Nondestructive sensing technologies for food safety

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Abstract

In recent years, research at the Environmental Microbial and Food Safety Laboratory (EMFSL), Agricultural Research Service (ARS) has focused on the development of novel image-based sensing technologies to address agro-food safety concerns, and transformation of these novel technologies into practical instrumentation for industrial implementations. The line-scan-based hyperspectral imaging techniques have often served as a research tool to develop rapid multispectral methods based on only a few spectral bands for rapid online applications. We developed a newer line-scan hyperspectral imaging platform for high-speed inspection on high-throughput processing lines, capable of simultaneous multiple inspection algorithms for different agro-food safety problems such as poultry carcass inspection for wholesomeness and apple inspection for fecal contamination and defect detection. In addition, portable imaging devices were developed for *in situ* identification of contamination sites and for use by agro-food producer and processor operations for cleaning and sanitation inspection of food processing surfaces. The aim of this presentation is to illustrate recent advances in the above agro-food safety sensing technologies.

Key words : Line-scan imaging, hyperspectral, multispectral, reflectance, fluorescence, food safety, sanitation

Introduction

Concerns about agro-food safety are rising with every new outbreak of foodborne illness, both within the US and worldwide. Recent incidents include bacterial contamination of spinach, peppers, and peanuts. Chemical and biological food properties can often be nondestructively assessed by spectroscopic methods, while machine vision is already ubiquitous for sorting items by physical attributes such as size, shape, and color. However, high speeds and product volumes present significant challenges to improving real-time online inspection across agro-food industries—when not otherwise mandated by law, routine random sampling performed offline is common.

Researchers at the Environmental Microbial and Food Safety Laboratory (EMFSL), Agricultural Research Service (ARS), United States Department of Agriculture (USDA), Beltsville, Maryland, have developed various imaging methodologies and technologies to address food safety concerns for food production and to aid in reducing food safety risks in food processing. Major research objectives were the development of automated online poultry inspection systems for detecting pathophysiological abnormalities in poultry, with a goal of commercial implementation as part of existing or new poultry processing systems; image-based, rapid online detection techniques for fecal contamination and defects on fruits and vegetables; and portable low-cost optical devices for *in situ* identification of contamination sites for use by food producer and processor operations with goals of commercial implementation for cleaning and sanitation inspections, and expansion to use in other areas such as military and government food safety inspection programs.

The goal of this paper is to illustrate the recent advances of sensing technologies developed at the EMFSL to address agro-food safety-sensing needs that range from automated high-speed online food processing lines to offline portable devices for localized sanitation inspection of food processing surfaces. The sensing technologies are based on visible to near-infrared (NIR) reflectance, and fluorescence.

Hyperspectral Imaging Techniques

Conventional monochromatic or RGB-based imaging methods are limited to evaluating basic physical attributes such as size, shape, and color of agricultural commodities. In contrast, spectroscopic (i.e., hyperspectral) imaging allows a thorough characterization of physical, chemical and biological perturbations indicative of agro-food product safety and quality. Hyperspectral imaging techniques have been developed to combine the advantages of spectroscopy and machine vision in addressing agro-food quality and safety problems. Hyperspectral imaging methods provide full spectrum data—often hundreds of spectral data points—for every pixel in the image of a food product, enabling spectral and spatial analysis for correlation to composition, contaminants, and physical attributes such as size and shape.

Fundamentally, there are two ways to acquire hyperspectral imaging data from an object: a band sequential imaging method and a push-broom (line-scanning) imaging method. The band sequential imaging method captures a full spatial scene at individual wavelengths to form a three-dimensional hyperspectral image cube. The push-broom method captures a line of spatial information with a full spectral data per spatial pixel, and the composites of a set of many spatial line-scans form a hyperspectral image cube.

