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ORIGINAL PAPER

X-ray detection of defects and contaminants in the food industry

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Abstract The ability of X-rays to traverse through matter and reveal hidden contaminants or defects has led to their extensive use in manufacturing industries for quality control inspection. The difficulties inherent in the detection of defects and contaminants in food products have kept the use of X-ray in that industry limited mainly to the packaged foods sector. Nevertheless, the need for non-destructive internal product inspection has motivated a considerable research effort in this field spanning many decades. Improvements in technology, especially more compact and affordable high voltage power sources, high speed computing, and high resolution detector arrays, have made many X-ray detection tasks possible today that were previously unfeasible. These improvements can be expected to continue into the future. The purpose of this article is to give a review of research activity related to the use of X-ray imaging for the detection of defects and contaminants in agricultural commodities and discuss improvements in technology required to improve these detection capabilities.

Keywords X-ray · Sensing · Defects · Detection · Inspection · Contaminants

Introduction

Recent outbreaks of bacterial contamination in food have led to an increased emphasis on food safety in the United States and elsewhere. Although bacterial contamination such as *Escherichia coli* and *Salmonella* may present the greatest health threats and attract the most headlines, many other defects and contaminants found in food have been persistent problems both in terms of food safety and quality. Potentially carcinogenic toxins produced by mold have been an area of particular concern and active research over the past decade. Access to many foreign markets for corn and tree nuts is dependent on compliance with strict limitations on the amount of toxins present in the product, especially aflatoxin, and rejection of large amounts of product under these limitations is becoming more and more common. For many products, the incidence of toxin production has been correlated with insect damage, and the prevention and detection of infestation has taken on increased importance for food producers and processors. Perhaps less perilous but still annoying contaminants such as pits and pit fragments, unwanted seeds, bones or bone fragments, sticks, rocks, metals, plastics, etc. continue to be a nuisance for producers and consumers alike, resulting in many injuries and lawsuits each year.

In response to a number of food scares in Europe during the 1990s, the Commission of the European Communities released the White Paper on Food Safety in July 2000 [1]. This report contained recommendations for ensuring food safety at all points in the food supply chain, known as the "Farm to Table" approach, and a number of these recommendations had direct impact on food processors. New regulations were introduced that cover all agriculture across the EU, replacing a multitude of regulations in different countries. For food processors, the major impact of the new regulations is that they have the primary responsibility to ensure the safety of their product, and failure to use available technology leaves them liable for injuries or illnesses caused by their product. This has led to

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a huge expansion in the market for real-time X-ray inspection systems, with a multitude of companies entering the market. Since imports to the EU are also affected by the new regulations, this trend is likely to spread outside of the EU as well, and the market for all types of food inspection systems, including X-ray, is likely to see substantial growth.

There are many types of inspection systems for food quality and safety. Machine vision, using visible light cameras, is common for the inspection of the surfaces of food products for defects, such as bruises on apples. Color sorters also use visible light, but measure light intensities at specific wavelengths rather than produce images. Sorters using near infrared sensors are routinely used to sort food streams or inspect for unwanted contaminants, such as pit fragments in prunes. Even sound is used for some applications, such as the removal of closed shell pistachio nuts [2]. An excellent review of the many detection technologies, including metal detectors, magnets, optical systems, microwave reflectance, nuclear magnetic resonance (NMR), radar, electrical impedence, ultrasound, and also X-rays can be found in a book edited by M. Edwards [3]. There are also a number of review articles available that summarize the various techniques for detection of foreign materials in food [4–8]. The objective of this article is to present a focused review of the use of X-ray technology for inspection of food products.

X-ray inspection has a distinct advantage over most other detection technologies as it allows non-destructive imaging of interior features of a sample to detect hidden defects or contaminants. However, it also has a number of disadvantages, including a relatively high cost, the need for radiation shielding and the dangers inherent in using radiation, and the need for high voltage power supplies to generate the X-rays. For these reasons, X-ray inspection is generally considered the option of last resort. In spite of this, its use continues to expand in the food industry because it is often the only viable option.

In recent years, X-ray inspection has become increasingly common in certain segments of the food industry. This is particularly true for processed foods, including product that is packaged in cans, bottles, or jars, presumably due to the ever-increasing emphasis on food safety. It is now an accepted fact that X-ray inspection is superior to traditional metal detection technology for the detection of metallic contaminants, and adds the potential to eliminate other foreign non-metallic material such as bone, glass, wood, plastic, and rocks. Technological advances in the areas of high voltage power supplies, solid-state detectors, and computation power and speed have made X-ray systems more affordable, reliable, and easier to use while improving image quality and detection capabilities. A variety of improvements in sensor technology have improved resolution, including CsI crystals and improved CCD arrays.

