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REVIEW

X-ray imaging methods for internal quality evaluation of agricultural produce

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Abstract A number of non-destructive methods for internal quality evaluation have been studied by different researchers over the past eight decades. X-ray and computed tomography imaging techniques are few of them which are gaining popularity now days in various fields of agriculture and food quality evaluation. These techniques, so far predominantly used in medical applications, have also been explored for internal quality inspection of various agricultural products non-destructively, when quality features are not visible on the surface of the products. Though, safety of operators and time required for tests are of concern, the non-destructive nature of these techniques has great potential for wide applications on agricultural produce. This paper presents insight of X-ray based non-destructive techniques such as X-ray imaging and Computed Tomography (CT). The concepts, properties, equipment and their parameters, systems and applications associated with the use of X-rays and CT for agricultural produce have been elaborated.

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Introduction

Quality of agricultural produce is always of prime concern for success in market. In agricultural industry, the quality evaluation still heavily depends on manual inspection, which is time consuming, laborious and costly. Manual inspection may easily be influenced by physiological factors including subjective and inconsistent evaluation results (Du and Sun 2006). Brosnan and Sun (2004), focused on necessity to improve quality evaluation of food products to satisfy greater expectation of consumers, increased awareness and sophistication.

Non-destructive quality evaluation of agricultural products has become a major area of interest for the agricultural processing industry. Researchers have been working to find techniques for evaluating internal quality attributes of agricultural and food products nondestructively. Availability of advance technology has expanded avenues for non-destructive food quality determination. Techniques such as X-ray imaging, Computed Tomography (CT), Magnetic Resonance Imaging (MRI) and ultrasound have been explored for non-destructive evaluation of indicators not visible on the surface of variety of agricultural products (Gunasekaran et al. 1985; Chen and Sun 1991; Abbott 1999). The quality of agricultural commodities is characterized based on individual or a combination of various properties, viz. physical, mechanical, optical, sonic, electrical, electro-magnetic, thermal, hydro and aero dynamic, etc. (Gunasekaran et al. 1985; Mohsenin 1986; Brennan et al. 1990; Thompson 1996). Advent of modern image acquisition techniques such as solid state TV camera, line-scan camera, X-ray scanning, ultrasound scanning and MRI (erstwhile known as nuclear magnetic resonance – NMR imaging), CT scanning, NIR (near infrared) imaging in conjunction with image processing techniques, have presented many potential avenues for non-destructive quality evaluation of agricultural products (Chen and Sun 1991; Kim and Schatzki 2001).

X-ray imaging is one of the most prominent techniques for medical diagnostics. Besides medical imaging, there are many applications of X-rays such as checking luggage at airport, inspecting industrial components, security etc. Use of X-rays in inspection of agricultural commodity is still in primary stage. Use of X-ray imagery for agricultural product inspection offers considerable advantages and complements present inspection techniques (Casasent et al 1998). In recent years, X-ray based systems have increasingly been used effectively as a research tool for the detection of internal defects in agricultural products. X-ray inspection is one of the most promising techniques as it is a non-contact sensor and is currently (for larger sample materials) considerably cheaper than the second major sub surface imaging technique, nuclear magnetic resonance (Webb 1988; Yacob et al. 2005).

Next to two-dimensional radiography used in medical field and line-scan X- ray inspection, X-ray computed tomography (CT) is one of the most commanding methods for internal quality evaluation. CT can generate two and three dimensional images from the accumulated data to study physical and physiological indicators (Sonego et al. 1995; Okochi et al. 2007). X-ray computed tomography (X-ray CT) is a proven method for evaluating a cross-section of an object using a movable X-ray source and detector assembly to accumulate data from a thin projected slice of a sample. The basic principle behind the CT is that the internal structure of an object can be reconstructed from multiple projections of the object (Curry et al. 1990).

Tollner and Murphy (1991) discussed the physics of X-ray absorption with CT scanners at length. The CT scanner includes an X-ray tube, collimators, turntable and multi-channel detector installed in a shielded chamber. A collimated X-ray beam is directed on the product and the attenuated remnant radiation is measured by a detector whose response is transmitted to a computer (Barcelon et al. 1999a). A CT scanner measures X-ray beams over several non-parallel paths through the object, computes a three dimensional projection and then computes a 'slice' of that projection (Abbott 1999). During scanning, an X-ray generator and several detectors rotate 360° around an object. The detectors measure the quantity of X-rays transmitted through a scanned cross section of the object. The numerical data from multiple ray sums are then computer processed to reconstruct an image. The major constituents are differentiated on the resulting images because they have different X-ray attenuation values (Haseth et al. 2007). According to Haseth et al. (2008), the voltage setting of the X-ray tube strongly influences the energy spectrum of the emitted X-ray photons. Photons of higher energies are less likely to be attenuated, and therefore CT values decrease with increasing tube voltage.

The aim of this paper is to describe some of the basics related to X-rays and their interaction with matter, and hardware used in imaging. The paper also illustrates protocols used in X-ray imagery and CT for quality evaluation of agricultural and food products, and challenges associated with them.

X-rays and their interaction with matter

X-rays

X-ray radiation was discovered by Wilhelm Conrad Röntgen in 1895 by bombarding electrons on a metallic anode. It is interesting that the first use of X-rays were for an industrial (not medical) application, as Roentgen produced a radiograph of a set of weights in a box to show his colleagues (Anon 2010).

X-rays have a wavelength in the range of 0.01 to 10 nm, corresponding to frequencies in the range 30 to 30000 Petahertz (3×10E16 Hz to 3×10E19 Hz) and energies in the range 120 eV to 120 keV. Short electromagnetic waves, such as X-rays, behave like particles as well as waves while interacting with matter. These particles are discrete bundles of energy and are called photons or quanta.

Some of the basic properties of X-ray are that they: travel in straight lines, are not deflected by electric field or magnetic field, have high penetrating power, can blacken a photographic film, cause glowing in exposed fluorescent materials, can produce photoelectric emission and ionization of a gas.

Incident X-ray photon transfers energy to electrons and nuclei of the target material while passing through matter. An electron can be ejected from the atom with the subsequent creation of an ion. The amount of energy lost to the electron depends on the energy of the incident photon and the type of material through which it travels. Three basic methods in which X-rays interact with matter are: photoelectric effect, Compton scattering, and pair production.

