Design of an automated cart and mount for a hyperspectral imaging system to be used in produce fields

Alan M. Lefcourt, Ross Kistler, S. Andrew Gadsden

Design of an automated cart and mount for a hyperspectral imaging system to be used in produce fields

Alan M. Lefcourt[a*], Ross Kistler[a,b], S. Andrew Gadsden[b]
[a]USDA Agricultural Research Service, Beltsville, MD, USA 20705; [b]University of Maryland, Baltimore County (UMBC), Baltimore, MD, USA 21250

ABSTRACT

The goal of this project was to construct a cart and a mounting system that would allow a hyperspectral laser-induced fluorescence imaging system (HLIFIS) to be used to detect fecal material in produce fields. Fecal contaminated produce is a recognized food safety risk. Previous research demonstrated the HLIFIS could detect fecal contamination in a laboratory setting. A cart was designed and built, and then tested to demonstrate that the cart was capable of moving at constant speeds or at precise intervals. A mounting system was designed and built to facilitate the critical alignment of the camera's imaging and the laser's illumination fields, and to allow the HLIFIS to be used in both field and laboratory settings without changing alignments. A hardened mount for the Powell lens that is used to produce the appropriate illumination profile was also designed, built, and tested.
Keywords: automated cart, fluorescence imaging, food safety, produce, hyperspectral imaging, fecal materials

1. INTRODUCTION

Food-borne illness is an ever-present problem in American society. According to the Center of Disease Control and Prevention, food-borne illness is responsible for the hospitalization of 128,000 Americans and 3000 American deaths each year (2). Of the 9.6 million annual incidents of food-borne illness in the United States, 2.2 million (22%) are attributed to leafy-green produce (10). Leafy green produce can be contaminated prior to harvest, and one of the most common sources of contamination is fecal material (3). To reduce the risk of food-borne illness, current practice is to have produce fields inspected by workers for fecal material and signs of animal intrusion before harvest (1). The goal of this project is to develop an autonomous system to augment this current practice.

CALGMA recommends a pre-planting and pre-harvest assessment be performed to check for fecal material or signs of animal intrusion. Signs of animal intrusion include damaged produce, evidence of feeding, fur, feathers, animal tracks, and other signs of animals in sufficient quantities. Problem sites are marked and nothing within a designated distance of the site is harvested (1).

The Environmental Microbial and Food Safety Laboratory (EMFSL) has developed methods that use fluorescence responses to detect fecal materials (4-9, 11). One method is laser-induced fluorescence and time-resolved hyperspectral line-scan imaging (11). To use this laboratory system in produce fields, a field deployable mounting system and a motorized cart are needed. The goals of this study are modify the imaging system for field use, to develop a motorized cart, and to design and build a system to mount the imaging system on the cart. Again, the purpose of this new apparatus will be to detect feces in produce fields.

2. METHODOLOGY

An existing laboratory-based imaging system the used a pulsed UV laser of fluorescence excitation and an ICCD camera for gated image acquisitions was modified for field use. A cart is developed to serve as a vehicle for transporting the imaging system through produce fields. An optics mounting system is designed and built that allows the imaging system to be calibrated in the lab and then moved directly to the cart for immediate use.

2.1 Imaging System

Images are acquired using a gated, intensified, camera (iStar; Andor Technologies, Belfast, UK) with a minimum gate width of less than two ns, 1024 x 1024 pixels, 16-bit resolution, and responsivity in the visible wavelengths through the very near infrared (fig. 1, 2). The camera is thermoelectrically cooled to -20 °C and incorporates a digital delay generator that is used to control image acquisitions. After enabling an image acquisition, an image is acquired after a programmed

Sensing for Agriculture and Food Quality and Safety VIII, edited by Moon S. Kim, Kuanglin Chao, Bryan A. Chin,
Proc. of SPIE Vol. 9864, 98640R · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2229493

delay following input of a pre-lase trigger signal. For hyperspectral, line-scan, imaging a spectral adapter (ImSpector V9; Specium, Oulu, Finland) is inserted between the camera and a fixed focus lens (M2514-MP2 2/3" 25mm F1.4; Computar, Tokyo, Japan). Images are acquired using a program written in Visusl Basic Version 6 (Microsoft, Seattle, WA) and an SDK (Andor Technologies), are corrected for dark current, and saved in either 16-bit TIF or ENVI formats (11).