X-ray system components

X-ray sources

X-rays are produced when high-energy electrons strike a target material, typically Tungsten. An X-ray tube is similar in design to a light bulb, except that the electrons shedding from the heated filament are subjected to a high voltage, causing them to accelerate and strike the target at high energies. As these high energy electrons decelerate in the target material, electrons of target atoms are first excited to higher energy levels, and then decay to their ground states with the emission of X-ray photons. The size of the target area over which X-rays are generated is called the focal spot size, and has consequences for the characteristics of the imaging system as will be discussed in a later section. The X-rays themselves have two characteristics that are important in the operation of the X-ray machine; energy and current. The energy refers to the maximum energy that an X-ray photon can possess when exiting the tube (generally between 20 and 100 KeV for food inspection) and defines the penetrating power of the X-ray beam. The current, measured in mA, is associated with the number of X-ray photons being generated. The power supply has a maximum power (the product of the energy and the current) rating, and a balance is therefore required between the energy and current, which has consequences for the resulting image quality. The result of this power limitation is that most X-ray inspection systems are limited to less than 10 mA of current, many much less, and a discussion of the consequences of this will follow.

Detection and imaging

The first X-ray detector was a sheet of paper coated with barium platinocyanide used by Roentgen in 1895. The paper fluoresced when impacted by X-rays, and led to their initial discovery. Since that time, many different materials have been observed to react to the presence of X-rays and have led to many different types of detectors. Modern X-ray inspection units generally fall into one of three categories: film, linescan machines, and direct detection semiconductor materials. Of these, film is the most widely used because of its high resolution and dynamic range. Besides the huge quantity used for medical and dental purposes, it is also used for inspection purposes for numerous manufactured products. It is also used for quality inspection of many food products.

There are several reasons why alternatives to film are desirable. Manufacturing and developing film creates toxic waste. Medical and dental X-rays must be stored for long periods of time, causing problems in the amount of space required and in the inefficiency of retrieval. Digitizing the film with a scanner alleviates these problems, but is awkward and some resolution is lost. Additionally, film is relatively slow in terms of exposure and developing time, and is therefore unsuitable for real time inspection.

While phosphors have been used since the time of Roentgen to display radiographic images, they could not compete effectively with film until the arrival of computer technology which could display digital images. Since then, phosphor based X-ray detectors have become commonplace in linescan type machines such as those seen in airports for luggage inspection. Phosphors are a class of luminescent material, which absorb electromagnetic radiation and re-emit it at a longer wavelength. When used as an X-ray detector, the phosphor will absorb X-ray photons and emit visible light photons which are subsequently detected by either photodiodes or CCDs. Some linescan detectors bypass the use of phosphors by using modern semiconductor materials that convert incident X-ray energy directly into an electric current. In a linescan array, hundreds or thousands of detectors, either photodiodes overlaid with phosphor or semiconductor crystals, are placed in a row perpendicular to the direction of sample flow. While the sample moves over the array at a fixed rate, the output of the photodiodes are repeatedly read at a rate that is synchronized to the speed of the sample. The image is then constructed row by row. Since the creation of the image is dependent on the motion of the sample across the line of detectors, this arrangement is ideal for high-speed inspection. Most high-speed applications employ a side view arrangement, as opposed to a top view system common in luggage inspection equipment (Fig. 1). In the side view configuration, the conveyor belt is not included in the image, allowing for improved image quality.

The majority of high-speed X-ray inspection systems on the market today employ the linescan configuration because its design is dependent on the motion of the sample, which introduces image distortions for image intensifier systems that use cameras.

Some linescan systems incorporate dual energy detection technology to differentiate between soft and hard materials. Two detector arrays are used, one on top of the other. The lower energy X-ray photons are absorbed by the first detector array while higher energy photons pass through to the second array. The difference between the two images represents the softer material. This technique is widely used in luggage inspection, allowing identification of softer organic material as well as harder metals.

A third class of X-ray imaging system, commonly known as X-ray fluoroscopy, involves the use of image intensifiers. These devices, which amplify light, are commonly used in low light situations such as night vision. A typical image intensifier uses a photocathode to convert incident light photons to electrons, which are accelerated across a large potential onto an appropriate phosphor material, which in turn converts the electrons back into visible light photons. The energy acquired by the electrons as they are accelerated results in photon gains of up to 30,000 in the most modern intensifiers. Unlike linescan inspection systems, image intensifiers produce an image that can be observed directly or cast onto a screen. However, image capture applications require coupling to a camera. CCD cameras are generally used for digital image acquisition, forming a real time digital imaging system. For X-ray imaging, the photocathode is overlaid with a material that fluoresces in the presence of X-rays, converting the incident X-ray photons into visible light.

