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WIRELESS SENSOR NETWORKS FOR IN-SITU IMAGE VALIDATION FOR WATER AND NUTRIENT MANAGEMENT

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ABSTRACT:

Water and Nitrogen (N) are critical inputs for crop production. Remote sensing data collected from multiple scales, including ground-based, aerial, and satellite, can be used for the formulation of an efficient and cost effective algorithm for the detection of N and water stress. Formulation and validation of such techniques require continuous acquisition of ground based spectral data over the canopy enabling field measurements to coincide exactly with aerial and satellite observations. In this context, a wireless sensor *in situ* network was developed and this paper describes the results of the first phase of the experiment along with the details of sensor development and instrumentation set up. The sensor network was established based on different spatial sampling strategies and each sensor collected spectral data in seven narrow wavebands (470, 550, 670, 700, 720, 750, 790 nm) critical for monitoring crop growth. Spectral measurements recorded at required intervals (up to 30 seconds) were relayed through a multi-hop wireless network to a base computer at the field site. These data were then accessed by the remote sensing centre computing system through broad band internet. Comparison of the data from the WSN and an industry standard ground based hyperspectral radiometer indicated that there were no significant differences in the spectral measurements for all the wavebands except for 790nm. Combining sensor and wireless technologies provides a robust means of aerial and satellite data calibration and an enhanced understanding of issues of variations in the scale for the effective water and nutrient management in wheat.

1. INTRODUCTION

Water and Nitrogen (N) are critical inputs for wheat production. Judicial application of these inputs is essential for environmentally sustainable and profitable agricultural production. Standard practice is to apply N fertilizers at a uniform rate based on the field level average available soil N or target grain yield (Zillmann et al. 2006). Optimizing the N availability is crucial as N is a vital component for vegetative growth, chlorophyll formation (Gooding and Davies 1997) and grain development in wheat (Wright Jr. 2003). On the other hand, excessive availability of N can heighten the risks of frost damage, foliar disease (Olesen et al. 2003) and can also delay crop maturation (Gooding and Davies 1997). If excessive rates of N are applied, which are not balanced by stored soil water and/or in-crop rainfall, then this can result in moisture stress which in turn results in premature ripening of the crop; referred to as 'haying-off' (Herwaarden et al. 1998). Surplus N application also leads to potential off-farm movement of nitrogen into surface and ground water and can have strong effects on the structure and function of both terrestrial and marine ecosystems like eutrophication (Smith et al. 1999).
Application of the optimal rates of N based on spatial variability of soil conditions at high spatial resolutions could lead to cost effective and environmentally sustainable crop production (LaRuffa et al. 2001). Remote sensing techniques are powerful tools for monitoring spatial variations in crop growth characteristics non-destructively. These techniques are based on the spectral reflectance characteristics of the plant canopy which in turn is dependent on the spatial distribution/orientation of plant leaves and supporting structures, the nature of pigments contained within the individual leaves and internal leaf structure (eg mesophyll arrangements) (Chappelle et al. 1992; Myers 1983).

Nutrient status detection using remote sensing is a relatively new concept, made possible by the development of high spatial and spectral resolution sensors. Over the past few years a number of studies have shown the potential to use remote sensing for the detection of nitrogen status of grains (Haboudane et al. 2002a; Lilienthal et al. 2000; Strachan et al. 2002). These studies have however been unable to resolve the problem of the interacting causes of plant-growth limitation, such as water-shortage and nutrient limitation. A few studies have shown that combining optical narrow band imaging with thermal imaging may provide a solution to this problem (Fitzgerald et al. 2006b; Tilling et al. 2007). These studies demonstrated the utility of hyperspectral and narrow-band multispectral remote sensing techniques, utilizing the canopy reflectance characteristics in wavebands 445, 670, 705, 720, 750 and 790 nm, for the detection of spatial variation in the N status of the crop. Indices such as the Canopy Chlorophyll Content Index (CCCI) (Barnes et al. 2000; Rodriguez et al.

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2006) were proposed as an effective tool for the detection of canopy level N status because it also accounts for changes in canopy N concentration during the season.

