Chapter 3

SYSTEM SCANNING HARDWARE OVERVIEW

Since all the image data need in this research were collected from the highly modified AS&E 101ZZ system, it is important to give an overview to this scanning hardware. Section 3.1 gives a system hardware overview. Section 3.2 discusses issues regarding x-ray detectors and image preprocessing. Section 3.3 discusses the relationship between the x-ray signal intensity and the image gray level. Section 3.4 discusses the noise present in the AS&E system. Section 3.5 summarizes this chapter.

3.1 System Hardware Overview

To obtain the necessary experimental data, an x-ray dual-energy transmission and low-energy scatter imaging system is needed. This scanner used is a highly modified AS&E 101ZZ system. An overview of the system's electronics is shown in Figure 3.1-1. The 101ZZ system is originally equipped with two x-ray sources and three detectors: a transmission detector and a backscatter detector for one side of the luggage and a backscatter detector for the other side. The second x-ray source was removed from the new system, and its corresponding backscatter detector was moved to create a forward scatter detector. The 101ZZ system is equipped with a computer controllable x-ray source controller, and two infrared beam break sensors are used to determine the position of the container on the conveyor belt. It also uses a motor controller for the conveyor belt [ARV97].

The 101ZZ system uses a digitizing pre-amplifier board to convert the analog voltage from an x-ray detector to a digital signal. These boards use a differential pair bus for communications and require external control, since they contain no "intelligent" hardware for autonomous operation. There are three pre-amplifier boards in the system, one for each of the three detectors. The original AS&E pre-amplifier boards are used in the prototype, since they provide a simple external interface and are integrated in the AS&E system [DRA98].

To control the pre-amplifier boards and transfer data to the PC, a Differential Pair Interface Board (DPIB) was developed at the Spatial Data Analysis Lab at Virginia Tech. The DPIB interfaces to the three digitizing boards and multiplexes the output onto a single bus. The DPIB board was designed as an ISA device [DRA98].

A Multiple Channel PCI (MCPCI) board, also developed at the SDA Lab, is used to transfer image data to the host computer through the PCI bus. The MCPCI is a PCI bus master DMA device and can achieve data rates over 100 times faster than ISA hardware, allowing real-time system data collection. The DPIB and the MCPCI communicate over an external Zee bus, a high-speed data bus developed for inter-board communications [ARV97].

In the modified system, the DPIB also interfaces to the conveyor belt motor and infrared sensors of the 101ZZ system. The on/off state and the direction of the conveyor belt, as well as the status of each infrared sensor, are accessible through software on the host computer [ARV97].

A single IBM compatible PC running Windows NT 4.0 is currently used for system control, image processing, and material characterization. Windows NT was chosen for its stability, user friendliness, and multi-tasking and multi-processor capabilities. The image processing algorithms, detection algorithms, and Graphical User Interface (GUI) are executed on this PC. The GUI presents the processed images to the operator and allows simple image manipulation functions, such as zooming and inverting.