Illumination for fluorescence excitation is provided by a frequency-tripled Nd:YAG pulsed laser (~6 ns pulse width; Ultra 100 THG WS MVAT, Quantel USA, Bozeman, MT, USA). The laser power supply (ICE450) generates a TTL signal pulse 100 ns prior to the Q-switch trigger. The 355-nm laser has a maximum pulse rate of 20 Hz and a maximum energy of ~31 mJ per pulse, and includes an attenuation module programmed using a serial interface. A Powell lens with a fan angles of 30° (Powell, 1987; 8.9 mm lens dia. for 4 mm beam dia., BK7 glass, Laserline Optics Canada, Osoyoos, BC) is used to convert the Gaussian energy profile of the laser beam into a line illumination source more appropriate for use with line-scan imaging. To address spillover from the 532-nm intermediate wavelength and possible back-reflection from the expansion optics, a 4 mm iris and a 355-nm laser window tilted 5° from the optical axis (Techspec 1/20λ high-power laser-line window, Edmund Optics Inc., Barrington, NJ, USA) are inserted between the laser and the Powell lens. The expansion optics are mounted in standard 1/2" lens tubes. The Powell lens is mounted in a rotation mount (CRM05, Thorlabs, NJ, USA) after first inserting the lens into a hole drilled into the center of a threaded plug (SM05PL, Thorlabs). The rotation mount allows the angle of the illumination profile to be adjusted to match the field of view of the hyperspectral adapter. Offsets are addressed by adjusting the position of the camera relative to the laser.

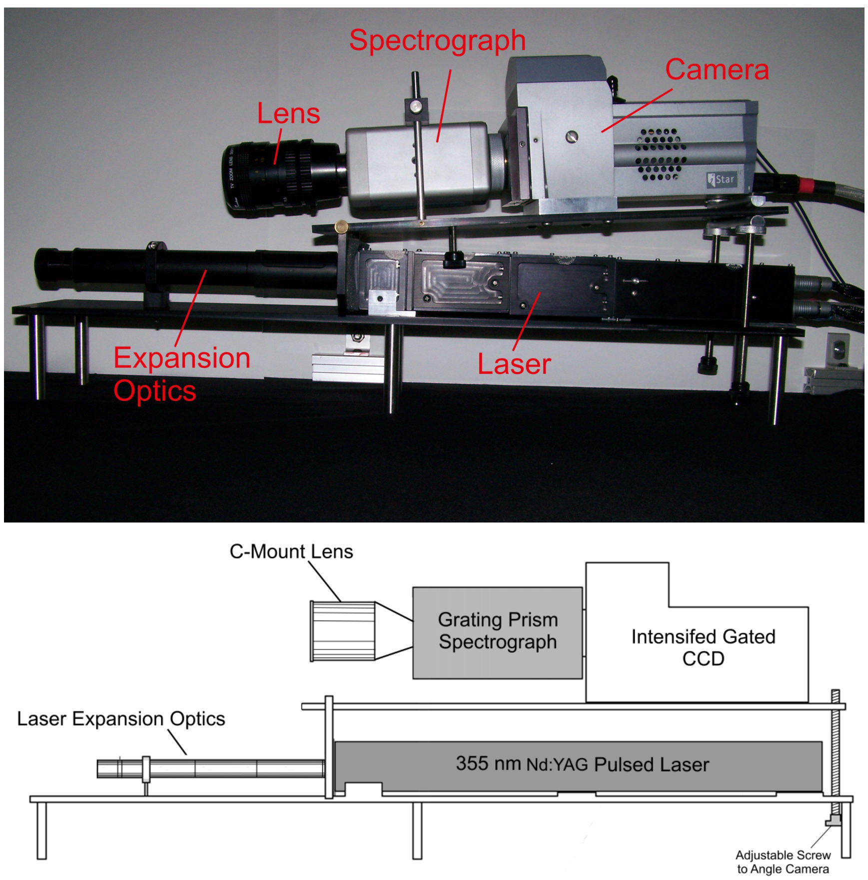

Figure 1. Laboratory based hyperspectral, laser-induced fluorescence, line-scan imaging system.