A variation on X-ray linescan imaging that allows three dimensional images is computed axial tomography, or CT imaging. An X-ray source rotates around the sample with detectors positioned opposite the source. Multiple “slices” are progressively imaged as the sample is gradually passed through the plane of the X-rays. These slices are combined using a mathematical procedure known as tomographic reconstruction to form a three dimensional image. Helical or spiral CT machines incorporate faster computer systems and advanced software to process continuously changing cross sections. As the sample moves through the X-ray circle, three dimensional images are generated that can be viewed from multiple perspectives in real time on computer monitors. CT scans produce images of superior quality to traditional X-ray systems, but the high cost and lengthy scanning and data processing times make it an

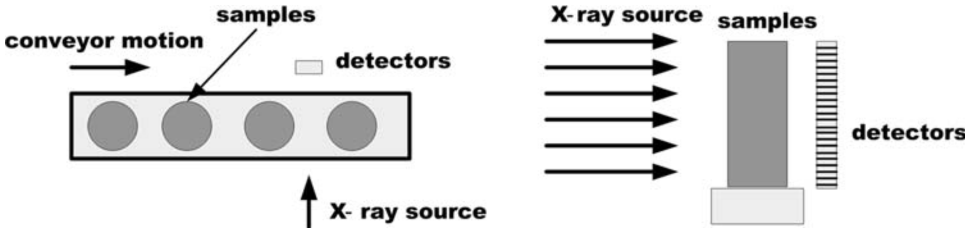

Fig. 1 Schematic of a side view linescan X-ray machine shown from the top (left) and the front of the conveyor (right). The linear array of detectors constructs an image of the sample row by row

impractical method for real time food inspection at present. Nevertheless, there have been a number of research projects demonstrating the efficacy of using CT systems to nondestructively assess food quality. If technology and computer processing times improve, and system prices fall, CT scanning could replace traditional X-ray imaging as the predominant method for real time inspection of food products.

While the three classes of X-ray systems described above represent the majority of systems currently in use, there are some other systems that have been investigated for their potential use in food inspection. Linescan machines with dual orthogonal beams, basically a simplified version of CT scanning, have been shown to alleviate noise problems and allow the detection of long thin contaminants which often go undetected by normal linescan machines [9]. Other systems have been designed that combine the X-ray image of a linescan machine with either machine vision or laser imaging to allow depth perception [10–12]. X-ray micro computed tomography has been proven effective for food inspection, although cost and throughput speed would seem to eliminate it as a practical method [13]. Advanced X-ray technologies that do not generate images, i.e. diffraction tomography [14] and characteristic scattering analysis [15, 16] have also been used to distinguish contaminants from the surrounding food medium, but again practical limitations appear to limit their potential for adoption by the industry.

Many companies that produce X-ray equipment provide overviews of X-rays and X-ray systems. An excellent review of the use of X-ray systems for food inspection is given on the website of the Safeline Corporation [17].

A critical component of an automatic inspection system is the image processing and detection algorithm. It is not practical to attempt to describe each method that has been presented in the literature. The majority of detection algorithms for X-ray images of food products use a variation of discriminant analysis [18], neural networks [19–21], or simple/adaptive thresholding [22]. Spectral filtering of the X-ray image has also been shown to be an effective tool [23, 24]. References cited here are for illustrative example only, as the field of image processing and statistical analysis, including the techniques listed, is extensive and a review of that field is beyond the scope of this article.

Image quality parameters

Three important parameters associated with X-ray image quality are resolution, signal to noise ratio (SNR), and contrast between the material of interest and its surroundings. Noise is broadly defined as an additive or multiplicative contamination of an image [25]. For X-ray imaging systems, the sources of noise can generally be divided into two categories: quantum (shot) noise and electronic noise. Quantum noise is a consequence of the (random) statistical nature of both the X-ray photons incident on the detectors, light photons emitted by the detectors, and the movement of charges within the detector and in electronic circuits. Electronic noise is created by the imaging system itself, and there are many potential sources.

Given an array of detectors in the vicinity of an X-ray source with no sample in between, or with a uniform sample, an equal number of X-ray photons would be expected to strike each detector, resulting in a uniform image. In actuality, the number of photons striking each detector at any given time follows a Poisson distribution. Only with a large number of incident photons will the mean behavior result in the expected uniform distribution. This is the source of quantum noise, and is an important consideration in the design of X-ray machines as it is generally desired to limit exposure time, whether to increase throughput in inspection systems or to limit patient dose in medical applications.

Quantum noise decreases as the square root of the number of incident photons, i.e. a fourfold increase in the photon count corresponds to cutting the quantum noise in half. Alternatively, with incident intensity unchanged, a fourfold increase in the collection area of the detector will result in a twofold reduction in quantum noise. For this reason, there is a tradeoff between quantum noise and resolution in any X-ray detector.

