Chapter 1. Introduction

1.1 Motivation

The commercial airline industry is an important part of today's global economy. Each year hundreds of millions of people use aircraft to travel around the world. The national and international flow of passengers, mail and cargo depends on the safety and security of the civil aviation system. Airplanes in flight, by their very nature and design, are extremely susceptible to bombs and present an attractive targets for terrorists, where the objective is to inflict mass casualties. From 1985 to 1997, eight commercial aircraft were lost or damaged due to suspected terrorist bombings [NOV92] [OFF97], and about 1100 people died in these tragedies:

- On June 23, 1985, an Air India Boeing 747 crashed into the sea as the result of an explosion in the cargo hold.
- On November 29, 1987, Korean Air flight 858 was destroyed in flight from an explosive device inside the cabin.
- On December 21, 1988, Pan Am flight 103 was destroyed by a 12-ounce bomb hidden in a portable radio over Lockerbie, Scotland.
- On September 19, 1989, a UTA flight was destroyed over the Sahara from an explosion in the forward cargo component of a DC-10 aircraft.
- On November 27, 1989, an Avianca Boeing 727 was destroyed by an explosive device in the cabin.

- On July 17, 1994, an Alas Chiricanas Airline EMB-110 crashed from a bomb explosion in the cabin during the flight from Colon City to Panama City.
- On December 11, 1994, a Philippine Airlines Boeing 727 was attacked in flight from a bomb explosion in the cabin.
- On July 9, 1997, an explosive device in the passenger cabin detonated on a Transporte Aereo Mercosur Fokker 100 during the flight.

In response to a series of criminal attacks against aviation, the U.S. Congress mandated, through amendments to the Federal Aviation Act of 1958, that the Federal Aviation Administration (FAA), as part of the Department of Transportation (DOT), assume primary responsibility for civil aviation security. The need for special aviation security measures was first recognized in 1969. Since then, FAA has developed and administered a number of programs designed to prevent criminal acts against the aviation industry. In its early years the program focused on the hijacking threat and included the development of weapon detection technologies and equipment, such as metal detectors and x-ray machines. In 1974, U.S. Congress passed the Anti-hijacking Act which essentially established the FAA's responsibility for conducting a research, engineering and development program in the area of aviation security, to counter the terrorist threat. In 1976, precipitated by a terminal bombing at LaGuardia Airport of New York City, the FAA began a research and development program in explosives detection. Experts convened to discuss the threat and recommended a long-term security program and associated technologies. In addition to x-ray techniques, several technologies were suggested and investigated, including thermal neutron analysis (TNA), nuclear magnetic resonance (NMR), and vapor detection (VD).

The Pan Am flight 103 bombing, which killed 270 people, helped spawn the Aviation Security Improvement Act of 1990. On August of 1989, Executive Order 12686 established the Presidential Commission on Aviation Security and Terrorism. A report was released in May of 1990, which recommended that the FAA pursue a more rigorous program in aviation security research and development to counteract the terrorist threat. In November of 1990, Congress passed the Aviation Security Improvement Act to accelerate research and development of technologies and procedures to counteract terrorism. The Act instructed the FAA to fund the development of *E*xplosive *D*etection *S*ystems (EDS), establish EDS certification standards, and test and certify potential EDS for eventual deployment. The FAA initiated the movement to develop and assess the performance of the new technology.

From 1991 to 1996, the FAA invested 153.3 million dollars in developing technologies specifically designed to detect concealed explosives. These expenditures have funded approximately 85 projects for developing new explosives detection technology [FUL96]. The FAA relies primarily on contracts and grants with private companies and research institutions to develop these technologies and engages in some limited in-house research.

Organized and sponsored by the FAA, the First International Symposium on Explosive Detection Technology was held on November 13-15, 1991 at Atlantic City, New Jersey. Its purpose was two-fold: 1) provide a forum for the exchange of ideas, information and technology among program managers, scientists and engineers working in the area of civil aviation security; and 2) determine the direction of research and development in the critical area of global civil aviation security [KHA91]. A total of 430 civil aviation security experts from U.S. and abroad participated. More than 100 papers, spreading in bulk detection, vapor detection, testing and field experience, signal processing and simulation, and systems integration, were presented at the symposium by scientists and engineers from nineteen universities, fourteen national and defense laboratories and equivalent organizations from Canada, France, Germany and the UK. Later, FAA continued to sponsor or co-sponsor several more symposiums, including the Second Explosives Detection Technology Symposium and Aviation Security Technology Conference in November 1996.

