Chapter 1

INTRODUCTION

1.1 Motivation

There are two major categories of illicit materials: drugs and explosives. Most illicit materials, explosives in particular, present threats to the general public. Terrorists' attacks on aircraft using explosives, especially plastic explosives, has been a major threat to national security [USD92]. To counteract the terrorist threat, the first line of defense, as in guidance provided by the Presidential Commission Report, is to use explosive detection devices to prevent terrorists' placing explosives onto aircraft [PCA90].

A screening device must possess the capability of characterizing materials inside containers or bags. Since illicit materials such as plastic explosives can be molded into almost any shape and placed inside any object, a material cannot be simply characterized by using its shape information. A device is required to characterize a material at the molecule and atom level.

Under the sponsorship and leadership of Federal Aviation Administration (FAA), researchers at Virginia Tech formed a project team to develop such a screening device using existing x-ray technologies. Due to the size and complexity of this project, ten graduate students and two faculty members were involved with different parts of the project development. The people can be roughly divided into three groups: 1) the group that was responsible for developing the project related hardware; 2) the group that studied x-ray detection physics and was to develop new methods for x-ray material detection; and 3) the group that was to develop an advanced image-processing algorithms to enhance the detection accuracy.

Because it is impossible for us to study all types of illicit material detection problems with our limited time, funding, and other resources, we choose to focus on the study of explosive detection in passenger luggage. Explosive detection in passenger luggage represents one of the most complex problems in illicit material detection problems. The complexity is due to the types and number of objects appearing in this detection environment. It is actually more complicated than cases such as detecting drugs in a cargo vehicle or other types of illicit materials in shipping containers. Being able to design a system that can successfully detect explosives in luggage represents a significant advance in the field of illicit material detection.

The FAA demanded us to concentrate on the study of one-view x-ray technology. This is because most existing airport luggage screening systems are one-view x-ray systems. The research results from our study can be directly applied to those existing one-view systems to improve their detection accuracy. X-ray technology provides the ability to determine some important characteristics of an object's material. The most useful information that x-ray technologies can provide is an object's *density*- and *effective atomic number* or Z_{eff}-related information. There are other characteristic values about an object that x-ray technology can provide, but none of those values is as effective as these two pieces of information. Theoretically, using *density* and Z_{eff}, an object's material type can be uniquely determined [EIL92]. X-ray technology has been developed for nearly a century, and the x-ray physics is well understood. X-ray technology is very sophisticated also in terms of x-ray source, detector, and electronics equipment. The inspection throughputs of one-view x-ray devices are usually high enough to meet the requirements by the needed agencies. X-ray devices are actually considered as *the* devices used for the first line of defense [GRO91].

The attraction of one-view x-ray technology to many agencies is that compared to other types of technologies, one-view x-ray systems are relatively inexpensive and are affordable. Although multiple-view x-ray technologies and Computed Tomography (CT) may have higher detection accuracy than one-view x-ray technologies, their detection throughput cannot meet the requirement set down by the FAA. They are also much too expensive. So our focus on the improvement of one-view x-ray technologies is very meaningful for the illicit material detection community.

Further research on x-ray physics has shown that there are different types of x-ray technologies that can be used for illicit material detection. However there is no single x-ray technology can provide both the *density* and Z_{eff} values that are needed to unambiguously determine an object's material type [FAI92, GRO91, NAS91, OTA91, OTA92]. Take an example of x-ray transmission technology, a value S can be measured [FAI92, GRO91, OTA91]. Value S is proportional to the combination effects of *density* and Z_{eff}. This technology has trouble in distinguishing between a thin sheet of a strong absorber, such as metal, and a thick sheet of weak absorber, such as explosives. Dual-energy transmission systems use two transmission mode x-ray systems, with beams that are generated by a source that peaks at different energies, producing two independent images [FAI92]. Using dual-energy transmission technology, R, a Z_{eff}-related information can be determined. Organic materials can be separated from inorganic materials and metals using R [ZOU98]. But it has trouble to separate innocuous organic materials from illicit materials, because the difference between those materials lies in *density*. Forward and backscatter systems measure the incoherent scattering effect [FAI92, GRO91, OTA91, KRU91]. Using scatter technology, L, a *density*-related information can be computed [ZOU98]. Denser materials can be distinguished from less dense materials using L, but materials with high Z_{eff} cannot be distinguished from materials with low Z_{eff}.

