Air Cargo Screening System

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Abstract

A air security system is required for the planned Thames Estuary airport, intended to be built in the next decade to replace Heathrow airport. A combination of technologies provide a system proposal that can detect illicit substances and relevant threats currently posed to airports and air travel, both in passenger hold baggage and in commercial air cargo.

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Contents

DISSALLOWED AIR CARGO HOLD SUBSTANCES
Oxidisers and organic peroxides, including bleach and car body repair kits
Acids and alkalis (spillable 'wet' batteries etc.)
Corrosives or bleaching agents, including mercury and chlorine
Vehicle batteries and vehicle fuel systems
Defensive/disabling sprays including mace, pepper spray and tear gas
Radioactive materials, including medicinal or commercial isotopes
Poisons and toxic substances, including rat poison
Infectious substances or biological hazards (infected blood, bacteria, viruses etc.)
Material that could spontaneously ignite or combust (burst into flames)
Fire extinguishers
Guns or firearms of any kind (includes air rifles, starting pistols etc.) - Check with Airline
Blasting caps
Detonators and fuses
Replica or imitation explosive devices, including replica and model guns
Mines, grenades and other explosive military stores
Fireworks and other pyrotechnics
Smoke canisters
Smoke cartridges
Dynamite
Gunpowder
Plastic explosive, including black powder and percussion caps
Flares in any form
Hand grenades
Gun cigarette lighters
Oxygen cylinders
Diving cylinders that are above 280 kPa (2.8 bar or 40 psi) cannot be carried.
Cigarette lighter
Fireworks, flares and other pyrotechnics, including party poppers and toy caps
'Strike anywhere' matches (non-safety matches)

Figure 1: From nidirect.gov [2], A table of all UK banned air cargo hold items

1 Introduction

If approved the proposed Thames Estuary Airport will open within the next two decades and will have an approximate total budget of £50 billion[1]. A significant fraction of this budget will go towards air cargo and baggage security screening systems.

2 Threats and Illicit Substances

This security system must comply with the expectation for all UK outbound flights to have air cargo and baggage scanned for explosive threats before being loaded into the planes hold. In addition system must screen both outbound and inbound flights for dangerous substances such as radioactive material and weapons, or illicit substances such as A class drugs. In addition to Illegal substances a complete list of all banned air cargo hold items is shown in figure 1.