The ARS hyperspectral imaging systems have utilized the push-broom, line-scan approach and are capable of both reflectance and fluorescence imaging. Figure 1 illustrates critical components of the ARS hyperspectral imaging system. Typically, the spectral range for reflectance measurements is approximately 400-1000 nm and for fluorescence measurements is 400-700 nm (with UV excitation), with approximately 5 nm spectral resolution. Spatial resolution is adjustable to accommodate small and large samples, from individual grains of wheat to whole chicken carcasses.

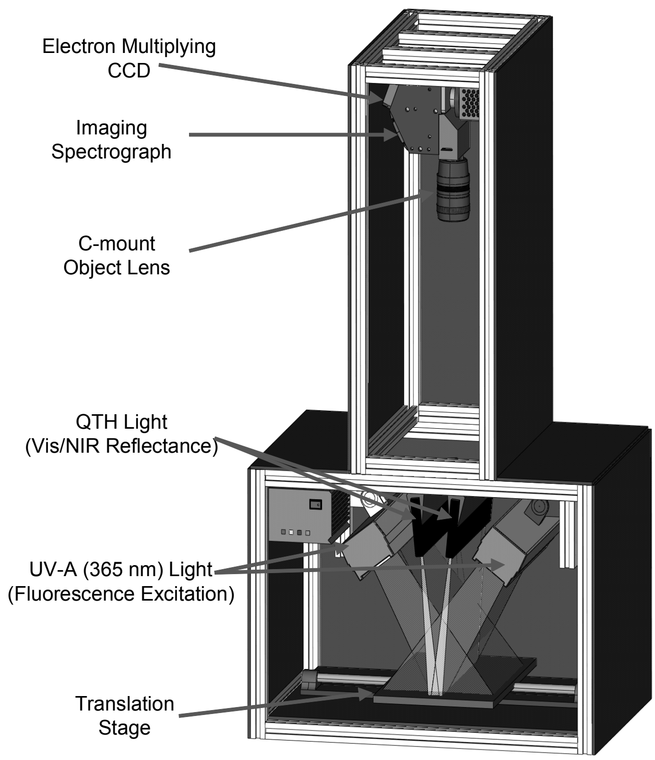

Figure 1. Schematic of the ARS line-scan hyperspectral imaging system.

Due to speed restrictions for data acquisition and processing, hyperspectral imaging has often been used as a research tool to develop rapid multi-spectral methods based on only a few spectral bands for rapid online applications (Kim et al., 2001). Multivariate analysis such as principal component analysis as a systematic method for selecting key spectral bands has been used to determine multispectral bands to implement in rapid industrial multi-spectral imaging inspection applications. In addition, multispectral image fusion/ratio analysis methods can further enhance detection sensitivity. An example of this is the development of a method to detect fecal contamination on apples, for which a two-band fluorescence ratio was used to detect a range of dilutions of bovine feces on apples (Kim et al., 2008).

Newer line-scan-based spectral imaging technologies can deliver high-speed online safety and quality inspection of food and agricultural products on high-throughput processing lines. We have developed a new line-scan hyperspectral imaging platform for high-speed inspection on commercial processing lines, capable of simultaneous multiple inspection algorithms for different safety and quality problems.

Line-scan Hyperspectral Imaging for Online Inspection

Rapid line-scan imaging is ideal for processing line inspection because a rapid series of narrow spatial images can be captured as objects cross a linear field of view. Full-spectrum hyperspectral data can be selectively processed using multispectral algorithms for specific tasks in contaminant detection and disease identification.

For fruit and vegetable producers and processors, fecal contamination detection is only one detection problem among many safety and quality concerns affecting their products. To be of practical benefit, an effective product screening system must be able to address multiple inspection tasks. A line-scan spectral imaging system was specifically developed to simultaneously capture NIR reflectance and fluorescence, and was applied to address a combination of safety and quality inspection tasks (multitasking) for apples on a processing line.