An improvement to the current technology is to use data-fusion techniques so that all the information can be integrated together to arrive at an improved detection result. Unfortunately, almost all the multisensing-systems currently in the market are so called "pseudo-multisensing" systems. They are multisensing systems because their systems have been equipped with several x-ray technologies. Those systems are "pseudo-multisensing systems" because the detection of a single type of material utilizes only one technology. For example, the system developed by Vivid Technologies uses both the dual-energy transmission and scatter technologies for illicit material detection [KRU96]. But the dual-energy transmission is responsible for regular illicit material detection, while the scatter technology is responsible for sheet explosive detection only. Detection results can be perceived to have higher detection accuracy, but the results can be further improved if Z_{eff}- and *density*-related information can be derived simultaneously for an object of interest. The best combination of such a multisensing system is dual-energy plus scatter technologies [ZOU98].

The goal of our team is to develop a system that uses an *R-L* based method to detect explosives. The x-ray technologies used in this case are the combination of dual-energy transmission technology plus scatter technologies. *R-L* detection method is a new invention in the illicit material detection community that seems to be a very promising technology.

This project was based on a team effort. Individuals were responsible for different parts of the development. As I have said earlier, the development of this project were divided into three major parts: hardware development, *R-L* plane method development, and image-processing system development. The development of these different parts proceeded in parallel. Dr. Thomas H. Drayer was in charge of the hardware component development. Ms. Shubin Zou and Mr. Xinhua Shi were responsible for *R-L* plane based materials characterization algorithm development. The *R-L* plane is used for threat assessment, and Mr. Shi is the person who is responsible for development a complete module for threat assessment. The core of this dissertation, which is my major responsibility in this project, was to develop an image-processing system to enhance the detection capability; or more specifically, to find methods that can effectively eliminate the overlapping effects of an object of interest in order to determine its *true* gray levels.

As I have said earlier, using dual-energy transmission technology, *R*, a Z_{eff}-related quantity can be computed; using scatter technology, *L*, a *density*-related quantity can be computed [ZOU98]. Our research has shown that in the *R-L* plane, illicit materials can be separated from metal, inorganic materials, and other innocuous organic materials. The *true* gray levels of an object is important to know because *R* and *L* material characteristic values can only be calculated using *true* gray levels. Once *R* and *L* of an object are known, this object can be tested in a *R-L* plane, where a boundary is drawn that separates illicit materials regions from innocuous materials. The object's material type can then be uniquely determined. The *true* gray level of an object can be explained as follows: when an object of interest is placed in air, and there is no background objects appearing, the gray level measured is called the *true* gray level of this object. If the average is used to compute an object's *true* gray level, then an object has only one *true* gray level for one sensing modality. Apparently, the object would have four *true* gray levels if the object has been measured in four sensing modalities. In this case, I often refer this set of *true* gray levels simply as the *true* gray levels of this object.

The number of objects that appeared in a passenger luggage bag is often very large. Different objects may appear in a bag in arbitrary orientations and most of them are ***overlapped*** with other objects. Illicit materials are typically mixed with those commonly seen innocuous objects, which makes their detection very difficult. The ability of eliminating overlapping effects is absolutely essential towards material characterization. By eliminating the object overlapping effects, the *true* gray level of an object is revealed.

Although the usage of *true* gray levels is different for each technology, the image-processing system for eliminating background effects is actually needed for almost every type of x-ray detection. Unfortunately, most existing systems fail to develop very sophisticated image-processing systems. In fact, there are no known published papers that clearly define the concept of *true* gray levels. There is no known published algorithm that explicitly tries to resolve this problem. This may be due to the fact that most companies believe improvements in the hardware components such as x-ray source and detectors will play a bigger role in improving detection accuracy than developing image-processing software. However, there are always certain limits on how far one can improve the system detection accuracy just by using better hardware components. It is now the time to change such a view, because it is obvious that better image-processing modules that can eliminate the overlapping effects will significantly help to improve the detection accuracy. The entire dissertation focuses on the discussion of developing such an image processing system and verifying its capability in improving the detection accuracy.

1.2 Limitation and Scope

There are some limitations of my study. It is difficult to obtain complete information about existing commercial systems or even about data obtained from these systems because of proprietary considerations. The necessary data need for our research had to be collected from our own device. The data set collected was extremely limited to the small set of passenger luggage bags that we managed to obtain from U.S. Air. Fortunately, using this small set of bags, I have been able to create very complicated scenarios that I feel are representative of those encountered when inspecting passenger luggage bags at airports.