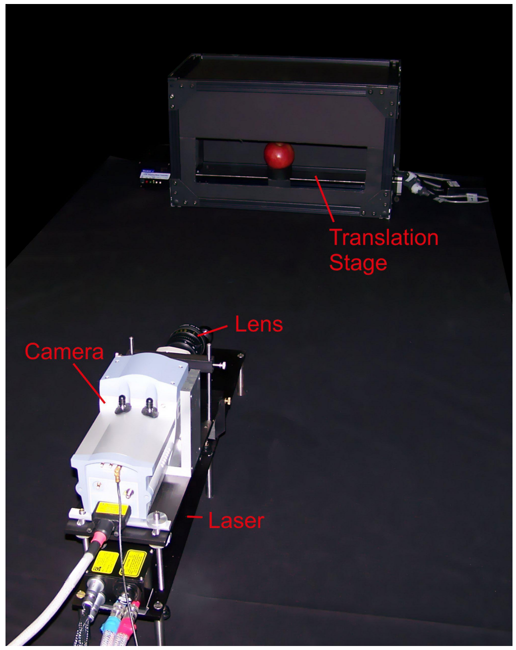

Figure 2. As hyperspectral data is acquired using line-scan images, a translation stage is used to incrementally move objects in front of the system. For field use, the imaging system will be mounted on a cart that moves through produce fields.

2.2 Cart

The cart was built using 40 mm by 40 mm black anodized aluminum extrusions and standard fastening components (Parker Hannifin Corporation, 2005). Requirements for cart operation are that the cart can be programmed to proceed either at a continuous speed with a maximum speed of .5 m/s or in incremental steps with a minimum step size of 5 mm. To address these requirements, individual stepper motors (AR98MK-PS36-3, Oriental Motor U.S.A. Corp, Braintree MA) are used to independently power the front two wheels. A single controller (EMP Series Programmable Motion Controller, Oriental Motor U.S.A Corp) connected to the two motor drivers allows motor functions to be addressed using ASCII commands and a serial connection. Motor mounts (SPL-9SB, IndustrialeMart, Mundelein, IL) are used to attach the motors to the cart frame; PPB8 pillow block housings and 1/2" steel shafts are used to attach the 6.25" dia. wheels (6" Traction Tires with VersaHub, VEX Robotics, Greenville, TX). Drive connections between motors and wheels use 15 tooth sprockets sized for the stepper motor’s 18 mm shaft diameter, 22 tooth wheel sprockets, and ANSI 35 roller chains. A 24 VDC 5 Amp Power Supply (PSB24-120S, AutomationDirect, Cumming, GA) is used to power the motors and the control electronics. All electronics are mounted on a DIN rail in a waterproof enclosure (Attabox Polycarbonate Enclosure Clear Cover, 18” x 16” x 10”, Attabox, Jacksonville, TX). Cart movement is controlled using a laptop computer and a program written in Visual Basic Version 6 (Microsoft).

2.3 Optics Mounting System

Constraints for the optics mounting system include the ability to transfer mounted imaging components between the laboratory and the cart without need for realignment, and preservation of alignments when the optics system is subject to vibration associated with the cart moving through produce fields. These constraints were addressed by using a single 1/4" thick aluminum platform to mount both the laser and the camera. This solution required determination of the optimal offset and angle between the camera and laser. A program was written that considers the fan angle of the Powell lens, the field of view of the camera lens, the distance of the mounting system from the ground, the maximum height of the crop, and the angle of the mounting system relative to the vertical axis.

3. RESULTS AND DISCUSSION

Imaging techniques and systems developed by the Environmental Microbial and Food Safety Laboratory have used both continuous-wave and pulsed-laser UV illumination sources (4-9, 11). The use of laser-induced fluorescence imaging was chosen for field use due to the sensitivity of the method for detecting fecal material against a background that includes plants (11), the ability to detect fluorescence responses in full daylight, and the ability to use the technology to model potential responses of less costly and less sophisticated imaging techniques. Fluorescent responses are ubiquitous in areas subject to sunlight; however, the responses are masked by reflected energy from sunlight. The energy in short-term (~20-40 ns) fluorescence responses to high-energy laser pulses is magnitudes greater than comparable energy found in sun light at the response wavelengths. Use of a gated, intensified, camera allows these short-term responses to be imaged; thus, allowing information related to the fluorescence response, including measures of the decay characteristics of the response, to be captured regardless of the intensity of ambient illumination.