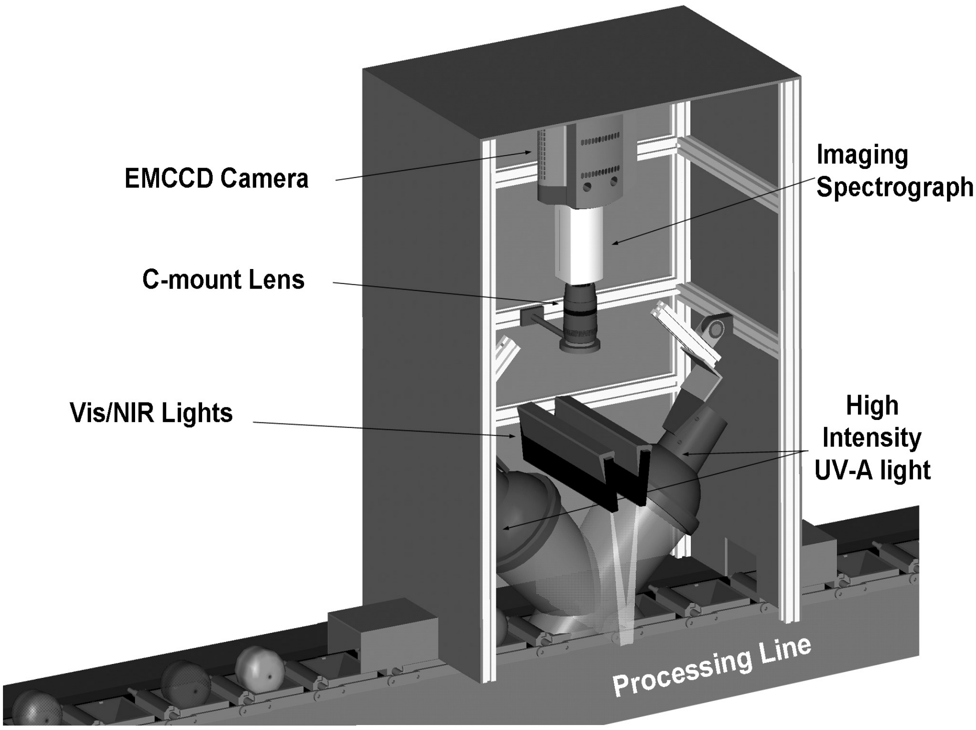

Figure 2. Critical sensing components of the multitasking online line-scan imaging system on apple processing line.

Figure 2 shows the critical components of the multitasking online line-scan imaging platform. The imaging spectrograph disperses incoming light into a continuous spectrum across the electron-multiplying charge-coupled device (EMCCD) camera. Not only is the EMCCD camera suitable for imaging with very short exposure times, its hardware performs image binning and waveband selection and also fast pixel readout. These features are critical to the system's processing speed and flexibility for both hyperspectral and multispectral imaging. Visible fluorescence and NIR reflectance images can be acquired simultaneously (Figure 3). System software developed in-house can perform real-time hypercube image visualization and hyperspectral image analysis for selection of wavelengths for multispectral algorithms.