Electromagnetic waves with wavelengths ranging from 0.1 to 10 nm with corresponding energies of about 0.12 to 12 keV are called soft X-rays. Due to low penetration power and ability to reveal the internal density changes soft X-rays are more suitable to be used on agricultural products. Neethirajan et al. (2007b) reported that the soft X-ray method was rapid and took only 3–5 s to produce an X-ray image.

One of the major concern while using X-rays is that they can ionize and thus damage the living cells (Farkas 2006). This property of X-rays on one hand can be used for microbial and enzymatic inactivation in foods but on the other hand poses harm to humans, if exposed to. Machine generated X-rays of up to 5 MeV kinetic energy do not induce radioactivity in the exposed food or its packaging material (Farkas and Csilla 2011), hence use of radiography and CT imaging could be safe on food products. Proper shielding of the equipment would be helpful in preventing human exposure to X-rays.

Attenuation coefficient

When an object is subjected to X-ray exposure, the X-rays interact with matter and an exponential decrease in the total energy of the X-ray beam occurs as it traverses through the object. This phenomenon is called attenuation (Curry et al. 1990). The attenuation coefficient is a measure that describes how easily a material can be penetrated by a beam of light, sound, particles, or other energy or matter. A large attenuation coefficient means that the beam is quickly "attenuated" (weakened) as it passes through the medium, and a small attenuation coefficient means that the medium is relatively transparent to the beam. Attenuation coefficient is measured using units of reciprocal length. The attenuation coefficient is also called linear attenuation coefficient, narrow beam attenuation coefficient, or absorption coefficient. The mass attenuation coefficient is a measurement of how strongly a chemical species or substance absorbs or scatters light at a given wavelength, per unit mass. In addition to visible light, mass attenuation coefficients can be defined for other electromagnetic radiation (such as X-rays), sound, or any other beam that attenuates. The mass attenuation coefficient is also called mass absorption coefficient or mass extinction coefficient (Anon 2011a). The attenuation coefficient has units of inverse-length, while density has units of mass per volume. Since the mass attenuation coefficient is the ratio of these two, we find that it has units of (length-squared) per mass. The SI unit is m^2kg^{-1}. X-ray attenuation is widely used in material thickness gauging in industry (Arslan et al. 2000).

The photons in a soft X-ray beam, when passed through an object, are either transmitted, scattered (Compton scattering) or absorbed (photoelectric collision). As a result, the intensity of incident photons reduces exponentially (Curry et al. 1990) and is given by

$$I = I_0 e^{-\mu_m z \rho}$$

Where: I is the intensity of photons exiting through a body; μ_m is mass attenuation coefficient in mm^2/g (M^{-1} L^2); ρ is material density in g/mm^3 (M L^{-3}); and z is thickness in mm (L) through which the X-rays pass. The intensity of X-ray beam is directly related to the energy content of the beam. The attenuation coefficient is a function of photon energy (Hubbell and Seltzer 1995) and for monochromatic radiation it is constant for a material. X-rays generated from X-ray tubes have photons of varying energy, and therefore are polychromatic, therefore a term μ_{av}, representing the average coefficient of absorption for the range of wavelengths is sometimes used. μ_{av} is higher for elements with a high atomic number (Lenker and Adrian 1971). However, attenuation coefficient of a material changes with thickness when measured under polychromatic X-rays (Paiva et al. 1998). Buzzell and Pintauro (2003) defined 'R-value' for a material as the ratio of the attenuation coefficient at low-energy level to that at high-energy level. The range of wavelengths produced, depends on the voltage of the X-ray tube generating the beam and any filters the beam passes through. The mass attenuation coefficient for a material is a function of the atomic number of the absorbing material and incident photon energy. The exiting photon energy depends on material properties, including thickness. If the absorbing material consists of more than one element, the mass attenuation coefficient of the composite material will be a function of mass attenuation coefficients of individual elements and their mass fraction in the path of the photon beam (Kotwaliwale et al. 2006). Radiography and CT intends to capture the difference in transmitted X-ray photons, due to material difference in the form of a visual contrast in the image (Curry et al. 1990).

CT number

In general, the detection of foreign materials using X-rays is based on their absorption characteristics which vary with different material densities. The X-ray absorption characteristics of tested materials have been expressed as X-ray CT numbers (Ogawa et al. 1998). In CT system, the studied object is illuminated from specific directions by an X-ray source. The intensities of X-rays going through the object are measured by detectors, digitized, and used in the reconstruction of a digital image of the test object using CT numbers. The CT number is based on linear X-ray absorption coefficients and, in general, is expressed by brightness data in an image (Kotwaliwale et al. 2011). The CT number is defined as

$$\text{CT number} = (\mu - \mu_w).k/\mu_w$$

Where

- μ object linear X-ray absorption coefficient (m^{-1})
- μ_w linear X-ray absorption coefficient of water (m^{-1})
- k constant (1000)

In the case of $k=1000$, the CT number is called a Hounsfield unit. Ogawa et al. (1998) computed Hounsfield numbers as CT numbers, and the measuring range was from −1,000 to +4,000 with the CT number for air being −1,000 and the CT number for water being 0.

X-ray and CT imaging

Unlike a normal visible light picture, which is reflectance image, X-ray image is a transmittance image. X-ray photons not fully attenuated during interaction with matter get transmitted through different layers of the matter. Contrast in the intensity of transmitted photons, form the image that is a transmittance projection of the material coming across the X-ray path. X-ray imaging intends to capture this contrast and quality of image depends on four basic elements: (a) X-ray source; (b) X-ray converter; (c) imaging medium and (d) casing for imaging medium (Kotwaliwale et al. 2011). X-ray source produces X-ray photons with appropriate intensities, the X-ray converter, e.g. phosphor screen, stops X-rays from reaching the imaging medium and produces a visible output proportional to the incident X-ray photons. The imaging medium, e.g. photographic medium captures the image while the casing protects the imaging medium from surrounding visible radiations (Kotwaliwale et al. 2007a). Recent years have seen the development of devices such as X-ray tubes with small focal spot size, high sensitive image intensifiers, and high-resolution CCD cameras (Okochi et al 2007).

X-ray source

Radioactive substances and X-ray tubes are the two principal sources of X-rays. In X-ray tubes, X-rays are generated by interactions between the energetic electrons and atoms of the target. Bombardment must take place in a vacuum to prevent ionization of air (Oghabian 2008).