Due to the same proprietary considerations, how well existing commercial systems perform is also unknown to us. Consequently, comparisons between our system and the currently available commercial systems are impossible. I have to construct a set of test scenarios that are representative; based on the test results on this set of data, I can evaluate the performance of our system.

My experimental data were collected from a device that is ten-year-old technology. The data collected from this system have severe noise problems. Many efforts have been put into the algorithms in order to eliminate the effects of this noise. The current state-of-the-art x-ray technologies provide systems that can collect images with much higher image quality. The efforts to eliminate the noise effects may not be needed for the newer systems. Hence, the performance of my image-processing system should be significantly better in this low noise environment, an improvement that is obtained without modifying the algorithms.

Our study focuses on the detection of explosives in bags. However, storing and handling real explosives are extremely dangerous. So instead of using explosives, explosive simulants are used for my experiments. Those simulants possess the same *density* and *effective atomic numbers* as real explosives. The simulants have inert characteristics; they are safe to store and handle. They are perfect for my experiments. However, real explosives should be used when a system is tested for practical use.

1.3 Assumptions

The purpose of the image-processing system is to provide information to the threat assessment system tries to characterize the materials making up the object of interest. The assumption is that if an object's *true* gray levels are determined, the threat assessment system will be able to characterize the object's material type in a relatively precise manner. The research on the threat assessment indeed supports this assumption. Furthermore, the research has indicated that if additional information such as this object's thickness and distance information is provided, the results may be more precise.

A bag is assumed to have the following properties. The bag is limited to the size that the entire bag can be probed by the existing x-ray imaging device. Thus the width must be less than 3 feet long, and the height must be less then 2 feet tall. A bag should not be too thick; otherwise, the outgoing signal is too weak to be used for material analysis. The preferred thickness is 8 inch or less. The bag's covers should be made of materials such as plastic, which do not shield the radiation from entering the bag. The contents of a bag such as food and films are not damaged by the x-ray radiation beams used to probe the bag.

Due to safety considerations, the energy of x-ray radiation source cannot be higher than 150 keV. However, lower energy of the x-ray radiation source means lower penetration power of the inspected luggage bags. The assumption is that most bags can be penetrated by this x-ray energy level. If a bag is too thick to be examined by x-ray screening devices, it should be subjected to manual search.

The scope of my study is limited to the discussion of detecting explosives in passenger luggage bags. But the methods and concepts can seemingly be used for detecting drugs as well. The detection of explosives is actually more complicated. There are more than one hundred types of explosives for military and civilian use, but there are only about twenty types of illicit drugs which are commonly seen. Drugs have similar characteristics to explosives. The methods that work for explosive detection should also work for drug detection. On the other hand, a bag poses a very complicated detection environment. The number of objects and the types of objects appearing in a bag are significantly large. Other detection environments, such as cargo containers, may have objects in a larger number. However, the methods and concepts used for detecting illicit materials should be similar. The image processing algorithms just have to process a larger size of x-ray images.

The computation power of personal computers has increased dramatically and the cost has decreased significantly. The inexpensive personal computers can run very sophisticated image-processing algorithms in real-time without specialized hardware. So it is my belief that the image-processing algorithms developed in this dissertation can be effectively implemented in real-time.

1.4 Objectives

The goal of my research is to develop an image-processing system that can enhance the overall detection capability of our scanning system. This is accomplished by designing an image-processing system that can determine an object's *true* gray levels. Here is a list of tasks that need to be accomplished in order to compute the *true* gray levels:

1. Design an algorithm for spatially registering images collected from the different imaging modalities.
2. Design a robust segmentation technique that can identify the object of interest either partially or in its entirety in a very complex environment.

3. Develop the overlapping models for transmission and scatter modalities.
4. Design an algorithm for determining the *true* gray levels of an object.

To design an algorithm for registering images is important, because multi-sensing technologies are used for collecting images. Objects in different imaging modalities need to be registered before any further computation can be done. The purpose of segmentation is to group pixels into meaningful regions. Then information can be computed on region bases. The unique and most important contribution of this dissertation is to develop the overlapping models for transmission and scatter modalities, and to implement the algorithm for determining the *true* gray levels of an object. No similar models or methods previously exist in any publication. The overlapping models provide mathematical models for eliminating the effects caused by background objects' effects. The algorithm utilizes those models to compute the *true* gray levels of an object of interest.