The amount of quantum noise varies between imaging systems. All other things being equal, it is dependent on the exposure time on the detectors. For X-ray microscopes, where exposure times can be made as long as required, quantum noise levels can be very low. For high speed inspection exposure times are necessarily low, and quantum noise is the predominant source of noise. The plot in Fig. 2 was generated by taking multiple images of a flat, homogeneous material on a linescan X-ray machine. The images were averaged to simulate the effect of longer exposure time on each detector. Noise was measured as the standard deviation of pixel values over a uniform region and plotted against the number of images averaged. The plot indicates that at least 80% of the noise in the system is due to quantum noise [26]. The detectors in this particular system were a linear array of 500 µm photodiodes overlaid with Gd_2O_2S:Tb phosphor.

Incident X-ray photons are not the only source of quantum noise in a detection system. There is also randomness in the emission of photons from a phosphor, motion of charges within the photodetector, or in any electronic circuits that are part of the detection system [27]. As demonstrated in Fig. 2, for high speed X-ray imaging systems these sources of noise are generally small

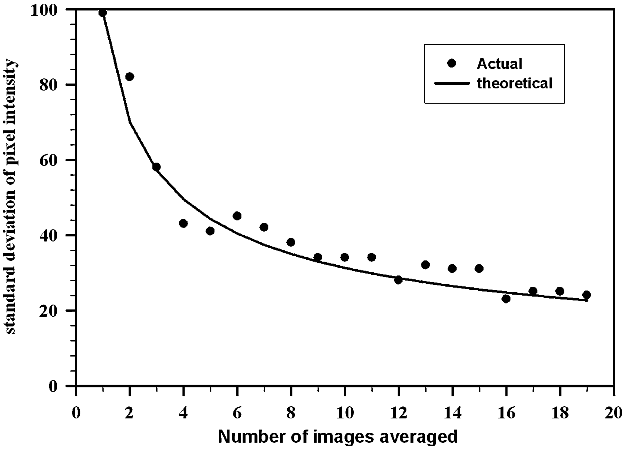

Fig. 2 Result on noise of averaging images on a linescan X-ray machine. As the number of images averaged (n) becomes large the quantum noise becomes very small. The remainder then represents noise from other sources. In this case, for large n total noise reduces to about 20% of the value for $n = 1$. The 80% drop in noise indicates that the majority of noise in the system is due to quantum noise [26]

compared to the noise resulting from the distribution of the X-ray photons at the detectors.

Resolution describes the differentiation of small, close objects, such as sets of bars on a resolution chart [28]. There are several ways that resolution of an image can be expressed, the most common being line pairs per millimeter (lp/mm) as measured using an X-ray test pattern containing pairs of lead lines spaced with increasing frequency. Often the resolution of a system is simply expressed as the size in microns of half of a line pair.

The resolution of an imaging system can also be expressed in terms of the modulation transfer function (MTF) at various frequencies. Expressing resolution in terms of the MTF is essentially the equivalent of measuring the impulse response, or point spread function, of the imaging system. In real terms, this is accomplished by measuring the response of the system when X-rays are incident in the direction of a single detector. MTF measurements are difficult to accomplish and require sophisticated equipment and techniques. Furthermore, it is difficult to interpret MTF results in practical ways, such as translating an MTF measurement to an lp/mm value. MTF measurements are more commonly used to compare resolutions between systems.

There are several factors that affect the resolution of an X-ray imaging system. The size and spacing of the detectors determines the ideal resolution. For phosphor based detectors, resolution is lost through light scattering in the phosphor material. The focal spot size of the X-ray tube can have an impact on the resolution of the output image in a number of ways, depending on the geometry of the imaging system. Changing the distance between the sample and the detectors has a magnification effect, affecting the resolution. However, this increase in resolution is offset to some degree, depending on the focal spot size, as shown in Fig. 3.

For X-ray tubes with relatively large focal spot sizes the loss of resolution is minimized when the sample is placed directly against the detectors and the distance between the X-ray source and the detectors is kept as large as possible. X-ray tubes with very small focal spots are commercially available which allow very high resolution via geometric magnification without the focal spot resolution effects. These “fine focus” tubes, which are the basis for X-ray microscopes, are limited to low filament currents, as the electrons striking the anode are concentrated onto a small area and excessive heating can occur. The low tube current has the consequence of increased image noise, unless compensated with long exposure times, and X-ray microscopes are thus unsuited for high speed inspection. On the other hand, they are suitable for sampling, as in a quality assurance operation.