Whereas, the radioactive substances may generate monochromatic X-rays (almost all the photons having same energy level), X-ray tubes generate polychromatic beam. The literature shows that X-ray tubes of different types have been used as X-ray sources in radiography of agricultural produce. The variations in tubes are in the maximum tube voltage, current, focal spot size (Zwiggelaar et al. 1997; Kotwaliwale et al. 2006 & 2007b; Okochi et al. 2007), window material (Diener et al. 1970; Lenker and Adrian 1971; Keagy et al. 1996; Schatzki et al. 1997; Kotwaliwale et al. 2006 & 2007b), electrode material (Schatzki et al. 1997; Kotwaliwale et al. 2006 & 2007b; Okochi et al. 2007), tube cooling system etc.

X-ray tube has been predominantly used for generating X-rays for radiography of agricultural produce. Use of X-ray tube gives advantage of producing X-rays at varying intensity (within the limits of tube). X-ray tube parameters (peak voltage, current and exposure time) can also be programmatically controlled using appropriate hardware. When not in use, X-ray tube does not require any special care that is required to store the radioactive materials.

Transformer

Intensifying screens are used to convert X-rays into light, to which film is much more sensitive. Ogawa et al. (1998) used xenon gas scintillator as X-ray detector in X-ray CT scanning experiment. The two most common screens contain terbium-doped gadolinium oxysulfide (Gd_2O_2S: Tb) (Kotwaliwale et al. 2007a) or terbium-doped lanthanum oxybromide (LaOBr:Tb) (Anon 2008). Gruner et al. (2002) identified phosphors and semiconductors as two types of X-ray converters. Semiconductors directly convert X-rays into electrical charge, i.e. they act both as X-ray converters and imaging medium.

Imaging medium

Historically, X-ray imaging has been done on photographic plates or films (Curry et al. 1990). In general, the acquisition of X-ray images can be either film-based or digital (Jiang et al. 2008). Haff and Slaughter (2004) have commented that different types of detectors, including film, have different responses to X-ray exposure. It is therefore not expected that different X-ray systems could, or should, use the same energy and current settings to produce similar results. Table 1 summarizes the different imaging methods used for radiography of several agricultural commodities.

Photographic plate/film

In film or plate based X-ray imaging, which is similar to that of conventional photography, the X-ray is transmitted through the inspected object and a sensing film is exposed to form the object image. After developing the film, an X-ray image with high resolution can be obtained (Jiang et al. 2008). Haff and Slaughter (2004) compared radiography with many physical methods to identify insect infestations in grain and concluded that X-ray with film was the only method that could identify early stages of infestation.

In the earlier periods, X-ray inspection with film was studied by many authors (Table 1) X-ray films for general radiography consist of an emulsion-gelatin containing radiation sensitive silver halide crystals, such as silver bromide or silver chloride, and a flexible, transparent, blue-tinted base. The emulsion is different from those used in other types of photography films to account for the distinct

Table 1 Comparison of different imaging mediums used for radiography

S. No.	Imaging medium	Advantage/Limitation	Agricultural product/ commodity and application	Reference
1	Photographic plate/ film	High resolution, cheap, easy to use, needs development, no instantaneous results, storage requires physical space.	Wheat, corn, sorghum (insect infestation), Apple (Bruised apple sorting)	Milner et al. (1950), Kirkpatrick and Wilbur (1965), Mills and Wilbur (1967), Diener et al. (1970), Sharifi and Mills (1971a, b), Stermer (1972), Schatzki and Fine (1988), Keagy and Schatzki (1991)
	Fast industrial radiography film	Fine grain and high resolution	Mango (seed weevil detection), Apple (Watercore damage), Tree ring measurement	Thomas et al. (1995), Schatzki et al. (1997) and Okochi et al. (2007)
	Digitizing the radiography film	Ease of storage and retrieval and possibility of image processing. Cannot be online, digitization requires special effort and device	Pistachio nuts (Worm damage), Almonds, Wheat, Citrus, peach, guava (infestation)	Keagy et al. (1996), Casasent et al. (1998), Kim and Schatzki (2001), Fornal et al. (2007), Jiang et al. (2008), Haff and Slaughter (2004)
2	Photodiode	Solid state device, digital output, device requires cooling, resolution not as good.	Lettuce heads (differentiate mature from immature heads), grain (infestation), scattered radiation measurement, Apple (watercore)	Lenker and Adrian (1971), Stermer (1972), Zwiggelaar et al. (1997), Schatzki et al. (1997)
3	Camera	Solid state device, digital output, available in variety of resolutions, real time analysis possible, expensive, special triggering systems required if used online	Wheat (insect infestation), detection of soft materials by selective energy of X-ray transmission imaging, pecan quality evaluation	Schatzki and Fine (1988), Zwiggelaar et al. (1997), Kotwaliwale et al. (2007a, b)
	Line scan camera	More suitable for imaging while the sample is moving on a conveyor, available in variety of resolutions, real time analysis possible. The sample needs to be placed under radiation for a longer time compared to area scan cameras.	Detection of Apple watercore, quarantine inspections for detecting alien pests in imported fruits	Kim and Schatzki (2000), Jiang et al. (2008)
4	Intensifiers/ Fluoroscopes/ Intensifier coupled to CCD camera/ Combination of fluoroscope, B/W digital camera, and image digitizer		Wheat (insect infestation), wheat and corn flow rate, wheat infestation, horticultural peat (detection of glass contamination), wheat infestation, wheat fungal infection	Karunakaran et al. (2003b), Arslan et al. (2000), Haff and Slaughter (2004), Ayalew et al. (2004), Karunakaran et al. (2004c, 2004d), Neethirajan et al. (2006a) and Narvankar et al. (2009), Morita et al. (1997)

characteristics of gamma rays and X-rays, but X-ray films are sensitive to light (Anon 2010a).

Digital images by scanning of film radiographs have been helped in performing digital image processing and electronic storage of film based radiographs. Different resolutions and bit depths have been reported for different products. Keagy et al. (1996) obtained Twelve-bit digital images at a resolution of $(0.125\ \text{mm})^2$/pixel from pistachio nuts raduigraphs. While Casasent et al. (1998) scanned X-ray images of pistachio nuts at 173 μmol per pixel for detection of navel orange worm damage. Kim and Schatzki (2001) digitized X-ray films at 0.17 mm×0.17 mm pixels of 8-bit resolution and commented that, in general, scanned film images were sharper, less noisy, and had higher resolution, but they took more time to acquire. Fornal et al. (2007) scanned wheat X-ray films to a resolution of 0.127 mm^2/pixel at 8-bit.