There are various methods of acquiring remote sensing data, all of which can be useful to farmers, depending on how the methods fit into their management operations. For example, it is possible to use satellite imagery or mount equipment on a light aircraft, to acquire imagery on-demand, but other means of data acquisition include tractor-mounted sensors for on-the-go sensing that can be used to control variable-rate equipment for precision nutrient inputs. All these approaches require the development of robust algorithms that are applicable across different scales/platforms so as to detect canopy nutrients independent of ground cover, water stress and other factors, such as solar zenith angle. Simultaneous and real-time ground based observations are highly beneficial for formulation and validation of such algorithms incorporating airborne or satellite remote sensing data for application from paddock to regional scale.

Acquiring real-time ground based remote sensing data over a continuous period will enable ground observations to coincide exactly with other scales (airborne and satellite) of data acquisition. Deployment and maintenance of multiple ground based sensors at isolated field sites is a labour-intensive exercise. Development of a wireless sensor network (WSN) is considered as a reliable, efficient and cost effective solution to this problem.

A WSN consists of sensor nodes distributed across a geographic area and each sensor node has wireless communication capability and some level of intelligence for signal-processing and networking of data (Li 2008). A WSN system is comprised of radio frequency (RF) transceivers, sensors, microcontrollers and power sources (Wang et al. 2006). WSN has diverse applications and allows Micro-Electro-Mechanical-System (MEMS) sensors to be integrated with signal-conditioning and radio units to form "motes". A mote is a node in a WSN and normally consists of a processor, radio module and one or more sensors connected to it. This enables motes to acquire data from the sensors, process and communicate with other motes in the network. Motes promote large scale deployment owing their low cost, small size and low power requirement (Akyildiz et al. 2002; Crossbow Technology Inc. 2007; López Riquelme et al. 2009; Wang et al. 2006)

Wireless communication provides enormous flexibility in locating sensor installations, allowing deployment where wired connections are impractical or impossible. The ease with which widely spread sensors can be arranged results in significant reduction in the cost of data acquisition by avoiding installation and maintenance of costly transmission lines. This has led to a myriad of uses of this technology in diverse fields. WSNs have the potential for widespread application in precision agriculture, particularly in the areas of crop and irrigation management, variable rate chemical input application and modeling crop performance (López Riquelme et al. 2009).

A mobile field data acquisition system was developed (Gomide et al. (2001) in Wang et al. 2006) to collect data for crop management and spatial-variability studies. A ZigBee[TM] / Institute of Electrical and Electronics Engineers, IEEE 802.15.4 (Baronti et al. 2007; IEEE 2003) wireless acquisition device network was established (Morais et al. 2008) for monitoring air and soil temperature, solar radiation and relative humidity for precision viticulture applications. Radio modules IEEE 802.15.4 (IEEE 2006) were used in motes in the formation of wireless network for monitoring soil moisture, water quality and environmental conditions. Vellidis et al. (2008) developed and evaluated a real time, smart sensor array using Radio Frequency IDentification (RFID) tag for irrigation scheduling.

Studies involving integration of hyperspectral or narrow band multispectral sensors into WSNs for real time monitoring of crop spectral characteristics are very limited. These data sets have been shown to be highly successful in monitoring chlorophyll content (Gitelson and Merzlyak 1994; Haboudane et al. 2002b; Penuelas et al. 1994), light use efficiency (Trotter et al. 2002), N status (Filella 1995; Fitzgerald et al. 2006a; Tarpley et al. 2000; Tilling et al. 2007) and disease conditions (Bravo et al. 2003; Devadas et al. 2009; Moshou et al. 2005). In this context, an experiment was carried out to establish a WSN, integrating seven narrow band sensors (470, 550, 670, 700, 720, 750, 790 nm), critical for real time monitoring of N and water stress in crops (Fitzgerald et al. 2006a; Tilling et al. 2007). By establishing this WSN, the project aims to record *in-situ* ground based remote sensing data concurrently with aerial and satellite image acquisition. Airborne imagery at various spatial scales will form the bridge between ground and satellite remote sensing data. Through these simultaneously acquired remote sensing data from different spatial scales within a sampling framework, this project will attempt to quantify issues of scaling up-linked to the mapping of N and water stress in wheat. This paper illustrates the outcome of the first phase of the experiment involving instrumentation set up and analysis of spectral data recorded by the WSNs.