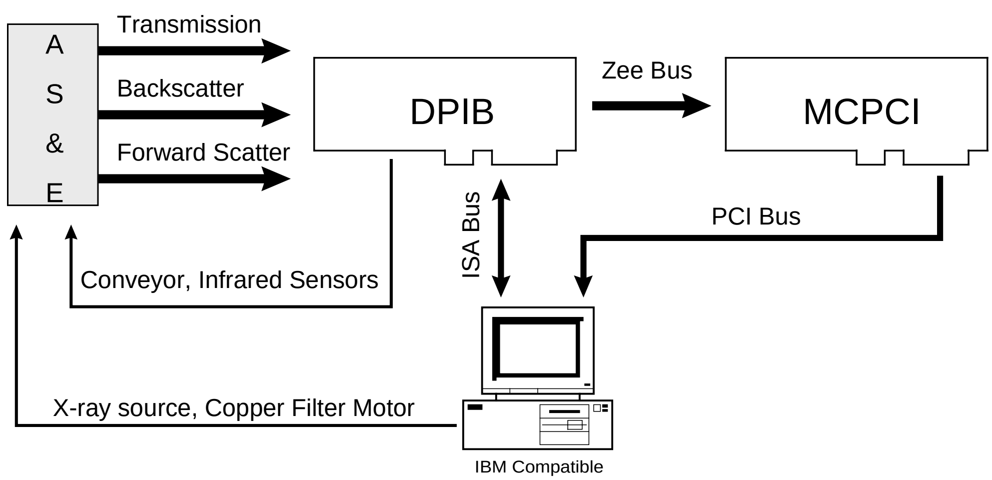

Figure 3.1-1 Highly modified AS&E 101 ZZ system overview.

Figure 3.1-2 shows the placements of the modified source and detectors. Since the material characterization methods require image information from a single x-ray source, the second source of the original system that used to generate only backscatter information was removed. The backscatter detectors used with the removed source on the original system were removed and placed directly in front of the transmission detector in order to obtain forward scatter images. The digitizing board was connected to the new forward scatter detector.

To produce x-ray transmission, forward scatter, and backscatter images simultaneously, the flying spot technology is used [ANN92]. The technique used is shown schematically in Figure 3.1-3. A rotating chopper wheel and a stationary slit are used to form a thin pencil beam of x-radiation. The pencil beam is used to raster scan a bag. A transmission detector is used to collect the transmitted radiation and to convert it to an electrical signal. This signal is digitized, stored, and used to create a visual image of the transmission characteristics of the bag.

At any given time, only a single small line of sight in the container is scanned by x-ray beam. This line of sight corresponds to a single pixel in the transmission x-ray image. Therefore, if the froward scatter and backscatter signals are measured at the same time, the amount of forward scatter and backscatter coming from the container associated with that specific pixel in the transmission image is known as well. By doing this for all the pixels, the forward scatter and backscatter image are perfectly registered to their corresponding pixels in the transmission image.