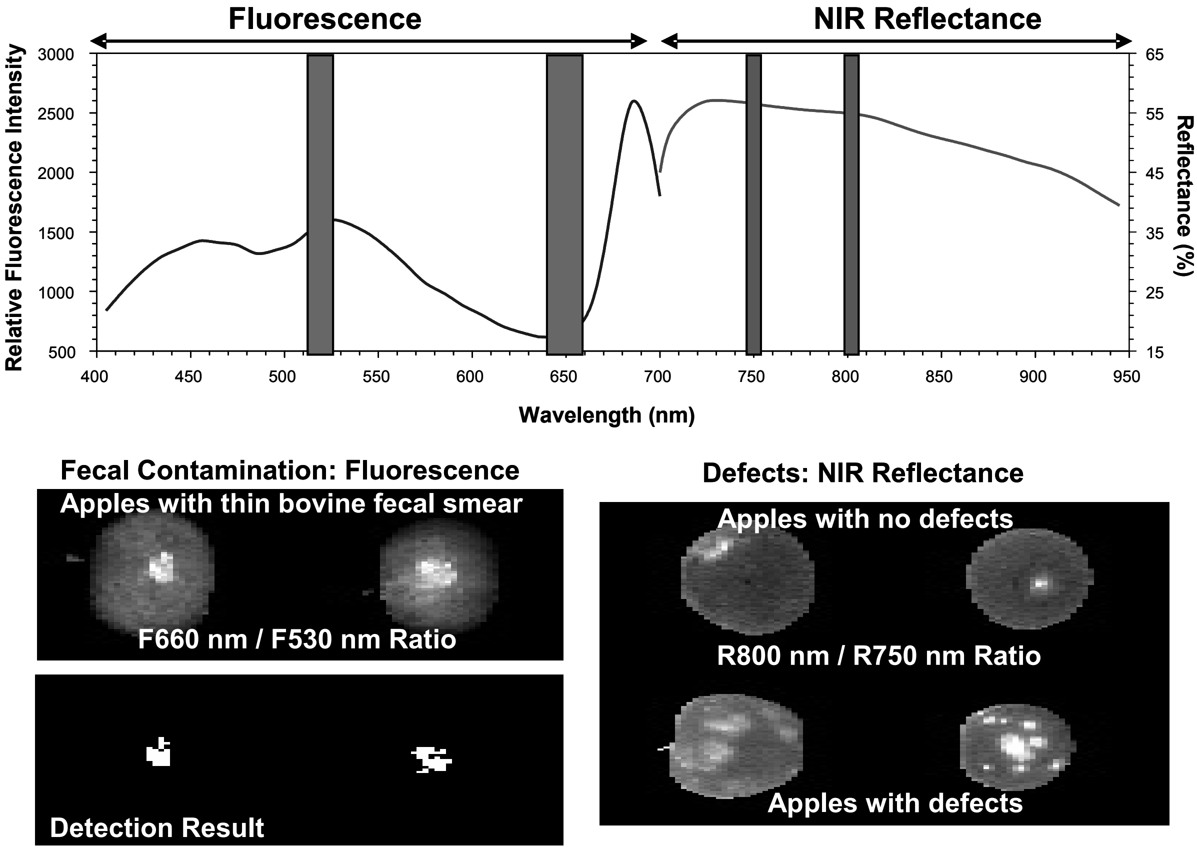

Figure 3. Key spectral bands region for multitask inspection of apples for surface fecal contamination (by fluorescence) and for defect and disease detection (by NIR reflectance). Fluorescence and NIR reflectance ratio images demonstrate the detection of fecal contamination and defects, respectively.

For the multi-task apple inspection system, algorithms were developed to detect and differentiate individual apples on a commercial sorter operating at 3-4 apples per second. Samples included uncontaminated normal Red and Golden Delicious apples, uncontaminated apples exhibiting surface defects, and normal and defective apples contaminated with smears of fecal matter both visible and visually indistinguishable. Reflectance images at 750 nm and 800 nm could identify defects such as cuts and rotted spots; fluorescence images at 530 nm and 665 nm detected fecal contamination and differentiated it from surface defects (Figure 3). Simultaneous fluorescence images and NIR reflectance images were enabled by using an NIR long wavelength pass filter (750 nm) on the Vis/NIR lights to eliminate reflectance in the visible spectrum and a long pass filter (450 nm) over the C-mount lens to remove 2nd-order effects of the UV light. This multitask line-scan imaging system demonstrated over 98% accuracy in online inspection of apples at speeds of 3-4 apples per second, for surface fecal contamination by fluorescence and for defect and disease detection by NIR reflectance.

A line-scan imaging system for wholesomeness inspection of freshly slaughtered chickens was developed and tested on processing lines in commercial poultry plants (Chao et al., 2007). Wavebands at 580 nm and 620 nm were selected through analysis of 55-band hyperspectral images acquired online. Multispectral algorithms used these wavebands to detect and classify individual birds as being either wholesome or unwholesome. Online multispectral inspection of over 100,000 chickens at 140 birds per minute during two eight-hour shifts demonstrated over 99% accuracy in identifying unwholesome birds for removal. These results show that a line-scan inspection system could significantly increase efficiency, reduce labor costs, and improve inspection programs for poultry processors. Efforts to commercialize the system are underway.