There were two major problems with the previous generation of the laboratory LIF systems with regard to field use. First, a complex gimbals mount system with 6-degrees of freedom was originally used to align the Powell lens with the laser beam. This mount system was replaced by a system where the lens is mounted in a lens tube with a fixed location for the center of the lens. The only degree of freedom is the rotational position of the lens. This new mount reduces the possibility of changes in alignment with movement and field use. Figure 3 is an example of the illumination field provided by the Powell lens expansion optics that demonstrates the uniformity of the illumination profile in terms of line-scan imaging.

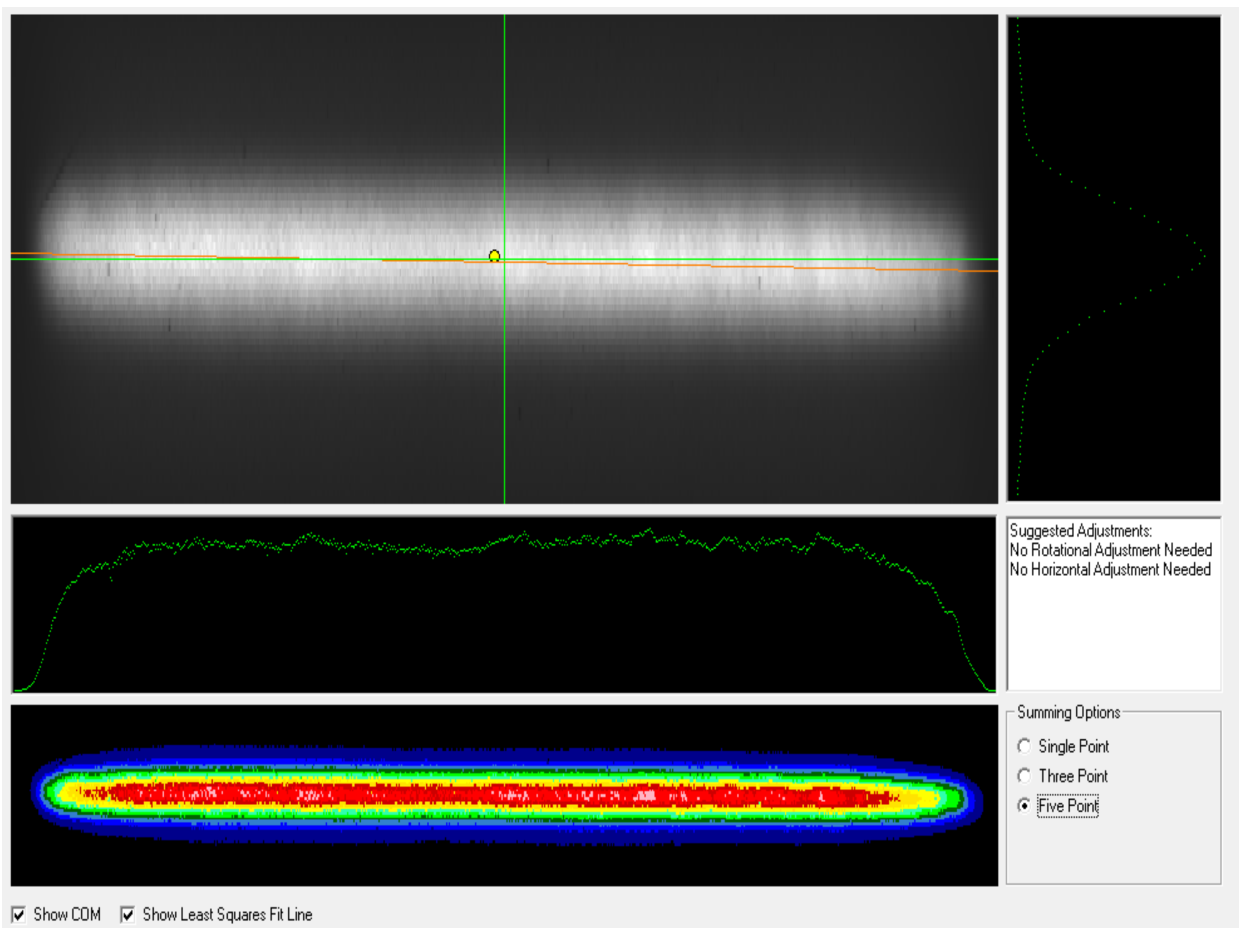

Figure 3. The bottom figure shows a false color image of the illumination profile for single laser pulse using the Powell lens. The five point average across the center of the profile that is displayed immediately above the false color image demonstrates the uniformity of the profile.