Camera

With the availability of advance X-ray source and digital X-ray scanning sensors, digitized X-ray images can be acquired and analyzed in real time. As this allows online inspection of material/food produce, the applications of digital X-ray imaging in industries have increased significantly in recent years (Jiang et al. 2008). Although use of still cameras is predominant (as shown in Table 1), use of video camera to detect infestation in wheat kernels was also reported by Schatzki and Fine (1988).

Variety of imaging mediums is now available for X-ray imaging. However the interest of researchers is shifting more towards the digital media. Use of digital X-ray cameras present various advantages such as instantaneous image visibility, ease of transmission and storage, on-line processing and decision making and other advantages associated with digital computers. Haff and Slaughter (2004) reported an approximate time savings of a factor of 4 in digital observations vs. film radiographs.

Hardware for computed tomography

Computed tomography is also known as computerized axial tomography (CAT). As suggested by its name, modern digital computer is an essential component of a CT system (Kotwaliwale et al. 2011). Different types of computer systems are used by equipment manufacturers to control system hardware, acquire the projection data and reconstruct, display, and manipulate the tomographic images (Cunningham and Judy 2000). Other important components of CT system are X-ray tube, collimators and detectors (Curry et al. 1990). All CT scanners (except fifth-generation system) use bremsstrahlung X-ray tubes as the source of radiation. The power requirements of these tubes are typically 120 kV at 200 to 500 mA, producing X-rays with an energy spectrum ranging between approximately 30 and 120 keV (Cunningham and Judy 2000). Ideally, the radiation source for CT should supply a monochromatic X-ray beam (i.e. consisting of photons having the same wavelength) for simpler and more accurate image reconstruction (Curry et al. 1990).

The X-ray beam is collimated at two points, one close to the X-ray tube and the other at the detector(s). The collimator at the detector is the sole means of controlling scattered radiation. According to Curry et al. (1990) the collimators also regulate the thickness of the tomographic slice (i.e. the voxel length).

According to Cunningham and Judy (2000) X-ray detectors used in CT systems must have three basic properties; (a) high overall efficiency and a large dynamic range, (b) stability with respect to time, and (c) be unaffected by temperature variations. The most common detectors for CT scanners are xenon-filled ionization chambers. Because xenon has a high atomic number (66), there is a high probability of photoelectric interactions between the gas and the incoming X-rays. As X-rays ionize the xenon atoms, the charged atoms are collected as electric current at the electrodes (Anon 2011b).

X-ray parameters used for radiography of agricultural materials

It has been shown that the small contrast in the transmission images can be enhanced by a suitable selection of the X-ray photon energy (Zwiggelaar et al. 1996; 1997).The quality of the X-ray image for different kinds of fruits depends greatly on the selection of proper tube voltage and current because of the variable thickness, density and X-ray absorption characteristics of different fruits (Jiang et al. 2008). Different types of detectors, including film, have different responses to X-ray exposure. Haff and Slaughter (2004), therefore commented that it is not expected that different X-ray systems could, or should, use the same energy and current settings to produce similar results. In general, the goal is to determine the parameters for a given system that produces the best results for that system, and contrast among different internal objects can be considered as a good results.

Previous researchers theorized that optimization of X-ray energy levels would enhance the obtainable details and thereby increase the efficiency of the radiographic method (Katz et al. 1950; Milner et al. 1950 and 1952). Other factors affecting efficiency of radiographic method were mentioned as film type, and placement of the specimen. In particular it was shown that the image contrast between softly attenuating materials can be enhanced by optimally selecting the X-ray energy and improving the spatial resolution (Zwiggelaar et al. 1997). Typically, lower electron current values have been used for the higher kVp values to avoid saturation of the image. The use of X-ray imaging in quality evaluation of variety of agricultural products has been reported by several researchers. The X-ray parameters used for different commodities and applications have been summarized in Table 2. It is noteworthy that in general, X-rays generated at low voltage have been used for small products like grains compared to large products like apple, peach etc.

The X-ray parameters shown in Table 2 and reported by various researchers are the parameters at which images with maximum possible features could be captured. In general it can be stated that images captured at higher voltage and/ or higher current would result in saturated image, i.e. X-ray photon are not attenuated enough to show the contrast among different constituents of material. While images captured at voltage and/ or current lower than appropriate would result in a dark image, i.e. most of the X-ray photon are attenuated and thus do not form a transmission image to show the contrast among different constituents of material. Curry et al. (1990) commented that besides material thickness, density difference and atomic number difference, radiation quality (kVp and mA-s) affects the contrast in resulting image. Effect of the imaging parameters on image quality has been reported by Kotwaliwale et al. (2007b). They found that for generation of pecan radiographs (at integration time of 460 ms), seven combinations of tube voltage-current (25 to 50 kVp and 1 to 0.25 mA) were more appropriate than other 33 tested combinations in terms of