The third critical image quality parameter of interest is contrast, defined as the difference in output for a given difference in input [29]. Related is the dynamic range, which describes the ratio between the smallest and largest pixel values in an image. For an 8 bit image, maximum dynamic range (and contrast) occurs when the darkest image pixel has a value of 0 and the brightest pixel has a value of 255. Matching the dynamic range of the scene (X-ray intensity) to that of the detector to achieve maximum contrast in the resulting image is an area of interest in all types of imaging, including X-ray and food inspection [30, 31]. Increasing contrast within a particular area of interest in the X-ray image can improve detection of inclusions [32]. It has also been shown that image contrast between soft materials is dependent on X-ray energy and spatial resolution of the imaging system, and for organic materials such as food best contrast is achieved at low

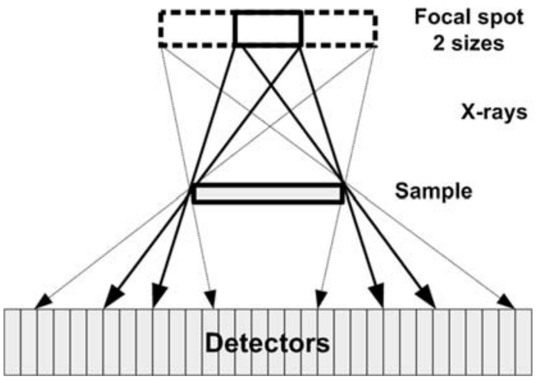

Fig. 3 Effect of focal spot size on resolution. Moving the sample toward the X-ray source increases the magnification but also increases the loss of resolution due to the focal spot size

energies and high resolution [33]. This has been tested and verified by human recognition studies of insect larvae in X-ray images of infested grain [34] as well as through computer simulation programs [35].

Image quality is dependant on the interaction of the different components of the X-ray system, including the X-ray source, conveyor mechanism, detector arrays, image capture, processing, and display. It is therefore important to optimize the components to give the best image possible. Techniques for doing so have been investigated and reported [3, 36]. Methods for correcting image deficiencies that are introduced by the X-ray system itself have also been described [37].

X-ray inspection of food products

Luggage inspection for contraband food products

While most X-ray applications of food products involve detecting defects or contaminants within the product itself, there is also an important field of study involving X-ray detection of food items concealed within a container, generally luggage. Efforts to protect agricultural crops from invasion by foreign pests makes this area of study particularly crucial. Research efforts have shown that automatic shape recognition software combined with dual energy imaging is an effective tool for detecting many concealed food products [38–42].

Packaged foods

It is in the packaged foods segment of the industry that X-ray inspection has traditionally been implemented to the greatest extent. Product packaged in bottles or cans is ideally suited for high speed X-ray inspection, with linescan units routinely processing more than 20 samples per second. The processing plant environment introduces the possibility of contamination of the product by metals, plastics, glass, bone fragments, etc. Linescan X-ray units are rapidly replacing metal detectors because of their ability to detect all kinds of contaminants. The uniformity of packaged materials as compared to fresh produce makes it a better candidate for quality X-ray images. Finally, the types of inclusions generally of interest in packaged foods (metal, plastic, glass, etc.) provide much higher contrast in X-ray images than do the typical defects or contaminants of interest that are found in fresh produce (insect infestation, physiological defects, etc).

Areas of reported research include detection of common contaminants as described above through system development [43–47] or rejection algorithm development [48, 49]. Simulation studies have indicated that CT scanning using CT numbers as opposed to X-ray absorption coefficient could give the ability to detect inclusions smaller than the physical resolution of the CT scanner due to the smooth transition of CT number between the inclusion and surrounding material [50]. These results were obtained through theoretical simulation and not verified using actual product. Furthermore, practical considerations such as cost and exposure time currently make CT an impractical detection method. Nonetheless, it does suggest that future technologies could increase the detection capabilities of X-ray systems in general.

Poultry inspection

Poultry inspection is another segment of the food industry that employs X-ray inspection on a routine basis. The inclusion of greatest interest is bone fragments, often left behind by the de-boning process. While standard linescan systems are effective for detection of heavier contaminants such as metal or rock, detection of softer material is hampered by the irregular shape and non-uniform thickness of the product. From an algorithm approach, this problem has been addressed by applying adaptive thresholding to the image [22] or using local contrast enhancement [32]. In addition, a new X-ray imaging system combining laser range images with X-ray image data is designed to determine thickness at any point in the image [12, 51, 52].

Grain inspection

Of all food commodities, the greatest amount of research found in the literature regarding X-ray inspection is devoted to grain. Most of this research effort has been devoted to the problem of insect infestation in wheat kernels. Scanned film images of wheat kernels infested by larvae of the Granary Weevil, *Sitophilus granarius* (L.), are shown in Fig. 4.

In spite of considerable research effort spanning several decades, bulk grain is still not routinely inspected by X-ray. The reason for this is twofold: the size of grain kernels mandates inspection speeds beyond the capability of even the fastest computers plus the inability of current high speed X-ray systems to detect larvae at their earlier stages.