The second problem with the laboratory system was the sensitivity of offset adjustments for the position of the camera relative to the laser that allowed alignment of the illumination and imaging fields. The solution adopted to address this problem is discussed in the section below that deals with the optics mounting system.

3.1 Cart Design

Stepper motors were used for propulsion to enable the cart to be moved incrementally as well as at a fixed speed. With incremental movements, the optics system can be programmed to take a series of images at each step. The ability to acquire sets of images allows comparison of the efficacy of selected imaging techniques and methods under identical, real world, conditions. The downside is that it can take many seconds to take large numbers of images at each step. The selection of the motors actually used was based on torque calculations. Figure 4 shows the torque curves for the motors selected along with the estimate torque needed to initiate motion.

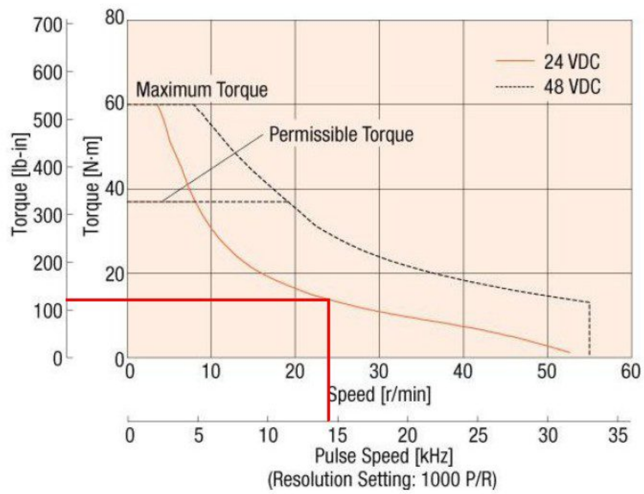

Figure 4. Torque-Speed chart for stepper motor, red line indicates the maximum torque the stepper motor can produce at 22.33 rev/min when powered by 24 VDC.

The cart was constructed using aluminum beams and a plywood platform for supporting instrumentation (fig.5). The motor drive is shown in figure 6. The vertical support for the optics components can be positioned forward of the plywood platform as desired. The current concept is that the cart will proceed down crop rows autonomous and then be repositioned to the next row manually. Steering is accomplished by changing individual motor speeds. With two wheel drive, only small changes in direction can be easily accomplished. The design allows the cart to be modified for four-wheel drive if more complex control of steering is needed.

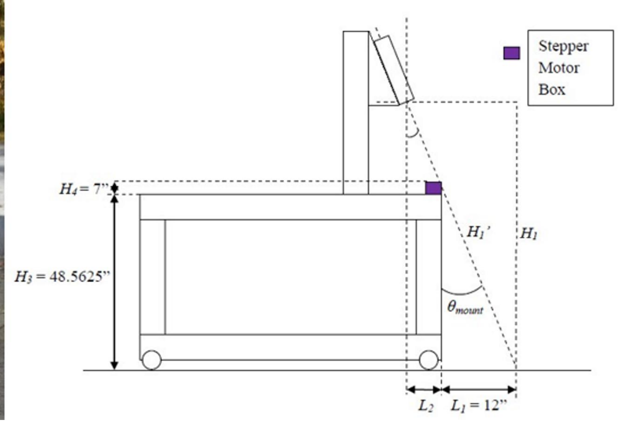

Figure 5. Left, photo of cart. Right, schematic of cart showing dimensions and variables used for imaging field calculations.

