Institution: Nottingham Trent University

Unit of Assessment: B15 General Engineering

Title of case study: X-ray imaging for security screening applications

1. Summary of the impact (indicative maximum 100 words)

Pioneering research at NTU on 3D X-ray imaging signalled a breakthrough in multiple-view imaging which has had significant and worldwide impact on the security industry and public safety. It is a prime tool in tackling terrorist activity, particularly explosives concealed in luggage. NTU's divergent beam technique is central to many Advanced Technology Systems used by international security manufacturers. Image Scan Holdings plc was formed by the University in 1996, to exploit original research. Its main trading subsidiary, 3D X-RAY Ltd, now has a wide portfolio of advanced real-time X-ray screening systems with applications deployed internationally in both the security and industrial inspection markets.

2. Underpinning research (indicative maximum 500 words)

Professor Paul Evans has conducted research on 3D security X-ray imaging for over 25 years. In 1993 he was working on a unique divergent beam X-ray technique as part of a collaborative team led by Professor Max Robinson at NTU and at the Home Office by Professor Dick Lacey, Chief Scientist Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE).

A major problem for aviation security was the total lack of depth information in simple X-ray scans. The screener searched routinely for threats such as weapons and improvised explosive devices amongst everyday objects. Serious misinterpretations of objects caused increased false alarms and reduced throughput.

Drawing upon Robinson's earlier work, Evans conceived a breakthrough that high-quality stereoscopic images could be produced using folded detectors. This insight enabled him to design the world's first X-ray scanner incorporating a stereoscopic folded array. It comprised dual energy detectors enabling "organic" and "metallic" objects to be encoded with different colours. This research was in collaboration with Professor Lacey's team, notably Nick Murray and Patrick Mason at the Home Office Research Labs, Sandridge.

A single X-ray source [6] enabled a compact and cost-effective solution. Critically, the technology offered the same throughput as standard single view 'workhorse' machines. In 1996, Image Scan Holdings PLC was formed to exploit original research by the University led by Robinson on stereoscopic X-ray imaging. The main trading subsidiary of Image Scan, 3D X-RAY Ltd was led by Nick Fox and AIM listed in 2002 (the year Robinson retired).

To remove the requirement for stereo glasses Evans devised a new multiple-view technique to produce dynamic depth [5]. Assisted by his PhD student Hock Woon Hon (2000); a small scale version was demonstrated to the Home Office (Evans; Home Office Scientific Development Branch; Introduction of Motion Parallax into Line-scan X-ray Images, 2000). The technique exploited kinetic depth effect (KDE), which enables the observer to work out the shapes of objects with remarkable accuracy from their shadows during a rotation. This was the first demonstration of KDE using divergent beams. A full scale scanner was built in collaboration with Lacey at the Home Office (Evans; Home Office Scientific Development Branch; Multiple View X-ray Acquisition System, 2000-2002) and EPSRC (EP/C520351/1).

The US Dept of Homeland Security funded a six-year rolling research programme (Evans; 2004-2010, KDEX Imaging for Security Screening) to evaluate the performance of kinetic depth X-ray Imaging for luggage screening. This work culminated in a Broad Agency Announcement (BAA) by the US Dept of Homeland Security to US industry to build a prototype KDE scanner. Evans liaised with the US security manufacturers under the BAA. Following prototypes and field trials, Astrophysics Inc (USA) has released a product range.

To reduce the cost of the detector arrays required for KDEX, Evans conceived a new type of 'castellated' dual energy detector [4]. Assisted by PhD student Jer Wang Chan [2004] he demonstrated that the total number of detector elements composing an array could be reduced by 50% without affecting the quality of the imagery. The work formed the basis for a range of products now commercially available through 3D X-RAY Ltd. Funded by the EPSRC (GR/N08858/01) and in collaboration with the HOSDB this work was featured in a "Crime and security special report" Journal of EPSRC.