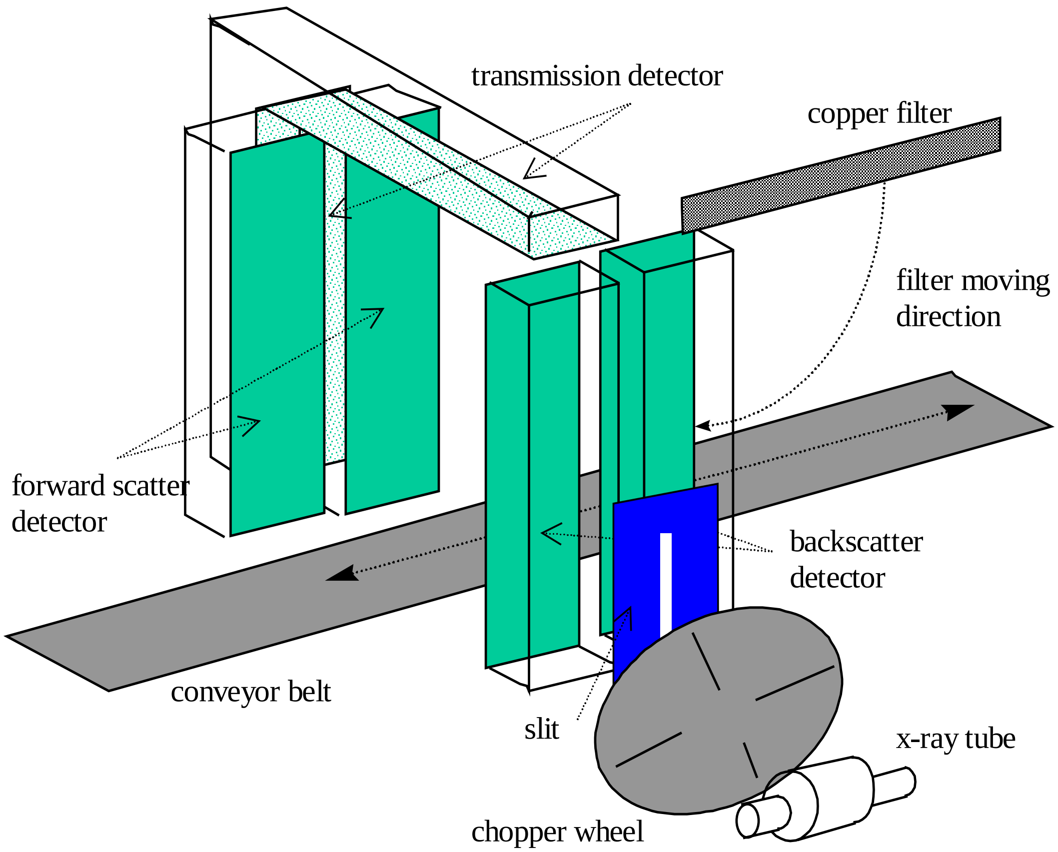

Figure 3.1-2 The modified source and detectors placement.

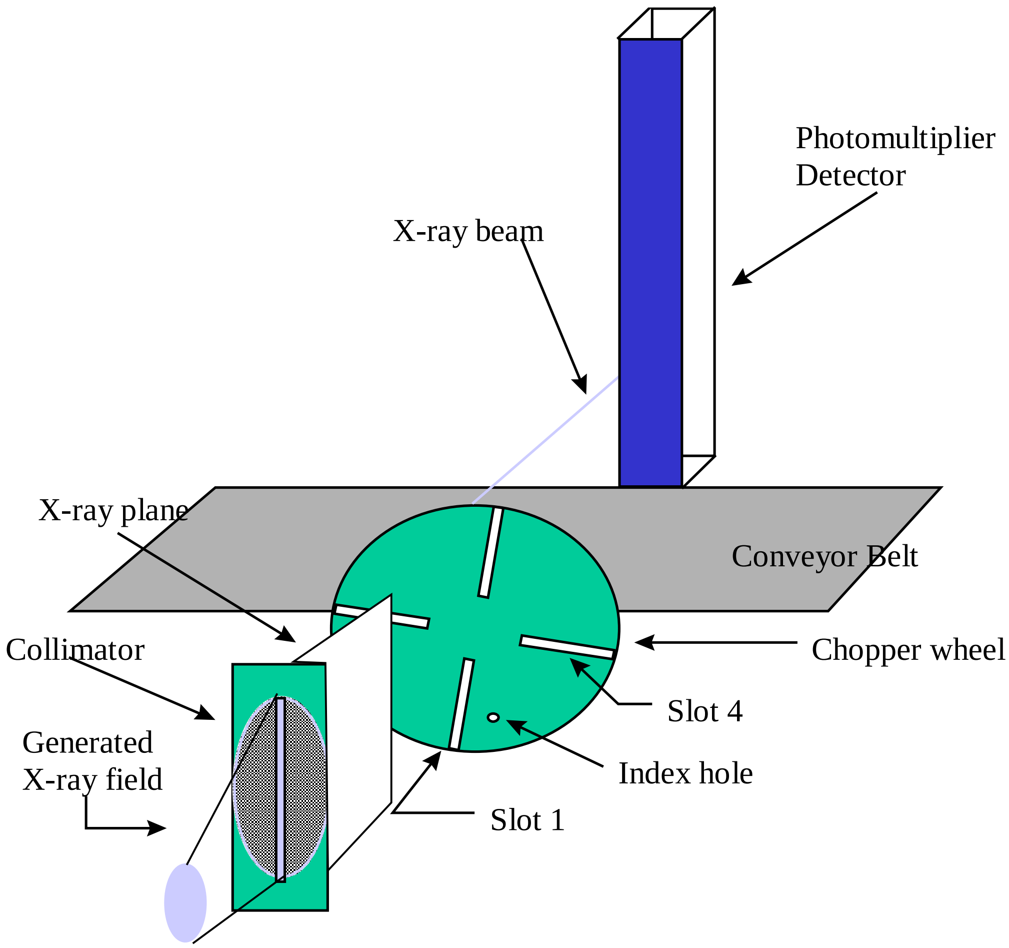

Figure 3.1-3 Principle of operation of a flying spot scanner.

