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Imaging from an unmanned aerial vehicle: agricultural surveillance and decision support

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Abstract

In September 2002, NASA's solar-powered Pathfinder-Plus unmanned aerial vehicle (UAV) was used to conduct a proof-of-concept mission in US national airspace above the 1500 ha plantation of the Kauai Coffee Company in Hawaii. While in national airspace, the transponder-equipped UAV was supervised by regional air traffic controllers and treated like a conventionally piloted aircraft. High resolution color and multispectral imaging payloads, both drawing from the aircraft's solar power system, were housed in exterior-mounted environmental pressure pods. A local area network (LAN) using unlicensed radio frequency was used for camera control and downlink of image data at rates exceeding 5 Mbit s^{-1}. A wide area network (WAN) allowed a project investigator stationed on the US mainland to uplink control commands during part of the mission. Images were available for enhancing, printing, and interpretation within minutes of collection. The color images were useful for mapping invasive weed outbreaks and for revealing irrigation and fertilization anomalies. Multispectral imagery was related to mature fruit harvest from certain fields with significant fruit display on the tree canopy exterior. During 4 h "loitering" above the plantation, ground-based pilots were able to precisely navigate the UAV along pre-planned flightlines, and also perform spontaneous maneuvers under the direction of the project scientist for image collection in cloud-free zones. Despite the presence of ground-obscuring cumulus cloud cover of ca. 70% during the image collection period, the UAV's maneuvering capability ultimately enabled collection of cloud-free imagery throughout

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most of the plantation. The mission demonstrated the capability of a slow-flying UAV, equipped with downsized imaging systems and line-of-sight telemetry, to monitor a localized agricultural region for an extended time period. The authors suggest that evolving long-duration (weeks to months) UAVs stand to make a valuable future contribution to regional agricultural resource monitoring.

Keywords: Unmanned aerial vehicle; Pathfinder-Plus UAV; Multispectral imaging; Local area network; Ripeness monitoring; Weed mapping; Fertigation; Coffee

1. Introduction

Agriculture is becoming an increasingly knowledge-based industry in response to economic and environmental considerations. To help meet the need for observational data, aircraft and satellite remote sensing is playing an expanded role in farm management (e.g., LeBoeuf, 2000; Lu et al., 1997; National Research Council, 1997). However, many crop monitoring and damage assessment applications are highly demanding with respect to such key image acquisition and processing aspects as temporal frequency (1–3 days revisit) and product delivery time (1–24 h turn-around) (Moran et al., 1997). At the same time, spatial resolution requirements are driven by the growers' minimum management unit, which can be on the order of 1–10 m. Knowledge-based agricultural approaches are intended to increase farming efficiency, enhance profitability, lessen environmental impacts, and are expected to drive further technological innovation (Snyder et al., 1999; Johnson et al., 2001).

One potential beneficiary of remote sensing is the coffee production agribusiness segment. Coffee is one of the most valuable primary commodities worldwide. Traditionally, the crop has been cultivated on small (<50 ha) farms where repeated hand picking is the standard harvesting procedure. There is now a global trend toward larger-scale production on plantations exceeding 200 ha, using mechanical harvesters. These vehicles proceed over each row of coffee trees with an array of flexible rotating spokes. Coffee "cherries" are mechanically dislodged, collected, and transported to a sorting and processing mill. Generally, only a single pass is made through each field. As a result, critical decisions and irreversible actions are made on the basis of field ripeness assessments.

Coffee blossoms do not appear and develop uniformly throughout a plantation. The resulting fruit thus tends to ripen at different times, with spatial and temporal trends that are difficult to track and predict (Wormer, 1964; Cannell, 1975). Due to variations on individual trees as well as in different sections of a field, mechanical harvesting yields a mixture of unripe, ripe, and overripe fruit in varying proportions (Reddy and Srinivasan, 1979; Cannell, 1985). Ripe fruit has the highest value, followed by overripe and then unripe. To maximize value, crop ripeness stage is a main consideration of harvest managers (Watson, 1980; Willson, 1999). Managers typically rely on repeated manual cherry counts made by field scouts and taken on a few sample branches within each field. Without removing the fruit, the scouts visually sort cherries on each branch by ripeness category to estimate field-level percentages. Harvesters are then dispatched to those fields with the greatest estimated percentage of mature (ripe and overripe) cherries.

