Table of Contents

Chapter 1. Introduction 1

1.1 Motivation 1
1.2 Observations on Current X-ray Detection Technologies 5
1.3 Scope 12
  1.3.1 Project description 12
  1.3.2 Limitations 12
  1.3.3 Assumptions 14
1.4 Objectives and Contributions 15
1.5 Outline of Dissertation 17

Chapter 2. Overview of X-ray Detection Technologies 18

2.1 X-ray Generation and Spectra 18
  2.1.1 X-ray generation 18
  2.1.2 The Characteristic Spectra 19
  2.1.3 The Continuous spectra of x-rays 23
2.2 The Absorption and Scattering of X-rays 30
  2.2.1 Introduction 30
  2.2.2 The photoelectric effect 31
  2.2.3 Coherent scattering 32
  2.2.4 Incoherent (Compton) scattering 34
  2.2.5 Characterization of x-ray attenuation processes 35
2.3 X-ray Detectors 37
   2.3.1 Structure of scintillation detectors 37
   2.3.2 Processes involved in x-ray detection and measurement 38
2.4 Principles of X-ray Detection 39
2.5 X-ray Imaging systems 41
   2.5.1 Conventional x-ray screening systems 41
   2.5.2 Dual-energy x-ray imaging systems 42
   2.5.3 X-ray Imaging System with Scatter 47
   2.5.4 Computer Tomography (CT) Scanning System 53

Chapter 3. An X-ray Detection System 56
3.1 Configuration of The Prototype Scanning System 56
   3.1.1 AS&E 101zz x-ray machine 56
   3.1.2 Configuration of the prototype scanning system 59
3.2 The Prototype Scanner Model 62
   3.2.1 The block diagram of prototype scanner 62
   3.2.2 X-ray source emission 64
   3.2.3 Detected signals 65
   3.2.4 The verification and correction of the amplifier circuit 68
   3.2.5 Shading correction 74
3.3 Application of the Model 84

Chapter 4. Optimum Copper Filter Design 88
4.1 Requirement Specification 88
   4.1.1 Overview 88
4.1.2 Definition of optimum copper filter design 92

4.2 MCNP: Method of Solution 95

4.3 Design Result 96

4.4 Evaluation 101

4.4.1 Dual-energy measurements on step wedges with and without copper filter 101

4.4.2 An imaging example with and without copper filter 107

Chapter 5. A Numerical Optimization Method To Improve Materials Characterization 109

5.1 Thickness Effect on Dual-Energy Transmission Imaging 109

5.1.1 Thickness effect on transmission imaging 109

5.1.2 Effect of the material’s appearing in the field of view 110

5.1.3 Effect of the material orientation 115

5.1.4 Thickness effect on dual-energy transmission imaging 119

5.2 A Numerical Method To Overcome The Thickness Effect 126

5.2.1 Numerical expression of the transmission signal 126

5.2.2 Solving equations with numerical optimization 130

5.3 Implementation 132

5.4 Application Examples 133

5.5 Improvement Evaluation 143

5.5.1 Description of decision rule 143

5.5.2 Comparison of the probability of error 144

Chapter 6. The Treatment of Distant Dependent Scattering 149

6.1 Distant Dependent Scattering 149
6.2 Treatment of Variation 152
   6.2.1 Model description 152
   6.2.2 Solving for the coefficients with adaptive training 154
   6.2.3 Solving for the coefficients with Least Squares (LS) 158

Chapter 7. Experimental Study on Classification 162
   7.1 Characterization of Explosive Materials 162
      7.1.1 Atomic effect number and density 162
      7.1.2 Classification feature space in the prototype scanning system 163
   7.2 Test Objects 163
      7.2.1 Description of test objects 163
      7.2.2 Image examples collected using the prototype scanner 170
   7.3 Experimental Study on Classification 186
      7.3.1 Bayes decision theory 186
      7.3.2 Minimum-error-rate classification 187
      7.3.3 Classifiers, discriminant functions and decision boundaries 188
      7.3.4 Classification rules in the prototype x-ray imaging system 190
      7.3.5 Classification results 194