The FAA believes that the greatest threat to aviation is explosives placed in checked baggage. In September 1993, the FAA published a certification standard that explosives detection systems for checked bags must meet before they are deployed. The standard is classified and sets certain minimum performance criteria for 1) the explosive substances to be detected; 2) the probability of detection, by explosive; 3) the quantity of explosive; and 4) the number of bags processed per hour. In addition, the standard specifies the maximum allowable false alarm rate, by explosive. To minimize human error, the standard also requires that the devices automatically sound an alarm when explosives are suspected. This feature is in contrast to the conventional x-ray devices, whereby the operator has to look at the x-ray screen for each bag to determine whether it contains a threat.

The CTX5000, manufactured by InVision Technologies, passed the minimum requirement test at the FAA Technical Center in December 1994, becoming the first x-ray machine certified by the FAA for explosives detection. This EDS is based on the principle of computed tomography, which permits determination of the shapes and properties of objects that allow them to be identified as possible explosive materials with more certainty than is possible in single view x-ray systems. At the present time, no other system has been certified by the FAA for explosives detection.

The crash of TWA Flight 800 off Long Island in July of 1996, although later concluded not to be caused by criminal activity, lead to the formation of the White House Commission on Aviation Safety and Security. The President called for the Commission to rapidly develop an action plan to deploy high technology equipment for explosives detection. For use in improved screening of checked baggage, this plan includes purchase and installation of fifty-four CTX5000 SP systems (a modified version of the CTX5000), twelve non-certified dual-energy x-ray machines, several quadrupole resonance machines, and equipment for trace detection. Used in combination with passenger profiling, the deployment of high technology equipment can lead to enhanced aviation security. Combinations of these technologies can provide multiple levels of inspection to assist with false alarm resolution.

As stated in the keynote address of the First International Symposium on Explosive Detection Technology, “In this business, there is no silver bullet. … There will not be one piece of equipment that we can put into the field that will solve all of our problems. That should be encouragement for everybody in the field to work on equipment that they think will do a part of the job.” [ROB91]

For current and future research and development programs, the FAA’s plans for developing detection technologies for checked baggage include efforts to improve the certified system, develop new technologies, and evaluate a mix of technologies. The FAA believes that an appropriate mix of systems that individually do not meet certification requirements might eventually work together to detect the amounts, configurations, and types of explosive material that are required by the Aviation Security Improvement Act of 1990.

1.2 Observations on Current X-ray Detection Technologies

X-ray detection methods are the most common means to inspect luggage at airports. There are several technical reasons: 1) X-ray technology provides an ability to determine some important characteristics of the materials of interest. The most useful information that x-ray technology may provide is related to an object’s density (*d*) and effective atomic number (Z_{eff}). The term “effective atomic number” is the atomic number of the hypothetical single element that gives the same x-ray attenuation as a compound or mixture being measured. There are other characteristic values about an object that an x-ray can provide, but none of those values is as effective as these two pieces of information in term of material characterization. Theoretically, an object’s material type can be uniquely determined by using density and Z_{eff} [EIL92]. 2) X-ray technology has been developed for nearly a century. 3) X-ray technology is more safety to human being and to the contents inside luggage bags than some other technology, such as nuclear magnetic resonance. 4) X-ray physics is well understood; and x-ray technology is also very sophisticated in terms of x-ray source, electronic device, and detector.

X-ray EDS can substantially improve the airlines' ability to detect concealed explosives before they are brought aboard aircraft. While most of these technologies are still in development, a number of devices are now commercially available. However, none of the commercially available devices are without limitations. EDS based on CT scanning techniques, worth about one million dollars each, has a high probability of detection of a variety of different explosive materials with a range of configurations, and a relative low rate of false alarms, but it does not have an adequate throughput and is very costly. Dual-energy scanning systems, which are described further in Chapter 2, do not detect the quantities and configurations of the full range of explosives specified in the standards, but they have a high scanning throughput and are relatively cheap. X-ray imaging systems with scatter detection, also described in Chapter 2, generally have similar defects as dual-energy systems. However such a system gives density related information and has a higher throughput than CT scanning systems.