Figure 3.1-4 shows a schematic of the forward scatter and backscatter imaging system. The x-ray optics are the same as a normal x-ray imaging system. All that is added are forward scatter and backscatter detectors and associated image-forming electronics. Since the system is designed to collect dual-energy transmissions image as well, the control of source settings using a computer, such as x-ray voltage and current, is necessary. The AS&E 101ZZ system is equipped with a Gemini 2000 x-ray controller. By sending commands from a RS-232 serial port to the controller, the voltage and current of the x-ray source can be adjusted, and the x-ray tube can be turned on and off. Since the system is a true dual-energy x-ray system and there is only one x-ray source for the scanning, the x-ray source is first set to low-energy, and the bag passes through the x-ray imaging area to create the low-energy transmission and scatter images. The x-ray source is then set to high-energy, and the bag passes back through the x-ray imaging area a second time to create high-energy transmission image. The effective control of the x-ray source is thus very important for the collection of dual-energy images.

To allow the system to automatically collect images, infrared sensors reporting positions of the inspected objects were installed. The position information is used to enable and disable image collection, and also to turn the x-ray source on when the object is present, and off when the scanning tunnel is empty. The inspected object is transported by means of a conveyor belt. The modification on the motor controller allows the conveyor belt to transport in either the forward or reverse direction.

A copper filter is used when the high-energy transmission image is collected to further separate the dual-energy x-ray spectrum. The thickness of this filter is 1 mm. It is automatically inserted and removed when proper commands are sent to the motor controller of the filter’s step motor.