Another important and costly aspect of coffee production and harvest is weed proliferation. Weed eradication, which is required to maintain crop yield, poses significant production and environmental costs. With crop heights generally exceeding 2 m and between-row alleys generally difficult to negotiate, field interiors are not readily viewed or mapped from the ground. Large weeds in the form of grasses and vines can significantly slow the harvesting process, and thus adversely affect the overall schedule, as they become entangled in the harvest mechanisms and require machine down-time for extraction.

Water and nutrient availability are key production factors for coffee, as for most other crops. With regard to US production in Hawaii, rainfall can be limiting in the drier growing regions including southern Kauai, where supplemental irrigation is required. Fertilizer is required to replace substantial quantities of nutrients lost to harvest (Bittenbender and Smith, 1999).

Thus, there are several crop management aspects that might benefit from airborne observation. Unmanned aerial vehicle (UAV) platforms are evolving rapidly from technical and regulatory standpoints. Various different UAVs offer design and performance advantages over conventional photo-reconnaissance aircraft, such as small size, low weight, slow flight speed, extended range, extreme altitude, and extreme endurance. It is likely that UAVs will begin to offer new alternatives for agricultural and other users needing high spatial resolution imagery delivered in near-real time. The purpose of this study was to demonstrate safe operation of a slow-flying, long endurance UAV for remote sensing in US national airspace, while acquiring, enhancing, and distributing high-spatial resolution digital imagery for commercial agricultural decision support.

2. Methods

2.1. Study area

The Kauai Coffee Company is located on southern Kauai (Hawaii) at 21°55′N, 159°35′W (Fig. 1). The company operates the largest coffee plantation in the US, producing more than

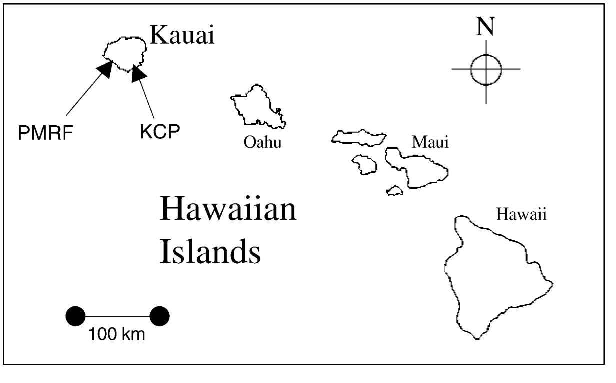

Fig. 1. Site map, showing locations of the KCP and the US Navy PMRF, which served as aircraft operations base.

half of all coffee grown in the USA. Occupying nearly 1400 ha, the Kauai coffee plantation (KCP) is one of the largest drip-irrigated coffee plantations in the world. The plantation encompasses over 40 fields, each of which is subdivided into 5–20 separate blocks. The blocks are typically further subdivided into fertigation (fertilizer applied through irrigation) zones. The primary cultivar grown is yellow catuai (*Coffee arabica* L. cv. Yellow Catuai), which displays green cherries when underripe, bright yellow when ripe, turning to dark yellow or brown when overripe. Mechanical harvesting is performed 24 h a day by a fleet of Korvan Model 9200 vehicles (Korvan Industries Inc.).

2.2. Aircraft

NASA’s Pathfinder-Plus UAV was used as an image collection platform. Pathfinder-Plus is a light-weight flying wing equipped with eight solar-electric motors (Table 1). The aircraft is an enlarged version of the initial Pathfinder UAV, which in 1997 established a world altitude record (ca. 21 km) for propeller-driven aircraft. During a subsequent, lower-altitude mission, NASA demonstrated the use of Pathfinder for image collection with multispectral and hyperspectral digital imagers over land areas and coastal zone waters (Hammer et al., 2001; Dunagan et al., 1998). Test flights of Pathfinder-Plus in 1998 established a new altitude record at ca. 25 km. The high-altitude test flights were conducted within special-use airspace of the US Navy’s Pacific Missile Range Facility (PMRF), located on western Kauai.