2. MAIN BODY

INSTRUMENTATION

Instrumentation set up involved three main steps: 1) sensor development, 2) sensor integration with motes and, 3) establishment of the wireless network.

2.1 Development of Sensor System

The primary component of the sensor system was a combined silicon photo detector and optical interference filter (T-5) (Intor, Inc., NM, USA). The filters were 8.4mm in diameter by 7.07mm high. The seven specific filters had central wavelengths of 470, 550, 670, 700, 720, 750 and 790 nm with 10 nm bandwidths.

These optical filters were assembled into a custom designed light sensor multiplexer and amplifier board (Figure 1).
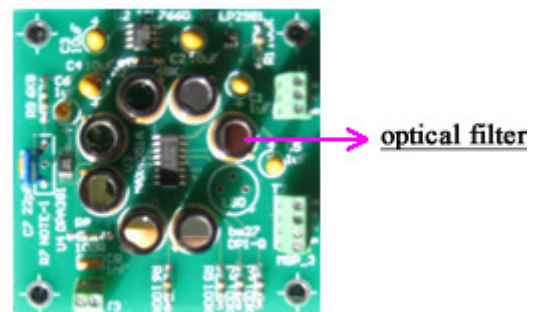

Figure 1. Fully assembled sensor board. One of the seven optical filters is indicated in the figure.

2.2 Housing of Sensor Boards and Calibration Set up

To derive reflectance measurements directly, two sensor boards were designed for each node. One was directed upward, to

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measure incoming radiation and the other one looked downward, to measure reflected radiation. This design enabled direct estimation of reflectance values for the specified bands as ratio of reflected to incoming radiation.

Both sensor boards were bolted to poly vinyl chloride (PVC) endcaps. For the downward looking sensors, a PVC pipe of 0.23m long with 0.10m diameter was attached to the endcaps, creating a 26° field of view (Figure 2). For the upward looking sensor boards, a PVC pipe of 0.04m was fitted to generate a field of view of 100°. The open or sensing ends of both the pipes were closed and sealed with 4mm thick flat Delrin (Polyoxymethylene), a polyplastic engineered to facilitate the diffusion of electromagnetic radiation and minimization of angular reflection effects.
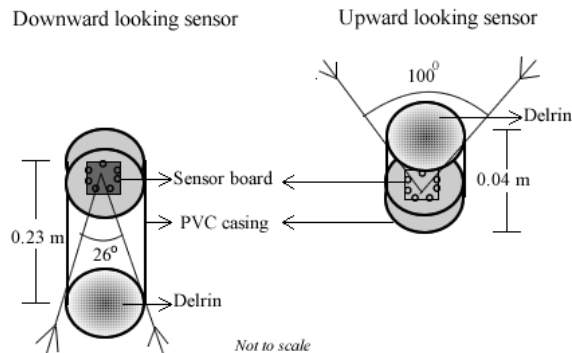

Figure 2. Structure of sensor board mounting with PVC tubes for downward and upward looking sensors.

Each sensor pair was calibrated using 99% reflectance Spectralon (Labsphere, NH, USA) reference panels measured with an Analytical Spectral Devices (ASD) FieldSpec® spectroradiometer (ASD, Inc., CO, USA).

2.3 Sensor Integration with Mote

Data collection, conversion and transmission were achieved using MICA2 wireless motes (Crossbow Technology), operating at an RF frequency of 433 MHz, interfaced to an MDA 300 analogue to digital converter board (Crossbow Technology). The motes were programmed with a version of Xmesh (Crossbow Technology Inc. 2007; Tiny 2009) software (Crossbow Technology) specific for the MDA300 A/D board. The standard Xmesh software was modified and customized (Dragonnorth Pty Ltd, Needham, MA, USA) to provide control of the sensor board used to coordinate the acquisition of readings from the seven sensors on two heads through tow data acquisition channels. A 6V sealed lead acid battery provided power for both the sensor boards and the mote

The network was routed through a gateway consisting of a MICA2 mote connected to a MIB510 serial interface board in turn connected to a laptop computer running the Xserve data acquisition software (Crossbow Technology). The stored data was accessed and the network was managed using the MoteView (Crossbow Technology) as the client.

