Institution: The University of Manchester		
Unit of Assessment: 10 (Mathematics)		
Title of case study: Image reconstruction algorithms underpin Rapiscan Systems' RTT110 baggage scanner, bringing benefits to airports and generating over USD215,000,000 in sales		
Period when the underpinning research was undertaken: 2007 – 2015		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (*e.g.* job title):**	**Period(s) employed by submitting HEI:**
William Lionheart	Professor	1999 onwards
Marta Betcke	PDRA	2007 – 2010
Nicola Wadeson	PhD student (2007 – 2010) Knowledge Transfer Associate (2011 – 2012) PDRA (2012 – 2015)	2007 – 2015
William Thompson	PhD student (2007 – 2010) Knowledge Transfer Associate (2011 – 2012) PDRA (2012 – 2014)	2007 – 2014
Period when the claimed impact occurred: August 2013 – July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Airports across the EU, Asia, Africa and USA have purchased 'Real Time Tomography (RTT) 110' scanners from Rapiscan Systems to screen cargo and hold baggage, resulting in at least **USD215,000,000** revenue for Rapiscan since July 2015. University of Manchester researchers developed new image reconstruction algorithms, which made the RTT110 Computed Tomography scanner's innovative no-moving-parts design possible. The RTT110 system benefits airports by saving them real-estate space, improving customer screening throughput by **300%**, and reducing maintenance costs by **35-50%**, whilst maintaining a leading 2% automated-decision rejection rate that **lowers operator fatigue**. The RTT110's success allowed Rapiscan to maintain their research & development and manufacturing presence in the UK, **employing approximately 200 people**, and is being leveraged to expand into new areas of biosecurity and agriculture.

2. Underpinning research

The Department of Mathematics was involved in the RTT development from its early prototype stages through research, which began in 2007. The previous generation of scanner designs relied on a moving gantry to generate slices through a target bag to reconstruct (albeit slowly) a 3D image. By contrast, the prototype Rapiscan RTT system used a novel geometric configuration of (static) X-ray emitters and detectors, which necessitated the development of new algorithms to reconstruct three-dimensional images of scanned objects. This geometry is the result of the design of the RTT, for which the baggage/cargo is the only moving part. This unique approach dramatically increases scanning speed and reduces equipment footprint and maintenance down-time.

The key insight was that multi-surface re-binning, a new algorithm developed by researchers at the University of Manchester (UoM) for the RTT system, would lead to faster, more accurate and more reliable reconstruction algorithms **[1, 2]**.

In addition, the research characterised the instability inherent in reconstruction from RTT data, proving a uniqueness result that demonstrates the RTT collects sufficient data for a reliable reconstruction, and led to an optimal source firing order that improves resolution of the image **[3, 4]**. As noted by Rapiscan Systems, as well as providing the new algorithms necessary for the RTT to function, this research "*informed some aspects of the physical design of the device, in particular the source firing sequence, leading to a maximization of the data acquisition efficiency for a given source and detector geometry*" **[A]**.

A final important step was the use of Monte Carlo simulation to calculate scattered X-rays, and thus develop both a scatter correction procedure and simulation software. These tools have been used as an aid to the design and development of RTT systems including the new

RTT110 **[4]**. Rapiscan Systems confirm, "*UoM image reconstruction algorithms and scatter correction algorithms were implemented onto the RTT systems*" **[A]**.

Elements of the research, described in **[1-4]**, were specifically applied to the Rapiscan RTT systems. The results of this work are captured in the form of two patents **[5, 6]**.

3. References to the research

The research described in this case study was published in highly regarded peer reviewed journals. The researchers' work received The Engineer's 2010 Innovation and Technology Award (Defence and Security).