The main attraction of this class of aircraft for certain monitoring and surveillance missions is their slow flight speed (generally $<50\,km\,h^{-1}$, depending on wind conditions) and hence their ability to loiter over localized areas for extended time periods. Currently, these periods are measured in terms of hours, but ongoing development of an on-board energy storage system may eventually allow extreme endurance flights lasting from weeks to months. It is anticipated that life-cycle costs for these types of aircraft will be among the lowest in the UAV industry (Morgan, 1996).

Our UAV mission occurred on 30 September 2002. The aircraft, ground-based pilots, and associated flight support crew were based at PMRF. The mission was performed under the auspices of a Certificate of Authorization issued by the US Federal Aviation Administration. The UAV was equipped with a transponder and its incursion into national airspace above

Table 1
Pathfinder-Plus UAV specifications

Specification	Description
Owner	NASA
Manufacturer	AeroVironment, Inc. (Monrovia, CA, USA)
Materials	Carbon fiber, Nomex, Kevlar, plastic sheeting, plastic foam
Motors	Eight (8) solar-electric, 1.5 kW max each
Wing span	36.3 m
Wing chord	2.4 m
Gross weight	318 kg
Payload capacity	67.5 kg
Airspeed	ca. $9\,m\,s^{-1}$ (wind dependent)
Endurance	ca. 15 h (daylight limited) + 5 h battery backup
Altitude ceiling	ca. 25 km

the KCP was monitored by Honolulu air traffic controllers. Total flight time was 12 h, and time on-station above the KCP was 4 h (11:30–15:30 Hawaiian Standard time). On-station flight altitude was 6.4 km above ground level.

2.3. Payload

Two complementary digital camera systems were configured for remote operation within the weight (68 kg) and power (500 W, solar generated) limitations of the UAV. A color high-resolution camera was used to collect images for qualitative interpretation and mapping, while a narrow-band multispectral imager was used for quantitative analysis of canopy color in relationship to crop ripeness. Both cameras provided 8-bit radiometric resolution, giving digital counts (DCs) of range 0–255 per channel.

A Hasselblad 555ELD camera body and lens, equipped with a Kodak Professional DCS Pro Back with a 4000×4000 CCD array, was used for high spatial resolution imaging. Using a color filter array, each pixel element was exposed to red, green, or blue light; automated software interpolation was subsequently performed to generate a full three-band color image. A 100 mm lens provided a 20.3° field of view in both the cross- and along-track dimensions. Spatial resolution was 0.5 m at flight altitude.

A DuncanTech MS3100 camera was used for multispectral imaging. A single lens and dichroic prism directed incoming light onto three separate 1280 by 1024 CCD arrays to provide true multi-band imagery. The arrays were co-registered to better than one-half pixel throughout. Narrow-band trim filters were inserted in front of each CCD array, giving channel centers at 760 nm (channel 1), 660 nm (channel 2), and 580 nm (channel 3). A Nikon 35 mm lens provided an 8.5 by 10.6° field of view. Spatial resolution was 1 m at flight altitude.

The cameras were housed in lightweight, thermostatically controlled pressure pods, each fitted with a $10\,\text{cm} \times 10\,\text{cm}$ anti-reflection coated window (Fig. 2). Table 2 shows the final specifications for payload volume, gross weight, and power consumption. Spectralon™ reflectance panels were used under solar illumination to determine appropriate gain and exposure settings for the expected range of vegetation canopy reflectance (0–25% in the visible region, 0–60% for near-infrared), and also to verify instrument response linearity. A flat-field test was performed with a laboratory integrating sphere to characterize sensor vignetting. Each pod was attached to the central section of the airframe (Fig. 3) and integrated into the UAV's power system.