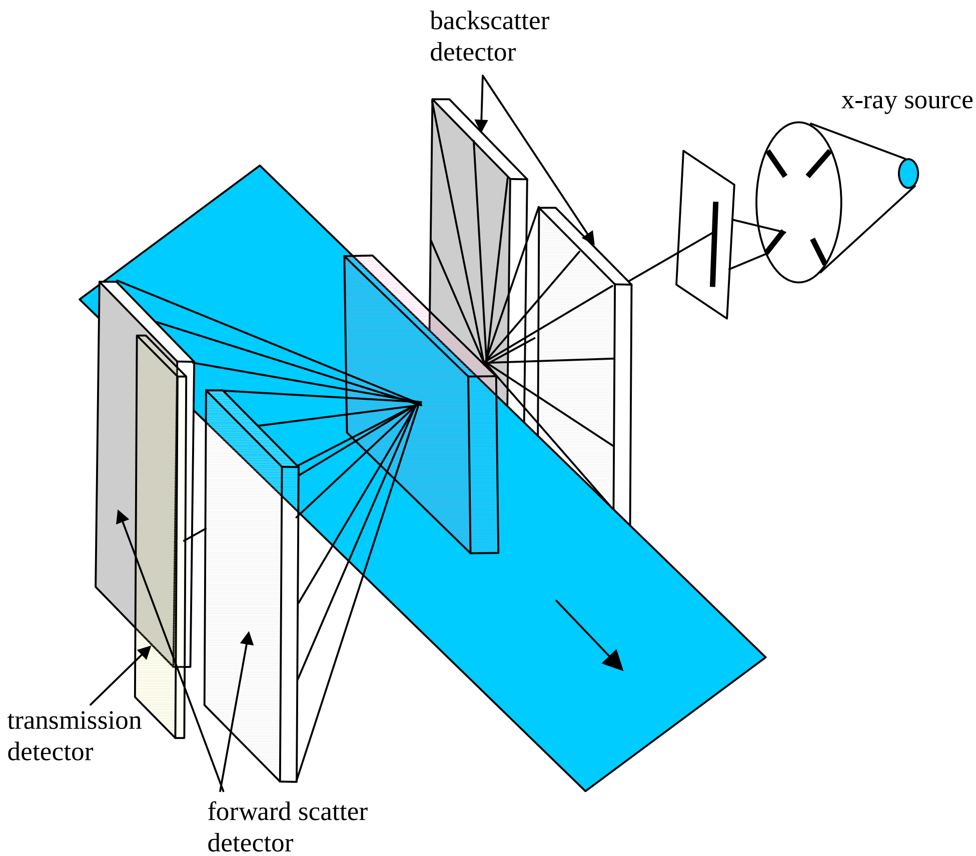

Figure 3.1-4 Principle of operation of a flying spot forward scatter and backscatter imaging system.

For the image-processing algorithm, four images need to be collected for each inspected object: high-energy transmission image Img^H; low-energy transmission image Img^L; forward scatter image Img^F; and backscatter image Img^B. Img^L, Img^F, and Img^B are collected at the same time using low x-ray energy voltage, and for the purpose of this research, the x-ray source is set to 75 keV. Img^H is collected on a second run with a higher x-ray energy voltage set to 150 keV. The collection procedure is described as follows.

The system needs to be warmed up before collection. Once the warm-up is finished, the system can start image collection. First, the inspected object is placed on the conveyor belt. The host computer sends a command to the x-ray tube and sets its energy to 75 keV. The copper filter is removed from the view. The conveyor belt then starts moving in a forward direction. Once the object breaks the first infrared object detect sensor, it enters the field of view of the imaging system and data collection starts. The high-speed data interface starts to download data coming from the detectors to the host computer. Three memory blocks are reserved for data downloading, one for Img^L, one for Img^F, and one for Img^B. When the front edge of the object hits a second object detect sensor, the entire object has exited the field of view of the imaging system. The data downloading stops and the conveyor belt also stops.

Now the host computer sets the x-ray tube voltage to high energy 150 keV, and the copper filter is moved down and inserted in front of the x-ray source. The conveyor belt is then reversed moving the bag through the imaging system. This time no data is collected. Once the bag has passed by the first infrared object detector, the conveyor is once again stopped. Its direction is reversed again and the conveyor is started again. When the bag enters the field of view of the x-ray detector again, the transmission detector collects the x-ray photons and coverts the energy into digital signals. The high-speed data interface immediately downloads the image data from the transmission detector to the memory block reserved for Img^H. When the trailing edge of the object passes the second object detect sensor again, the data downloading stops. The conveyor belt continues to run until the object falls off the belt. The system then is reset to get ready for another scanning run: the x-ray tube energy is set to low; the copper filter is removed; the image data are saved to the disk.

3.2 X-ray Detectors and Image Preprocessing

In this section, more details are provided about the x-ray detector used in the modified AS&E system. The detector used in the AS&E system is different from many traditional systems. The traditional x-ray detector is made of a sensing array as seen in Figure 3.2-1 (a). Each sensing element is made up of a cube of scintillation material and a photodiode. The cube of scintillation material converts some of the incoming x-ray photons into visible light. The photodiode converts this visible light into electrical energy. Instead of using a large array of sensing elements, AS&E detector has only two large photomultiplexers, which are placed at the top and bottom ends of the detector as seen in Figure 3.2-1 (b). The inner walls of the detector are covered with sheets made of materials that can reflect x-ray photons. X-ray photons entered into the detector box will eventually be hitting the photomultiplexers after many times of reflections and converted into electronics signals.

The AS&E detector uses a different technique to collect image data in both the transmission and scatter modalities. To generate image data, a collimator and a chopper wheel fabricated of shielding material are placed in the x-ray path as seen in Figure 3.1-3. The wheel has four narrow slots and rotates at a constant speed. The effect of the wheel is to block the collimated x-ray plane and create a narrow beam. As the wheel turns, the beam moves from bottom to top, scanning an entire vertical line. The movement of the beam creates a pixelated image, eliminating the sensor array that is usually used in a detector. Instead, two large photo-multiplier tubes are used for each detector. The operation of the flying-spot technology is shown in Figure 3.1-3. Using a traveling beam allows control of both the horizontal and vertical resolution. Since the detector has a large area, this makes it possible to detect scattered photons.