Chapter 8. Conclusions and Future Research 200

References 203

Appendix A. An Overview of Monte Carlo N-Particle Software 213
   A.1 MCNP Input File 213
   A.2 Physics Treatment of Photon Interaction in MCNP 221
A.3  MCNP Output  223
A.4  An Example of MCNP Input File  223
# Table of Figures

| Figure 1.2-1 | Schematic description of theoretical measurements versus practical measurements. | 10 |
| Figure 1.2-2 | Schematic descriptions of measurement errors’ effects on classification. | 11 |
| Figure 1.3-1 | Relationship among four groups | 13 |
| Figure 2.1-1 | Schematic description of x-ray tube. | 19 |
| Figure 2.1-2 | Energy levels and characteristic x-ray transitions. | 21 |
| Figure 2.1-3 | Spectra simulated by XL and measured by [FEW81], for an incident electron energy of 70 keV. | 27 |
| Figure 2.1-4 | Comparison of simulated spectrum with the spectrum measured by [FEW81] for incident electron energy of 140 keV. | 28 |
| Figure 2.2-1 | Photoelectric effects of interaction and absorption. | 31 |
| Figure 2.2-2 | Schematic description of coherent scattering. | 32 |
| Figure 2.2-3 | Compton interaction and scattering. | 35 |
| Figure 2.3-1 | Schematic illustration of the structure of an x-ray detector. | 38 |
| Figure 2.5-1 | An image example to show regions of high attenuation. | 41 |
| Figure 2.5-2 | An image example to show the concealed objects can be identified in SECURE 1000 image system [SMI91]. | 42 |
| Figure 2.5-3 | X-ray absorption through a rectangular block of an uniform material. | 43 |
| Figure 2.5-4 | A pair of transmission images from a dual-energy x-ray scanning system in Virginia Tech’s SDAL. | 46 |
| Figure 2.5-5 | A possible threat as identified by a dual-energy x-ray machine in SDAL of Virginia Tech. | 47 |
Figure 2.5-6  Transmission and scatter images scanned at SDAL of Virginia Tech. 49

Figure 2.5-7  Transmission image of a suitcase. 51

Figure 2.5-8  CT image reconstruction of a layer in the suitcase 3 inches above the bottom. The shoe trees and the top of the aerosol can are visible [SHR91]. 52

Figure 2.5-9  CT image reconstruction of a layer in the suitcase 2.3 inches above the bottom. The heels of the shoes, coat hangers, and the aerosol can are visible [SHR91]. 53

Figure 2.5-10 CT image reconstruction of a layer in the suitcase 2 inches above the bottom. The coat hangers, coins and a cigarette lighter are visible [SHR91]. 54

Figure 2.5-11 CT image reconstruction of a layer 0.3 inches above the bottom of the suitcase. The simulated explosive, a battery pack, a pocket calculator, and wires are clearly visible. There is a very little evidence of the overlapping structure that is apparent in the transmission image [SHR91]. 55

Figure 3.1-1  Schematic diagram of “flying spot” in AS&E 101zz. 58

Figure 3.1-2  Schematic geometry of the prototype image sensors and source. 60

Figure 3.2-1  Block diagram of the prototype scanner. 62

Figure 3.2-2  Coordinate representation of the imaging geometry. 64

Figure 3.2-3  Block diagram of the amplifier circuit. 67

Figure 3.2-4  Comparison of the measured voltages (circles) and calculated voltages (solid lines). 71

Figure 3.2-5  Common photo-multiplier structures. 75

Figure 3.2-6  Non-uniformity of the transmission image: (a) before shading correction, (b) after shading correction; where y is the column index and x is the row index. 78