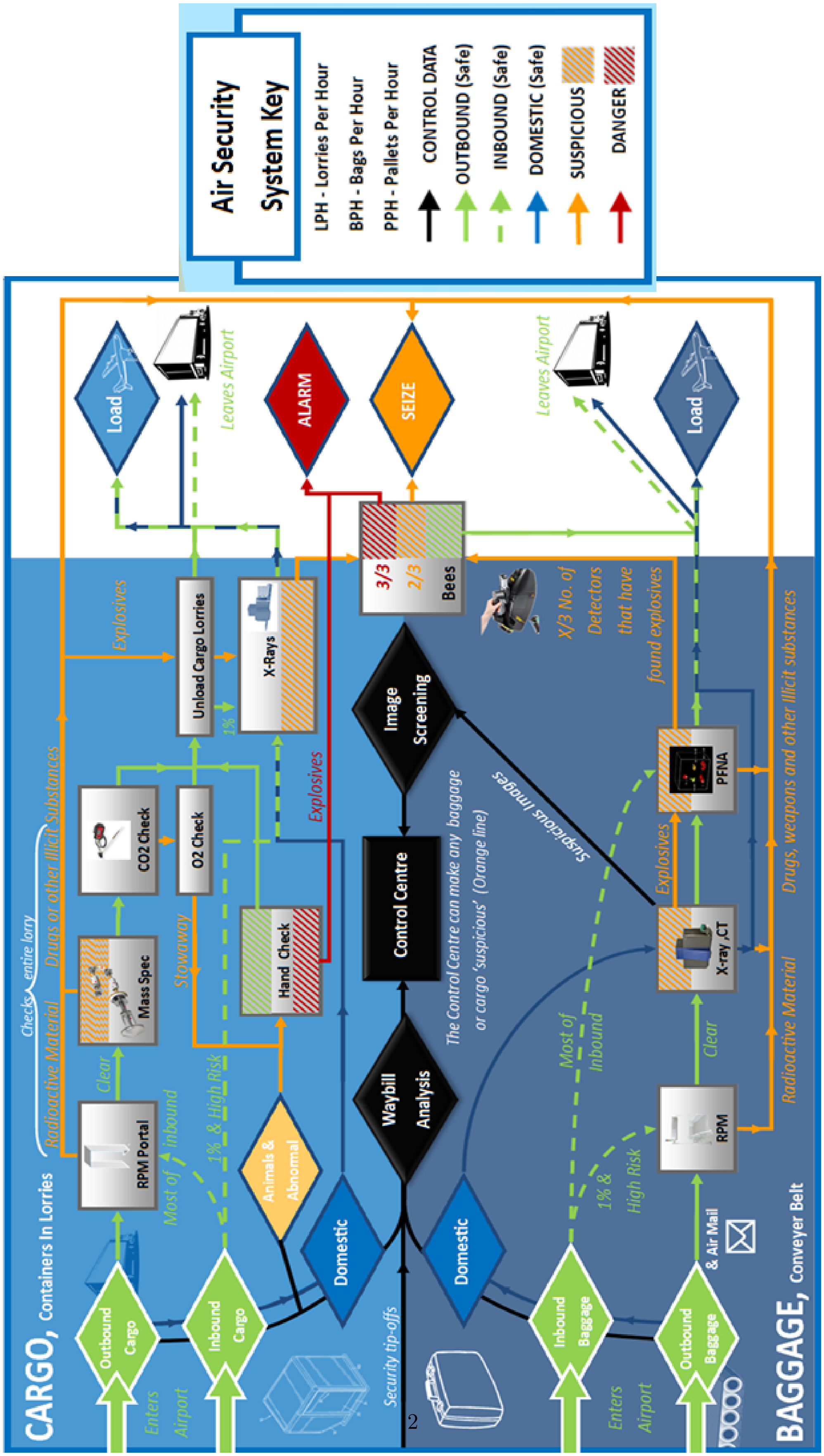

Figure 2: Flow chart for our proposed air cargo security screening system

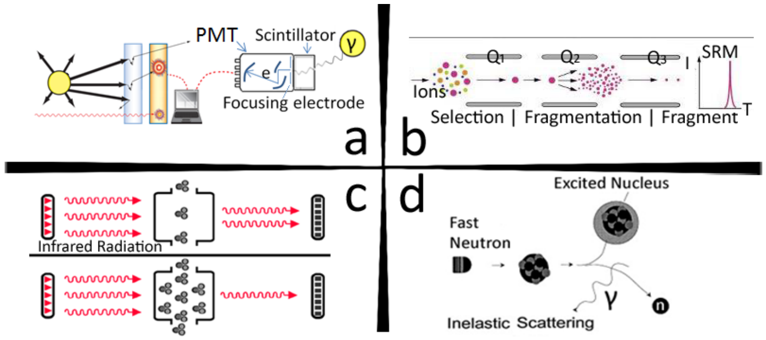

Figure 3: a- from gao.gov [5] , rays or neutron detection. b - from Opinion in Chemical Biology Vol 54 [6] , Quadrupole Stages. c - from howequipmentworks [7] , Radiation incident on CO2 sample. d - from Talanta Vol.41[8], Fast neutron collision

3 The System Proposal

Figure 2 is the visual representation of our system proposal for UK air cargo security. The system split air cargo treatment and Suitcase (and other baggage) treatment into two separate systems.