During the research, I have found that an object's thickness and distance information are factors that affect the determination of an object's material type. Since my research focuses on improving detection accuracy of one-view systems, only some minor discussions will be given to adding an orthogonal view to the one-view system in order to obtain the thickness and distance information.

To develop overlapping models requires knowledge of x-ray physics. So it is fair to say that my research involves research in physics as well as image processing. However, I present my research as a computer vision problem because it provides a clear framework on which the x-ray physics can be more easily presented.

Figure 1.4-1 gives an overview to the proposed illicit material detection system. The image-processing system can be conceptually decomposed into five components: 1) the x-ray image scanning module; 2) the image segmentation module; 3) the module for determining an object's *true* gray levels; 4) the module for determining an object's thickness and distance information; and 5) the threat assessment module.

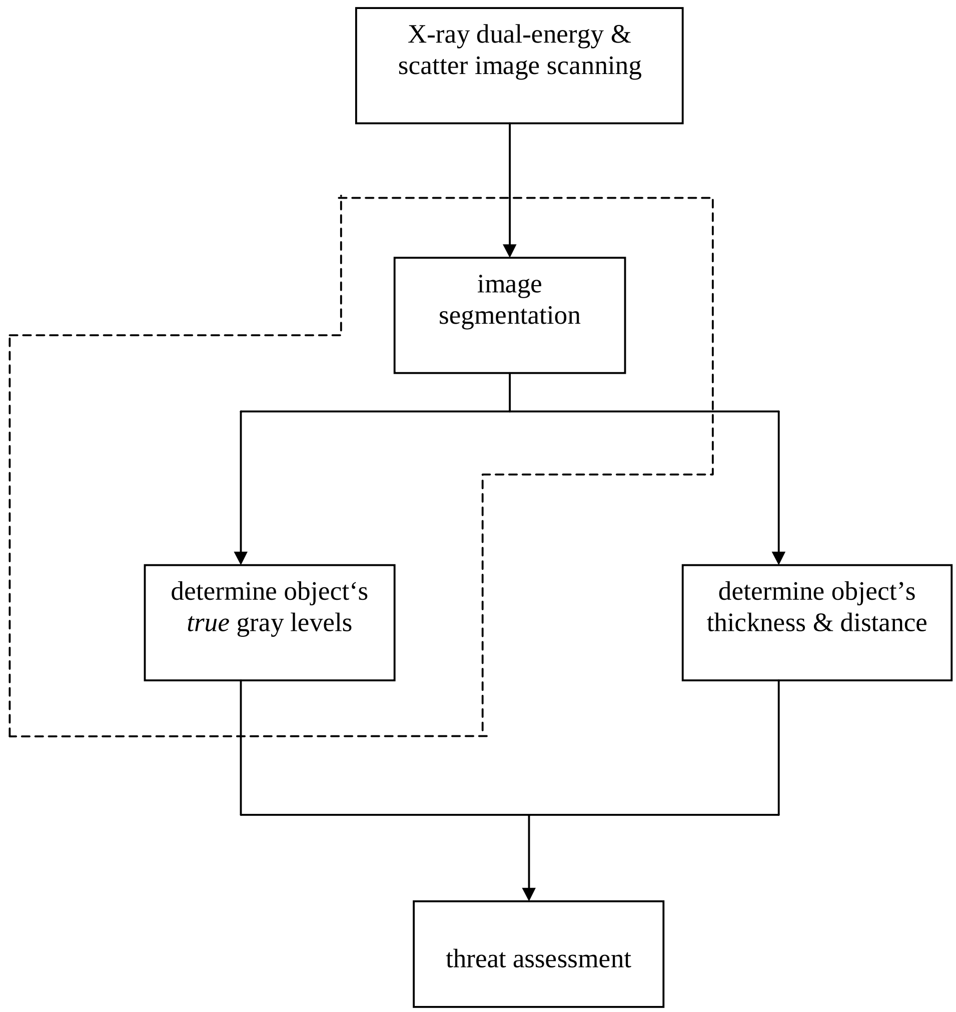

Figure 1.4-1 Diagram of the overall system for detecting the illicit materials.