Figure 3.2-7  Dark current on the backward scattering image: (a) before correction, (b) after correction; where y is the column index and x is the row index. 79

Figure 3.2-8  Dark current on the forward scattering image: (a) before correction, (b) after correction; where y is the column index and x is the row index. 80
Figure 3.3-1  A transmission image scanned using the prototype scanner. 85
Figure 3.3-2  Transmission image $T_L$ after correction of Figure 3.3-1. 86
Figure 3.3-3  A backward scatter image scanned using the prototype scanner. 87
Figure 3.3-4  Backward scatter image after correction of Figure 3.3-3. 88
Figure 3.3-5  A forward scatter image scanned using the prototype scanner. 89
Figure 3.3-6  Forward scatter image after correction of Figure 3.3-5. 90

Figure 4.1-1  Energy spectrum of x-ray tube obtained by MCNP. 90
Figure 4.1-2  Block diagram of the copper filter design approach. 91
Figure 4.1-3  Explanation of spectrum overlap and signal unbalance. 94
Figure 4.3-1  Simulated x-ray source energy spectra with insertion of the copper filter. Variable $t$ in $I_{145}$, $t$ stands for the thickness of the copper filter. 97
Figure 4.3-2  Unbalance of output signals varying with thickness of copper filter. 98
Figure 4.3-3  Spectrum overlap varying with thickness of copper filter. 99
Figure 4.3-4  Cost function varying with thickness of copper filter. 100
Figure 4.4-1  Step wedges used in our measurements. 102
Figure 4.4-2  Transmission image of a typical luggage bag scanned at low energy. 107
Figure 4.4-3  Transmission images at high energy: (a) without the copper filter, (b) with the copper filter. 108

Figure 5.1-1  An example of the thickness effect on transmission imaging. 111
Figure 5.1-2  Schematic descriptions of material’s appearance in the field of view. 112
Figure 5.1-3  Relative variation of pass-through thickness versus the incidence angle for an object placed perpendicularly on conveyer belt. 113
Figure 5.1-4  Variation of the received signal intensity due to material’s location (given as row number) in the field of view. 114

Figure 5.1-5  Schematic description of material orientation. 116

Figure 5.1-6  Variation of the transmitted signal intensity versus the incidence angles (given as row number) with different orientation: (a) $\alpha = 68^\circ$, (b) $\alpha = 126^\circ$. 117

Figure 5.1-7  White plastic step wedge scanned at: (a) 75 keV; (b) 150 keV. 120

Figure 5.1-8  Clear plastic step wedge scanned at: (a) 75 keV; (b) 150 keV. 121

Figure 5.1-9  Aluminum step wedge scanned at: (a) 75 keV; (b) 150 keV. 122

Figure 5.2-1  Composite rule as a sum of simple rule. 128

Figure 5.5-1  Estimated probability density functions of three dual-energy classes and the discriminant boundaries for three step wedges. 146

Figure 5.5-2  Estimated probability density functions of dual-energy measurements and the discriminant boundaries for three step wedges. 147

Figure 6.1-1  Backward scattering of a polyethylene plate. 150

Figure 6.1-2  Variation of scattering gray levels with distance. 151

Figure 6.1-3  Variation of the averaged scattering gray levels with distance. 152

Figure 6.2-1  Block diagram of adaptive modeling. 155

Figure 6.2-2  Learning curve of LMS algorithm 157

Figure 6.2-3  Output of the combination network processed with adaptive modeling. 158

Figure 6.2-4  Output of the combination network processed with the linear least squares. 161

Figure 7.1-1  Characterization of common materials found in luggage. 163

Figure 7.1-2  Measurements on real luggage materials, step wedges and explosive simulants. 165