3.1 Flow Chart Analysis

The Control Centre is the hub of the system, it deals with way-bill information such as the known contents and location of origin, it also may receive security tip offs, and it deals with any computed tomography received by the system. In accordance to the inefficiency of biased scanning, an outcome of Bayesian statistics[3]; the control centre does not discriminate cargo, however it can flag known dangers. Should one of the technologies in Figure 2 or the control centre flag a piece of cargo or baggage, the flow chart line becomes orange. If this detection is one of illicit substances or radioactive material the object is immediately seized, if it is a danger of explosives the object quickly continues through the next appropriate explosive detection scanner (EDS) and final a third highly precise technology, Sniffer Bees. Due to the European Legislation the compensation cost alone of closing an airport is *"up to €600 per passenger from the airline"[4]*, an emergency alarm is only raised if all three EDS technologies detect explosives or an obvious threat is shown on the computed tomography visuals. If 2/3 EDS flag an object, that object is seized.

The majority of outbound cargo is not individually scanned; its portal scanned for radioactive materials, explosives, illicit substances, and stowaways whilst still in the lorry by the Radiation Portal Monitor, Mass Spectrometry and Carbon Dioxide Detector. Saving costs and reducing throughput times. When unloaded a random 1% of cargo is further individually dual view X-ray scanned.

Animals and abnormal sized cargo (NOT stored in LD containers or pallets of known dimensions) must be hand checked. The screening of domestic cargo is kept to a minimal; it goes through EDS but has less focus on illicit substances. The screening of inbound cargo is focused on illicit substances, but a random 1% of all cargo or baggage goes through the entire system. Air mail follows the same path as outbound baggage.

4 Individual Technologies

Figure 3 is a visual representation of all the technologies.

4.1 Radiation Portal Monitors - RPM

The starting technology in our system is RPM is the process of gamma rays or neutrons from a radioactive source being detected from a scintillator or conversion material respectively.[9]

In the first case a NaI plastic scintillator is used where the gamma photons enter and produce a measurable current via electrons e-, this can commonly only detect unshielded trace amounts of plutonium. See equation 1 below. [10]

$$\gamma + NaI \rightarrow NaI^{+} + e^{-} \tag{1}$$

This is used in combination with a thick moderator wall that detects thermal neutrons commonly emitted by plutonium or other radioactive sources, even when shielded by lead. Equation 2 should the incoming thermal neutron n on the Helium 3 He^3 moderator producing a reaction with a measurable amount of energy[10] . This form of RPM has 0.001% false alarm rate.[9]

$$n + He^{3} \rightarrow H^{3} + p + Energy \tag{2}$$

RPM is used as both a lorry portal monitor and a conveyor belt detector for cargo and baggage respectively.

4.2 Triple Quadrupole Mass Spectrometry MS

Whilst still in the lorries the cargo is then tested using Triple Quadrupole MS. As can been seen in figure 3 (b), this is the application of 4 parallel metal rods; 2 of which are given a positive applied potential and the other 2 a negative potential. Samples of gas from the lorries are injected into the Quadrupole and the trajectory of ions from the gas traveling through this Quadrupole are recorded whilst the potential on the quadruples is changed[6] . The potentials are equal to equation 3, with angular frequency ω.

$$\pm(U + Vcos(\omega t))[6] \tag{3}$$

By changing the potential through either varying ω or U and V, a quadruple can select a certain substance, defined by its mass over atomic mass m/z, by making the electric field hold this substance's trajectory through the quadruple. A second Quadrupole forces the selected substance to collide with a known collision gas, fragment and then a third Quadrupole records an MS spectrum of the fragments. Hence this is a triple Quadrupole MS that can select and check for dangerous or illicit substances. [11]

4.3 Carbon Dioxide - C02 and Oxygen Monitors - O2

Cargo is checked for stowaways, this is done quickly for every lorry by using a device that emits infrared radiation. C02 absorbs this radiation. Any re-emitted radiation has distinct absorption spectrum [12]. This as has a 0% false alarm rate in the lab, and is accurate to an upper estimate of 10000 parts per million (ppm) [13].