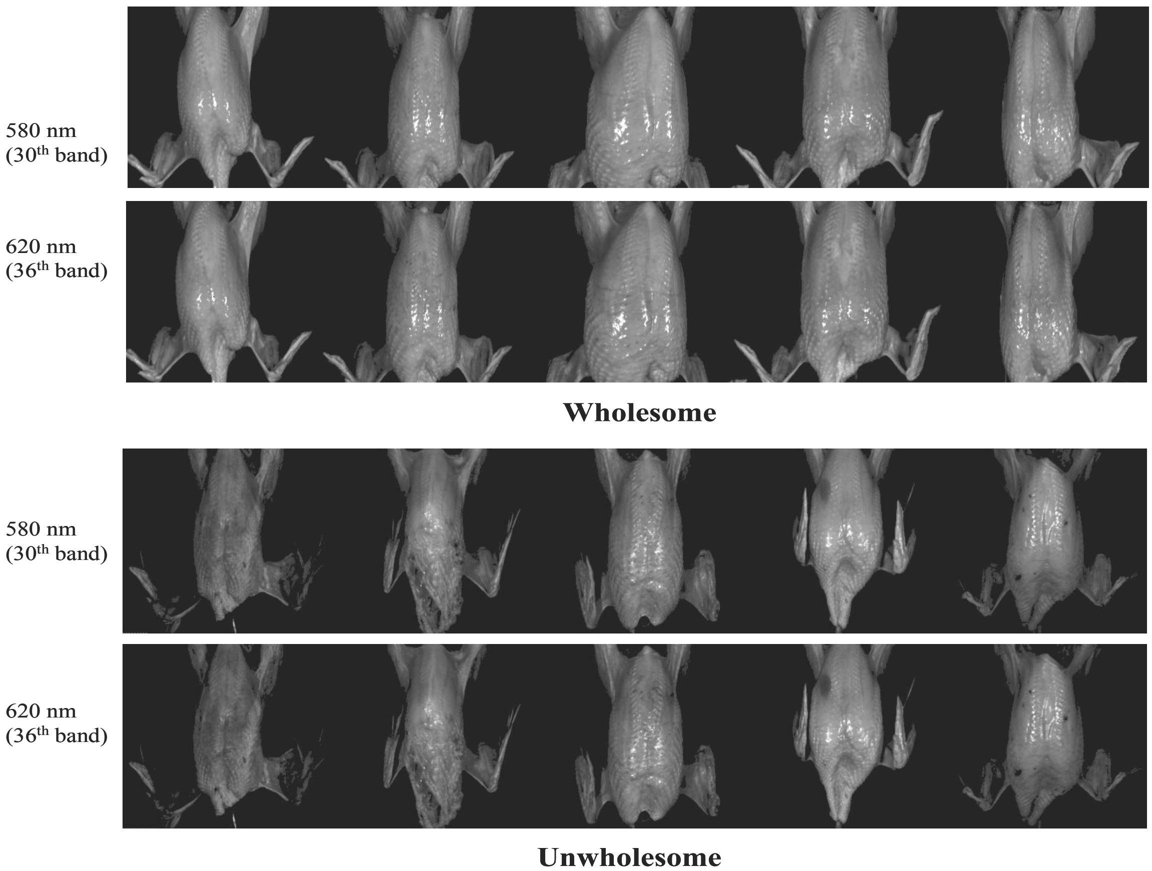

Figure 4. Multispectral images of wholesome and unwholesome chicken carcasses at two key spectral wavebands, acquired during in-plant testing of the ARS hyperspectral/multispectral poultry inspection system.

Further research is being conducted to develop inspection systems suitable for commercial processing of other fresh produce such as leafy greens. Effective detection of contamination by fecal matter and bacterial biofilms, for example, is important due to their association with common bacterial causes of foodborne illness. Adaptable to a broad range of problems and commodities, the line-scan hyperspectral imaging platform will be critically useful for both research and commercial food safety and quality inspection applications.