Broadband connection of the local server to the Internet was provided using a CDM882-SEU wireless router (Call Direct, Sydney, AU) using the Next G network (Telstra, Melbourne, AU).

2.4 Establishment of Wireless Network

Establishment of the wireless network and real-time data acquisition involved 3 software tiers: 1) *Mote layer*- sensor

nodes were connected to form a multi-hopping mesh network and a gateway node forwards data messages into and out of the mesh, 2. *Server layer*- facilitated translation and buffering of data from the wireless mesh network and forms the bridge between the wireless motes and the internet clients, and 3. *Client layer*- provided the user visualization software and graphical interface at PC terminal for managing the network.
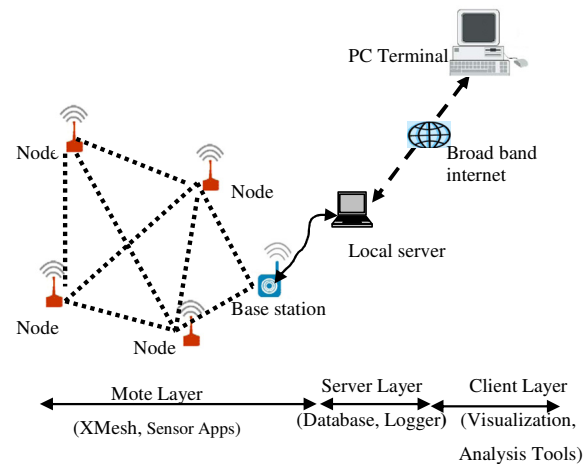

Figure 3. Software and hardware framework for establishment of wireless network.

2.5 Field Installation

For field (ground) installation, sensors were attached to square (width: 3.5mm) base steel poles, such that the sensors were positioned circa 2m above the soil surface (Figure 4). This configuration created a 0.9m diameter footprint, for the download looking sensor with the 26° field of view (FOV), allowing 4-5 rows of crop to be sensed.
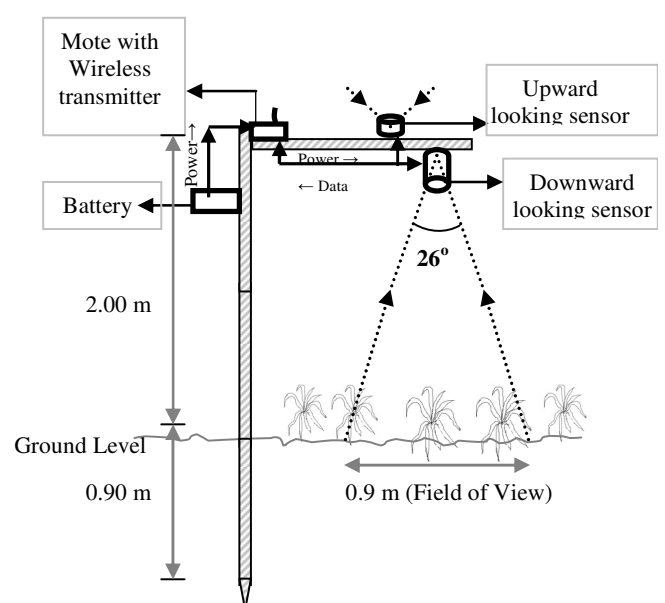

Figure 4. Design of wireless sensor field unit. A voltage regulator in the battery case provides 3V input power to mote box and 6V power to two sensor boards through a terminal board in the mote box.