Table 2 X-ray parameters used for radiography of agricultural materials

S. No.	Combination	Typical parameter values	Commodities/Application	Remark	References
1	High voltage and high current	50 kV and 300 mA	Classification of split pit peaches and normal pit peaches	Higher risk in use, chances of beam hardening artifacts, requires less imaging and exposure time, may not produce good contrast images for certain commodities	Han et al. (1992)
		40 kV and 800 mA-s	Seed weevil detection in mangoes		Thomas et al. (1995)
		25 to 70 keV and 10 to 100 mA	Apricot		Zwiggelaar et al. (1997)
2	High voltage and low current	295 kV	Whole corn	Higher risk in use, chances of beam hardening artifacts, useful for commodities of bigger dimensions like fruits, vegetables etc.	Martel and Belanger (1977)
		35 kV and 10 mA	Bruise detection in apple		Diener et al. (1970)
		45 kVp, 3 mA and 2 to 4 min exposure (film exposure)	Detection of bruises, senescence browning, rot, watercore and insect damage in apple		Schatzki et al. (1997)
		50 kVp, 13 mA, 8.3 ms/line for line scanning			
		49.9 to 50 kVp and 9.9 to 13 mA	Watercore damage in apples		Kim and Schatzki (2000)
		50 kV and 0.3 mA	Sorting of mature lettuce heads		Lenker and Adrian (1971)
		70 kV, 1 mA	Onions		Tollner et al. (2005)
		40–90 kV and 110–250 μA	Citrus, Peach, Guava infestation		Jiang et al. (2008)
		70 kVp, 1.5 mA and 40 kVp, 25 mA	Detection of glass contamination in horticultural peat		Ayalew et al. (2004)
3	Low voltage and high current	12 keV and 99 mA (for real time imaging)	Granary weevils in wheat	Relatively safe to use, less chances of image artifacts due to X-ray beam hardening, useful for commodities of smaller dimensions like grains, nuts etc.	Haff and Slaughter (2004)
		25 keV for 90 s	Pistachio nuts		Keagy et al. (1996)
		30 kV and 3.0 mA	Flow rate of corn		Arslan et al.(2000)
		32 keV and 3 mA for exposure time 60 s on films and 35 keV and 30 mA for 3 ms in case of line scan	Pinhole detection in almonds		Kim and Schatzki (2001)
4	Low voltage and low current	17.5 kVp and 3.0 mA	Insect infestation in grain	Typically useful for commodity of small size, low density, more safe, may require higher exposure time for good contrast image	Stermer (1972)
		15 kVp and 3 mA	Insect infestation in wheat		Schatzki and Fine (Brayant) (1988)
		25 kV for 0.5 min	insect detection in wheat		Keagy and Schatzki (1991)
		15–17 kVp and 65–70 μA for 3–5 s	Insect infestation in stored wheat		Karunakaran et al.(2003a; b; 2004a; 2005), Neethirajan et al (2006a)
		20 keV and 3 mA for 90 s (for film)	Granary weevils in wheat		Haff and Slaughter (2004)
		13.5 kV, 185 μA	Classifying vitreousness in durum wheat		Neethirajan et al. (2007a)
		26 kV, 11 μA	Classifying vitreousness in durum wheat		Neethirajan et al. (2007b)
		20 kV and 60 μA for 120 s	Wheat grain infested by granary weevil		Fornal et al. (2007)
		13.6 kV and 184 μA	Fungal infection in wheat kernels		Narvankar et al. (2009)
		25–50 kVp and 0.25–1 mA at 460 ms	Quality evaluation of pecans		Kotwaliwale et al. (2007b)

sufficient image contrast. The parameters listed in Table 2 were mainly chosen based on physical properties of the radiographed material (size, shape etc.) besides the features in the available hardware.

Decision support system for radiography

Defect inspection and classification have been difficult problems in the development of non-destructive sorting systems for agricultural commodities. This is because various types of defective tissues with differing severity, as well as other features, may occur on the product. These features may be due to unpredictable natural environmental conditions, insects, pathogens, physiological disorders or inherent biological diversity. Spectral imaging, machine vision and pattern recognition techniques are considered effective tools to identify defective tissues on agricultural products. Before introduction of digital imaging and image processing the decision system for identification of desired or undesired features has been manual. Computer based image processing algorithms may be combined with reasoning, decision making and task management in an integrated system for the diagnosis of internal defects in food commodities. This opens the prospects of online detection of disorders and development of sorting machines.

Manual

There are many reports where features like insects at different stages, fruit stones, physiological or physical damage etc. have been identified by observing the film directly. Physical aides such as microscope (Stermer 1972; Schatzki and Fine 1988), video magnification (Keagy and Schatzki 1991), digital representation (Keagy et al. 1996; Haff and Slaughter 2004) have also been reported for better readability of images.

Stermer (1972) commented that the efficiency of manual decision based on X-ray film observation was nearly 100% for grain infested with full grown larval and pupal stages and about 80 to 90% with eggs or tiny larval stages of insects. Schatzki et al. (1997) observed that when images were scrolled across the screen at increasing rates, recognition fell off to unacceptable compared to when still images were viewed on a computer screen.

Image processing

The potential of image processing techniques in the agricultural and food industry has long been recognized (Tillet 1991). Different types of image processing algorithms have been adopted for enhancement of images to aid decision on attributes. The image processing algorithms have been improving with improvement in computational skills and hardware. Whereas the initial works included morphological image processing techniques to enhance features of interest, the recent approaches use stochastic and advanced techniques leading to automatic decision support.

Some primary image processing algorithms like subtraction of images taken at a specific time interval have been suggested to determine relative movement of live insects infesting the kernels (Gonzalez and Woods 2001; Karunakaran et al. 2003b).

Thresholding based on pixel intensity has been the most common algorithm used for separating areas of interest from other areas. Han et al. (1992) developed threshold equation, which considered the maximum and minimum intensities for each individual peach. Morphological processing, filtering, masking etc. have been reportedly applied on digitized/ digital X-ray images before or after thresholding to emphasize features and to consolidate the area of interest. Morita et al. (1997) suggested use of unsharp masking filtering while Shahin and Tollner (1997) used an 11×11 Gaussian filter and morphological image processing operation 'open' to denoise the X-ray image, then binarized the image at a threshold of 150 (in 8 bit image) gray level. Shahin et al. (1999) recommended use of a Gaussian filter for noise removal in X-ray images of moving apples and onions. Kim and Schatzki (2001) developed an alogorithm based on first-order (pixel intensity) and second-order (intensity change) information to identify pinhole damaged region of almonds. Their algorithm also used filtering and averaging to remove small noise associated with the X-ray imaging system. Karunakaran et al. (2003a, b) and Neethirajan et al. (2007a) used simple thresholding method to separate objects from their back ground. Yacob et al. (2005) performed region of interest segmentation using edge detection filters. They used canny followed by 'sobel' edge detector. Fornal et al. (2007) developed three-stage algorithm for detection of infested wheat kernels that comprised of image enhancement, "Local equalisation" filter and thresholding. Kotwaliwale et al. (2007b) performed image subtraction of blank image from captured image to segment the region of interest (ROI), i.e. pecan samples, from the image background. They commented that pixel intensity-based algorithms and algorithms based on high-frequency emphasis were not successful in segmenting the region of a pecan weevil, nor were the morphological operations like image erosion and histogram based operations. Jiang et al. (2008) also observed that it was difficult to segment the infestation site with global (single) threshold values and it was not useful for the follow-up image processing. They therefore used adaptive unsupervised thresholding algorithm based on the local gray-level distribution, this process was followed by morphological operations to segment the ROI. Narvankar et al. (2009) observed that it was difficult to remove a kernel from the background by a simple thresholding method without losing significant information from the kernel. Some other morphology based processing operations reported are: binary watershed algorithm to segment individual pistachio nuts and nutmeat in single nut from a cluster image (Casasent et al. 2001), and for wheat kernel (Narvankar et al. 2009); reverse water flow and twice OTSU algorithm to segment defected parts in pecan radiographs (Mathanker et al. 2011).