Professor Evans leads a collaboration with Professor Rogers at Cranfield to combine the two primary but discrete fields that evolved and developed disparately from the discovery of X-rays i.e. radiology and crystallography, with scatter enhanced KDEX [1], EPSRC linked (EP/F017596/1) & (EP/F017804/1). To develop 'true' high speed materials identification capability a new patented tomographic approach employing hollow X-ray beams [2,3] increases by orders of magnitude the intensity of the material signatures. The work is funded under CONTEST the UK's counter terrorism strategy (Evans; IRC HotSpot X-ray Diffraction Imaging for Materials ID, 2008-2011) and (Evans; IRC HALO Tomography, 2011-2014). To exploit this work in security, process control and diagnostic medical imaging we are funded by the TSB (TSB/202158) & EPSRC (EP/K020196/1) and formed a joint NTU and Cranfield spin-off company, HALO X-ray Technologies Ltd.

Our Full Proposal, [text removed for publication], in response to the US DHS S&T Directorate's BAA 13-05: Advanced X-ray Material Discrimination was selected for funding by a panel of experts in July 2013; NTU (Evans lead), Cranfield University (Rogers) and HALO X-ray Technologies Ltd.

3. References to the research (indicative maximum of six references)

Three references indicating the quality of the underpinning research

[1] Dicken, A; Rogers, K; Evans, P; Chan, J.W; Rogers, J; Godber, S; Combined X-ray diffraction and kinetic depth effect imaging; (2011); OPTICS EXPRESS; Vol. 19 p6414; DOI http://dx.doi.org/

[2] Evans, P; Rogers, K; Chan, J; Rogers, J; Dicken, A; High intensity X-ray diffraction in transmission mode employing an analog of Poisson's spot; (2010); APPLIED PHYSICS LETTERS; Vol. 97 p; DOI http://dx.doi.org/10.1063/1.3514235

[3] Rogers, K; Evans, P; Rogers, J; Chan, J W; Dicken, A; Focal construct geometry - a novel approach to the acquisition of diffraction data; (2010); JOURNAL OF APPLIED CRYSTALLOGRAPHY; Vol. 43 p264; DOI http://dx.doi.org/10.1107/S0021889810005248

Additional references indicating the quality of the underpinning research

[4] Chan, JW; Evans, JPO; Yen, SY; Monteith (Home Office), A; Title: Wire transfer function analysis for castellated dual-energy X-ray detectors; (2004); APPLIED OPTICS; Vol. 43 p6413; DOI http://dx.doi.org/10.1364/AO.43.006413

[5] Evans, JPO; Hon HW; Dynamic stereoscopic X-ray imaging; (2002); NDT & E INTERNATIONAL; Vol. 35 p337; DOI http://dx.doi.org/10.1016/S0963-8695(01)00061-5

[6] Evans, JPO; Robinson, M; Godber, SX; A new stereoscopic X-ray imaging technique using a single X-ray source: Theoretical analysis; (1996); NDT & E INTERNATIONAL; Vol. 29 p27; DOI http://dx.doi.org/10.1016/0963-8695(95)00036-4

Key Research Grants

[G1] J.P.O. Evans; **Integrated Stereoscopic X-ray Camera (GR/N08858/01)** *(assessed overall as Outstanding);* Collaborator: Home Office, e2v Technologies plc, Image Scan Holdings plc; EPSRC; (2000-2002); £50k.

[G2] J.P.O. Evans; **Introduction of motion parallax into line-scan X-ray images**; Home Office Science & Technology Group; (2000); £4.5k.

[G3] J.P.O. Evans; Grant title: **Dynamic Stereoscopic X-ray Acquisition System**; Home Office Science & Technology Group (funded via the DETR); (2000 to 2002); £62k.

[G4] J.P.O. Evans; Grant title: **Kinetic Depth X-ray (KDEX) Imaging for Security Screening**; Collaborators: Home Office Science & Technology Group, Sponsor: Science & Technology

Directorate within the USA Dept of Homeland Security; Rolling 2004 to 2010; $458,000.