If the spectrum indicates an amount of C02 that a living creature would produce then a second oxygen level check is undertaken before hand checking the cargo. Commonly an electrochemical device records the current induced by the oxidisation of lead caused by incident hydroxyl ions, the density of ions depending on the number of oxygen molecules in the sample air. [14]

4.4 Pulsed Fast Neutrons Analysis - PFNA

PFNA is the baggage systems second EDS and illicit substance detector. It bombards the baggage with pulses of order 2-14Mev neutrons[8]. Within this energy range inelastic scattering is the most common process; in figure 3 (d) the neutron would rapidly enter the target nucleus, excite the nucleus to a higher energy level then exit the nucleus along with a detectable photon[8]. The excitation photon has characteristic energy depending on the density and effective atomic mass of the nucleus; hence the substance may be identified.

ESTIMATED THROUGHPUT (bold = used in our system)				TO SCAN AN HOURS WORTH OF BAGGAGE IN HALF AN HOUR
	Boxes per hour	Lorries per hour	Bags per hour	No of Units of Technology Needed
CO2 monitor	180	**180**	180	-
PFNA			**360**	110
RPM		**180**	**600**	66
X rays and CT	**1800**		**1800**	44
X rays	1800		1800	-
Mass spec		**30**		-
Dogs (2)		40		-
Bees	**60**		**60**	8

ESTIMATED COSTS				
		COST FOR FIRST YEAR + START UP	People	Minimum wage UK
Cargo	CO2	6000	24230.4	12115.2
	Mass Spec	14195456		2 units, replaced twice a year
	RPM	420000		
	X rays	300000	1% inbound, 1% normal + all domestic + high risk	
	Bees	negligable	high risk	
Subtotal		14921456		
Baggage	RPM	13860000		
	X rays	52800000		
	Neutrons	7700000	-	
	Bees	negligable	high risk	
Subtotal		74360000		
Total		£ 89281456		

Figure 4: [18] [19] Estimates On Throughputs, Number of scanning units and first year with start up costs.

PFNA can emulate a 3rd dimension by using pulses of neutrons and calculating volume elements (voxels) from time of flight calculations. [15]

The first EDS for baggage is X-ray Computed Tomography (CT), covered in the latter half of this report.

4.5 Why Sniffer Bees?

Honey Bees can be conditioned to block a light gate if they smell a substance, up to an accuracy of 78 ppt [16]. Over twice the accuracy of current sniffer dogs (200ppt). In addition 500 sniffer bees can be trained in five hours whilst one sniffer dog can take upwards of six months [17]. With an (estimated) slower throughput of 1 per minute, the system uses them as the 3rd EDS.

5 Estimated Cost and Throughputs of Entire System

The following data is from Heathrow [18] and various manufacturers [19], By taking quoted throughputs and cost estimates and an upper estimate of the potential maximum cargo moving through Thames estuary airport, the number of scanning units and overall cost for the first year (includes power consumption) with start-up costs is approximated. See figure 4. Our systems throughput can successfully scan an hours worth of maximum possible cargo in a half hour whilst assuring maximum safety and the seizure of illicit goods.

6 Dual View X-ray Scanning and X-Ray Computed Tomography

X-rays are the staple of screening technologies because of detailed radiography images that are obtained by understanding how photons scatter off objects at these energies. The basis of X-ray screening is that attenuation depends on the density, the effective atomic mass Z_{eff} and thickness t of the material being scanned [20], hence by detecting attenuation of X-rays after passing through a substance, that substance can be identified.

