Institution: Nottingham Trent University (NTU)		
Unit of Assessment: B12 - Engineering		
Title of case study: X-ray imaging for security screening applications		
Period when the underpinning research was undertaken: 1 Jan 2000 to 31 Dec 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Names:	**Roles:**	**Periods employed by submitting HEI:**
Paul Evans	Professor, Royal Society Wolfson Fellow	1993-present
David Downes	Senior Lecturer	2006-present
Hock Hon	Post-Doc. Research Fellow	2001
Jer Chan	Post-Doc. Research Fellow	2004-2011
Yen Yong	Post-Doc. Research Fellow	2004
Period when the claimed impact occurred: 1 Aug 2013 to 31 Jul 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Pioneering research at NTU on 3D X-ray imaging produced 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 detecting weapons and explosives concealed in luggage. The worldwide total number of the travelling public that have been screened and kept safe by NTU-enabled X-ray systems is estimated as 9.8 billion (person-journeys). Transportation Security Administration (TSA) officers used NTU-enabled X-ray systems to find and confiscate a total of 20,884 guns at US checkpoints. NTU research is central to Advanced Technology Systems (through end of 2019 it is estimated that 6,446 units containing NTU-enabled X-ray systems are deployed for aviation security worldwide). The total revenue generated from NTU-enabled X-ray based system sales is around $1 billion. The AIM listed NTU spinoff, 3DX-RAY Ltd, manufactures a portfolio of advanced X-ray screening systems for the security, industrial inspection; nuclear, pharmaceutical and medical device markets. Systems are deployed internationally [text removed for publication].

2. Underpinning research

A major problem for aviation security was the total lack of depth and material composition information in simple X-ray scans. The screener searched routinely for threats such as improvised explosive devices and weapons amongst everyday objects. The superposition of object features along the direction of the X-ray beam (or depth) is exploited to hide or camouflage threats. Serious misinterpretations and mischaracterizations of objects caused increased false alarms and reduced throughput.

The NTU group has developed three distinct, compact and cost-effective advanced X-ray technologies to address these fundamental problems.

1. Divergent Beam Technology (**R1**, **R2**) was pioneered by Evans and his team at NTU in collaboration with the Home Office and funded by EPSRC (**G1**), to employ a single stationary X-ray source producing divergent fan beams incident upon a folded array of dual-energy X-ray detectors. This method enables well-balanced colour stereoscopic image pairs to be collected simultaneously to provide information on depth. Prior to this innovation, two separate X-ray sources would have been required to provide physically intersecting (convergent) beams. In comparison, NTU's technology provides a highly compact and cost-effective solution. It reduces significantly the physical footprint/length, weight/radiological shielding and hardware complexity of an X-ray scanner requiring more than one view, which is the fundamental requirement for volumetric analysis. Critically, NTU's technology also offered the same throughput as standard single view 'workhorse' machines.

2. Multi-View Technology (**R3**, **R4**, **R5**) was invented and developed by Evans and his team at NTU to leverage the advantages of divergent beam technology but with far greater depth fidelity and angular coverage, without the requirement for stereo viewing mechanisms. A series of highly correlated perspective views are collected during a single linear scan using multiple divergent fan-beams and folded dual-energy detector arrays. The resultant images realise a number of different

2D and 3D imaging modes. A pilot version was demonstrated to the Home Office (**G2**). The technique exploited kinetic depth effect (KDE), which enables the observer to work out the shapes of objects with remarkable accuracy during a rotation. This was the first demonstration of KDE using 1D detectors. Building on this initial success a unique full-scale multi-view dual-energy (colour) scanner was built to NTU's design in collaboration with Professor Richard Lacey's (former Chief Scientist CBRNE chemical, biological, radiological, nuclear and explosives) team at the Home Office (**G3**) and EPSRC (**G4**) in collaboration with the US Dept of Homeland Security (DHS), UK Home Office, and 3DX-RAY Ltd.

The successful results from the NTU/Home Office collaboration led to the award of a six-year rolling research programme by US Dept of Homeland Security to NTU (**G5**) to evaluate the performance of kinetic depth X-ray imaging for luggage screening. To support this programme the experimental scanner was extensively reengineered by the NTU team. Comparative studies were undertaken of various full-scale (luggage) imaging modes, which included single view, stereo, and multi-view/KDEX incorporating dynamic 3-view, 7-view or more (divergent beam) views (**R3**, **R4**, **R5**). The team's work culminated in a Broad Agency Announcement (BAA) by the US Dept of Homeland Security to US industry to build prototype scanners. Evans liaised with nine different US security manufacturers under the BAA, which provided funding for prototypes and field trials e.g. Astrophysics Inc (USA) incorporated the NTU Multi-View technology into a new range of scanners.

