Institution: University of Portsmouth

Unit of Assessment: UoA 12: Engineering

Title of case study: Improved anomaly detection algorithms to benefit manufacturing and aviation

Period when the underpinning research was undertaken: 2006-2013

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: Pure
Dr Edward Smart	Senior Research Fellow	01/03/2011 - date
Dr Hongjie Ma	Senior Research Fellow	06/01/2016 - date
Professor David Brown	Professor of Industrial Systems	07/10/1998 - 31/12/2018
Dr Farshad Fahimi	Senior Research Associate	04/05/2009 - 06/02/2013

Period when the claimed impact occurred: 2013-2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

University of Portsmouth researchers have developed anomaly detection algorithms which are better at detecting faults, revolutionising two different sectors' engineering practices. Our algorithms were deployed in three dairies operated by Stork (a supplier of dairy filling machines), where 31 faults were detected early. These faults would have led to chains of escalating damage and cost (breaches of contract, lost product, equipment repair bills) costing GBP15,000,000. These algorithms have also transformed how flight data is analysed for a civil aviation company (Flight Data Services) resulting in the development of a world first product (Express Readout) to detect errors in flight data recorders. This key product led to the company's acquisition by a multi-billion dollar defence firm for GBP8,000,000 including the purchase of the IP that linked directly to our research.

2. Underpinning research

In multiple industries, data on faults or anomalies is sparse or non-existent, meaning that operators/engineers of machinery are often not aware of faults until they cause damage which is costly to repair. Therefore fault/anomaly detection is a key part of aviation and manufacturing processes. Researching learning algorithms which detect rare or abnormal events from industrial data can prevent equipment damage and save money. The underpinning research into anomaly detection was conducted at the University of Portsmouth in the UoA's IIR Group (Innovative Industrial Research Group, and until 2017 the Institute of Industrial Research) and was led by Brown, Smart, Ma and Fahimi. University of Portsmouth staff were the sole academic contributors to the referenced publications in Section 3 which were in collaboration with a range of industry co-authors.

Key advances and role of the researchers

The references (R1, 2, 3, 6) show how anomalies can be detected whilst learning from real-world 'normal' industrial data. Our key advances from this body of research are:

- Detecting Known/Unknown Anomalies: Previous approaches needed examples of anomalies. Our approach uses only normal/healthy data and can therefore detect a wider range of anomalies than was previously possible.
- Quantifying Machine Health: Previous approaches used either true/false or a traffic light system to measure machine health. Our approach quantifies machine health in more detail, enabling earlier anomaly detection, leading to higher machine availability.

The publication (R5) demonstrates the system working on multiple dairy fillers.

The patent (R4) demonstrates how to detect sensor anomalies within an aircraft 'black box', which is a world first.

Application to Manufacturing

The advances described above were adapted for complex electromechanical machinery for Stork Bottling and Blowmoulding Ltd (Stork); a supplier of dairy filling machines. Stork was introduced to the IIR in 2009, who immediately identified how anomaly detection could benefit the dairies.

The previous approach to fault finding involved hand-held vibration monitors and relied on experienced staff spotting problems “by eye” or “by ear”. The anomaly detection algorithms (R1, 2, 3) were adapted during a double KTP (G2, 3) (between 2010 and 2013) to detect anomalies from vibration and current sensors attached to key parts of the fillers. A key innovation was that the anomaly detection algorithms could be trained on synthetic data, meaning they could work on any dairy filler without retraining (R5). Furthermore, the algorithms quantified the level of abnormality, allowing fault detection at the earliest stages, allowing more time to resolve the fault without affecting production (R6). There are three particular advances from our research without which this tool would not have been possible: The use of wavelets (a mathematical tool) applied to signals helped to extract the key fault indicators which are often deeply buried in the signal, amongst noise. Secondly, one class classification techniques where the algorithm can learn only from healthy data (removing the obstacle of there being a lack of unhealthy data on which to train – no other product does this to our knowledge). The third is our novel health score which allows for anomalies to be quantified.

Application to Aviation

In 2006, Flight Data Services approached the University with a view to enhancing airline safety through data science and machine learning. Existing flight safety approaches were threshold based and could only detect severe safety anomalies. KTP1 (G1) and the EPSRC PhD programme (between 2006 and 2011) developed anomaly detection algorithms to detect safety incidents during flight. During KTP2 (G2), the anomaly detection algorithms developed were adapted to detect flight data recorder anomalies. The IIR research was supported by a KTP (G1) and an EPSRC Industrial CASE PhD studentship (G4) (between 2006 and 2011). It introduced our single class classification approaches (R3, 6) to the aviation sector for the first time. These approaches are semi-supervised, in that they are trained on known ‘normal’ flight data and tested on unknown data. All airlines have Standard Operating Procedures that guide how the aircraft should be flown; these inform how we selected the “normal” data on which the single class classification approaches were trained. We found we could detect over 3 times as many anomalies as with existing approaches. Furthermore, they could be quantified, allowing earlier detection (R1, R2).