Sanitation Inspection of Food Processing Surfaces

Current safety and sanitation inspection for food processing equipment surfaces is based on visual examination or spot checks by human inspectors, a process that limits productivity and is prone to human error and inconsistency. EMFSL scientists developed handheld imaging inspection devices based on fluorescence techniques, first to detect/highlight the presence of fecal contaminants (Figure 5a), and later expanded to include organic residues and bacterial biofilms (Figure 5b), on the surfaces of food processing/handling equipment. Note that biofilms can act as harbor sites for micro-organisms on food and equipment surfaces.

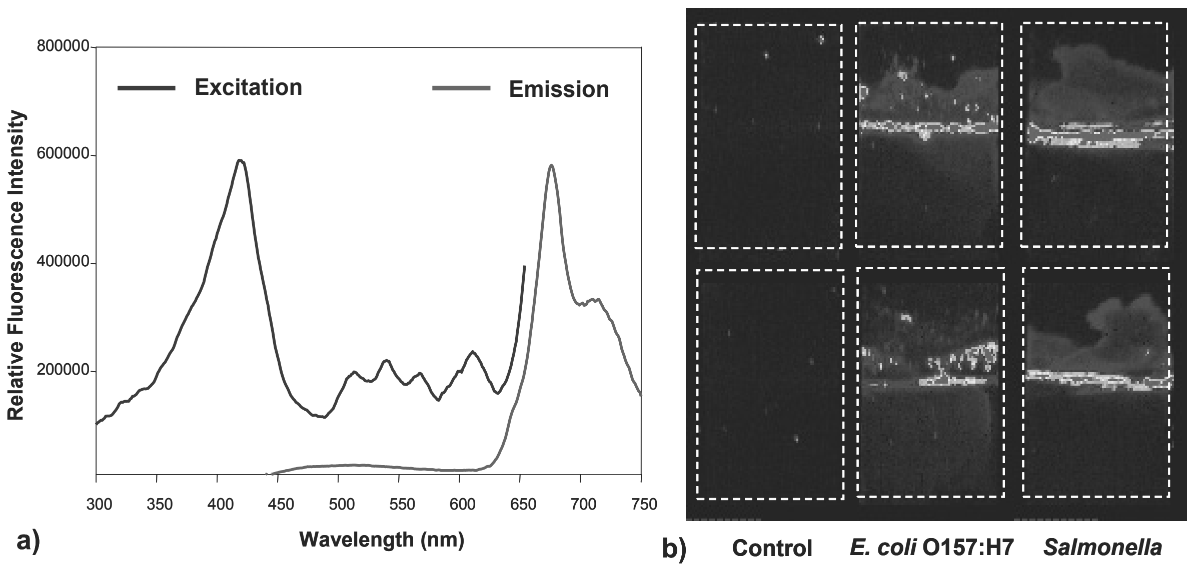

Figure 5. a) Representative fluorescence excitation and emission spectra of bovine feces. b) Representative fluorescence emission images (blue band at 480 nm) of biofilms formed by *E. coli* O157:H7 and *Salmonella*, on stainless steel coupons (i.e., food processing surface material), acquired with the hyperspectral imaging system. Approximately half of each coupon was submerged in a 50-ml tube containing 15 ml minimal growth medium (M9C) broth for 6 d at 37°C without shaking.

The optical image-based visual aid devices utilize miniaturized illumination and cameras with portable/wearable computer displays, and wireless technologies for image data storage, analysis, and management that can accommodate simultaneous use of multiple devices by several inspectors (Figure omitted for brevity). The devices can be used for safety and sanitation inspection in large and small food processing facilities, and other handling/distribution points such as markets and restaurants.

Conclusions

In this paper, recently developed ARS sensing technologies to address agro-food safety and sanitation concerns are presented. We envision that the multitasking line-scan spectral imaging technologies can deliver concurrent safety and quality inspection for a variety of agricultural products on high-throughput processing lines.

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