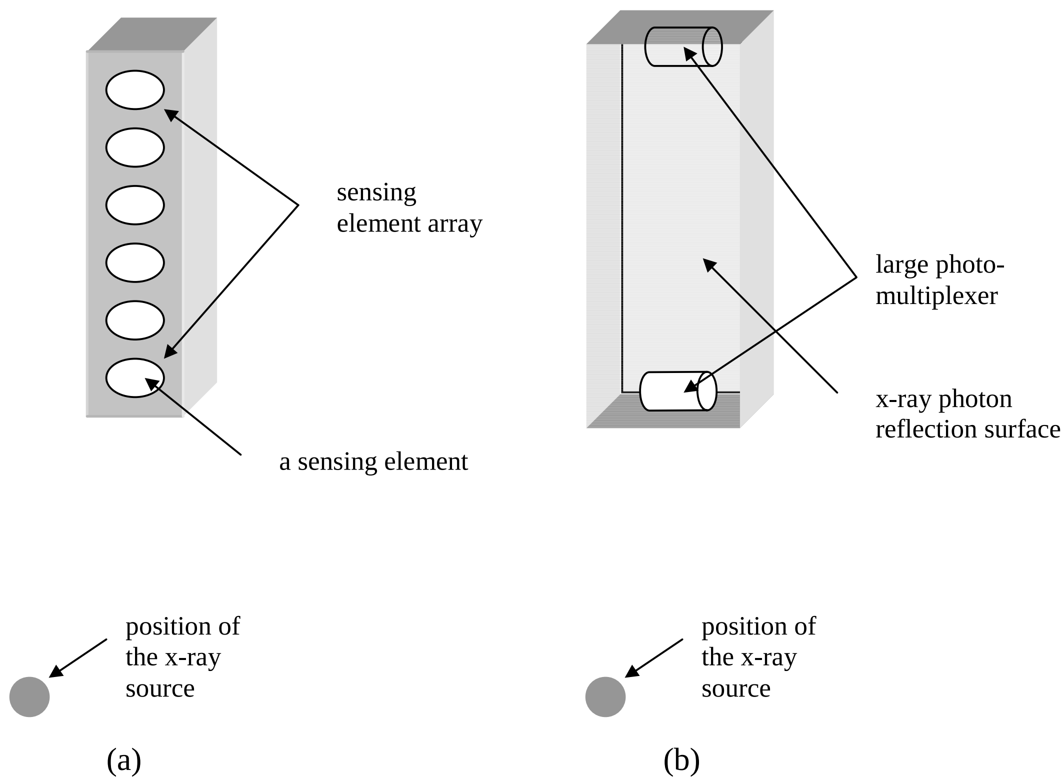

Figure 3.2-1 Illustration of x-ray detectors. a) A traditional x-ray photon detector that is made of a large sensing element array. b) AS&E x-ray photon detector. The detector inner walls are covered with materials that can reflect x-ray photons. Two large photomultiplexers are placed inside the detector to convert x-ray photons into electronics signals.

Furthermore, signals collected from the transmission, forward scatter, and backscatter detectors at the same time correspond to the same spatial position of a scanned object. Using this method images from the transmission, forward scatter, and backscatter detectors are spatially registered.

A problem with the AS&E detector is that when an x-ray beam with a constant intensity enters the detector, the strength of the photomultiplier tubes' output is different for different vertical portions of the beam. This is illustrated in Figure 3.2-2. The right plot shows that the output signal strengths are the strongest when the x-ray beam enters from the top or the bottom portion of the detector. The signal gets weaker when the x-ray beam enters from the middle portion of the detector. This would cause row-wise image non-uniformity. This problem can be corrected by using shading correction technique.