Figure 7.2-1  A typical luggage bag used in these experiments. 168
Figure 7.2-2 Plastic simulants used in this research. 169
Figure 7.2-3 Explosive simulants used in this research. 169
Figure 7.2-4 Images scanned for six explosive simulants. 171
Figure 7.2-5 Images scanned for plastic simulants. 173
Figure 7.2-6 Images scanned for white plastic step wedge. 175
Figure 7.2-7 Images scanned for clear plastic step wedge. 176
Figure 7.2-8 Images scanned for aluminum step wedge. 177
Figure 7.2-9 Images scanned for a common luggage bag with one explosive simulant. 178
Figure 7.2-10 Images scanned for a common luggage bag inserted with two step wedges. 180
Figure 7.2-11 Images scanned for a common luggage bag with one explosive simulant. 182
Figure 7.2-12 Images scanned for a common luggage bag with two explosive simulants. 184
Figure 7.3-1 A pattern classifier [DUD73]. 189
Figure 7.3-2 An example on decision boundary for discriminating two-class materials. 199

Figure A.1-1 Outline of MCNP input file Cards 214
Figure A.1-2 The right-handed coordinate system used in MCNP. 217
Figure A.1-3 The cell and surfaces cards for a box bounded by planes. 218
Table of Tables

Table 2.1-1 Mass stopping power parameters for tungsten [TUC91]. 26
Table 2.1-2 Thomson-Whiddington constants for different incident electron energies [BIR79]. 26
Table 2.1-3 Parametrization of the mass attenuation coefficients of tungsten from 20 keV to 200 keV, \( u = E/(100 \text{ keV}) \) [TUC91]. 27

Table 3.2-1 Outputs of the amplifier circuit for transmission imaging with no object in the x-ray path. 68

Table 4.4-1 Dual-energy for aluminum step wedge with and without the copper filter. 103
Table 4.4-2 Dual energy for white plastic (polyethylene) step wedge with and without the copper filter. 104
Table 4.4-3 Dual energy for clear plastic (polymethyl methacrylate) step wedge with and without the copper filter. 105
Table 4.4-4 Separation of dual-energy among three typical materials without the copper filter: \( |\bar{R}_j - \bar{R}_k| \). 106
Table 4.4-5 Separation of dual-energy among three typical materials with the copper filter: \( |\bar{R}_j - \bar{R}_k| \). 107

Table 5.1-1 Transmission signals and dual energy values obtained from the prototype scanner for aluminum step wedge. 123
Table 5.1-2 Transmitted signals and their dual energies obtained from the prototype scanner for white plastic step wedge. 124
Table 5.1-3  Transmission signals and dual energy values obtained from the prototype scanner for clear plastic step wedge.  125
Table 5.4-1  Dual energy for white plastic plate of 2.54 cm with $\alpha = 0^\circ$.  134
Table 5.4-2  Dual energy for white plastic plate of 5.08 cm with $\alpha = 0^\circ$.  135
Table 5.4-3  Dual energy for white plastic plate of 15.24 cm with $\alpha = 0^\circ$.  136
Table 5.4-4  Dual energy for white plastic plate of 2.54 cm with $\alpha = 68^\circ$.  137
Table 5.4-5  Dual energy for white plastic plate of 2.54 cm with $\alpha = 126^\circ$.  138
Table 5.4-6  Dual energy for white plastic plate of 5.08 cm with $\alpha = 68^\circ$.  139
Table 5.4-7  Dual energy for white plastic step wedge.  140
Table 5.4-8  Dual energy for clear plastic step wedge.  141
Table 5.4-9  Dual energy for aluminum step wedge.  142
Table 5.5-1  Summary of dual-energy moments for three step wedges.  145
Table 7.2-1  List of standard simulants used in the experimental study.  167
Table 7.3-1  $R$ and $L$ values for six explosive simulants.  193
Table 7.3-2  $R$ and $L$ values for aluminum step wedge.  193
Table 7.3-3  $R$ and $L$ values for clear plastic step wedge.  194
Table 7.3-4  $R$ and $L$ values for white plastic step wedge.  195
Table A.1-1  MCNP surface cards [LOS93].  217