2.4. Command and control

The Kodak data system incorporated a commercial off-the-shelf design approach involving use of the Windows XP (Microsoft Corp.) operating system. A micro AT motherboard

Table 2
Payload specifications

System	Volume (m^3)	Weight (kg)	Power (W)
Kodak/Hasselblad	0.04	17	75
DuncanTech	0.05	13	125

Fig. 2. DuncanTech pod attached to underside of Pathfinder-Plus UAV wing.

computer system incorporating an integrated drive electronics disk interface, IEEE 1394 high speed serial camera interface, and on-board Ethernet were used. Kodak DCS Camera Manager software was used for image acquisition in either manually triggered or automatically timed mode. Other system components included a data logger for recording local

Fig. 3. Pathfinder-Plus UAV in flight over Kauai on 30 September 2002. Cameras are housed in environmental pods suspended near wing center.

temperature, pressure, and relative humidity, a serial-to-Ethernet converter, and an Ethernet hub. The operator interface used a combination of commercial and custom software to enable remote access to the flight computer by wireless Ethernet, and remote execution of vendor software for camera and data logger operation.

The DuncanTech operator interface was built on the Red Hat Linux v6.2 operating system. A menu-driven interface was used, requiring transfer of only a few ascii characters for instrument control. The data acquisition program included subroutines for image assembly, hard disk access, systems health monitoring, quick-look image evaluation histograms, and camera configuration. An algorithm was developed to automatically trigger image acquisition at prescribed distance intervals along flight lines. Data system hardware architecture included an industrial grade single-board computer with on-board SCSI disk controller, Ethernet, and serial devices, mated to a PCIMG^{TM} passive backplane. Additional peripheral component interconnect slots expanded the serial communications capacity, provided a dual networking option, and interfaced to a commercially available frame-grabber (Imaging Technology PCDig) operating under a custom-developed device driver.

A wireless, line-of-sight local area network (LAN), based on commercially available hardware, was configured for camera control and data download (Fig. 4). The hardware configuration for both cameras was identical, each with an Aironet 342 (Cisco Corp.) bridge radio located inside the pressure pods and interfaced to the data system by Ethernet. The 100 mW output of the bridge was amplified to 1 W and broadcast through omni blade antennas mounted in the bottom of the pods. To avoid cross-talk interference, the bridges

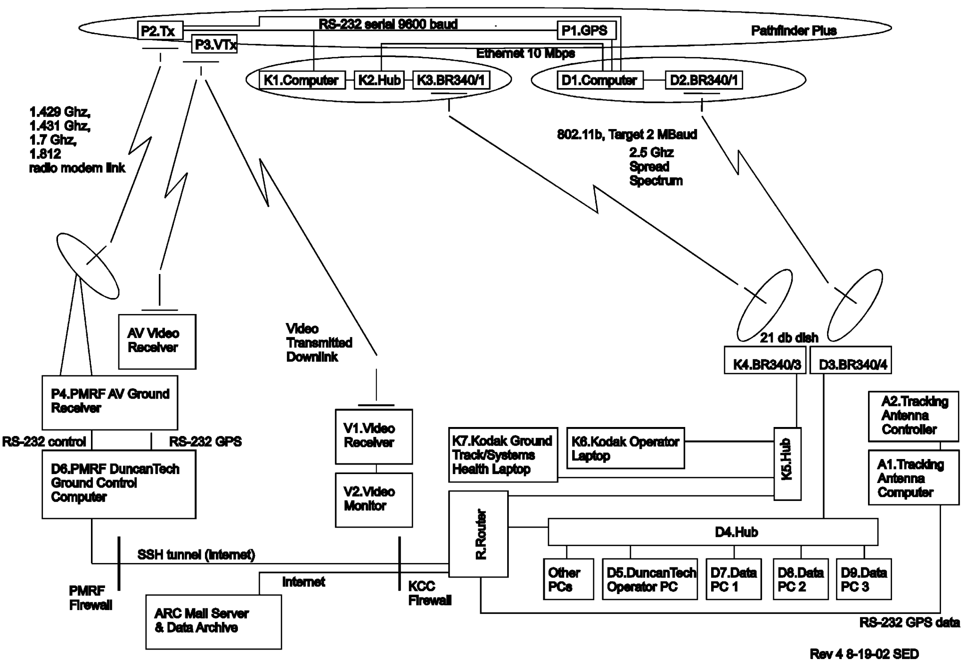

Fig. 4. Network and communications diagram.

were configured to operate at opposite ends of the unlicensed IEEE 802.11b frequency spectrum, with the Kodak set to channel 1 (2.412 GHz center frequency) and the DuncanTech to channel 11 (2.462 GHz). Each ground system used an Aironet bridge radio attached to a 21 db gain dish antenna. Both antennas were mounted on a single tripod and a computer controlled azimuth-elevation tracking device was used to continuously point the dishes at the aircraft. Prior tests over Kauai with a conventional twin-engine aircraft had demonstrated successful broadband (11 Mbit s^{-1}) connectivity between a rapidly moving (ca. 300 km h^{-1}) airborne LAN and ground station (Herwitz et al., 2002a,b).