The following are the overall observations on x-ray detection technologies that have important implications for their use at airports [FUL96]:

- First, these devices vary in their ability to detect the types, quantities, and shapes of explosives.
- Second, explosive detection devices typically produce a number of false alarms that must be resolved either by human intervention or technical means. These false alarms occur because the devices use various technologies to identify characteristics, such as shapes, densities, and other properties, to indicate a potential explosive. Given the huge volume of passengers, bags, and cargo processed by the average major U.S. airport, even relatively modest false alarm

rates could cause several hundreds, even thousands, of items per day to need additional scrutiny.

- Third, and most important, these devices ultimately depend upon human beings to resolve alarms. This activity can range from closer inspection of a computer image and a judgment call, to a hand search of the item in question. The ultimate detection of explosives depends on extra steps being taken by security personnel, a correct judgment by them, to determine whether an explosive is present. Because many of the devices' alarms signify only the potential for explosives being present, the true detection of explosives requires human intervention. The higher the false alarm rate, the greater is the system's need to rely on human judgment. This reliance could be a weak link in the explosive detection process. In addition, relying on human judgments has implications for the selection and training of operators for new equipment.
- Fourth, although these devices can substantially increase the probability of discovering an explosive, their performance in the field may not be as good as in laboratory tests. For example, the FAA-certified system, CTX5000, has not performed as well in operational testing at two airports as in FAA's certification test [FUL96]. The need to rely on operators to resolve false alarms still exists.

One major problem stated above is the false alarm rate. The author believes it is caused by three factors:

Firstly, some materials are non-separable to systems based on x-ray attenuation methods, which are designed to distinguish materials by their physical density and effective atomic number. In statistical pattern recognition, the term “no-separable” means that we cannot find a decision function that exactly distinguishes any one class from others. Otherwise, we say they are separable. This is because there are numerous materials that possess the similar attenuation profiles as explosives. For example, in the (Z_{eff}, d) domain, some plastics and rubbers fall in the black powder area, and the others fall in the smokeless powder area

[KRA96]. If all black powders and all smokeless powders are set to threat in our automated alarm scheme, we would false alarm some plastics and rubbers. Otherwise, we would miss detection of some explosives.

Secondly, the characterization for a certain material may spread into a wider range in feature space due to the method actually used. For example, most explosives can be separated from innocent materials by using two-dimensional information, (Z_{eff}, d). But in order to obtain Z_{eff} and d, it is necessary to know exactly the material composition, weight fractions, and its geometry information for each object in luggage bag. The technology vision has not been proven that it is indeed possible to get such an information by using the dual-energy x-ray system up to date. Under such a circumstance, some extrinsic parameters, such as thickness and orientation of that material would negatively affect the material characterization. An explanation is given in Figure 1.2-1. Two classes, C_1 and C_2, are shown in this figure. They would be linearly separable if theoretical measurements (x_1, x_2) are available (see Figure 1.2-1a). But unfortunately, sometimes the practical measurements ($x_1^{'}$, $x_2^{'}$) have to be adopted instead of theoretical measurements, therefore the designated classification boundary for this case does not exist any more (see Figure 1.2-1b). The extrinsic parameters cause uncertainty to a system. A good feature vector in pattern recognition should be obtained in such a way that the extrinsic parameters have no effects on our classification rules.

Thirdly, there exist errors in any detection system. Errors in a system change the statistical distribution of any class. There is no doubt that this will make the system classification performance worse by either increasing false alarm rate or decreasing detection rate, even if materials are separable. Figure 1.2-2 shows a two-category example. The a posteriori probability density functions for two classes, C_1 and C_2, are $p(x|C_1)$ and $p(x|C_2)$. The mean values and variances for two classes are (x_1, σ_1^2) and (x_2, σ_2^2) respectively. By applying Bayes decision theory to this two-category classification problem, we have a decision rule as: "choose C_1 if $p(x|C_1) > p(x|C_2)$, otherwise choose C_2". This supposes that their a priori probabilities are equal. With this decision rule, the probability of a classification error can be expressed as:

$$P(\text{error}) = P(\text{choose } C_1 \text{ and } x \text{ actually from } C_2) + P(\text{choose } C_2 \text{ and } x \text{ actually from } C_1) \quad (1.1)$$

