Computers and Electronics in Agriculture 141 (2017) 27–34

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Multi-modal sensor system for plant water stress assessment

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ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form 7 July 2017
Accepted 10 July 2017

Keywords:
Water stress
NDVI sensor
Multispectral camera
Canopy temperature
Thermal imager
IR thermometer
Apple tree

ABSTRACT

Plant stress critically affects plant growth and causes significant loss of productivity and quality. When the plant is under water stress, it impedes photosynthesis and transpiration, resulting in changes in leaf color and temperature. Leaf discoloration in photosynthesis can be assessed by measurements of leaf reflectance changes and leaf temperature changes in transpiration can be identified by thermography. To address these physiological properties, a multi-modal sensing system was developed and evaluated for a rapid, automated scouting of plant stress status in an apple orchard with irrigated and dry trees. The multimodal sensor system was installed on a mobile vehicle and includes an IR thermometer array, a thermal imager, a multispectral camera, and two sets of NDVI sensors with a digital camera and an ultrasonic range finder. Soil water status was continuously monitored using soil moisture sensors that were installed at the 15-cm depth for both irrigated and dry trees. A low-cost solution of canopy temperature sensing was developed using an IR thermometer array and validated to substitute the thermal imager with the advantage of rapid 2-D thermal mapping at up to 10 Hz. An NDVI sensing system was developed to enhance filtering process of the background noise signals by supplemental assistance from a digital camera and a range finder. NDVI responses and 2-D thermal maps were created while driving and recorded weekly for 7 weeks during the growing season. The experimental results identified significant difference of canopy temperature (2.6 °C) and NDVI (0.235) between the irrigated and dry trees and supported further development of low-cost real-time system for decision support of plant stress detection and management.

1. Introduction

Plant stress caused by biotic or abiotic factors adversely affects plant growth and significantly reduces the yield and quality of tree fruits. Severity of damage for plant stress depends on the duration between onset and time of detection. At the orchard level, the effectiveness of any remedial measures demands the timely detection and identification of the cause of stress, as well as the timely application of appropriate interventions. The overall goal in this thematic area is to develop a multimodal sensing system for detection of plant water stress to facilitate rapid, automated scouting of apple orchards.

Plant stress detection has been widely studied by using remote sensing of plant spectral signature such as canopy reflectance and temperature. The canopy reflectance is light energy reflected off the plant canopy in visible (VIS) and near-infrared (NIR) spectral range of 400–1500 nm, whereas leaf temperature is light energy emitted from the thermodynamic bodies of leaf surface in the thermal infrared (TIR) spectral range of 3–15 μm. The healthy plant absorbs the VIS light, carbon dioxide (CO_2), and soil water (H_2O) to drive the photochemical reactions of photosynthesis generating oxygen (O_2) and glucose ($C_6H_{12}O_6$). When the plant is under water stress, however, it closes stomata and impedes photosynthesis and transpiration, resulting in changes in leaf color and temperature (Nilsson, 1995). Leaf temperature changes in transpiration can be identified by thermography (Martin, 2009) and leaf discoloration in photosynthesis can be assessed by measurements of leaf reflectance changes of increase in VIS and decrease in NIR (McMurtrey et al., 1994; Suarez et al., 2009). Those reflectance differences in two bands are used to calculate (NIR − VIS)/(NIR + VIS) known as a normalized difference vegetation index (NDVI) and have been used for many remote sensing applications using multispectral cameras and active spectral sensors.

Prior studies reported the estimates of plant water stress by measuring canopy reflectance (Perez-Priego et al., 2005; Sonmez et al., 2008; Takayama et al., 2008). Shimada et al. (2012) used narrow-band reflectance at 490 nm and 620 nm for water stress detection with the highest correlation of 0.86. The highest

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http://dx.doi.org/10.1016/j.compag.2017.07.009
0168-1699/

correlation to water stress was reported with red edge NDVI in narrowband indices and NDVI in broadband indices for apple trees (Kim et al., 2011), green NDVI for sweet corn (Genc et al., 2013), and red edge NDVI for pear orchard (Van Beek et al., 2013). Although these studies proved the concept and potential use of spectral sensing, improvements are still required, for example, to cope with background noise signals from non-vegetation area.

Canopy temperature has been widely investigated to correlate with the plant water stress and measured by using thermal imagery (Nagy, 2015; Naor, 2008; Sepulcre-Canto et al., 2006) and infrared thermometer (Evans et al., 2000; Fuchs, 1990; Wang and Gartung, 2010). Nagy (2015) deployed a thermal imager in an apple orchard and identified 1.85 °C higher in the non-irrigated tree than the irrigated tree. Glenn et al. (1989) examined stomatal responses on peach trees by assessing canopy temperature. Wang and Gartung (2010) measured canopy temperature for postharvest deficit irrigation treatments on early-ripening peach trees. Canopy temperature was measured for water management in other orchard crops for olive trees (Ben-Gal et al., 2009), grapevine (Moller et al., 2007), and almonds and walnuts (Udompetaikul et al., 2000). Thermal sensing was also used for disease (Calderon et al., 2015; Oerke et al., 2011) and pathogen (Stoll et al., 2008) detection on orchard trees. Calderon et al. (2015) measured the normalized canopy temperature for early detection of verticillium disease on olive trees using aerial remote sensing at orchard scale and found overall accuracy up to 79%. Stoll et al. (2008) reported the potential for pre-symptomatic diagnosis of the fungal pathogen (*Plasmopara viticola*) with the result of higher leaf temperature in the infected tree on the irrigated grapevines. Ni et al. (2015) demonstrated leaf temperature of maize could reflect variations in the physiological state of plants during early water stress. Although prior studies on thermal sensing have shown potentials for plant water stress, there is a difficulty to implement this technology for rapid sensing in large-scale plant production systems due to the operational limitations of the thermal imager and the thermometer, as the thermal imager is implemented in a static mode in order to capture a focused still image of the target, whereas the thermometer delivers only a point data in narrow FOV.