Image intensity histogram based approaches have been reported successful by several authors. Histogram features such as the number of pixels in histogram bins and four statistical features of the nutmeat histogram: mean, varience, skew and kurtosis have been found useful in identification of insect damage in tree nuts (Keagy et al. 1996; Casasent et al. 1998). Other histogram properties such as the total gray value, mean gray value, standard deviation of gray levels, and five histogram moments of orders 2 to 6 have been successfully used by Karunakaran et al. (2003a, 2003b, 2004b, 2004c, 2004d) to identify uninfested and infested wheat kernel and Neethirajan et al. (2006a, 2007b) to distinguish between sprouted and normal wheat and between vitreous and non vitreous durum wheat. The features thus extracted were used in appropriate stochastic models and success rate of as high as 100% has been reported. Mathematical and stochastic methods like discriminant analysis (Karunakaran et al. 2003a), hold-out method of the parametric and non-parametric classifiers (Karunakaran et al. 2003b and Neethirajan et al. 2006a), artificial neural networks (Yacob et al. 2005 and Narvankar et al. 2009) have been reported successful for feature recognition in different commodities. Pattern recognition using k-nearest neighbor (kNN) algorithm and artificial neural network has been reported useful for detection of watercore in apples by (Kim and Schatzki 2000).

Tao and Ibarra (2000) developed a thickness compensation algorithm to detect bone fractions in poultry. The algorithm required knowledge of thickness of material at each pixel point in the image. On the other hand image processing methods have been employed for estimation of thickness of object from digital radiographs. Arslan et al. (2000) and Kotwaliwale et al. (2007b) applied image processing algorithms based on the equations for exponential decay of photon intensity passing through a material relating to the grayness of image to estimate thickness of the material at various points in the radiograph.

Manual observation for decision making is a strong tool but may require more time and efforts. Moreover, certain tiny features may be omitted from observation due to limitation of human eye or minor defects in the radiograph. However, initial manual observations form the basis for image understanding and processing algorithms. Also, flexibility and human intelligence involved with the manual decision making process make a system flexible enough to accommodate out of range variability in the agricultural products. Image processing techniques have been used effectively for image enhancement, segmentation and stochastic feature extraction to aid to decision making process. The image processing has progressed with advancement in computation power. Initial work has been limited to primary processing of images using established mathematical operations while recent work includes application of complex numerical and stochastic models. Although all the work has been focused on processing of monochromatic images, there are no golden algorithms or protocols like those used in medical imaging. Researchers still have to develop customized process algorithms suiting to the product, its detectable features and the imaging parameters.

Dual energy X-ray imaging

Dual-energy X-ray imaging is a technique which produces two separate images corresponding to two different X-ray energies. There are two ways of performing dual-energy imaging. The first method uses two X-ray exposures, one applied immediately after the other, with different kVp values of the X-ray tube. Because the X-rays in both scans contain a range of energies, some manipulation of the data is necessary to produce the final images (Ayalew et al. 2004; Neethirajan et al. 2007a). The second method uses a single exposure with two detectors. The first detector, usually made from Y_2O_2S or BaFBr, which is placed directly beneath the object, preferentially absorbs lower energy X-rays. This detector effectively hardens the X-ray beam incident on the second detector, which is typically made from Gd_2O_2S. Therefore, the image from the first detector corresponds to a low X-ray-energy, high contrast image, and that from the second detector to a high X-ray-energy, low-contrast image (Anon 2003; 2008).

Dual energy X-ray imaging is an alternative technique to simple transmission X-ray imaging. A small contrast in a X-ray transmitted image can be enhanced by a suitable selection of two X-ray photon energies (Zwiggelaar et al. 1997). Dual energy X-ray imaging has been successfully used to detect glass contamination in horticultural peat (Ayalew et al. 2004); to evaluate meat tenderness (Kroger et al. 2006), to classify vitreousness in durum wheat (Neethirajan et al. 2007a) and to predicts carcass composition from live sheep and chemical composition of live and dead sheep (Pearce et al. 2009).

Use of dual energy radiography has shown some success. The image processing algorithms used with dual energy radiography have been computationally less challenging. However there are some practical limitations like need of double detectors and/ or source, requirement of special detectors or extra time required for double exposure.

Applications—success and limitations

Radiography

During the ongoing development of digital radiography based non-destructive quality evaluation, various researchers have shown success and limitation of their techniques (shown below in chronological order). Diener et al. (1970) found that X-ray scan line detection system could detect bruises on apples. But the system required fruit to be oriented before passing through the scan line system to prevent confusion between calyx and stem voids and surface bruises. Lenker and Adrian (1971) differentiated mature and immature lettuce heads with a low powered X-ray generator and a photodiode that sensed X-ray transmission through the heads. However changes in sensitivity of the photodiode with temperature required its cooling in hot days. Stermer (1972) found that trained examiner could detect 100% insect infestation at medium and late larval stages by observing a grain radiograph while for eggs and young larval stages the accuracy was 80–90%. Schatzki and Fine (1988) found that manual radiograph analysis of wheat kernels was too slow to be practical. Further, they commented that X-ray radiography to detect only third and later instar hidden insects appeared to be feasible; detection of earlier instars was not possible with their method. Han et al. (1992) developed a method and process that could nondestructively distinguish, with 98% success, between peaches with split pits and peaches with normal pits. However, the method required specific orientation of fruit during radiography. Keagy et al. (1996) concluded that it was possible to identify many, but not all, insect infested pistachio nuts with X-ray images and machine recognition.