Suppose our goal is to detect an object in C_2 from other objects in C_1, "P(choose C_1 and x actually from C_2)" is actually undetected probability, and "P(choose C_2 and x actually from C_1)" is so-called false alarm rate. Both undetected probability and false alarm rate introduce classification errors. From Figure 1.2-2, we have,

$$P(\text{error}) = A + B \quad (1.2)$$

Higher variances causes increment on A and B, this will result in a bigger probability of classification error. In Chapter 5, we will give an example to calculate P(error) in detail. System error and uncertainty may due to x-ray source, system configuration, detector non-uniformity, system noise, image scanning, and image processing though there is a different for various applications.

The error and uncertainty change the statistical distributions of classes; this has a negative effect on object classification. Actually, the practical measurements mentioned in the second reason affect the classification performance in like manner due to extrinsic parameters' effect.

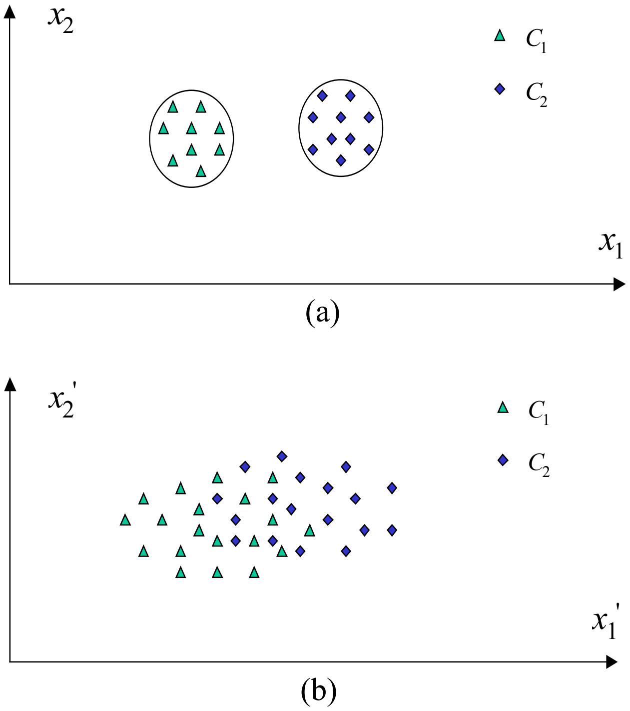

Figure 1.2-1 Schematic description of theoretical measurements versus practical measurements. (a) Distinguish class C_1 from class C_2 by using theoretical measurements (x_1, x_2); (b) Distinguish class C_1 from class C_2 by using practical measurements (x_1', x_2'). The identification errors occur in (b).