[1] Betcke, M.M., Lionheart, W.R.B., "Multi-Sheet Surface Re-binning Methods for Reconstruction from Asymmetrically Truncated Cone Beam Projections. I: Approximation and Optimality", *Inverse Problems*, **2013**, *29*, 115003; DOI: 10.1088/0266-5611/29/11/115003

[2] Betcke, M.M., Lionheart, W.R.B., "Multi-Sheet Surface Re-binning Methods for Reconstruction from Asymmetrically Truncated Cone Beam Projections. II: Reconstruction on Multi-Sheet Surfaces and Axial Deconvolution", *Inverse Problems*, **2013**, *29*, 115004; DOI: 10.1088/0266-5611/29/11/115004

[3] Thompson, W.M., Lionheart, W.R.B., Morton, E.J., Cunningham, M., and Luggar, R., "High Speed Imaging of Dynamic Processes with a Switched Source X-ray CT System", *Measurement Science and Technology*, **2015**, *26*, 055401; DOI: 10.1088/0957-0233/26/5/055401

[4] Wadeson, N., Morton, E.J., and Lionheart, W.R.B. "Scatter in an Un-collimated X-Ray CT Machine Based on a Geant4 Monte Carlo Simulation", *SPIE Medical Imaging 2010: Physics of Medical Imaging*, 15-18 February **2010**, San Diego, USA, 76223E; DOI: 10.1117/12.843981

Additionally, the research described above was incorporated into **two patents**, held jointly between University of Manchester and Rapiscan researchers:

[5] Granted Patent: Betcke, M.M., Lionheart, W.R.B, Morton, E.J. "System and method for image reconstruction by using multi-sheet surface rebinning" Patent Number: **WO2011008787-A1, 2011**

[6] Granted Patent: Thompson, W., Lionheart, W.R.B, Morton, E.J.. "Optimization of the Source Firing Pattern for X-Ray Scanning Systems." Patent number: **US2018128754A1, 2017**

This research was supported by a number of grants, including:

"**Tomographic Imaging**", W.R. Lionheart (Co-I), EP/M022498/1, Sep15-Aug20, £238.7k; "**X-ray imaging: Learning from other disciplines**", W.R. Lionheart (Co-I), EP/F013329/1, Oct07-Mar09, £270k; "**A Reconstruction Toolkit for Multichannel CT**", W.R. Lionheart (Co-I), EP/P02226X/1, Apr17-Mar20, £505.7k; "**Analysis of Anisotropic Inverse Boundary Value Problems**", W.R. Lionheart (PI), EP/F033974/1, Oct08-Jun12, £287.6k; "**Next Generation Multi-Dimensional X-Ray Imaging**", W.R. Lionheart (Co-I), EP/M010619/1, Feb15-Feb20, £1.22m; "**Tomographic Imaging**", W.R. Lionheart (Co-I), EP/J010456/1, Feb12-Sep15, £469.6k; "**X-ray CT reconstruction algorithms for airport security and process tomography**", W.R. Lionheart (PI), EP/E010997/1, Feb07-Apr10, £503.6k (£250,000 from CXR Limited, later Rapiscan).

Wadeson's KTA with Rapiscan was funded by an EPSRC KTA, £57k (+£15k from Rapiscan), March 2011 – March 2012. Thompson's KTA was funded by an EPSRC KTA, £60k (+£23k from Rapiscan), November 2011 – December 2013.

4. Details of the impact

Context

Continued growth of passenger air travel, together with a more rapid expansion of cargo and parcel air transport, is combining with greater aviation security concerns to require new technology for scanning systems. All passenger baggage must be scanned at airports; for hold baggage, the primary purpose of this scanning is explosive detection. As an example, Charles de Gaulle international airport (which uses RTT scanners) needs the scanning capacity to accommodate an average of around six million passengers per month. To achieve this throughput, automated systems identify potentially risky baggage to go for additional screening by a highly trained operator. High false alarm rates lead to operator fatigue and decrease overall safety, so the goal of scanning systems is to perform rapid and accurate automated screening of baggage with minimal false alarms.

In this context, the use of real time tomography (RTT) scanning for both airport baggage and cargo has become increasingly important. Consequently, Rapiscan Systems developed a prototype RTT 3D scanner that combines high speed, high resolution and a low false-alarm rate in automated screening. The Rapiscan RTT system uses a stationary array consisting of a very large number of micro X-ray emitters, which capture tens of thousands of views of each bag. This approach generates images with significantly better resolution in all planes, at much greater speed, and keeps maintenance costs low **[B]**. However, reconstructing 3D images from the planar data collected by the new hardware design required new mathematical solutions.