3. Castellated (dual-energy) Detector Technology (**R6**) was invented and developed by Evans and his team at NTU to reduce the cost of dual-energy detectors providing colour-coded materials discrimination for Multi-View (or single view) scanners including computed tomography (CT) scanners. Assisted by Chan he demonstrated a 50% reduction in the total number of detector elements without affecting image resolution. This was achieved by creating a patchwork (1D or 2D) of detector elements to replace the industry standard configuration of a double layer, with low-energy elements positioned in front of the high-energy elements. The work formed the basis for a range of products now commercially available through 3D X-RAY Ltd. Funded by the EPSRC (**G1**) £50k and in collaboration with the Home Office this work was featured in a "Crime and security special report" Journal of EPSRC.

NTU's research excellence and exceptional impact in the field of X-ray security imaging was recognised by a Queen's Anniversary Award for Higher Education 2015 (Safety and Security of Citizens). Evans won the Times Higher Education Award in 2016 (outstanding contribution to innovation and technology), and The Institute of Physics Dennis Gabor Medal and Prize 2017 (industrial application of physics), and appointment as a Royal Society Wolfson Fellow in 2018-2023 (this scheme, "*supports UK universities … to recruit and retain outstanding senior research scientists*").

3. References to the research

The quality of the underpinning research has been evidenced by rigorous externally peer reviewed grants and outputs.

R1. ***Evans J.P.O**.; Stereoscopic imaging using folded linear dual energy X-ray detectors; (2002); INSTITUTE OF PHYSICS - J. OF MEASUREMENT SCIENCE AND TECHNOLOGY, Vol. 13, 9, p1388; http://doi.org/10.1088/0957-0233/13/9/303

R2. **Wang T.W.; *Evans J.P.O.**; Stereoscopic dual-energy X-ray imaging for target materials identification; (2003); IEE PROCEEDINGS - VISION, IMAGE AND SIGNAL PROCESSING; Vol. 150, no. 2, pp. 122-130, http://doi.org/10.1049/ip-vis:20030166

R3. ***Evans, J.P.O.; Hon H.W.**; Dynamic stereoscopic X-ray imaging; (2002); NDT&E INTERNATIONAL; Vol. 35 p337; http://dx.doi.org/10.1016/S0963-8695(01)00061-5

R4. **Hon H.W.; *Evans, J.P.O.**; Multiple-view line-scan imaging; (2002); IEE PROCEEDINGS - OPTOELECTRONICS; Vol. 149, (2), pp. 45-50; http://doi.org/0.1049/ip-opt:20020231

R5. ***Evans, J.P.O., Liu, Y., Chan, J.W.; Downes, D.**; View synthesis for depth from motion 3D X-ray imaging; (2006); PATTERN RECOGNITION LETTERS; Vol. 27 (15), pp. 1863-1873. https://doi.org/10.1016/j.patrec.2006.02.001

R6. **Chan, J.W.; *Evans, J.P.O.; Yen, S.Y.;** Monteith, A. (Home Office); Wire transfer function analysis for castellated dual-energy X-ray detectors; (2004); OSA - APPLIED OPTICS; Vol. 43 p6413; http://dx.doi.org/10.1364/AO.43.006413

The high quality of the underpinning research is further indicated by the following major funding investments in the research and its dissemination:
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); £45k.
G3. **J.P.O. Evans**; Dynamic Stereoscopic X-ray Acquisition System; Home Office Science & Technology Group (funded via the DETR); (2000 to 2002); £62k.
G4. **J.P.O. Evans**; 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)
G5. **J.P.O. Evans**; 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.

4. Details of the impact

Commercial adoption of new innovative imaging technologies that substantially enhance the safety and security of the travelling public

NTU-enabled systems have an estimated installed base of over 6,400 machines (**S1**) and include the Advanced Multi-View Technology (AT) scanner class, used in cabin baggage screening systems, hold baggage screening systems, and staff screening X-ray systems.

"NTU technology is fundamental to the operation, imaging capability and usefulness of such multi-view X-ray systems; detector arrays are the "eyes" of an X-ray system." (**S1**)

Protecting the safety and security of the travelling public:

- "*Just the US alone (where 100% of passengers are screened using NTU-enabled technologies) accounts for 5.56 billion passengers protected by NTU enabled technologies from 2014-2019* (**S1**)
- "*From 2014-19, a total of 9.8 billion passengers worldwide are estimated to have been screened and protected by NTU-enabled X-rays.*" (**S1**)
- "*In the US alone, the 100% deployment of NTU-enabled X-ray systems resulted in the discovery and confiscation of 20,884 guns*" (**S1**)

Commercial benefits:

- "*Through end of 2019 a total of 11,761 total units, of which an estimated 55% - 6446 units - contain NTU-enabled X-ray systems are deployed for aviation security worldwide.*" (**S1**)
- "*The estimated total sales revenue of these systems is roughly $4.9 billion.*" (**S1**)
- "*From August 2013-2019, the total revenue generated from NTU-enabled X-ray based system sales is at minimum $1.1 billion (based on available company press releases).*" (**S1**)
- "*In addition to annual sales, service and support revenue (at an industry average of 7% of system costs) is roughly $33 million.*" (**S1**)