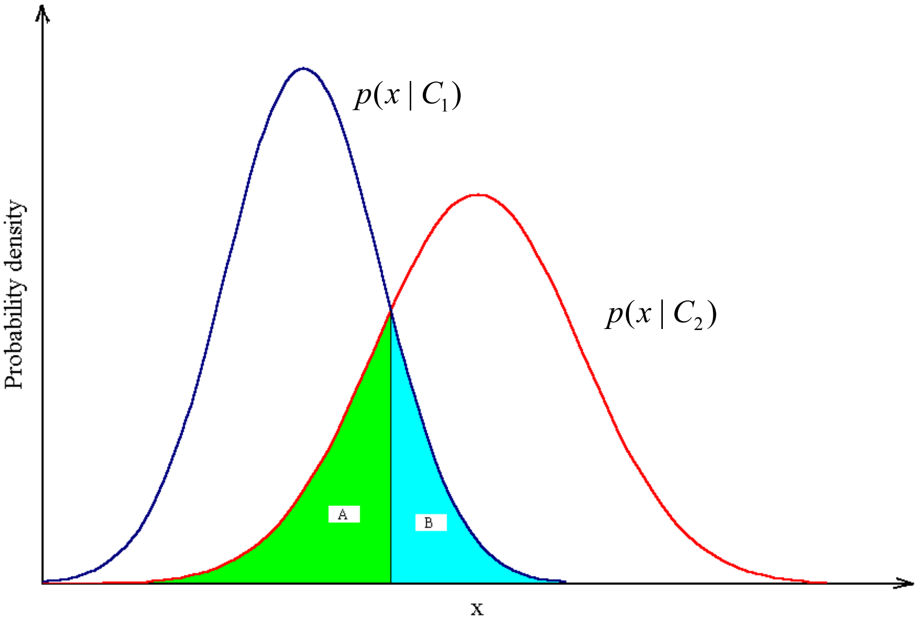

Figure 1.2-2 Schematic descriptions of measurement errors' effects on classification.

1.3 Scope

1.3.1 Project description

To improve the overall performance of materials characterization, efforts should be made in three directions. One is to use additional or alternative methods, such as elemental composition analysis. Second is to improve the existing system. The last one is to evaluate the mix of technologies.

Under sponsorship of FAA, “Multiple x-ray sensor approach to explosive detection using data fusion techniques” has been conducted at Spatial Data Analysis Laboratory (SPDL) of Virginia Tech [CON96] [ABB96]. Our efforts mainly focused on the second and third directions. That is to improve the existing system and to evaluate the mix of technology. From 1994 to present, totally fifteen people, including twelve graduate students, one visiting scholar, and two professors, have participated in this project in varying degrees.

The people can be roughly divided into four groups: 1) the system group that was responsible for the system configuration, testing, and developing the project related hardware and software; 2) the physics group that worked on x-ray detection physics and simulations; 3) the image processing group that was to develop advanced image-processing algorithms to extract “true” x-ray attenuation information for each object from the very complicated luggage, to detect elongated objects by image-match processing, and to investigate CT detection technology by using single-view image scanning system; and 4) the group that was to develop new methods for improving materials characterization. The relationship among four groups is shown in Figure 1.3-1. The physic group supports the research efforts for all other groups. The system group provides x-ray images for the image processing group. The image processing group gets images from scanner and send information for each object to materials characterization group. The material characterization group characterizes the objects and feeds new proposals back to the system for further modification.

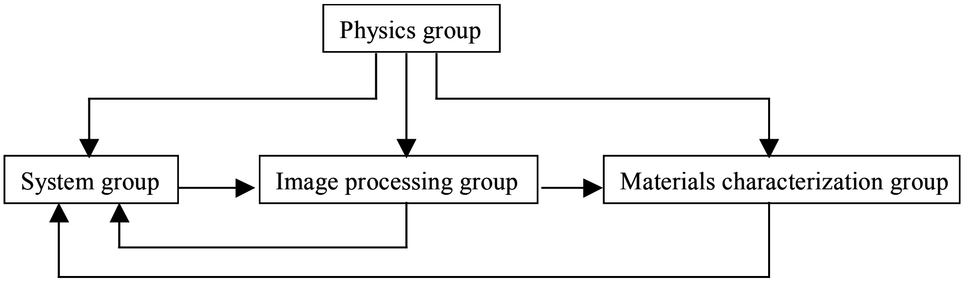

Figure 1.3-1 Relationship among four groups

To effectively support all research efforts, a prototype x-ray scanning system was built up at the SDAL by combining dual-energy transmission technology and scattering technology [DRA98]. Using dual-energy transmission technology, information related to Z_{eff} is obtained. Organic material (low Z), can theoretically be distinguished from inorganic materials and metals (high Z). Using scattering technology, information related to density can be computed. Denser materials (usually explosives have a high density) can be separated from less dense materials. In Chapter 2, we will review principles of x-ray detection technology in detail.

As it has been pointed out in Section 1.2 and will be described further in the following chapters, the x-ray intensities for each object are not only related with its material composition which reflects the intrinsic property, but also some extrinsic parameters, such as position, orientation, and thickness. For a practical application, all above extrinsic parameters are undetermined, and they will negatively affect the performance of the materials characterization. This is one major problem on the existed dual-energy x-ray detection systems.

The goal of our team is to develop an x-ray scanning system that use *R-L* based method to detect explosives efficiently.