The hardware design group was responsible for most of the development in the image-scanning module. I was responsible for developing some of the image preprocessing algorithms for the first module, all the algorithms in the second and third module. Some minor discussions are given to the module for determining an object's thickness and distance information. The x-ray physics group was responsible for researching on x-ray physics and developing the algorithms used in the threat assessment module. The modules for image segmentation and *true* gray level determination are the core modules for determining an object's *true* gray levels. This has been indicated by the dashed-line box in Figure 1.4-1.

The image segmentation module can be further divided into three blocks, as seen in Figure 1.4-2. The first block is image registration, the second block is image smoothing, and the third block is region growing. The module for determining the object's *true* gray levels across all sensing modalities consists of two blocks, as seen in Figure 1.4-3. The first block is to compute all possible gray levels. The development of this block involves modeling the overlapping effects for transmission and scatter sensing modalities. The second block is to select the most likely candidate gray levels as the *true* gray levels. In order to compute the object's *true* gray levels, object overlapping models must be established first. To establish those models has proven to be the most difficult problem encountered in this study.

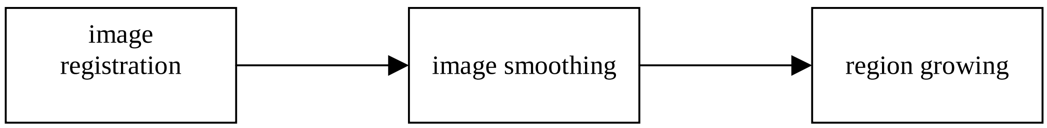

Figure 1.4-2 Segmentation module.

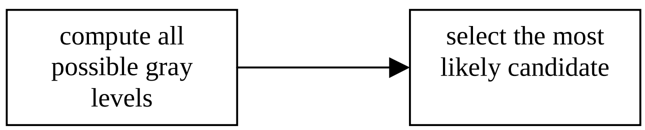

Figure 1.4-3 Module for determining the object’s *true* gray levels across all sensing modalities.

Now, it is necessary to give a brief introduction to the threat assessment system. This system determines an object's material type by using an object's *R* and *L* values. *R* and *L* are computed from this object's *true* gray levels. Some additional information such as an object's thickness, and distance information may also be used to improve the detection accuracy. The object then is placed in the *R* and *L* plane to see if it falls into the region of illicit materials. If the object of interest is found to be an illicit material, the system will send an alarm to the operator about the potential threat. If none of the objects in a bag have been positively identified as an illicit material, then the system proceeds to the next bag. The detailed discussion of the material characterization sub-system is beyond the scope of this dissertation, and can be found in the dissertation that is being prepared by Mr. Xinhua Shi.

A number of strategies have been incorporated into my system to make the system more flexible and robust. A bottom-up (data-driven) strategy is used throughout most of the algorithm development. This is mainly because little is known about the types, orientations, and overlapping situations that occur in the detection environment. Uncertainty reasoning is incorporated into the system because there is uncertainty in all stages of the system, especially when the *true* gray levels of a region must be decided. Each solution has been embedded into a different module so the maintenance and modification become very easy and flexible. The programming language used is C++, an object-oriented programming language. The modular structure is particularly good for designing an image processing system that means to solve general problems in a domain. In addition, to reduce the development life cycle, some fast prototyping utilities are used, such as the MATLAB and Khoros software package.

1.5 Contributions

This dissertation makes a number of contributions. First, this image processing system contributes to the new technology, *R-L* plane detection technology. This technology is a new technology that will hopefully significantly improve the detection accuracy for one-view x-ray systems. Second, the mathematical formulas that model the x-ray overlapping effects in different sensing modalities have not been discussed anywhere else in any publication. I am the first researcher who developed such models. Third, the algorithm for determining an object's *true* gray levels using those overlapping models is unique. Fourth, during the algorithm development, I have created new implementations for existing algorithms to make them run significantly faster. This is extremely important, since my ultimate goal is to develop a screening device that can run in real-time. Finally and most importantly, this dissertation has demonstrated the importance of using image-processing systems to improve an explosive detection system performance, i.e., detection accuracy.

1.6 Organization

This dissertation consists of 5 chapters. Chapter 2 provides the overview of the proposed study and the background for illicit material detection using x-ray technologies. Chapter 3 describes the image segmentation module and the module for determining the *true* gray levels for objects. Chapter 4 gives experimental results that demonstrate the performance of these modules. Chapter 5 concludes the dissertation, providing a summary and recommendations for future research.