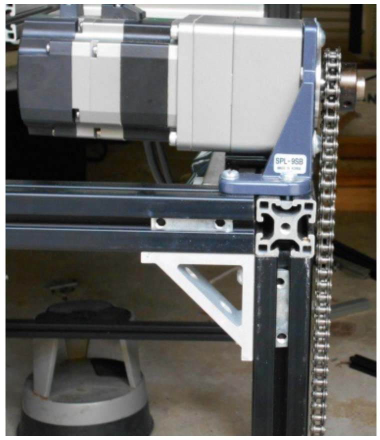

Figure 6. Motor mount and drive.

3.2 Cart testing

The cart was tested by programming the motor to move at selected speeds and time was recorded for movement over a given distance. The period of acceleration prior to reaching constant velocity was not use in calculations. Tests were also conducted by programming the cart to move a number of times at a selected interval. Preliminary results showed that the cart performed as programmed. For example, a pulse rate of 672 Hz produced the programmed cart speed of 0.25 in/s, and 13398 Hz corresponded to 5.0 in/s. More detailed tests are currently being conducted using a video camera to address consistency of performance.

3.3 Optical mount design

There are a number of considerations given that the camera and laser do not share a common aperture and the optical system is being used in a line-scan mode. For example, the components can be mounted in a "flat" or a "stacked" configuration. For both configurations, the illumination field and the imaging field will only fully overlap at fixed distance from the optics (fig. 7). One advantage of stacked mounting is the imaging field will always be at the center of the illumination field, so changes in focal distance will not influence measured fluorescence responses given the demonstrated uniformity of illumination along the central axis of the illumination (fig. 2). In addition, the usable focal distance can be expanded by increasing the length of the illumination profile relative to the imaging profile.

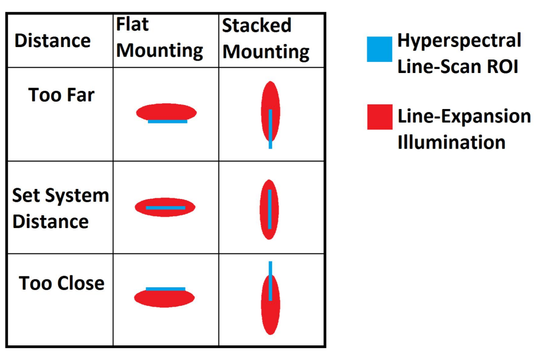

Figure 7. Alignment of imaging and illumination fields as a function of distance from the optics and the positioning of the laser relative to the camera.

With stacked mounting, there is still the question of how the camera and the laser should be angled to allow the greatest overlap. The configuration chosen for use is zero angle for the camera and a slight angle for the laser. Determining the appropriate angle and offset for the laser relative to the camera requires selection of a number of operating parameters. The most critical parameter is the length of the area to be imaged, which is directly related to the width of the crop rows and tracks on each side of crop rows. Given common field configurations, a width of ~40" was deemed appropriate. The best matching camera lens and Powell lens that could meet this criterion are a 25 mm camera lens and a 30° Powel lens. Another consideration is the height of the optics components and the angle of the components relative to vertical. Practicality requires that the imaging system be angled forward so that there is a clear view in front of the cart. Figure 8 shows orientation, variables, and equations used to calculate the width of illumination and imaging fields. Figure 4 shows the variables related to the placement of the imaging system on the cart. A possible solution using a 30° Powell lens and a 25 mm camera lens has H_1 = 108", offset (b) = 4.136", θ_{laser} = 2°, θ_{mount} = 12.2°. This solution was used to construct the aluminum mounting plate for the camera and the laser.