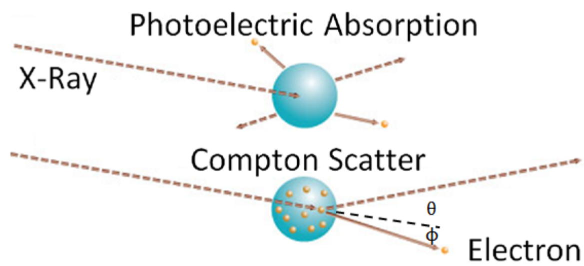

Figure 5: From Lawrence Livermore Laboratory [20] , Photoelectric Absorption and Compton Scattering

6.1 Standard X-Ray Radiography

A particular attenuation cannot simple be directly attributed to a certain material. For example the X-ray beam may pass different thicknesses of multiple materials; a thick low density material could match the attenuation of a thin high density material. In general density and Z_{eff} cannot be resolved from measuring attenuation at single energy X-ray beam from one angle, in order to build a picture of an object the scanning must be over multiple energy levels, multiple angles, or both.

Multiple energies is useful because at high energy x-rays (>80Kv) attenuation becomes more density dependent, whilst at low energies (<80Kv) it is more thickness and Zeff dependent [21].

6.1.1 Scattering Types

There are two physical phenomenon that dominate X-ray attenuation at 50-100keV. See figure 5.

The first is Compton Scattering, where the incident photon strikes an outer electron of the substance; it departs some of its energy, ejecting the electron from its nucleus at an angle ϕ, whilst the photon continues on at an angle θ from its original trajectory [22].

The second is Photoelectric Absorption where the X-ray departs all its energy into an inner electron. This inner electron is excited with enough energy to eject from its nucleus.[22]

A third process known as pair production would occur for high energy photons (dominated by 5-10Mev), where the photon produces a positron-electron pair.[22]

How measured attenuation depends on these effects is quantified by their cross-sections, In Compton scattering the cross section of the X-ray photon is just equal to the number of electrons multiplied by those electrons cross-sections, hence it is proportional to Z, see equation 4. [23]

$$\sigma_{com} = Z\sigma_{electron}[23] \tag{4}$$

In photoelectric absorption the cross section has a much greater dependence on atomic mass Z^5. Figure 6 shows the dominant effects at different energies and atomic masses. [24]

$$\sigma_{pe} \sim 10^{-37}\frac{Z^5}{(hv)^{7/2}}[24] \tag{5}$$

6.1.2 Resolving the Attenuation Coefficient

To solve for the attenuation coefficient, consider the intensity of an x-ray beam through a substance;

$$I(x) = I_0 e^{-\mu x}[24] \tag{6}$$

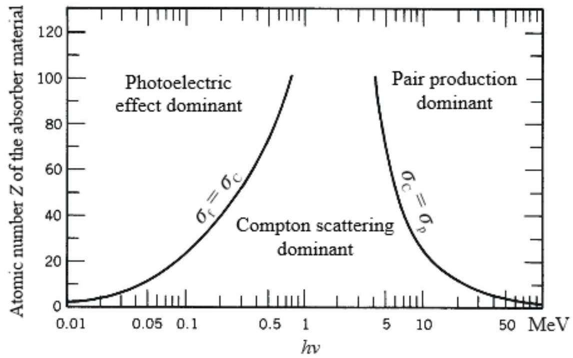

Figure 6: From Vilnius University [24], Dominating effects from 0.01kv-50MeV for different atomic masses

$$\mu = \sigma n_c [24] \tag{7}$$

I_0 is the intensity before, x is thickness and μ is the attenuation coefficient, where σ is cross section and n_c is the atomic concentration. This overall attenuation coefficient is a combination of attenuation coefficients due to Photoelectric Absorption and Compton Scattering. (Ignoring high energy pair production) [25]

$$\mu = \mu_{com} + \mu_{pe} [26] \tag{8}$$

The attenuation coefficient can also be divided by substance density to be written as the mass attenuation coefficient.