Arslan et al. (2000) demonstrated the use of low energy X-rays, up to 30 keV, densitometry for grain flow rate measurements through laboratory experiments. They also found that grain moisture (at typical values from 15 to 25%) had a negligible change on the X-ray attenuation coefficients and did not affect flow rate measurements. Kim and Schatzki (2000) explored the possibility of using two-dimensional X-ray imaging to detect internal water core damage in apples. The results of this study showed that the system was able to correctly recognize apples into clean and severe categories within 5–8% false positive and negative ratios. The results of this study also showed that the algorithm was able to recognize apples independent of apple orientation, but only if the stem-calyx axis made a fixed angle with the X-ray beam. Kim and Schatzki (2001) used scanned film images of almonds and succeeded in 81% correct recognition ratio with only 1% false positives to detect pinhole damage. Whereas for line scanned images, the algorithm correctly recognized about 74% of the pinholes with about 12% false positives. They commented that the performance of the algorithm on line-scanned images was much lower than on scanned film images due to the lower resolution (0.5 mm/pixel) of the line-scanned images than film scanned images (0.17×0.17 mm pixels of 8-bit resolution).

Success rate in the range of 73–99% has been reported in detection of insect or fungal infestation and other physiological disorders in different stored grains using soft X-ray radiography (Karunakaran et al. 2003a, 2003b, 2004a, 2004c, 2005; Haff and Slaughter 2004; Neethirajan et al. 2006a, 2007b; Narvankar et al. 2009). Haff and Slaughter (2004) commented that lower energy X-rays gave higher contrast in the resulting image, and the large current increased the signal-to-noise ratio by increasing the number of X-ray photons that generated the image. Kotwaliwale et al. (2006) successfully determined apparent linear attenuation coefficients of pecan nutmeat and shell at various X-ray tube peak voltages and sample thickness using digital radiography technique. Kotwaliwale et al. (2007b) showed that radiography at X-ray tube voltage of 40 kVp and current of 0.5 mA with 460 ms integration time could be used to detect physiological and insect damage to pecans. They further showed that the nutmeat weight could be estimated from the radiographs with mean estimation error of about ±0.09 g (±5.8%). Jiang et al. (2008) developed an adaptive image segmentation algorithm and implemented in the X-ray scanner for real-time quarantine inspection at a scanning rate of 1.2 m/min. Mathanker et al. (2011) were able to classify defects in pecans using AdaBoost classifier with reverse water flow segmentation or twice OTSU segmentation. The classification efficiency of more than 92% was achieved by them.

Ayalew et al. (2004) successfully applied dual energy X-ray absorptiometry for detection of glass fragments in horticultural peat. There was >75% detection of glass presence if thicker than 3 mm, but 100% detection of glass fragments thicker than 1 mm. However, they could not distinguish between glass and stone. Dual energy X-ray imaging was found more accurate than simple transmission based X-ray imaging by Neethirajan et al. (2007a). They could classify vitreous and non-vitreous wheat kernel with an accuracy up to 93%.

Technology for using radiography in non-destructive quality evaluation has been improving with time. The initial work was more of an exploratory type, to test the feasibility of the technique and therefore quite a few limitations were reported by the early researchers. With improvement in X-ray imaging hardware and computational powers, many of the limitations have now been surmounted. However, there are some new challenges like making the technique more field-worthy.

Computed tomography

Application of CT in non-destructive quality detection of agricultural products is still in nascent stage. Most of research work has been carried out using medical CT scanners and employing software developed for analysis of human anatomy. Despite these lacunae, several successful attempts have been reported. The feature identification process is manual however use of image processing algorithms (readily available or tailored) has been reported for image enhancement and better readability. A possibility of determining chemical composition of agricultural materials has also been explored using CT. Compared to radiography higher energy X-ray photons are employed to generate CT images. Requirement of shielding would therefore be more critical while using CT imaging. The parameters used for generating CT images of various agricultural commodities are listed in Table 3. Although, changes in hardware has now considerably reduced the time required for CT scan, but it is still a matter of concern. Lim and Barigou (2004) observed that to scan a 10 mm cube of cellular food products over 180° in 200 discrete steps of 0.9°, it took about 30–45 min.

Wooly breakdown of cool stored nectarines was monitored by Sonego et al. (1995). They observed that areas exhibiting wooliness appeared darker indicating presence of gas inclusions, which did not absorb X-rays. Ogawa et al. (1998) used a medical CT scanner for the detection of selected non-metallic materials embedded in various fluids and food materials. The author determined detection limits for foreign materials and commented that when the volume of the foreign materials was smaller than the physical resolution of the X-ray CT scanner, small parts may be detected as foreign materials but not correctly identified as being which type of materials. Lammertyn et al. (2003) found a clear contrast between healthy and brown tissue of 'Conference' pears. The highest pixel intensity value of the affected tissue was still lower than the lowest pixel intensity value for unaffected tissue, and one threshold value was sufficient therefore to separate both types of tissue. Lim and Barigou (2004) described imaging, visualization and analysis of the three dimensional (3D) cellular microstructure of

Table 3 X-ray parameters used for computed tomography of agricultural materials

S. No.	Commodity	Typical parameter range	Application	Reference
1	Grains & nuts	420 kV and 1.8 mA	To explain the airflow resistance difference of wheat, barley, flax seed, peas and mustard along the horizontal and vertical directions	Neethirajan et al (2006b)
		100 kV and 96 µA	To investigate structural features and internal defects of wheat	Dogan (2007)
		120 kVp, 33 mA for 57 s	Insect behaviour study in pecan	Harrison et al. (1993)
2	Fruits & vegetables	120 kV, 700 mAs	Imaging interior regions of apples under varying moisture	Tollner et al. (1992)
		80 kV, 40 mA with 2 s acquisition time	Wooly breakdown of cool-stored nectarines	Sonego et al. (1995)
		120 kVp, 230 mA for 9 s	Sweet potato weevil larvae development and subsequent damage in infested roots	Thai et al. (1997)
		25 to 70 keV and 1000 to 10 mA	Finding the apricot stone within fruit and to study root growth of a maize plant in a soil sample as it develops over time	Zwiggelaar et al. (1997)
		150 keV and 3 mA	Relating X-ray absorption with physic-chemical characteristics like density, moisture content, soluble solids, titrable acidity and pH of mangoes	Barcelon et al. (1999b)
		150 kVp and 3 mA	Study of internal changes associated with the ripening process of mango	Barcelon et al. (2000)
		53 kV and 0.21 mA	Study of development of core breakdown in 'Conference' pears	Lammertyn et al. (2003)
		60 kV and 167 µA	To investigate the effect of far infra red radiation (FIR) assisted drying on microstructure of a food viz. banana.	Leonard et al. (2008)
3	Others	120 kV, current varying from 140 mA-s to 585 mA-s	Detection of foreign material in various fluids and food materials such as bread, butter, cheese, fish-meal, sausage, hamburger, patty	Ogawa et al. (1998)
		100 kV and 96 µA	To derive useful 3D quantitative information of a variety of cellular food materials like aerated chocolate bar, strawberry mousse, honeycomb chocolate bar, chocolate muffin, and marshmallow	Lim and Barigou (2004)
		80 to 130 kV, 106 mA	Determination of quantity of sodium chloride in ground pork and dry cured hams	Haseth et al. (2007), Haseth et al. (2008)
		100 kV and 96 µA	To study ice crystal structure formation during freezing of meat, fish, chicken, carrot and cheese.	Mousavi et al. (2007)