Pathway to impact
Realising the need for major technological development in the prototype for RTT scanning, Rapiscan Systems approached the Department of Mathematics to develop new accurate algorithms for this novel scanning approach. The underpinning research described in this case study has been jointly funded by Rapiscan and the EPSRC, including three Knowledge Transfer Account projects and two sponsored PhD studentships. These industry-driven projects ensured rapid incorporation of the novel algorithms into the new generation of RTT scanners.

Rapiscan's Chief Technology Officer (CTO) emphasises that the RTT system is crucially dependent on the research contribution of the University of Manchester, saying "*University of Manchester research **contributed significantly** to the successful development and subsequent commercialization of Rapiscan RTT systems"* **[A]**. This activity began with an EPSRC grant, co-sponsored by Rapiscan (GBP250,000), during which *"UoM* [University of Manchester] *research was conducted to develop novel algorithms for 3D image reconstruction on the RTT systems, providing an alternative reconstruction approach to conventional algorithms*" **[A]**. Furthermore, "*UoM image reconstruction algorithms and scatter correction algorithms were implemented onto the RTT systems via KTA projects with Rapiscan, involving Dr William Thompson (2010–2011), and Dr Nicola Wadeson (2012)*" **[A]**. Wadeson undertook a secondment with Rapiscan for a year in order to enable technology transfer; specifically this was to use Geant4 modelling within Rapiscan Systems **[4]**. Thompson completed a concept and feasibility study to implement our reconstruction algorithms on a target graphics processing unit (GPU), again with Rapiscan, followed by a further year's work to complete GPU implementation and systems integration. The results of this work are captured in two Rapiscan patents **[5, 6]**, on which the listed inventors are Wadeson, Thompson and Lionheart (University of Manchester), and the CTO of Rapiscan.

The interaction between Manchester researchers and Rapiscan developed during the prototype phase of the RTT system, such that UoM research also informed some key aspects of the physical design of the device, in particular *"the optimization of the source firing sequence, leading to maximization of the data acquisition efficiency for a given source and detector geometry*" **[A]**. Additionally, The University of Manchester's contributions are "***currently enabling key image quality improvements** as part of the next-generation RTT development program at Rapiscan*" **[A]**.

Reach and significance of the impact
Rapiscan Systems' market success with RTT
Rapiscan Systems (a sub-division of OSI Systems Inc.) manufactures and sells a range of RTT systems, and here we will focus on the main RTT110 system, which is the largest, most commonly utilised and deployed globally.

Sales of the RTT110 system have made a major contribution to the ongoing financial success of OSI Systems Inc., the parent company of Rapiscan Systems. In August 2019, the CEO of OSI Systems Inc. stated "*Driven by growth in cargo and **RTT sales**, fourth quarter revenues in the division reached a **record $195 million***" **[C]**. Rapiscan state that "*Many RTT110 units have been installed at UK airports for screening hold baggage with the bulk of the systems being exported to customers in EU, Asia, Africa, and USA*" **[A]**.

Rapiscan have not disclosed precise details of all their revenues from the RTT110 system, which they consider commercially sensitive. However, public announcements of sales from July 2015 to date show they have generated revenues of **at least USD215,000,000 [D]**. Customers for these systems include major European airports, such as Charles de Gaulle and Orly airports in Paris, as well as Hamad International Airport in Qatar, and others in Asia, Africa and the USA **[A, D]**. As well as airports, these systems have been sold to companies whose business includes international logistics and air cargo **[D]**.

UK capability in manufacturing and R&D
Successful long-term collaboration between the University of Manchester and Rapiscan, alongside the financial success of the RTT110 system, has contributed to their decision to keep their research and development capacity within the UK. Rapiscan Systems confirm that *"collaborations with UK academic expertise, such as with The University of Manchester, are extremely valuable to Rapiscan Systems. As a result, we **reaffirm our commitment to keeping R&D in the UK, allowing us continued access to the exceptional knowledge and expertise of institutions such as The University of Manchester**"* **[A]**. The UK also remains a high-tech manufacturing base for the company, since "*by the end of 2019, Rapiscan will have manufactured several hundred RTT110 systems at its purpose-built factory in the UK which **employs around 200 people***" **[A]**.