This utility of the NTU technologies is recognised by the large-scale adoption of NTU-enabled technology as noted by a leading industrialist:

"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. Smiths Detection EDS systems and Astrophysics 3D/2.5D product range. This global impact is not surprising as the NTU

technique enables the real-time capture of 3D colour X-ray images, which was only previously possible with large and prohibitively expensive multiple sources and extended radiological shielding." (**S2**)

NTU commissioned an independent report (**S1**) from a member of the Association of Independent Aviation Security Professionals to establish the global impact of NTU-enabled systems in the aviation security screening sector. Based on their deep understanding of the worldwide security industry the expert provides detailed and specific justification for his estimates of the numbers of different X-ray systems using NTU multi-view or dual-energy detector technology; the numbers employed in airports across different regions as well as passenger traffic through the airports. Specific metrics include total deployed units, sales, systems, support revenues, total passengers protected, and guns (US only) confiscated.

The independent expert modelling and analysis (**S1**) applied to a range of data sources and references including: the World Bank, which obtains its data from the International Civil Aviation Organization, Civil Aviation Statistics of the World and ICAO staff estimates International Air Transport Association (IATA) data via FlightGlobal; data for US airports was obtained from presentations provided by TSA at the Airport Consultants Council (ACC) Workshop July 2019 (the preeminent aviation security conference for industry). Data on airport usage of X-ray based systems in European and Asian airports were provided via personal communications between the independent consultant and the Airport Security Managers at the two major airports (subject to strict security and confidentiality restrictions). Data on gun confiscation at US Checkpoints was obtained from the TSA.gov blog posts data (**S2**).

Commercial impact exemplar: 3DX-RAY® (AIM listed - NTU spinoff)
3DX-RAY has applied NTU's technology to additional commercial security sectors and industrial inspection markets. The company is the main trading subsidiary of Image Scan Holdings plc, a technology group, which was listed on the London Stock Exchange Market AIM in 2002. The group was formed to exploit novel tools and technologies invented and developed by the University.

"*The commercial impact attributable directly to the founding and pioneering research conducted at the University is described below." (**S3**)*

- "*3DX-RAY Ltd has attracted a sales revenue* [text removed for publication] *during the period 2014 through 2019*" (**S3**)
- "*The total number of units sold* [text removed for publication]. *Our worldwide installed base of systems* [text removed for publication]." (**S3**)

"*3DX-RAY has applied the same technology to the non-destructive industrial inspection market where our equipment is used to examine products with concealed features and components including nuclear waste, pharmaceutical medical device manufacturing and inspections systems for catalytic converters. The product range includes production in-line, batch and laboratory systems and has been installed in industrial plants globally.*" (**S3**)

"*The Company's customers include police, military, security services, bomb disposal teams, prisons, ports, airports, cargo handlers, freight forwarders, corporate HQs, mail rooms and stadia and events operators. The operational benefits include a higher probability of detection and reduction in false alarm rates, operator-training times and time to competency.*" (**S3**)

5. Sources to corroborate the impact

S1. Confidential report: Report and analysis by Aviation Security consultant. Steve Wolff is member of the Advisory Board for the Aviation Security International journal (https://www.asi-mag.com/), was (elected) Vice Chair of the first Concealed Explosives Detection Workshop in 2016 and the Gordon Research Conference on Illicit Substance Detection in 2013, led the International Air Transport Association's Checkpoint of the Future 2010 blueprint visionary team, and was previously a cofounder and V.P. of Marketing and Product Engineering for InVision Technologies (subsequently Morpho Detection LLC, and acquired by Smiths Group plc in 2017).

S2. Confidential report : Report and analysis by Aviation Security consultant. Annexes of Information Sources used: A Passenger Transport Statistics: World Bank; B: 2019 Passenger Growth Data; C DFNI European passenger growth article; D Rapiscan General Services Admin. Federal Supply Price List; E1 Smiths TSA Cabin Bag CT Order Press Release; E2 TSA Presentation stating number of Cabin Bag CT systems ordered; F1 Smiths TSA Hold Baggage CT Order Press Release; F2 TSA Presentation stating number of Hold Baggage CT systems ordered; G Cost of Hold Baggage AT X-ray, Smiths EDtS; H US Government Price List Smiths X-ray systems (ATiX); I Compendum of Company Press Releases 2013-2019 showing Sales Data; J Data on Guns found at US Checkpoints;

S3. Testimonial letter: CEO of 3DX-RAY Ltd, which is the main trading subsidiary of Image Scan Holdings plc, a technology group listed on the London Stock Exchange's AIM. http://www.3dx-ray.com/investor-relations/results-reports/