The objectives of this study are to develop and evaluate a multimodal sensing system for plant water stress detection using canopy reflectance and temperature and identify low-cost solutions of on-the-go in-field plant sensing system. Specific objectives are to (1) evaluate the spectral response of a multispectral camera, (2) develop an NDVI sensing system capable of noise filtering, (3) evaluate the canopy temperature response of a thermal imager, and (4) develop a low-cost on-the-go 2-D thermal mapping system.

2. Materials and methods

The multimodal sensor system was installed on an autonomous prime mover (APM) (Workman, Toro) with extended support pipes and positioned to aim side view of the tree canopy (Fig. 1). The sensor system includes a thermal imager (ThermoVision A40, FLIR Systems, Sweden), a multispectral camera (ADC Lite, Tetracam, Chatsworth, CA), an infrared (IR) thermometer (MLX90614, Parallax, Rocklin, CA) array, and two sets of NDVI sensors (GreenSeeker, NTech Industries, Ukiah, CA) with a digital camera (Dragonfly 2, Point Grey Research, Scottsdale, AZ) and an ultrasonic range finder (MB7060, MaxBotix, Baxter, MN). An adjustable vertical array of the IR thermometers was used to increase the spatial resolution of canopy thermal distribution and charaterize the different canopy structure of each tree. The APM also carries a GPS receiver (18x PC, Garmin, Olathe, KS) mounted on the center top of the guard rail to support the future use of on-the-go geo-referenced sensing and field mapping. Fig. 2 illustrates the diagram of the sensor integration and data flow.

Soil water status was also monitored by soil moisture sensors (Watermark, Irrometer, Riverside, CA) that were installed at a 15-cm depth for both irrigated and dry trees. The multispectral camera and thermal imager acquired images on a static mode and were used as references for the NDVI sensor and IR thermometer array, respectively, that run on a continuous mobile mode.

2.1. NDVI sensor with camera and range finder

The NDVI sensor measures a NDVI value that is calculated from a line scan of active spectral signals reflected off the canopy surface which may include non-vegetation areas between trees along the driving path. A new NDVI sensing system was designed to accommodate target tree variations in orchard trees by integrating a digital camera and a range finder that assist filtering invalid NDVI data based on canopy coverage and target distance. The digital camera was used to measure the canopy coverage within the sensor's scan line and filter out invalid NDVI when the coverage is below a set point. The distance between the sensor and the target surface is another source of noise and was measured by the ultrasonic range finder to remove invalid NDVI when the target distance is beyond a valid standoff distance. Those supplementary camera and range finder must be carefully aligned with the FOV of the NDVI sensor for synchronized measurements.

An algorithm was developed to employ color images and target distance to validate canopy presence within the valid range of the NDVI sensor in order to improve the accuracy of NDVI measurements of the canopy. A hardware mount was designed to attach

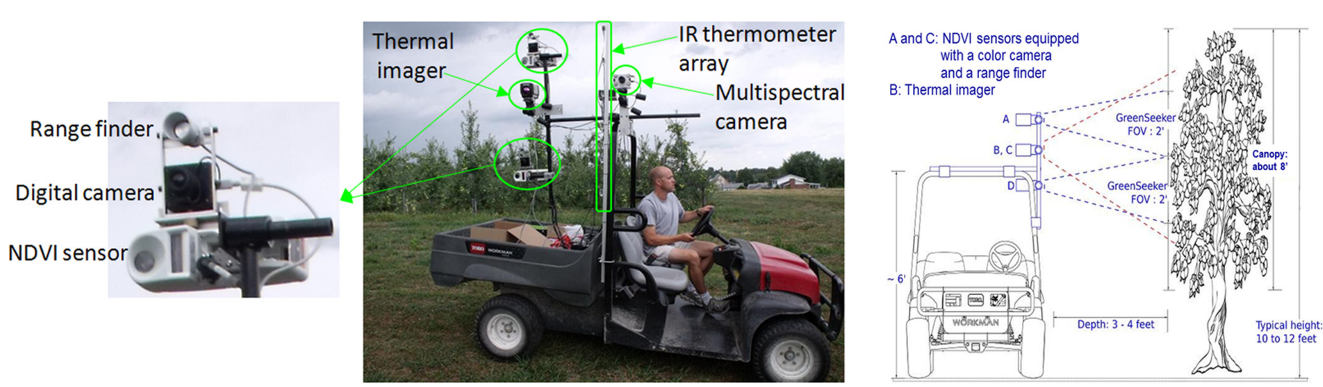

Fig. 1. Multimodal sensor system mounted on the APM for field experiment (August 11 – September 24, 2010) to evaluate plant stress detection by measuring canopy temperature and reflectance.