Besides row-wise image non-uniformity, there are three other problems. First, the x-ray detector has dark current; it needs to be removed. Second, the x-ray source sometimes drifts, and it causes column-wise image non-uniformity. The non-uniformity should also be removed. Third, the full range of the pixel gray level should be used. Those three problems can also be resolved by using shading correction technique [SAW77].

For each image pixel, two kinds of data values must be collected before shading correction can be proceeded: a gray level value that reflects the dark current effect; a gray level value that reflects the strongest signal the detector will receive.

Since the image is scanned on column bases, the dark current data and the brightest possible gray levels must be collected on column bases as well. To collect the gray level that reflects the dark current effect, the x-ray source is turned off, while three images $Dark^L$, $Dark^F$, and $Dark^B$ are collected at the low energy level, and one image $Dark^H$ is collected at the high energy level. The number of image columns collected for each image is usually over 100. Since the computation procedure is the same for all four images, the superscript is dropped to describe the general procedure.

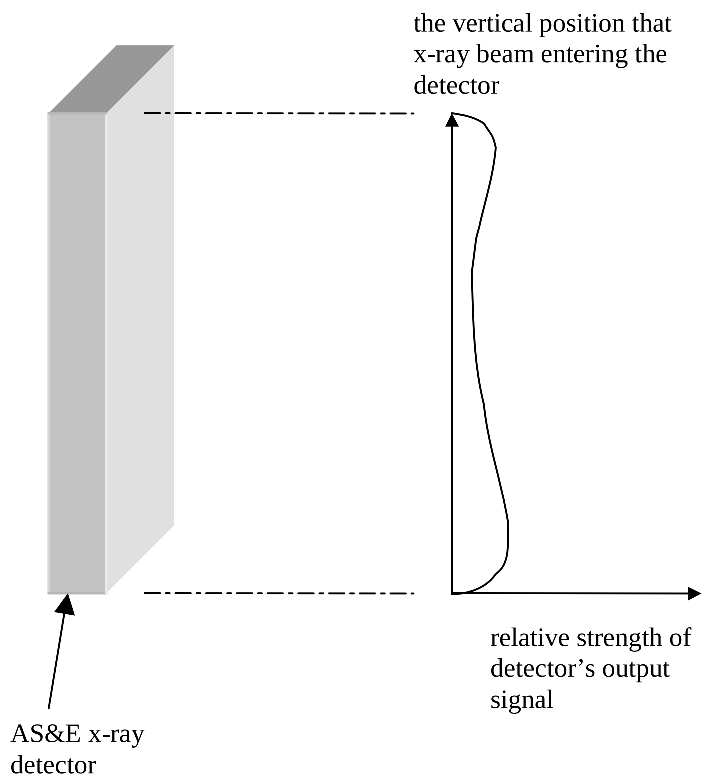

Figure 3.2-2 Illustration of the relative strength of the AS&E detector's output signal. On the left, an AS&E x-ray detector is shown. When an x-ray beam with a constant x-ray intensity entering the detector, the strength of the detector's output signal strength is different for different vertical entering position. The right plot shows that the output signal strengths are the strongest when the x-ray beam enters from the top or the bottom part of the detector. The signal gets weaker when the x-ray beam enters from the middle part of the detector.

Assume image *Dark* has *m* columns and *n* rows, and *Dark(i, j)* is the pixel at the i^{th} column and j^{th} row. To compute the dark current effect for a column *DarkLine*, *m* columns of data are averaged into one column. To do so the following equation is used

$$DarkLine(j) = \frac{\sum_{i=1}^{m} Dark(i, j)}{m} \qquad (3.2\text{-}1)$$

where the range of *j* is from *1* and *n*, and *DarkLine(j)* is the dark current value at position *j*. This averaging method is used to reduce the effects of thermal noise. The column data *DarkLine* is computed for all four image modalities.