a number of food products (aerated chocolate. Mousse, marshmallow and muffin) using X-ray micro computed tomography. Author determined a 3D model of the foam microstructure and by combining image analysis with a stereological technique; they obtained quantitative information on a number of parameters including spatial cell size distribution, cell wall thickness distribution, air cell connectivity and degree of microstructure anisotropy. Neethirajan et al. (2006b) developed the algorithms to determine total grain surface area, total airspace area, number of airflow paths, areas of the individual airflow paths and length of the individual airflow paths using CT images of five types of grains (wheat, barley, flax seed, peas and mustard). They further developed method to analyze pores that influenced fluid transport phenomenon inside grain bulks (Neethirajan et al. 2008). Quality evaluation based on voids has also been attempted by Mousavi et al. (2007) who showed that from the reconstructed 3D image based on a set of 2D images voids formed due to freeze drying could be measured in number of foods like meat, fish, chicken, potato, cheese and carrot. Leonard et al. (2008) illustrated the use of X-ray microtomography to investigate the effect of drying temperature on microstructure of a banana. 3D gray level images were formed by two phases: the pore space at low gray levels (dark voxels), and the banana skeleton at high gray levels (bright voxels). The author segmented the 3D image by assigning the value 1 to all pixels whose intensity was below a given gray tone value and 0 to others. From the 3D processed binary images the porosity was measured. Increase in drying temperature was found to lead to an increase in final porosity of the products.

Use of CT number has been explored by researchers to nondestructively determine certain quality parameters of agricultural products. Ogawa et al. (1998) commented that food materials possesses a range of CT number due to their inhomogenity and when CT number of a foreign material was within this range, a foreign material was not detectable even if it had a volume larger than the physical resolution of the X-ray CT scanner. Barcelon et al. (1999a) produced histogram for the peach image, reflecting the frequency of the CT number of peach slice under consideration. Judging from the histogram of the image, a fresh peach had less attenuation frequency between the CT numbers ranging from −300 to −1000. In contrast, peaches after 2 weeks of ripening had a considerable increase in attenuation frequency on this CT number range. This confirmed the presence of voids and a drier region that was probably developed due to the loss of moisture towards the outermost layer in the fruit. Author further determined relationship between CT number and the physicochemical contents. Further, Barcelon et al. (1999b, 2000) used X-ray CT technique to analyze the internal changes associated with the ripening process of mango. They evaluated mango fruits for X-ray absorption, density, moisture content, soluble solids, titrable acidity and pH. The author commented that CT image showed visible features of the internal structural changes between the fresh and ripened mangoes. They concluded that CT number, moisture content and titrable acidity decreased significantly with postharvest ripening time, while pH and soluble solids increased with postharvest ripening time. Similarly, Haseth et al. (2007) successfully modeled dependency of CT value on chemical composition of meat and the linear relationships between sodium chloride (NaCl) and CT value.

Computed tomography has been found to provide detailed 3-dimensional information using X-ray beam projection. The 2-dimensional slices extracted from CT imaging have been found to show better contrast among the constituents of the respective slice. However, it takes more time to generate 2-D and 3-D slices compared to transmission radiography. Therefore use of CT image based applications for on-line quality evaluation may not be practical at this stage. Determination of CT number of a slice at a predetermined location to evaluate certain quality parameters like moisture content, TSS, acidity etc. has some potential for practical applications.

Conclusions

X-ray based two imaging techniques namely radiography and computed tomography are powerful tools for non-destructive internal quality evaluation. After successful use in medical diagnostics and some industrial applications, researchers are employing these tools for quality evaluation of agricultural products. Due to their potential in checking quality parameters, researchers are concentrating towards study of many complex behaviors of physiological processes related to agricultural and food commodities. X-rays are low wavelength (0.01 to 10 nm) high energy (120 eV to 120 keV) electromagnetic radiations which can penetrate through many materials. The photons lose their energy while travelling through the matter and this attenuation helps creation of transmittance image. Attenuation coefficient is a material property that also depends on the intensity of incident X-ray beam. In CT domain the X-ray attenuation is also represented by CT number.

Radiography which was historically performed on photographic plates or films can now be performed online due to availability of digital technology. A radiograph is a 2-D projection of different constituents of a matter through which X-ray beam passes. On the other hand data from a CT imaging procedure (consisting of either multiple contiguous or one helical scan) can be viewed as images in the axial, coronal, or sagittal planes, depending on the diagnostic task. CT completely eliminates the superimposition of images of structures outside the area of interest. Because of the inherent high-contrast resolution of CT, differences between tissues that differ in physical density by less than 1% can be distinguished.

Generation of images with high contrast among the different constituents has been a challenge. Optimizing X-ray generation parameters (tube voltage and current) and camera parameters (integration and/or exposure time) for different commodities has been emphasized by researchers. Radiography of majority of agricultural products can be performed using low energy X-ray beam due to their smaller size and typical constituents of low atomic number in them. Whereas CT imaging is normally performed using higher energy X-rays.

Computers have played a vital role in decision support system that plays an important function in identification of desired or undesired features in an image. Variety of image processing algorithms have been employed for image reconstruction in CT, image enhancement, segmentation, and classification in both the techniques. Due to vast diversity of products and their cultivars, it has not been possible to develop standard image processing protocols yet. However, the tailored protocols have been successful in evaluating certain internal quality parameters and some field usable prototypes based on digital radiography have been developed. Harmful effects of X-rays are definitely cause of concern while using these two techniques, but properly designed shielding can prevent human exposure. With steady improvements in instrumentation and computational power, both in terms of hardware and software, it is expected that both these techniques would become more field-worthy in times to come.

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