During the image acquisition period, payload command and control aspects were controlled from a ground station established at the KCP headquarters, approximately 30 km from PMRF. The ground station computing exclusively used Pentium-class desktop and laptop platforms. All payload-related activities were coordinated with the US Federal Communications Commission and PMRF frequency control.

A wide area network (WAN) was established to enable UAV tracking and longer-range DuncanTech command and control. Tracking was performed deterministically using airborne GPS data collected by a receiver within the DuncanTech system. These data were sent by point-to-point protocol (PPP) radio link to the PMRF aircraft ground station. Here, the RS232 serial data were encapsulated into IP (internet protocol) packets, and transmitted over the WAN through an encrypted tunnel to the KCP payload ground station computers. The packets were then decapsulated, re-converted to serial format, and pointing instructions were sent by wire to the tracking antennas. The WAN employed encrypted communication protocols exclusively, allowing secure remote DuncanTech control from areas far beyond the reach of the LAN.

2.5. Kodak processing

Downlinked Kodak images were converted from native DCR to TIF format with the Kodak Photodesk software. This rendering process applied a proprietary interpolation algorithm to assign red, green and blue color information to each pixel in the frame. The higher priority frames were brightness- and contrast-enhanced with Adobe Photoshop and printed on photographic quality paper. Selected hardcopy frames were available for qualitative interpretation within 5 min of image capture.

2.6. DuncanTech processing

Several fields tentatively scheduled for harvest in the two-week time period following the UAV mission were selected for ripeness analysis. Corresponding DuncanTech image frames were selected for examination based primarily upon the extent of clear sky. Each selected frame was registered to a high-altitude aerial photographic basemap by manual selection of a set of 6–9 ground control points. A 3-band mosaic was then generated from the geo-registered frames. In order to reduce potentially confounding influences, a “masking” routine was applied to the mosaic to set pixel values, recorded as digital counts, associated with cloud, soil, and shadow to zero. The masking rules were as follows. First, any pixels with channel 3 (ch3) DC greater than 150 were assigned to cloud. Second, a vegetation index (VI) was calculated per pixel by combining the red and near-infrared channels as $[(\mathrm{ch1} - \mathrm{ch2})/(\mathrm{ch1} + \mathrm{ch2})]$. To retain the output in byte format, the observed V values (VI_{obs}) were scaled to the range 0–255 as $(VI_{obs} - VI_{min}) * 255/(VI_{max} - VI_{min})$ based on the image global maximum and global minimum VI. Generally, higher VI values are associated with vegetation and lower values are associated with soils and other non-vegetated targets (Tucker, 1979). Scaled VI values less than the global mean (here, $DC < 130$) were assigned to soil. Third, pixels with ch1 DC less than the global mean ($DC < 95$) were assigned to shadow. In this way, only directly illuminated canopy pixels remained. A spectral index was calculated for each unmasked (non-zero) pixel based on relative brightness of channels 2 and 3, for comparison with yield data. Specifically, the ch3/ch2 ratio was calculated to correct for multiplicative brightness differences related to solar zenith angle. A polygon layer of digitized field boundaries was digitally superimposed on the spectral index mosaic and the mean index value per field was calculated and extracted.

2.7. Harvest data

Yield data routinely collected by the grower were used to evaluate the image processing methodology for ripeness monitoring. As the harvest progressed, the grower measured parchment weights (coffee seeds encased in endocarp) yielded by each field. Mechanical sorting by the mill allowed the grower to track and assign ripeness level to parchment. Weights per ripeness level were divided by total yield to derive per-field percentages.