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The metal frames for attaching the sensors were comprised of three parts, one was inserted into the soil and the other two parts were erected above ground, one fitting inside the other to reach the 2m height. This enabled the above ground sections with sensors to be detached from the lower frame for relocation to other sample locations leaving the base poles in the ground throughout the crop season, out of the way of agricultural field equipment, such as tractors. This design provided the capability to deploy a large number of base poles inserted in the sample locations defined based on four different sampling strategies (Figure 5). This provided the flexibility to change sensor unit locations to accommodate the various sampling strategies without the need to install mounting points when sensors were moved.

The cost of each sensor unit was estimated to be A$1687 (in 2009 dollars).

Ninety sample positions were identified that encompassed the four sampling strategies in a wheat paddock in Inverleigh, Victoria, Australia (144° 2' 30" E and 38° 8' 10" S, Figure 5). Rapid static and Real Time Kinematic Global Positioning System (RTK GPS) surveys were undertaken to establish the position of the sample points to a x-y accuracy of +/-2cm. Positions were in GDA94/MGA94. The four sampling strategies were devised to facilitate the deployment and operation of 20-25 sensor units at a time. Base poles were inserted in these ninety locations.

In the first phase of the experiment in 2009, 14 sensor units were operational and data were recorded from *systematic pattern* locations, during the winter crop season from July to December.
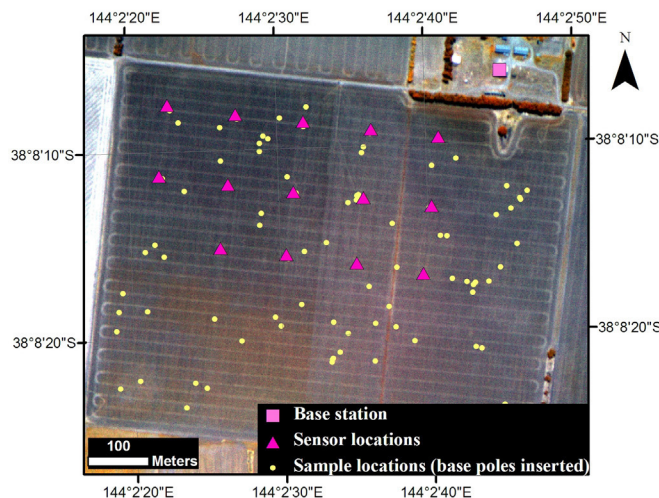

Figure 5. Aerial image of the study site showing the sensor locations.
Yellow dots indicate the 90 sample locations with base poles inserted. These locations were determined based on 4 sampling strategies. The triangles indicate the locations of the 14 functioning sensor units in 2009, which followed a systematic sampling pattern. Square symbols indicate the locations of the base station to which all the motes sent data messages. The aerial image shown here consists of three narrow bands, 790, 720 and 670 nm which are projected as red, green and blue, respectively.

DATA COLLECTION AND ANALYSIS

Wireless remote sensing data collection was observed and monitored through *MoteView* Graphical User Interface (GUI). Sensor nodes were tested for running in two different power modes for understanding the data relay efficiency and battery consumption in these configurations.

In this first phase of the experiment, 14 wireless sensors were introduced during different periods of the crop season, once they were assembled and tested. During this stage, priority was given to calibration of the sensors and analysis of the data quality in comparison with other hyperspectral sensors.

Ground-based hyperspectral data was collected using ASD FieldSpec® spectroradiometer (ASD, Inc., CO, USA) from the same locations as those of the wireless sensor units. The ASD data was integrated based on the bandwidth and central wavelength corresponding to that of WSN and two data sets were compared (Figure 6).
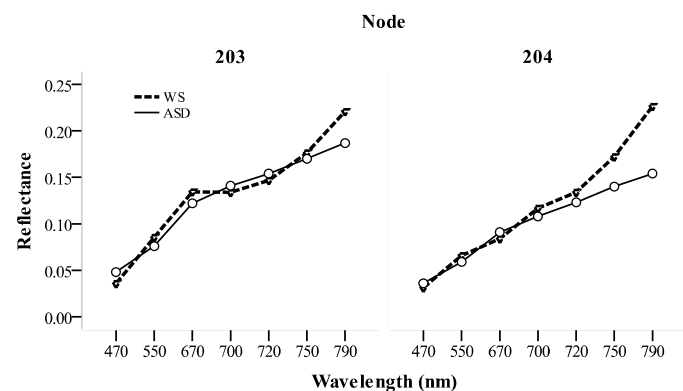

Figure 6. Comparison of the WSN and ASD data at 4 different locations. Sensor locations are represented here as node numbers, which were assigned during the mote board programming.

