emerging technologies offer opportunities for improved monitoring and management of the environment. In particular sensor networks promise a utopia of low cost high frequency data delivered in real time across a range of parameters [1]. The capacity to view the environmental dynamics on the world wide web before deciding on targeted field work is driving the involvement of many environmental researchers to understand this technology. However the reality of emerging technologies means the practical issues of deployment and operation are often critical yet remain secondary to the issues of developing ‘sparkling’ technology. Financial resources that are limited can be easily absorbed by technology that is of minimal assistance to the environmental monitoring professional.

The natural environment is very different in complexity in comparison to the sterile anthropogenic environments. The organic network of interacting agents have a diverse range of life cycles from seconds to centuries within multiple trophic layers. The resulting physical constructions from rainforests to coral reefs are subject to a never ending cycle of changes in the surrounding abiotic matrix. Within this complexity researchers and managers are attempting to address issues based on simplified suppositions. Questions like ‘how is humidity affected by boundary conditions in a rainforest’ or ‘what is the consequence of increased temperature on a coral reef’ require a detailed coupling of modelling and strategic data collection.

At the heart of the environmental monitoring is strategic data collection. To have the data captured at the right moments in the locations that suit spatial statistics is very difficult and rarely achieved. Compromised data sets mean lost opportunities, additional expenses and the potential failure to significantly support or refute a hypothesis. Any mechanisms that can increase the capacity to improve data collection are worth investigating [2].

One new promising technology is sensor networks. This technological package can gather a range of sensory data like temperature and deliver it back to the accessible computer network. With capacity for real time data collection combined with intelligent networking capacity the sensors can be located in the environment quickly and with minimal expense [3]. Initially the solution appears to be magically placed in front of all environmental managers [4]. Scenarios, such as a National Parks Ranger being able to visualise the humidity and temperature fluctuations in real time before initiating a fuel reduction burning activity, have generated high levels of enthusiasm.

Sadly the implementation is not straightforward and requires a practical perspective that this paper will attempt to describe. This is based on experiences at the Australian Institute of Marine Science using sensor networks designed to understand the marine environment [5]. While this paper focuses on the difficulties in making the system optimal this should not detract the reader from understanding that sensor networks are as exciting as they initially appear and will quickly infiltrate the world of environmental monitoring.

2. METHODOLOGICAL REQUIREMENTS
In this section I will focus on some key practical fundamentals that need to be overcome before the sensor network will deliver a basic flow of usable information. I will
not attempt to review the sophisticated research topics of data aggregation, energy efficiency or electronic developments.

Before a sensor network can be deployed there needs to be a clearly articulated set of questions and some basic history of monitoring for that location. This will then prepare the technician and researcher for the environmental dynamics and the corresponding intensity of sampling required. This statistical approach then establishes the scene for the practical implementation. The list of obstacles to overcome for most environmental sensor networks is long despite the high capacity and flexibility of the computing network.

2.1 Destructive environment
The organic environment will, from the first moment of installation, attempt to reduce all electronics to dust. Developing protective housings for the tiny computers and sensors is difficult and costly. Protection against large animals including humans, small insects especially ants, water, sunlight, wind and fouling is required. In our project monitoring marine temperature, the cost of housings ranged from five to fifty times the cost of the sensor network electronics. In order to reduce costs to a minimum we used off the shelf products combined with custom engineered parts. For example to protect and house the string of temperature sensors that extend into the water column we used a braided hydraulic hose that came with standard fittings (figure 1). Allowing for extra stress and strain in the system can be beneficial in the long term.

![Figure 1. The environment rapidly grows on this continually moving sensor buoy placing enormous strain (photo: O. Bondarenko).](image)

2.2 Data analyses and placement
Clearly the focus of deploying a sensor network is not just getting any data stream but one that will statistically support your evaluation of the driving questions. While this makes intuitive sense the reality in being able to capture the data, given spatial and temporal dynamics of the environment, is a major challenge. Sensors need to be deployed in accordance to designated stratified sampling design so that heterogeneity in the observed parameters is recorded. This requires some \textit{a priori} knowledge of the situation but also means that regular monitoring techniques may not be sufficient. For instance to monitor cold water intrusions mixing with a coral reef edge necessitates a series of thermistors strings placed in a clumped manner rather than regularly spaced across the reef edge [6]. The data analysis then assumes the buoys are static while the cold water dynamically moves through the grid. What can be said if the sensors are also moving so that two frames of reference are involved? Experimentation in the sensor time interval, spatial location and the adaptability to an ever changing environment is useful in confidently addressing the questions originally posed.