3. Results and discussion

3.1. System performance

The UAV climbed to altitude within PMRF-controlled airspace, and transitioned to national airspace above southern Kauai and the KCP. At this time, regional air traffic controllers seamlessly integrated the UAV into routine traffic monitoring operations. After 4 h on-station, the UAV returned to PMRF airspace for descent and landing. No safety or performance anomalies were noted by the aircraft operators during the 12 h flight. Both cameras performed successfully throughout the mission. About 50 Kodak and 300 DuncanTech scenes were acquired over the KCP, totaling in excess of 2 GB of image data.

Maximum observed operating range of the wireless LAN telemetry link was 29 km line-of-sight, where image data downlink rates of 3–4 Mbit s^{-1} were achieved. Best system throughput (5 Mbit s^{-1}) was achieved with the aircraft flying tangential to the antenna at a range of 5–10 km. Slightly degraded connectivity was evident with the UAV positioned directly above the payload ground station, due to a local null in the remote omni antenna transmission pattern. All images, in addition to being stored on the hard disks of the flight computers, were transmitted over the LAN while the aircraft was on-station. During the latter part of the flight, while the UAV was not on-station, the DuncanTech camera was fully controlled over the WAN link by a project investigator located 4000 km away on the US mainland.

Fig. 5. Portion of Kodak frame showing outbreak of exotic weed *Panicum maximum* (guinea grass) within several coffee blocks (field sub-sections). Area shown ca. 15 ha.

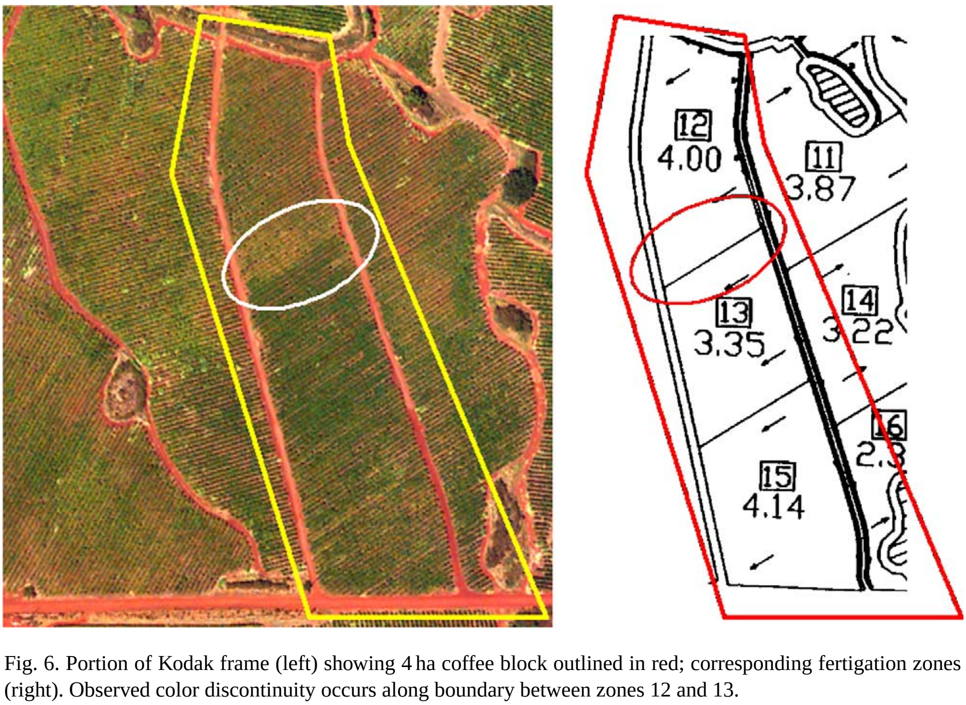

Fig. 6. Portion of Kodak frame (left) showing 4 ha coffee block outlined in red; corresponding fertigation zones (right). Observed color discontinuity occurs along boundary between zones 12 and 13.