$$\mu_m = \frac{\mu}{\rho} [24] \tag{9}$$

Recalling equation 4 and 5 the X-ray Intensity after passing through the substance equation 6 is dependent on both ρ and Z. Equation 6 can also be written as;

$$\frac{I}{I_0} = e^{-\mu_m X} [21] \tag{10}$$

Where X is the mass-per-unit area given by the rearrangement;

$$X = -\frac{1}{\mu_m} log \frac{I}{I_0} [21] \tag{11}$$

6.2 Dual View X-ray Scanning

For two separate energies$_(1, 2)$, equation 11 can be solved to find the ratio of mass attenuation coefficients, R. The left of figure 8 shows how a few measured linear attenuation points match known values.

$$R = \frac{\mu_{m2}}{\mu_{m1}} = \frac{log(I_2/I_{02})}{log(I_1/I_{01})} [21] \tag{12}$$

By carefully choosing the two energy levels at which to scan, the substance may be approximately determined. However there are still several problems with the dual energy or ‘dual view’ scanner. Most importantly the low energy X-rays which can distinguish the mass attenuation coefficients for lower density metals have a very small penetration depth; this reduces the detail with which the X-ray scanners can determine the content of thick objects. [21] A solution is to scan at much higher energies of 4-5 MeV, but to produce a monochromatic (mono-energetic) source at these energies is difficult and equation 6 is less valid for broad spectrum.

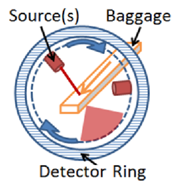

Figure 7: Visual representation of Computed Tomography cargo scanner

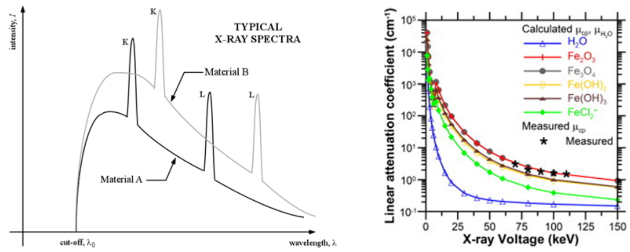

Figure 8: Left; Characteristic X-ray Spectrum of two materials with K and L peaks. Right; from Elsevier Vol 41. [29], Measurements of linear attenuation against theoretically calculated values.

In our system dual view is used for flagged cargo and 1% of all cargo, it is capable of seeing through most shielded objects. For detailed baggage analysis, X-ray Computed Tomography is used.

6.3 Computed Tomography - CT

A pencil thin x-ray beam is rotated with respect to the baggage(fig 7), with scintillating detectors placed at all angles to measure the beam intensity after passing through the baggage.

$$I = \int I_0(E) e^{\sum\limits_{i=1}(-\mu_i(E)x_i)} dE[22] \tag{13}$$

In equation 13 the system takes into account the X-ray is not a singular energy but an X-ray characteristic spectrum like that shown in the right of figure 8 and integrates the change in intensity I due to the sum of the attention coefficients μ over the pencil beams linear direction x, over all energies. However;

"most reconstruction strategies solve equation (13), insofar as they assign a single value to each pixel rather than some energy-dependent range" [20]

CT systems use algorithms to help solve this equation, aiming to reduce visual artefacts detected by the scintillators such as streaking [27](Caused by differences in the μ_{pe} for nearby substances)

CT corrects the raw data collected enough to form a series of 2D tomographs; images in which data recorded over time for a single detector (sinograms) have been convoluted [22] [28]. Each sinogram has its data represented by a CT number, an arbitrary resolution scale. CT numbers are linearly proportional to the attenuation coefficients and hence (approximately) proportional to density [22] [25]. Tomographs are combined into a volume of several images, each voxel (a volumetric pixel) of the image is therefore dependent on density. As in figure 9 each voxel shows a different density. [28]