The challenges have not discouraged research efforts. For detection of insect infestations, X-ray has been shown to be superior to NIR detection, except in the case where species identification is required [53]. CT scanning has been demonstrated to be an effective tool for rapid scanning of 100 g samples for insect infestation

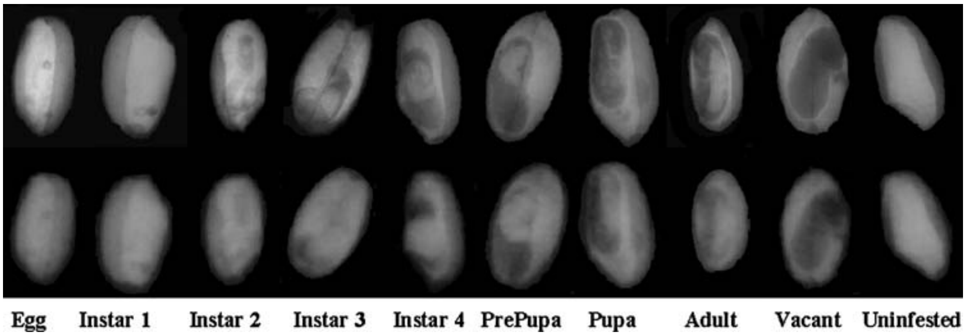

Fig. 4 Digital X-ray images (bottom) and scanned film images (top) for the various larval stages of the granary weevil in wheat kernels [58]. The bottom images were acquired on a high speed X-ray imaging system. Comparing to the scanned film images, it is clear that with existing equipment the earliest larval stages cannot be detected at high speed due to lower resolution and higher noise levels

[54, 55], but is too slow for bulk inspection. X-ray system parameters for maximizing recognition of insects in wheat kernels have been investigated [34, 56]. Human recognition studies based on scanned film images have shown that X-ray imaging is extremely reliable for quality control purposes [57–60] but is obviously of no use for bulk inspection. While several effective automatic recognition algorithms have been reported [18, 19, 26, 53, 61–64], in most cases the images used for training and testing were obtained using high resolution X-ray systems such as film, X-ray fluoroscopes, or X-ray microscopes that require exposure times that make bulk inspection unrealistic.

The fastest system reported is an X-ray image intensifier/CCD camera combination with an exposure time on the order of 143 m, or seven kernels per second [26, 58]. Although seemingly rapid, this is still far too slow for bulk inspection without introducing many channels at the same time, which is cost prohibitive. The CCD camera in this study was the limiting factor in terms of speed, and digital cameras with much higher frame rates exist today. However, efforts to increase the frame rate lead to the problem of image deterioration due to quantum noise.

It would seem, then, that the limiting factor for high speed automatic inspection of wheat for insect infestation is an X-ray tube with low energy, on the order of 20 KeV, coupled with very high current, on the order of hundreds of milliamps. Such a source installed in a high speed linescan system should make bulk inspection feasible. As equipment costs, especially in the area of power supplies, continue to decrease such a system may become available.

Although the bulk of X-ray work devoted to grain inspection has been for insect infestation, a few studies have used X-ray technology to detect other defects or quality parameters in grain. X-ray imaging and machine vision have been combined to detect multiple defects in cereal grain [11], and an X-ray fluoroscope system has been shown to be effective for mass determination in wheat kernels [65].

Apples

Research involving X-ray imaging of apples has concentrated on detection of codling moth damage, detection of watercore disease, and detection of core rot. Detection of codling moth larvae in apples (Fig. 5) has been investigated using CT [66], film [66–68], as well as linescan [67–69] X-ray systems. As with grain inspection, high quality images can be obtained using film and CT, which are unsuitable for bulk inspection, but image quality deteriorates in linescan images due to quantum noise and the capability for defect recognition declines. Watercore disease is a physiological disorder wherein fluid accumulates around the vascular bundles [70], leading initially to sweetening but eventually to core rot. Efforts to detect watercore have been reported using CT [71], film [67, 68], and linescan [67, 68, 72, 73]. Recognition of the disease is based on darkening of the affected areas in X-ray images, presumably because of fluid filling. Results are sketchy, with severe cases easily identifiable but more moderate cases generally going undetected. Detection of core rot has been shown to be relatively straightforward on any X-ray system [67, 68]. The X-ray absorption coefficient for certain apple cultivars has been experimentally determined using a CT system [74] then used to determine water content.

Tree nuts

X-ray images of pistachio nuts infested by the naval orange worm (NOW) have been used as training and validation sets for the development of algorithms for insect detection

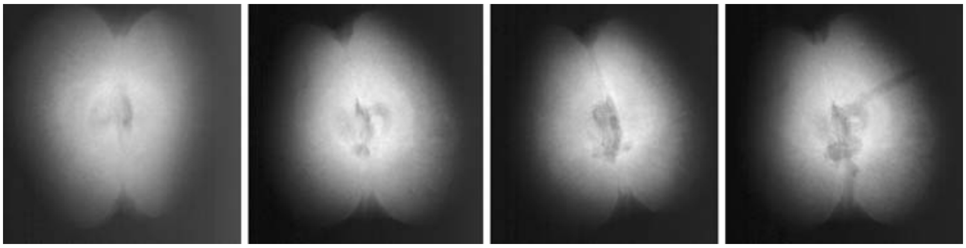

Fig. 5 X-ray images of codling moth infestation in an apple. The ages of infestation are, from left to right, three, twelve, fourteen, and seventeen days after the apple was inoculated with eggs. This again illustrates the difficulty of detecting insects at the earlier life stages