As is typical of conditions encountered in subtropical and tropical regions, low-altitude cumulus clouds persistently obscured an estimated 70% of the sky above the KCP while the UAV was on-station. The UAV exhibited the ability to accurately negotiate pre-planned flightlines during the first hour of the time window. The project scientist then activated a contingency plan whereby the pilots spontaneously maneuvered the UAV to cloud-free zones, as revealed by monitoring of on-board video feeds. This combination of strategies, combined with the UAV's loitering capability, ultimately enabled collection of cloud-free imagery over about 75% of the plantation.

3.2. Information extraction

The high-resolution Kodak imagery was immediately useful for mapping outbreaks of guinea grass (*Panicum maximum*) within coffee fields (Fig. 5). This exotic (African) weed is yellow–green in color and was visually separable from darker green coffee trees. This imagery also showed differences in overall ground cover within fields. Some of these patterns were due to the presence of vines (*Ipomoea triloba*, *Canavalia cathartica*) growing on the trees. Along with guinea grass, these vines are a costly hindrance that can affect the amount of time required to mechanically harvest the field. Also, the weeds can spread quickly from one year to the next if left unchecked. Other apparent ground cover differences were related to crop vigor, generally due to problems or inconsistencies in fertigation delivery (Fig. 6).

A spectral index derived from visible bands of the DuncanTech imagery was positively related to the percent mature cherries from seven study fields harvested post-flight ($r^2 = 0.81$, $P < 0.01$) (Fig. 7). These results raise the possibility of using image-based approaches to evaluate field readiness levels during the harvest period. It should be noted that in order to maintain productivity and manageability, coffee trees are severely pruned every 4 to 5 years. For approximately two years after pruning, the tree tops are leafy and conceal the fruit below. During this initial regrowth period we would not expect an image-based approach, as adopted here, to be of value for ripeness determination. The fields selected for this analysis were beyond this initial period and were amenable to remote observation due

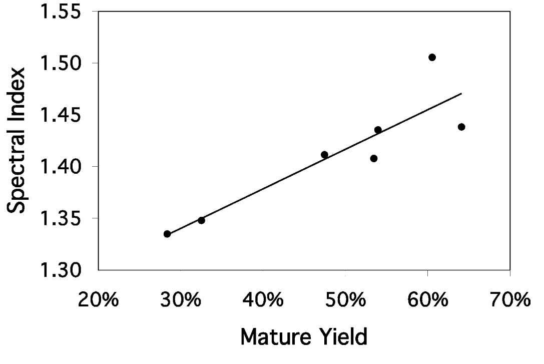

Fig. 7. Spectral index (ch3/ch2) derived from DuncanTech multispectral imagery, vs. percent mature cherries harvested from fields within 2 weeks of overflight.

to their comparatively sparse top-of-canopy leaf display and significant fruit display on the canopy exterior.

4. Conclusions

UAVs are expected to play an expanded role, complementary to that of satellites and conventionally piloted aircraft in agricultural support (e.g. Allen et al., 1999). Satellites are useful platforms for regional to global data acquisition, yet remain limited in their ability to provide imagery of adequate spatial and temporal resolution for many aspects of commercial agriculture. Conventional reconnaissance aircraft can overcome many of these problems, yet they are hindered by fuel limitations and pilot fatigue. Slow-flying UAVs, such as Pathfinder-Plus can essentially act as atmospheric geostationary satellites, providing high resolution, near-real time imagery for localized regions over extended time periods. In our demonstration, the capability to loiter for several hours was highly useful from the standpoint of cloud-cover avoidance. For scientific analyses, a loitering platform may be used to characterize diurnal variations in earth surface reflectance, such as from plant canopies. Food security monitoring is another application that may require essentially constant surveillance of specific localized targets, and would stand to benefit from evolving extreme duration platform capabilities.

Under mass production and operation, solar-powered UAVs may become cost-competitive with existing airborne assets. For instance, fabrication costs may be lower than those of conventional aircraft, while operating costs for fossil fuel and on-board crew are avoided. Depending on the degree of autonomy involved, it may be possible for a single ground-based pilot, located virtually anywhere on the globe, to monitor several platforms and payloads simultaneously. Imagers might be combined with other payloads, such as telecommunications or atmospheric samplers, to further reduce cost. As an additional advantage over highly capital-intensive satellite systems, long endurance UAVs can periodically return to base for maintenance of platform and payload. Additional research and development is needed in the following areas: UAV on-board energy storage, remote sensing payload miniaturization, WAN telemetry bandwidth (for enhanced data download), autonomous image data analysis, and improved air traffic avoidance capabilities.