Figure 9: From AVMI [28], A familiar image, a 3d CT image of a dogs skull. Density is proportional to CT number which is proportional to shading

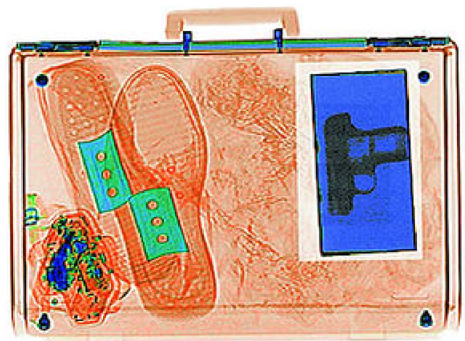

Figure 10: From Smiths Detection [19], Full 3D colour shaded Computed Tomographic air cargo security scan of a suitcase

6.4 Performance and Final Remarks

As stated by the University of Texas High resolution CT facility;

"Modern CT instruments are capable of discriminating between values of that differ by as little as 0.1%" [22]

Smiths detection one of the leading EDS manufactures state that their top end X-ray CT scanner HI-SCAN 10080 XCT has a throughput of up to 1800 bags/hour [19]. Given current research into more efficient automatic decision making, shaded surface display [28] and dual energy CT [27], where the process and presentation (see coloured image figure 10) of any threat or illicit substances is getting better every year. And given current design improvements such as helical cone beam computed tomography, which vastly improves the speed of computed tomography*("8 fold increase of performance[scan time]")* [30], by the time of the new airports construction both the precision and throughput of the computed tomography will have advanced beyond current top end values.

7 Bibliography

References

[1] Transport, Keep Moving *Growth is straining Londons infrastructure* *Available:* `http://www.economist.com/node/21557527` The Economist, Jun 30th 2012

[2] *Dangerous and Restricted Items Available:* `http://www.nidirect.gov.uk/index/information-and-services/travel-transport-and-roads/public-transport/air-travel/` nidirect Government Services, 2013

[3] Miguel A. Jurez *Bayesian Inference* *Available:* `http://www.shef.ac.uk/polopoly_fs/1.259428!/file/BayesInf.pdf` University of Sheffield, 2013

[4] *Establishing common rules on compensation and assistance to passengers* *Available:* `http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:046:0001:0007:en:PDF` Official Journal of the European Union, 2004

[5] Report to Congressional Requesters *TECHNOLOGY ASSESSMENT* *Available:* `http://gao.gov/assets/590/585514.pdf` United States Government Accountability Office, 2011

[6] Ruth Huttenhain et al. *Perspectives of targeted mass spectrometry for protein biomarker verification* *Available:* `http://www.sciencedirect.com/science/article/pii/S1367593109001367` Current Opinion in Chemical Biology Volume 13, Issues 56, December 2009

[7] *Canograph Available:* `http://www.howequipmentworks.com/` How equipment works.

[8] G.Vourvopoulos *Pulsed fast/thermal neutron analysis: a technique for explosives detection* *Available:* `http://www.sciencedirect.com/science/article/pii/S0039914000005440` Talanta, Volume 54, Issue 3, 10 May 2001, Pages 459468

[9] Feblau, P.E. *Integrated neutron/gamma-ray portal monitors for nuclear safeguards* *Available:* `http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=322832` Nuclear Science, IEEE Transactions on (Volume:41 , Issue: 4), Aug 1994

[10] Runkle, R.C. et al. *Analysis of spectroscopic radiation portal monitor data using principal components analysis* *Available:* `http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1645055&tag=1` Nuclear Science, IEEE Transactions on (Volume:53 , Issue: 3), June 2006

[11] Paul Gates *Tandem Mass Spectrometry (MS/MS)* *Available:* `http://www.chm.bris.ac.uk/ms/theory/tandem-ms.html` University of Bristol, 2004