[G5] J.P.O. Evans; EPSRC: **Dynamic 3D imaging for X-ray security screening: crime feasibility study (EP/C520351/1)**; Collaborators: US Dept of Homeland Security (DHS), Home Office Science & Technology Group, 3DX-Ray Ltd; EPSRC; (2005-06) £61K (+ £13K cash from 3DX-ray Ltd)

[G6] J.P.O. Evans; **Scatter enhanced 3D X-ray imaging (EP/F017596/1)**; Collaborators: Home Office Science & Technology Group, US Dept of Homeland Security (DHS), Durham Scientific Crystals Ltd, EPSRC; (2008-11); £306k (+Linked EPSRC EP/F017804/1 with K. Rogers at Cranfield U £138k)

[G7] J.P.O. Evans; **HotSpot X-ray Diffraction Imaging for Materials ID** Innovative Research Call in Explosives & Weapons Detection, Home Office Explosives & Weapons Detection Programme part of the UK CONTEST strategy; Home Office Scientific Development Branch (HOSDB), Dept for Transport (DfT), Centre for the Protection of National Infrastructure (CPNI), Metropolitan Police Service (MPS); (2008–11); £452k.

[G8] J.P.O. Evans; **HALO Tomography** (as above) UK CONTEST strategy; Sponsors: HOSDB, DfT, CPNI, MPS, US DHS: (2011-14); £400k.

[G9] S. Godber (HALO X-ray Technologies Ltd); J.P.O. Evans (NTU); K Rogers (Cranfield U) ; **HALO Tunable X-ray Technology - High Speed Materials ID (TSB 131257)**; Tech. Inspired CRD (Fast track) – Electron., sensors & photonics; TSB; (2013-14); £150k.

[G10] K Rogers (Cranfield U); J.P.O. Evans (NTU); N. Stone (Exeter U); R. M Martin (Bristol U); P. Zioupos (Cranfield U); Grant title: **Point-of-Care High Accuracy Fracture Risk Prediction (EP/K020196/1);** Collaborators: HALO X-ray Technologies Ltd; Radius Diagnostics Ltd; EPSRC; (2013-16); £776k (£302k to NTU).

4. Details of the impact (indicative maximum 750 words)

The prime impact of the University's divergent beam X-ray work over the preceding 25 years has been to counter the threat of terrorist activity, particularly in the form of concealed explosive devices in baggage being placed on board aircraft [C1]. A key development was the formation of Image Scan Holdings plc in 1996 to exploit the University's IPR under licence from University. The main trading subsidiary of Image Scan plc, 3D X-RAY Ltd was AIM listed in 2002 [C2]. **The specific impact of the University's research during 2008-13 is summarised below.**

Commercialisation & Product Development

3D X-RAY Ltd has developed a portfolio of advanced real-time X-ray screening systems with applications in both the security and industrial inspection markets. It has attracted revenue of over £10 million in the period 2008-2013, with £2.3 million of contracts secured since April 2013. Some notable post 2008 in-service applications of their Axis-3D product include: 20 units deployed at the **Beijing Olympics**, and London's **BT Tower**; numerous units have been supplied in confidence to high profile buildings and agencies across the world [C2]. http://www.3dx-ray.com/products

Astrophysics Inc. The evaluation of NTU's KDEX method was funded by a grant [G4] awarded by the Science & Technology Directorate within the US Dept of Homeland Security (DHS). Due to the success of NTU's programme of research a Broad Agency Announcement was issued by the DHS to US industry to build **prototype scanners** based on our technique. Evans was part of the Broad Agency Announcement process and was contacted directly by nine different US security manufacturers to advise on KDEX design and implementation [C3]. Ultimately, Astrophysics Inc. was awarded a contract and developed its *Surround View* **product range.** This technology enhances object identification while speeding up operator throughput and reducing the need for a secondary search [C3,C5]. *Surround View* was demonstrated at its product release by Evans during an interview broadcast by the **BBC TV World Service** [C6] from the Astrophysics stand at the Transport Security Expo Olympia London, Nov 2012. http://www.astrophysicsinc.com/