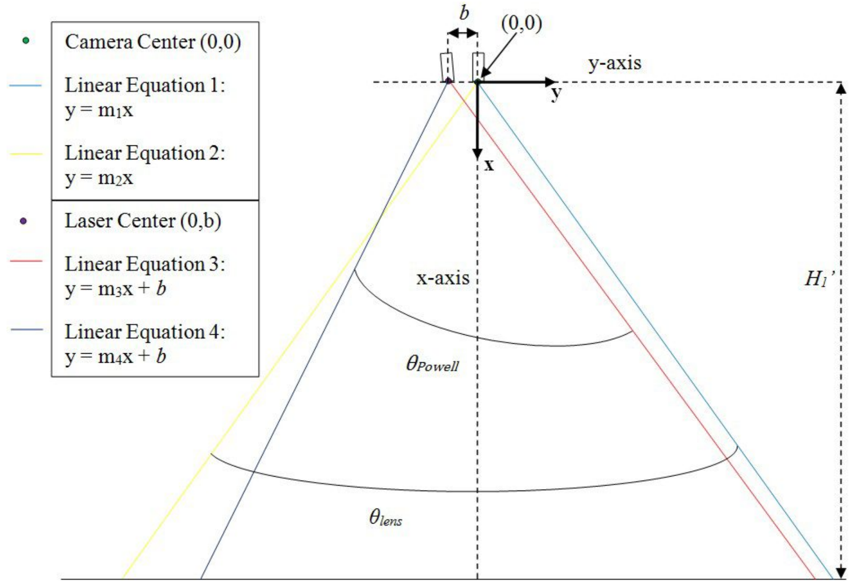

Figure 8. Imaging and illumination fields and equations when the camera lens' center is assumed to be at the origin. The laser lens' center is assumed to be along the y-axis and at an offset b from the center of the camera lens. Note $m_1 = \tan(\theta_{lens}/2)$, $m_2 = \tan(-\theta_{lens}/2)$, $m_3 = \tan(\theta_{laser} + \theta_{Powell}/2)$, and $m_4 = \tan(\theta_{laser} - \theta_{Powell}/2)$ with θ_{laser} being the angle of the laser relative to the camera.

To estimate the effect of the laser offset and angle on the illumination profile, estimates of the energy at 1° arc increments were calculated using the selected operating parameters. Figure 9 shows the result relative intensities related to energies if the laser was similarly situated but perpendicular to the ground. As can be seen, the maximum error in illumination is about 1.75%. Figure 10 shows the laser and camera mounted on the cart and in the lab.

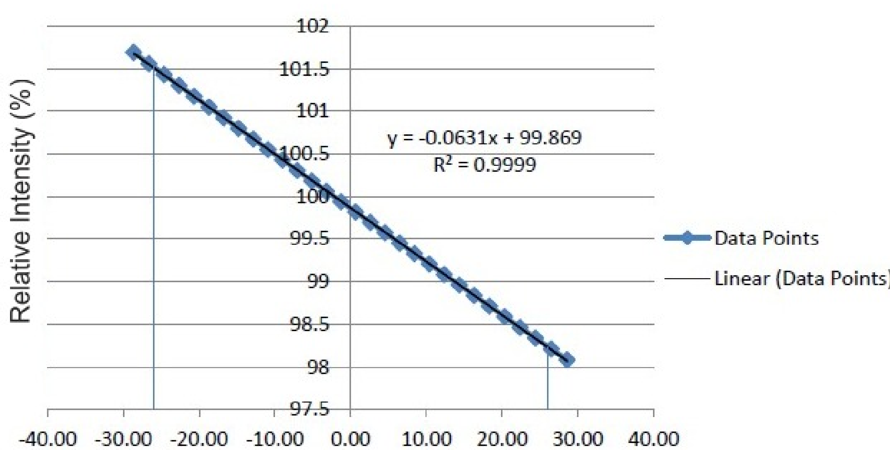

Figure 9. Relative intensity of the illumination profile as a function of distance (inches) from the centerline of the camera. The two blue vertical lines represent the outer edges of area encompassing a 40 inch wide crop row bounded by a 6 inch border on each side of the crop row.