Comparison of data from WSN and ASD clearly indicated that both sensors followed similar trends in monitoring crop characteristics (Figure 7).
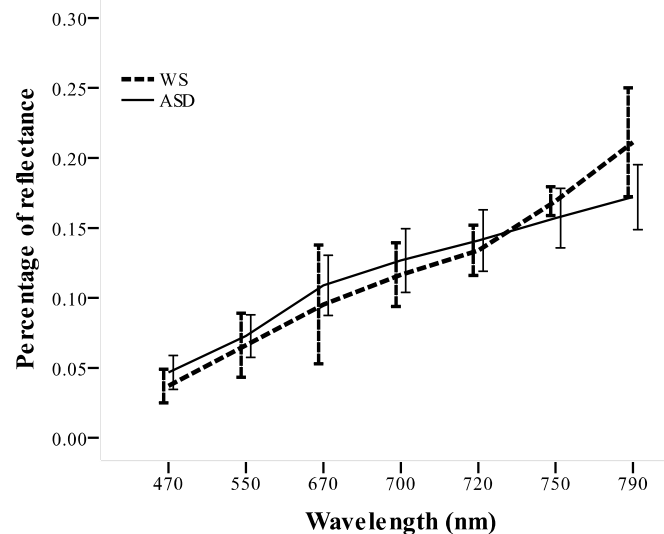

Figure 7. Comparison of mean percentage of reflectance for different wavelengths for the hyperspectral data recorded using WSN and ASD.
Error bars indicate 95% confidence interval.

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Further, Analysis of Variance (ANOVA) between spectral data from WSN and ASD for all the seven wavelengths were carried out. Analysis showed that there were no significant differences in the spectral measurements for all the wavebands except for 790nm. At the 790nm wavelength, the WSN data were significantly higher ($p <= 0.05$) compared to the ASD data. Estimated standard error value for the wavelength 790nm was 0.101 where for the rest of the wavebands it varied from 0.0033 to 0.0075 (Table 13).

Wavelength (nm)	Standard Error
470	.0033
550	.0046
670	.0075
700	.0047
720	.0045
750	.0044
790	.0101

Table 1. Standard error in percentage of reflectance between WSN and ASD for different wavelengths.

Analysis of the data obtained from the WSN clearly indicated the possibility of employing such sensor network for observing crop spectral characteristics, concurrent with airborne and satellite data acquisitions.

3. CONCLUSIONS

This paper has presented the first of phase of the experiment aimed at the development of a WSN for real time acquisition of spectral data for *in-situ* calibration and validation of aerial and satellite images. Comparisons were made with standard in situ field-based verification technology (ASD FieldSpec® spectroradiometer) and WSN. Data analysis showed that the WSN can record spectral data with reliable quality continuously for a reasonably long period of time. WSN is unique with its ability to control the acquisition of a real-time spatially distributed field data set from an office computing system. The capability of the WSN to operate with minimum disturbance to its surroundings (i.e. with high finesse, minimizing perturbation of the variable of interest) brings enormous flexibility of deployment. The technology is cost effective as it reduces the need for logistically expensive field visits.

In the next phase of the project, spectral data from different platforms/scales and crop biophysical data could be utilized for the formulation of robust algorithms for effective and real-time monitoring of N and water stress in crops. The study will also attempt to compare different sampling strategies for optimization of mapping of crop spectral characteristics at paddock level. This experiment is a part of larger Australian calibration and validation processes of satellite data products, under the Terrestrial Environmental Research Network AusCover (Jones et al. 2010).

Acknowledgment

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