1.3.2 Limitations

There are some limitations on this research. First, it is difficult to obtain complete information about existing commercial systems or even about data obtained from these systems due to proprietary considerations, no matter whether systems are certified or non-certified. The necessary data for our research had to be collected from our own device. The data set collected was limited to the small set of passenger luggage bags that we obtained from a commercial airline. Fortunately, we are able to create very complicated scenarios that are believed to be representative of those encountered at airports.

1.3.3 Assumptions

The number of objects that appear in a passenger luggage bag is often very large. Different objects may appear in a bag in arbitrary orientations with arbitrary shape and geometry; and most of them overlap other objects. Explosives are typically mixed with common innocuous materials, which makes their detection very difficult. Identifying overlapping effects is a fundamental task of the image processing group. More details can be found in [LU99].

This dissertation assumes that the individual x-ray intensities have been estimated. By this assumption it means that the x-ray intensity for each material under a particular situation, saying for a given position, orientation and thickness, is known.

1.4 Objectives and Contributions

The research objective for this dissertation is to improve methods for materials characterization, and then to enhance the overall detection capability of our prototype scanning system. As discussed in Section 1.2, this can be accomplished through 1) improving the materials characterization by reducing the uncertainties caused by the extrinsic parameters, such as thickness, orientation, and position; and 2) decreasing the system errors which might be introduced by detector non-uniformity, x-ray source dark current, and output signal unbalance between high transmission and low transmission. The work spreads over all parts of our prototype scanning system. The following is a list of tasks that need to be completed:

(1) Develop a model for the x-ray prototype scanning system in order to do system analysis and simulations;
(2) Design algorithms for image correction;
(3) Develop a method for selecting an x-ray attenuation filter;
(4) Design a algorithm for treating the scattering signals;
(5) Develop a method for reducing the effect of object thickness in materials characterization.

Some major achievements and results are described in this dissertation as follows:

- To reduce errors in the prototype scanning system, a system model is needed This model can also be used for the purpose of the system analyses, design and simulations. We use this model to predict some system errors, and to lead developing the algorithms for treatment of such errors. This model is also used to select an x-ray attenuation filter and in the development of a numerical method for eliminating thickness effect.

- In the prototype scanning system, the pixel values are varied for the same object due to the use of non-uniformity of the transmission detectors. A lot of measurements are done, and a correction algorithm is developed to reduce this error.
- The x-ray source output energy in the prototype scanning system is not monochromatic; it has a distribution over a wide range. To meet the design requirement on developing this dual-energy x-ray scanning system, two problems have to be dealt with. The first one is the overlap of the x-ray spectrum between high energy and low energy. The overlap will degrade the effect of dual-energy; the more overlapping, the less information we can get. The ultimate situation is if the spectrum at high energy and low energy is fully overlapped, so that the dual-energy x-ray system deteriorates to a single energy system. The second one is the output signal unbalance between high energy and low energy. This is due to the limited dynamic signal range of x-ray scanning system. If we adjust the x-ray scanning system and make it to fit for high energy, the output signal at low energy will be too small, and the noise would be bigger. But if we adjust the x-ray scanning system and make it to fit for low energy, the output signal at high energy will be saturated, resulting in information distortion. A copper attenuation filter is introduced and optimization concept is adopted to improve the system performance.
- The position of an object relative to x-ray source and detector has a strong influence on the detected forward and backward scatter signals, resulting in an input error to the classification system. Both an adaptive modeling technique and least squares method are developed to decrease this effect.
- A numerical method has been developed to reduce variations due to thickness in dual-energy sensing.
- Classification rules have been obtained to distinguish several explosive materials from other materials. Discriminate function has been developed experimentally.

1.5 Outline of Dissertation

The rest of this dissertation is arranged as follows: Chapter 2 gives a brief overview of x-ray physics. A prototype x-ray scanner and its model are presented in Chapter 3. This chapter also presents several algorithms for image correction and shading correction due to the use of non-linear amplifier circuit and non-uniformity of photon-multiplier-tube respectively. The design of an x-ray attenuation filter is described in Chapter 4. Chapter 5 introduces a new method for materials characterization using dual-energy sensing. Chapter 6 gives a method for reducing error of scattering images. An experimental study on classification is presented in Chapter 7. Overall conclusions are given in Chapter 8. Finally, a brief overview of MCNP simulation software is presented in Appendix A.