[12] Klock, B.A. *Selected Systems for the Detection of Human Stowaways in Air Cargo Containers. Carnahan Conferences Security Technology* Proceedings 2006 40th Annual IEEE International, 2006

[13] E Rado *Air cargo screening for stowaway detection: Carbon dioxide monitors and Heartbeat Monitor assessment and qualification. Security Technology (ICCST)e* University of Sheffield, IEEE International Carnahan Conference on 2012

[14] *Electrochemical Cells Used in Oxygen Analyzers* *Available:* `http://www.systechillinois.com/en/electrochemical-sensor_49.html` SYSTECH, Illinois, 2010

[15] N. E. Ipe et al. *A CARGO INSPECTION SYSTEM BASED ON PULSED FAST NEUTRON ANALYSIS* Radiation Protection Dosimetry, Vol. 116, 2005

[16] *Sniffer Bees Naturally inspired biosensor*
Available: `http://www.shef.ac.uk/polopoly_fs/1.269373!/file/SnifferBees.pdf` Inscentinel, 2013

[17] *Using sniffer bees for bulk screening of cargo*
Available: `http://www.porttechnology.org/technical_papers/using_sniffer_bees_for_bulk_screening_of_cargo/` Port Technology International, Edition 54, Customs and Security , 2013

[18] *Traffic statistics Available:* `http://www.heathrowairport.com/about-us/investor-centre/results-and-performance/traffic-statistics` Various Traffic Statistics, 2003-April 2013

[19] *HI-SCAN 10080 XCT*
Available: `http://www.smithsdetection.com/HI-SCAN_10080_XCT.php` Smiths Detection, 2013

[20] Caryn Meissner *Preventing Terror in the Skies*
Available: `https://str.llnl.gov/June11/martz.html` Lawrence Livermore National Laboratory, 2011

[21] Y. Liu, B.D. Sowerby, J.R. Tickner *Comparison of neutron and high-energy X-ray dual-beam radiography for air cargo inspection* ELSEVIER, Applied Radiation and Isotopes 66, 2008

[22] Dr. Matthew Colbert *High-resolution X-ray CT*
Available: `http://www.ctlab.geo.utexas.edu/overview/#anchor2-4` UTCT, University of Texas at Austin, 2013

[23] R E Alvarez and A Macovski *Energy-selective reconstructions in X-ray computerised tomography*
Available: `http://iopscience.iop.org/0031-9155/21/5/002` Phys. Med. Biol. 21, Issue 5, 1976

[24] Andrius Pokus *ATTENUATION OF GAMMA RAYS*
Available: `http://www.kkek.ff.vu.lt/uploads/erasmus/no10.pdf` Vilnius University, 2012

[25] Shantanu Banik *Landmarking and segmentation of 3D CT images*
Available: `http://www.shef.ac.uk/polopoly_fs/1.259428!/file/BayesInf.pdf` San Rafael, 2009

[26] Willi Kalender *Computed tomography : fundamentals, system technology, image quality, applications* 3rd rev. ed. Erlangen : Publicis, 2011

[27] Zhengrong Ying, Ram Naidu and Carl R. Crawford *Dual energy computed tomography for explosive detection Available:* `http://www.csuptwo.com/Journals/dual_energy.pdf` Journal of X-Ray Science and Technology 14 ,2006

[28] *Computed Tomography Available:* `http://www.avmi.net/newfiles/CT/CT.html`
Advanced Veterinary Medical Imaging, 2013

[29] Alexander Michel et al. *Cement and Concrete Research*
Available: `http://www.sciencedirect.com/science/article/pii/S0008884611001670` ELSEVIER, Volume 41, Issue 11, November 2011

[30] A. F. Kopp et al. *Multislice Computed Tomography: Basic Principles and Clinical Applications*
Available: `http://www.uc.pt/en/fmuc/phdhs/Courses/biomedicalimaging/CT_Article2.pdf` Siemens AG, Medical Engineering Group, Forchheim, Germany, 2000