[75–78] as well as separation of touching samples in X-ray images [21, 79]. Algorithm strategies include: neural networks that achieve 98% recognition with less than 1% false positives (good product classified as bad) on scanned film images, discriminant analysis routines achieving 89% accuracy in linescan images, and multiple feature extraction strategies. Although developed for insect detection in pistachio nuts, these algorithm strategies should be useful for other commodities as well, particularly the segmentation algorithms for separating touching samples. Algorithms have also been developed for the detection of NOW in almonds based on scanned film as well as linescan images [80] and the burrowing activity of the Pecan weevil has been studied using X-ray [81].

Miscellaneous food products

More limited research has been reported on a wide variety of food products. CT imaging has been used to determine maturity in tomatoes [82], monitor internal fruit changes in peaches during ripening [83], detect core breakdown in pears [84], and Woolly breakdown in nectarines [85]. Linescan imaging has proven effective for detecting voids and rot in onions with more than 90% accuracy [86–88], as well as insect infestation in guava fruit [69]. Other detection studies reported include seed weevil in mango [89], translucency in pineapple [90] (Fig. 6), hollow heart in potato [91], insect infestation in peaches [69], and the olive fruit fly [92] (Fig. 7).

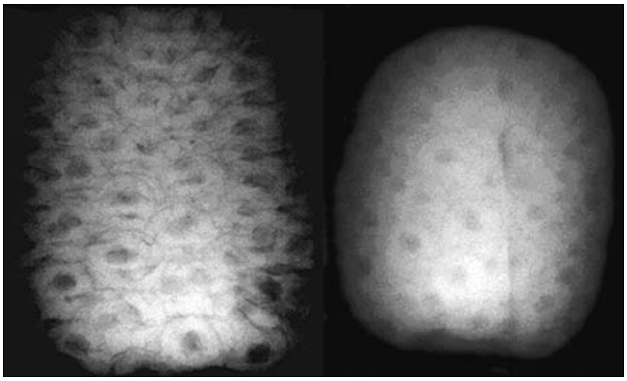

Fig. 6 X-ray images of pineapples with translucency disorder (right) and without (left). Translucency is associated with internal flooding of intercellular spaces, consistent with the washed out appearance in the X-ray compared to the healthy pineapple

Effect of the shape of agricultural products on image quality

X-ray images of food products may contain deficiencies resulting from the curvature of the sample. For packaged goods, the curvature of the container may contribute to this effect as well. This effect is illustrated in Fig. 8 (left) for the case of a spherical sample with no container. Since it is necessary to apply sufficient X-ray energy to penetrate the thick center of the sample, the edges can be washed out in the X-ray image due to saturation of either film or solid-state detectors at that location. The resulting image shows lower pixel intensity at the center of the sample compared to the edges. While this may not be a deterrent when inspecting for metal contaminants, which generally absorb all incident X-rays, less dense contaminants such as wood, bone, and even glass may not be detected if they are situated along the edges. Figure 8 (right) illustrates the additional effect of a container, which becomes thicker along the direction of X-ray attenuation towards the edges. For thin walled containers with low X-ray density, such as aluminum cans, this effect is minimal. For containers with thicker walls or higher density, such as glass or steel, the effect becomes more dominant. Note that for the case of a filled container, the two effects are competing.

This variation in pixel intensity is commonly addressed with a software correction to normalize the image. This is useful when automatic recognition algorithms are used to drive a rejection mechanism, as the algorithms can be affected by the lack of uniformity of image brightness. However, software corrections cannot recover information lost in the imaging process, such as the presence of a small object with low density situated along the edge of the sample that has been washed out due to saturation of the detectors.

Recent research has demonstrated that this problem can be overcome by introducing an attenuator between the X-ray source and the sample with a shape and X-ray density that compensate for the varying sample thickness,