HALO X-ray Technologies Ltd Nottingham Trent led the formation of this **spinout company**, in partnership with Cranfield University, in 2012 to exploit our work in X-ray diffraction imaging [G7,G8]. The Founding IP includes Granted Patent (2013) US 8462913; and pending Patents EP 2171435, US 2013/208859, EP 2583088, GB 1300869.3. A revenue stream, [text removed for publication], secured as part of the US DHS S&T Directorate's BAA 13-05, which was selected for funding in July 2013. http://haloxray.com/

Worldwide Industrial Impact

Nottingham Trent's *divergent beam technique* has become the de facto standard for obtaining multiple views from a stationary X-ray source. It is routinely incorporated into *Advanced Technology Systems* (i.e. featuring enhanced detection capabilities) by international security manufacturers to produce compact and cost effective machines. The Home Office Centre for Applied Science and Technology (CAST) are placed uniquely to corroborate this fact because they provide independent, objective evaluations, including Certification of commercially available systems for detecting explosives and weapons. They also provide scientific and technical support to the Central Home Office and other government departments [C1,C4].

Further independent corroboration is stated in the following letter excerpt from an international security manufacturer; *"There are examples of divergent beam techniques in the product ranges of all the major manufacturers of advanced technology (AT) X-ray screening systems e.g.* [text removed for publication]*. This global impact is not surprising as the NTU technique enables the real-time capture of 3D imagery, which was only previously possible with large and prohibitively expensive multiple sources and extended radiological shielding"* [C2].

Worldwide Influence

The University's research output and feedback provided to the US Department of Homeland Security and UK Home Office CAST as part of their Innovative Research Calls IRC2007 [G7] and IRC2010 [G8] research contracts has helped to inform and support scientific thinking in the UK and US Governments concerning the use of diffracted X-rays for the identification of explosive substances and contraband drugs [C1].

Other evidence includes the following personal invitations.

- Government Chief Scientific Adviser (GCSA), Government Office for Science personally invited Prof Evans onto a National Panel of Experts (in 2010). The panel incorporates a select number of leading academics [C1].
- Invited to speak at the *Gordon Research Conference on:* Detecting Illicit Substances: Explosives & Drugs; Switzerland; May 26-31, 2013 [C1].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[C1] Civil Service Corroborative Evidence for Research Submitted to the UK REF: Chief Scientist CBRNE Home Office Centre for Applied Science and Technology (CAST). Collaborated extensively with the NTU group and has detailed knowledge of the underpinning research and the wider impact of their work on the global security industry.

[C2] Letter from the CTO of 3DX-RAY, which is the main trading subsidiary of Image Scan Holdings plc, a technology group listed on the London Stock Exchange's AIM. Also see: http://www.3dx-ray.com/investor-relations/rns-announcements?action=view&newsID=56

[C3] US Government (DHS) approved news release regarding Nottingham Trent research and Astrophysics' new *Surround View* product range provided by Director of Government Programs Astrophysics Inc. USA.

[C4] Civil Service Corroborative Evidence for Research Submitted to the UK REF: Senior Manager National Crime Agency (NCA) formerly the Assistant Director, Central Sponsor for Information Assurance (CSIA) within UK Government's Cabinet Office. Prior to joining the NCA/CSIA this corroborator worked in the Home Office managing a team of scientists and engineers that worked closely with the NTU group for over 15 years.

[C5] http://www.totalpost.com/xray-baggage/astrophysics-vi7-surround-view/ *(Totalpost* - distributor in the UK, Ireland, Germany and South Africa).

[C6] http://www.youtube.com/watch?v=xYhPIrevPLA&list=PL49696C121A3AB1C2&index=1 BBC TV World Service – 5.5 minute broadcast from the Astrophysics stand at the Transport Security Expo London Nov 14-15; product release KDEX scanner, Broadcast Dec 2012.