Key regulatory approvals, standards and awards for RTT explosive detection
Thanks to its exceptional operational capabilities, enabled by this research, the RTT110 system has received approval by regulators, achieved the highest performance standards, and won awards. In January 2018, the RTT110 was the 2017 Platinum Winner in the Best Explosives Detection Product category in the 9th Annual Government Security News (GSN) Homeland Security Awards in the USA **[E]**. In November 2019, the RTT110 achieved the ECAC 3.1 standard for explosive detection systems (EDS) performance, which is the highest testing standard for explosive detection systems in the EU **[D]**. The following month, the RTT110 became the first high-speed CT explosive detection system to be approved for inclusion on the US Transportation Security Administration (TSA)'s Air Cargo Screening Technology List **[D, F]**.

Leveraging commercial success into new business areas
The success of the RTT110 system has helped Rapiscan to expand its business into new areas. As Rapiscan's Chief Technology Officer stated, "*revenue from sales of the RTT system has enabled further investment in research and development, including into areas in which Rapiscan had previously been unable to invest, such as applications in biosecurity and agriculture. These new application areas represent significant growth opportunities for Rapiscan Systems"* **[A]**. In January 2019, the Australian government selected the RTT110 system to identify biosecurity contraband. The Australian Minister for Agriculture and Water Resources said "*Biosecurity screening provides critical protection for Australia's **$60 billion** agricultural industries and the health of our communities, environment, and the national economy […] New technology like the RTT 110 from Rapiscan will be an **integral part of preserving our unique ecosystem** and creating a more seamless experience at the border*" **[G]**. Following the success of their initial use of the RTT110 system, the Australian Government placed a further order for RTT110 scanners worth **USD5,000,000** in July 2020, to be installed at Melbourne International Airport as well as Melbourne and Sydney-based air mail carriers **[D]**. The contract also employs Rapiscan to develop new algorithms for automated 'biosecurity risk item detection', demonstrating their confidence in the quality of the RTT110 system **[D]**.

Benefits for airport operations and procedures

Rapiscan Systems note "*UoM research […] resulted in numerous gains including higher throughput, smaller footprint*" for the RTT110 systems **[A]**. The throughput of scanned bags is industry leading, and the system has a three-fold improvement in baggage scanning rate compared to legacy CT systems **[B]**. From the perspective of airport operations, these key features mean *"…fewer conveyors are required to maintain decision-making performance standards. As measured by several major airports, this results in an* ***average baggage handling system space saving of 7 meters****. This saved space can be used for other retail and customer service space, which is* ***more profitable****"* **[A]**.

The RTT110 systems themselves "*provide significant cost savings ... with 98% of automated threat detection decisions made within 1 second of scanning"* **[A]**. The 2% rejection rates remain one of the lowest in the industry despite screening at a rate that is three times higher **[H]**. By determining the presence and position of a threat, the reconstruction process delivers optimal performance for the detection of materials in configurations typically difficult to detect **[B]**. This improves the baggage handling efficiency, **lowering operational costs** and **operator fatigue,** which results in fewer false alarms. The RTT110 reconstruction algorithms also quantify density levels in liquids, identifying threat liquids and alerting the operator to potentially concealed explosives **[B]**.

Owing to *"the unique design,* ***underpinned by novel image reconstruction algorithms****, Rapiscan RTT systems are* ***significantly more reliable*** *than scanning systems which require a moving gantry. As a result, RTT systems have* ***significantly lower cost of operation*** *and* ***reduced system down-time****"* **[A]**. Rapiscan estimate that RTT110 systems reduce typical maintenance costs by **35-50%** compared to legacy CT systems because of the stationary-gantry design made possible by new image reconstruction methods **[B]**.

5. Sources to corroborate the impact

[A] Letter from Rapiscan Systems' Senior Manager, Algorithms, and Chief Technology Officer, 19 December 2019.
[B] Rapiscan RTT Brochure (supports technical claims about the RTT device).
[C] Business Wire article – OSI Systems' Q4 2019 financial state
[D] Combined Rapiscan Systems Press Releases for RTT110 sales between August 2013 and December 2020 (pdf)
[E] Association of the United States Army – RTT110 Named Platinum Winner of GSN Homeland Security Award
[F] Bloomberg Business – RTT110 is first approved CT EDA on TSA Air Cargo Screening Technology List
[G] Business Wire article – RTT110 system selected for Biosecurity Risk Detection in Australia
[H] RTT product web page - https://www.rapiscansystems.com/rtt