To collect the gray level of the strongest signal, the method is different for different image modalities. Denote the image to be collected as *Bright* for a sensing modality. To collect $Bright^L$ and $Bright^H$, the x-ray source is set to low- or high-energy, and no objects are placed on the conveyor belt. To collect $Bright^B$, a very thick and large white plastic parallelepiped is placed on the conveyor belt for scanning. The thicker the parallelepiped is, the stronger the backscatter signal. Also, plastic material has very large x-ray scatter cross-section. Those two properties of this parallelepiped will produce the strongest backscatter signal. To collect $Bright^F$, a plastic cuboid is used, one that is 10 cm thick. The forward scatter signal peaks at certain object's thickness. For this plastic material, the signal peaks at 10 cm.

Similar to the computation of the dark current signal, the column data *BrightLine* can be computed using the following equation

$$BrightLine(j) = \frac{\sum_{i=1}^{m} Bright(i, j)}{m} \qquad (3.2\text{-}2)$$

where *j* ranges from 1 to *n*.

Assume *Img* is the image to be shading corrected, and *Img(i,j)* is the pixel at the i^{th} column and j^{th} row. The shading correction is done as follows [SAW77]:

$$Img(i,j)' = \frac{Img(i,j) - DarkLine(j)}{BrightLine(j) - DarkLine(j)} \cdot 255 \tag{3.2-3}$$

where *Img'* is the shading corrected image, and 255 is the number of gray levels for each pixel.

This very standard shading correction procedure is considered as part of the image collection procedure, and not part of the image-processing procedure. For convenience and simplicity, in the remainder of this dissertation, *Img* will refer to the shading corrected image rather than the original image collected from the system.

3.3 The Relationship Between Image Gray Level and Signal Intensity

It is now necessary to establish the relationship between an x-ray signal intensity and an image pixel gray level. This is important, because without the relationship, the x-ray formulas expressed in the forms of intensities cannot be associated with the images that are expressed in gray levels.

Unfortunately, the author was unable to establish the direct relationship between the x-ray photon energy and the pixel gray level output by the AS&E 101ZZ detector. This inability resulted from the fact that the model created for this detector had some undefined constants. Fortunately, the author was able to discuss this matter with former vice president of AS&E, Mr. David Shafer, who helped to design the AS&E 101 ZZ system. He confirmed that AS&E system was designed in a way that allows the pixel gray level to be in linear relationship to the x-ray intensity, or

$$g = cI \tag{3.3-6}$$

where g is the pixel gray level, I is the x-ray beam intensity, and c is a constant. This equation is generally true for all sensing modalities. The constant c is the same for high- and low-energy transmission modalities, but different for the forward scatter modality and the backscatter modality. Let c^T denote the transmission constant, c^F denote forward scatter constant, and c^B as the backscatter constant. These constants need not be estimated for purposes of this study, but this linear relationship between x-ray intensity and pixel gray level value is important for modeling the object overlapping effects.

3.4 System Noise

The noise coming out of the AS&E system is relatively large. This noise comes from the x-ray source, scintillator, system electronics, and data transfer interfaces. The noise can cause the gray level of an image pixel to vary up to ±10 gray levels in a 256 scale, which is about 4% of the entire dynamic range. This noise does adversely affect the accuracy of the methods that were developed in this research. However, this study is only a *proof-of-concept* study. The noise does not significantly affect the preliminary results, which is mostly to show that the design concepts of the suggested algorithms are correct. Clearly the lower the system noise the more reliable the processing results that will be obtained.

3.5 Chapter Summary

In this chapter, an overview is given to the scanning hardware of the modified AS&E system. The highly modified AS&E 101ZZ system is a true dual-energy system. The flying spot technology allows the system to collect a transmission, a forward scatter, and a backscatter images simultaneously. The dedicated data transfer interfaces allow the high-speed data transfer from x-ray detectors to the PCs. Problems of x-ray source and detectors cause non-uniformity in an image, and this non-uniformity can be corrected by shading correction. The image gray level is found to be in linear relationship to the x-ray signal intensity. The x-ray system noise will not affect the development of the image-processing system, though it does affect the accuracy of the results obtained.