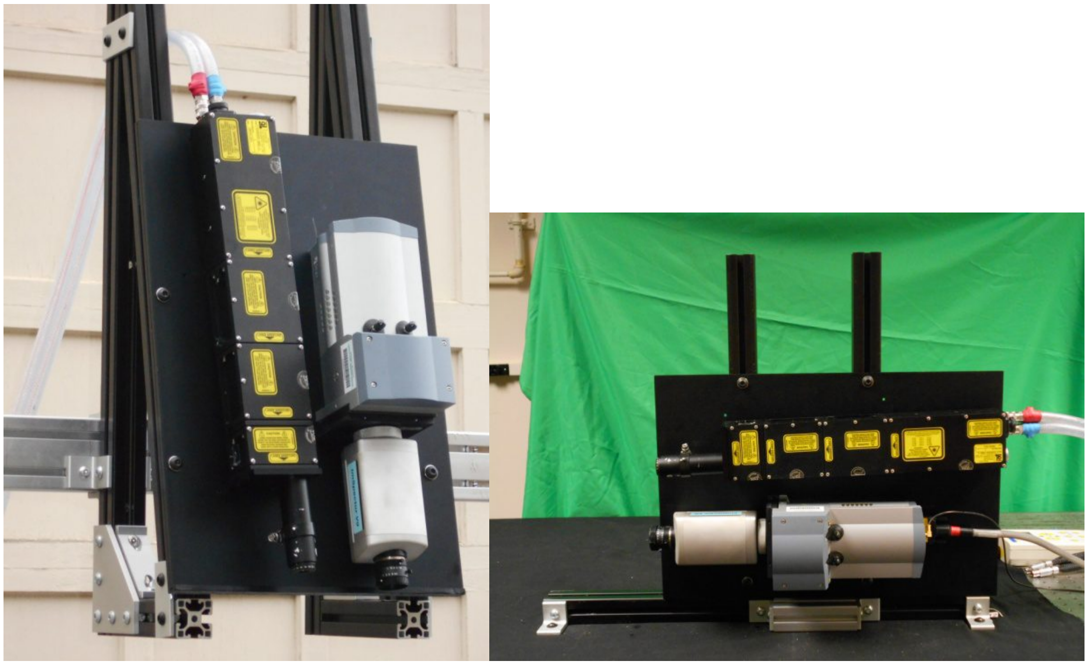

Figure 10. Left , the platform for camera and laser mounted on cart. Right, the platform mounted in lab.

4. FUTURE

The cart and mounting platform were tested to meet design criteria. The next step will be to determine if the alignment of the camera and laser can be maintained when mounted and used with the cart. If so, the system can then be used to examine cost and efficacy trade-offs of using different imaging techniques and sensitivity selections to detect fecal materials. Lower sensitivity selections would generally correspond to the potential use of less expensive instrumentation.

REFERENCES

[1] CALGMA (California Leafy Green Products Handler Marketing Agreement). Commodity Specific Food Safety Guidelines for the Production and Harvest of Lettuce and Leafy Greens (2013).

[2] CDC. CDC Estimates of Foodborne Illness in the United States: Findings (2011).

[3] FDA. Guidance for Industry: Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables (2008).

[4] Kim, M.S., Chen, Y.R. and Mehl, P.M. "Hyperspectral reflectance and fluorescence imaging system for food quality and safety," Trans ASAE, 44, 721-730 (2001).

[5] Kim, M.S., Lefcourt, A.M. and Chen, Y.R., "Multispectral laser-induced fluorescence imaging system for large biological samples," Appl. Optics, 42, 3927-3933 (2003).

[6] Lefcourt, A.M., Kim, M.S. and Chen, Y.R., "Method for detecting fecal contamination on the surface of fruits or vegetables using visible light fluorescent spectroscopy," Patent No. 7,547,508. Washington, D.C.: Commissioner of Patents and Trademarks (2009).

[7] Lefcourt, A.M., Kim, M.S. and Chen, Y.R., "Automated detection of fecal contamination of apples by multispectral laser-induced fluorescence imaging," Appl. Optics, 42, 3935-3943 (2003).

[8] Lefcourt, A.M., Kim, M.S. and Chen, Y.R., "Detection of fecal contamination in apples calyx by multispectral laser-induced fluorescence. Trans. ASAE, 48, 1587-1593 (2005).

[9] Lefcourt, A.M., Kim, M.S. and Chen, Y.R. (2005), "Detection of fecal contamination on apples with nanosecond-scale time-resolved imaging of laser-induced fluorescence, " Appl. Optics, 44, 1160-1170 (2005).

[10] Painter, J.A., Hoekstra, R.M., Ayers, T., Tauxe, R.V., Braden, C.R. and Angulo, F.J., "Attribution of foodborne illnesses, hospitalizations, and deaths to food commodities by using outbreaks data, United States, 1998-2008. Emerg. Infect. Dis. [Internet] (2013).

[11] Tewey, K.J., "Time-resolved hyperspectral line-scan imaging of pulsed-laser induced fluorescence: Food safety inspection, " *MS Thesis* University of Maryland, Baltimore County (2013).