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References

Allen, J.C., Kopp, D.D., Brewster, C.C., Fleischer, S.J., 1999. 2011: An agricultural odyssey. American Entomologist 45 (2), 96–104.

Bittenbender, H.C., Smith, V.E., 1999. Growing coffee in Hawaii. College of Tropical Agriculture and Human Resources, University of Hawaii.

Cannell, M.G.R., 1975. Crop physiological aspects of coffee bean yields: a review. Journal of Coffee Research 5, 7–20.

Cannell, M.G.R., 1985. Physiology of the coffee crop. In: Clifford, M.N., Willson, K.C. (Eds.), Coffee: Botany, Biochemistry and Production of Beans and Beverage. Croom Helm Ltd., Kent, UK, pp. 108–134.

Dunagan, S.E, Hammer, P.D., Slye, R.E., Smith, W.H., 1998. In: Proceedings of the 1998 International Geoscience and Remote Sensing Symposium Interferometric Imagery from a Solar-powered RPV, IEEE, Washington, DC, pp. 645–647.

Hammer, P.D., Johnson, L.F., Strawa, A.W., Dunagan, S.E., Higgins, R.G., Brass, J.A., Slye, R.E., Sullivan, D.V., Smith, W.H., Lobitz, B.M., Peterson, D.L., 2001. Surface reflectance mapping using interferometric spectral imagery from a remotely piloted aircraft. IEEE Transactions on Geoscience and Remote Sensing 39, 2499–2506.

Herwitz, S.R., Leung, J.G., Higgins, R.G., Dunagan, S.E., Arvesen, J.C., 2002a. Remote command-and-control of imaging payloads using commercial off-the-shelf technology. In: Proceedings of the 2002 International Geoscience and Remote Sensing Symposium, IEEE, Washington, DC.

Herwitz, S.R., Johnson, L.F., Arvesen, J.C., Leung, J.G., Dunagan, S.E., 2002b. Precision agriculture as a commercial application for solar-powered UAVs, In: Proceedings of the First AIAA UAV Conference, American Institute of Aeronautics and Astronautics Inc., Reston, VA.

Johnson, L.F., Bosch, D.F., Williams, D.C., Lobitz, B.M., 2001. Remote sensing of vineyard management zones: implications for wine quality. Applied Engineering in Agriculture 17, 557–560.

LeBoeuf, J., 2000. Practical applications of remote sensing technology—an industry perspective. HortTechnology 10, 475–480.

Lu, Y., Daughtry, C., Hart, G., Watkins, B., 1997. The current state of precision farming. Food Reviews International 13, 141–162.

Moran, M.S., Inoue, Y., Barnes, E.M., 1997. Opportunities and limitations for image—based remote sensing in precision crop management. Remote Sensing of Environment 61, 319–346.

Morgan, R., 1996. Unmanned Aerial Vehicles as Low Cost Science Platforms, Congressional testimony before House Aeronautics and Space Subcommittee, 17 April.

National Research Council, 1997. Precision Agriculture in the 21st Century. National Academy Press, Washington, DC.

Reddy, G.S.T., Srinivasan, C.S., 1979. Variability for flower production, fruit set and fruit drop in some varieties of *Coffea arabica* L. Journal of Coffee Research 9, 27–34.

Snyder, C., Havlin, J., Kluitenberg, G., Schroeder, T., 1999. Evaluating the economics of precision agriculture. In: Proceedings of the Fourth International Conference of Precision Agriculture, Part B, ASA-CSSA-SSSA. Madison, WI, pp. 1621–1632.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment 8, 127–150.

Watson, A.G., 1980. The mechanisation of coffee production. In: Proceedings of the Ninth International Coffee Research Conference, London, pp. 681–686.

Willson, K.C., 1999. Coffee, Cocoa and Tea. Crop Production Science in Horticulture Series No. 8, CABI Publishing, Oxford, UK.

Wormer, T.M., 1964. The growth of the coffee cherry. Annals of Botany 27, 47–55.