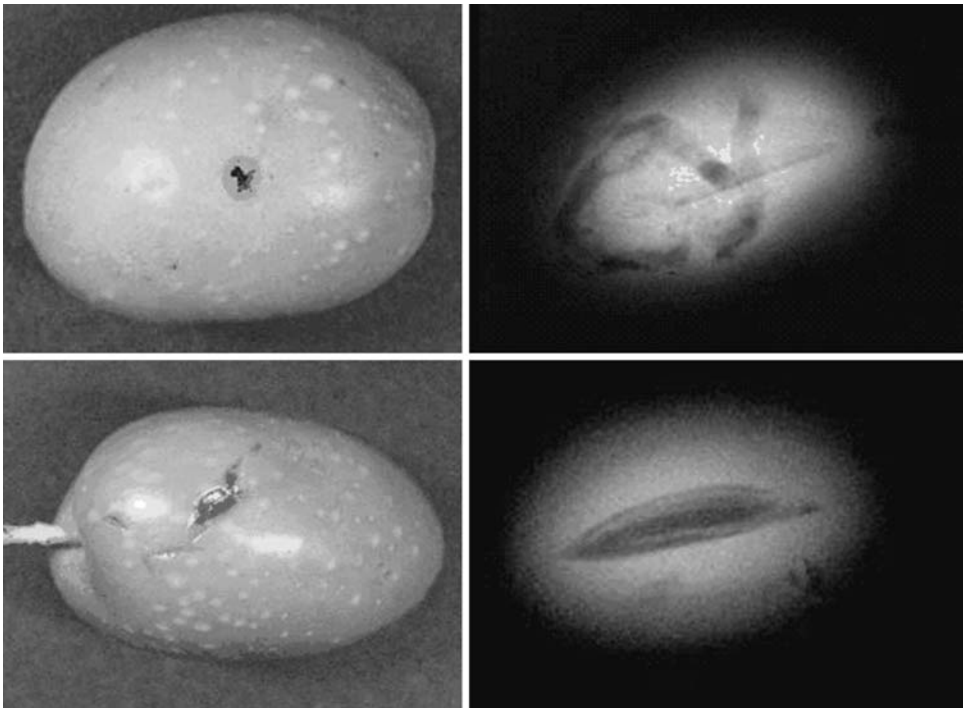

Fig. 7 Digital photographs and X-ray images of olives with fruit fly infestation (top) and without (bottom) [92]. Note that in the photographs both olives show what appears to be insect damage. For the first olive, X-ray imaging reveals that the internal damage is much greater than is apparent from visual inspection. For the second olive, external damage turns out to be uncorrelated with insects, as the X-ray image shows no interior infestation

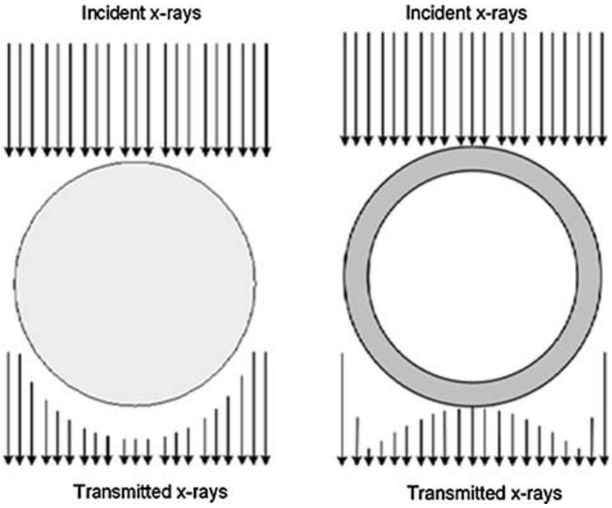

Fig. 8 X-rays of uniform intensity incident on a curved object (left) transmit X-rays of non-uniform intensity, resulting in an image with higher pixel intensity toward the edges. The object shown here is representative of a piece of spherical fruit. X-rays incident on an empty can (right) also transmit X-rays of non-uniform intensity, except with higher pixel intensity toward the center. In the case of a filled can, the two effects compete

essentially generating a transformation from a round sample to a flat sample as seen at the X-ray detectors [93]. While the results of the study demonstrated significant improvement in image quality (Fig. 9), implementation at high speed is cumbersome and significant research remains to be done before this technique can be realistically applied.

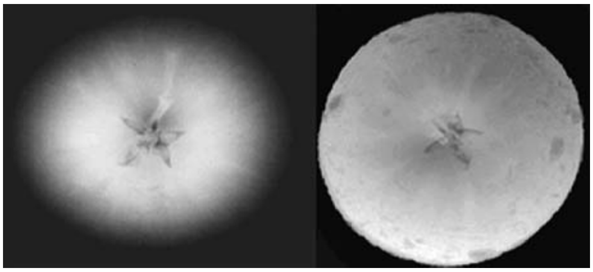

Fig. 9 Attenuated (right) and unattenuated X-ray images of an apple [93]

Conclusion

X-rays have found extensive use in manufacturing industries for quality control inspection. The difficulty of detecting defects and contaminants in food products have kept the use of X-ray more limited in that industry. Nevertheless, necessity has motivated a considerable research effort in this field spanning many decades. Improvements in technology have allowed X-ray detection of some defects that were not possible in the past. These improvements can be expected to continue into the future. Loss of signal to noise ratio in the images as the speed of the system increases is the limiting factor for the majority of desired detection abilities. What is needed is a high speed system, probably but not necessarily of a linescan configuration, with a low energy and very high current X-ray source. Such a system should be able to accomplish many of the real time high speed detection tasks that current X-ray systems cannot handle.

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