2.3 Radio transmission range
Possibly the most obvious difference between an environmental application and an industrial one is the range of the radio signals. In the natural environment maximising the radio range is a consuming task. Optimising the short range, that work so well on many commercially available systems, requires additional expertise in antennae design, radio frequencies and battery usage. Mounting high gain antennas on buoys or land based systems creates a new set of problems with wind loading, visual pollution and expenses. We found that to optimise the radio range we had to install antennae with an independent ground plane and increase the distance from the sea water (figure 2). We tried to raise the antennae into the air by one metre (as guided by Bruns’ path loss formula [7]) but this configuration caught the wind and tilted the buoy significantly. To help transmit the data across the 400m of coral reef flat we used a Campbell Scientific RF411 modem (http://www.campbellsci.com/rf411) which has a range of several kilometres. The solution for environmental networks will be a hierarchical approach that sees some nodes with high range capacity servicing the needs of the small clusters of sensors. Ideally if the nodes had the capacity to change their radio power output this would allow networks to be dynamically configured.
2.4 Information security
While the collection and publication of information about public lands is not controversial the application of sensors into private issues of land management can place a high level of pressure to increase confidentiality and security. For instance the collection of data regarding the use and distribution of artesian bores could influence the value of farming properties yet in many respects natural resources, like water, are increasingly being viewed as public assets that demand government regulation. Sensor networks with their simple protocols and broadcast mechanisms would be simple to intercept and misuse. The engagement with stakeholders at an early stage to determine the confidentiality boundaries is clearly a fundamental part of remote sensing. For our marine project we have engaged Debora De Freitas (JCU PhD student) to examine the engagement of coastal managers with sensor networks (see http://www.coastalzone.net/).

2.5 Parameter selection
The options about what sensors can be used to monitor the environment continues to expand [8]. This opportunity can also be distracting as effort is consumed understanding the various properties of each device. For our marine temperature project the time taken to understand how stable, accurate and dependable the Dallas DS18B20 sensors were across a range of temperatures and time periods was extensive. We spent one day alone calibrating 56 sensors over a 6 hour period across a 5 degree range. Utilising multiple sensor types would be difficult. Clearly the future of sensor networks will need a concise and accessible library of metadata about the various sensors. While the specification sheets are informative they do not address many of the specifications that apply to deployment in the natural environment.

2.6 Visual pollution
The small and quiet nature of sensor boards seems to coincide with the need to reduce our impact in the natural environment yet the ability to deploy many sensors raises the issue of visual pollution. Many people do not appreciate observing monitoring devices in national parks while in the farming environment being visible is potentially a key criteria to avoid being disturbed and to indicate the location of monitoring activity. For the marine project we have deliberately kept our systems small and difficult to observe so that despite having numerous sensors in place there is little impact on the coral reef values (figure 3). The downside of this minimal visual impact is that we struggle to locate the buoys in choppy sea conditions.

2.7 Down stream modelling
As the high volumes of data stream into the computer servers the ability to couple these observations with ecological or catchment models becomes critical. In particular the development of real time systems that can interpret and present visualisations of the environment will ensure the sensor network is engaged appropriately. The capacity to offer predictions based on observed trends in real time will make sensor networks invaluable. Our own work in assisting with the timing of plankton sampling based on real time observations will dramatically improve the effectiveness of this type of marine research [9]. A particular issue for ‘high noise’ environments is statistically determining that an event has occurred [10]. Temperature fluctuations across a coral reef is informative about cold water intrusions [11] but to accurately determine if there is such an event automatically can be easier said than done. We need to understand the fine scale temperature patterns before we can fine tune our models to account for duration and size of change.

Figure 2. Modelled radiation pattern of the antenna when placed at different heights above water developed by Eugen Moldovan, Ambient Systems.

Figure 3. Minimal visual pollution for the sensor buoys was important design criteria. The image shows the sub-surface float at very low tide and the floating surface buoy with antennae. The cylume stick was to help us locate the buoy for plankton sampling at night.
2.8 Quality control in real time

Observing the rapid fluctuations in a natural environment in real time can be very useful for environmental management however if there are errors they may be misinterpreted. Understanding how to correctly identify and then adjust for sensors that are faulty or perhaps reduced in their capacity to monitor is very difficult. Unless there is a high level of sensor redundancy in all dimensions the ability to detect a data problem will be complicated. In our marine deployment we replicated each transect and also made the density of sensors such that we can model spatial correlations (figure 4). We also have a complimentary program, eMarine Information Infrastructure (see www.imos.org.au/facilities/emarine.html) that will assist with real time data management.

2.9 Field testing and deployment

One of the major costs in utilising a sensor network is the deployment and maintenance costs. In particular for the marine environment the cost of operating boats can be several times the cost of the sensor equipment. Clearly the minimisation of field work is a necessity in order to satisfy limited budgets (sadly). This raises the issue of field testing with a variety of software and hardware options. For environmental monitoring it is required that the sensor network is constructed and tested before being deployed. However the conditions that the sensors will be operating in are impossible to replicate exactly in the laboratory. We found it was necessary to have a duplicated system in the laboratory that we could test new ideas on rather than expose sensitive electronics to sea water as configurations altered.

3. DISCUSSION

Establishing technology as the principle mechanism for environmental observations will require expertise both in the traditional areas of software and hardware design and also field operations. Experience in deployment and operation of sensor networks will become essential. Understanding radio communications combined with data management and spatial statistics will require a multi-disciplined team approach. A growing body of publications describing field deployments is already assisting with developing a sophisticated approach to using sensor networks. However until a series of long term deployments are adequately described then many practitioners will continue to operate in the research arena. The function of associations like Coral Reef Environmental Observing Network (CREON) and the Global Lakes Environmental Observing Network (see www.coralreefeon.org and www.gleon.org) combined with academic facilities such as the ARC Research Network on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP) provide an essential mechanism to promote sensor network installations.

Our own experience in the marine environment is still relatively immature and our small deployments continually raise new challenges. This paper addresses some of these challenges knowing that unforeseen issues will ensure deadlines are rarely met. However I do not want to leave the reader with a pessimistic view of sensor networks and firmly believe the future of environmental monitoring is with small distributed computers.

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