In the UK it is a legal requirement for each plane to carry a flight data recorder (FDR). Analyses of FDR data are not only of critical importance in an accident but can also play a crucial role in accident prevention. In the UK, for example, the law stipulates that flight recorders must be analysed at least once a year to detect flight errors occurring outside accepted safety parameters. Historically, this task was undertaken manually, a process that was time-consuming, expensive, and required complex technical skills. It was also prone to human error. Further research, supported by a double KTP (G2, 3) (between 2010 and 2013), adapted these algorithms (R1, 2) to automatically detect errors in the FDR such as poor calibration, incorrect installation and faulty recording (R4). This was a world first achievement and allowed an FDR to be completely analysed within minutes rather than over weeks.

3. References to the research

Publications

(R1) **Smart, E., Brown, D. J.,** & Denman, J. (2012). Combining Multiple Classifiers to Quantitatively Rank the Impact of Abnormalities on Flight Data. *Applied Soft Computing Journal, 12*(8), 2583-2592. https://doi.org/10.1016/j.asoc.2012.03.059

(R2) **Smart, E., Brown, D.,** & Denman J. (2012). A Two-Phase Method of Detecting Abnormalities in Aircraft Flight Data and Ranking Their Impact on Individual Flights. *IEEE Transactions on Intelligent Transportation, 13*(3), 1253-1265 https://doi.org/10.1109/TITS.2012.2188391

(R3) **Smart, E.,** Grice, N., **Ma, H.**, Garrity, D. & **Brown, D.J.**, (2020). One class classification based anomaly detection for marine engines. In R. Jardim_Goncalves., V. Sgurev, V. Jotsov, & J. Kacprzyk (Eds) *Intelligent Systems: Theory, Research and Innovation in Applications* (pp.223-245). Springer. https://doi.org/10.1007/978-3-030-38704-4_10

(R5) Aboutalebi, A., Labib, A., **Brown, D.,** Wasif, H., & Axel-Berg, L. (2012). Implementation and management of an advanced online condition monitoring system. *Proceedings of the 2012 IEEE*

Symposium on Industrial Electronics and Applications (pp. 257-262). Bandung, Indonesia https://doi.org/10.1109/ISIEA.2012.6496640

(R6) **Smart, E., Brown, D.,** & L. Axel-Berg, L. (2013). Comparing one and two class classification methods for multiple fault detection on an induction motor. *Proceedings of the 2013 IEEE Symposium on Industrial Electronics & Applications* (pp. 132-137). Kuching, Malaysia https://doi.org/10.1109/ISIEA.2013.6738982

Patent

(R4) Jesse, D., Jesse, C., Seldon, A., Rahman, N., & **Fahimi, F**. (2012). *Flight data validation apparatus and method*, *GB2494487B*.

Grants that supported this work

(G1) **Brown, D.** *Creation of an Intelligent Search Engine to Extract Flight Safety Information from Aircraft Data.* Knowledge Transfer Partnership (KTP1), KTP Number: 001136, 27 February 2006-26 February 2009, (GBP156,000).

(G2) **Brown, D.** *Semi-Automatic Testing of a Digital Flight Data Recorder System (DFDRS) in Accordance to a Method of Compliance for Airworthiness and Operational Approval.* Knowledge Transfer Partnership (KTP2), KTP Number: 001511, 28 June 2010-25 September 2013, (GBP217,000).

(G3) **PI: Brown, D.** *Condition Monitoring for Dairy Filters.* Knowledge Transfer Partnership (KTP3), KTP Number: 007935, 1 September 2010-1 August 2013, (GBP229,000).

(G4) **PIs: Brown, D., & Smart, E.** *Detecting Abnormalities in Aircraft Flight Data and Ranking their Impact on the Flight.* EPSRC Industrial CASE Studentship (EPSRC PhD), EPSRC Grant Number: GR/T18868/01, Voucher Number: VN06001600, 1 October 2007-1 April 2011, (GBP84,000).

(G5) **Brown, D., Ouelhadj, D., Hillstrom, A., & Smart, E**. *The Virtual Engineer. Funded by the Technology Strategy Board, November 2013-October 2015.* Innovate Collaborative Research and Development, 1 October 2013-30 September 2015, (GBP139,244).

4. Details of the impact

We have applied our methods across industry sectors in collaboration with beneficiaries to apply research findings for real world use. Maintenance methods have been improved through modern data analysis. The underpinning research has had significant impact at both Stork and Flight Data Services Ltd (FDS).

Stork Bottling and Blowmoulding Ltd UK

Stork is one of the largest builders and sellers of filling machines in the world, with a focus on dairy products. The dairy sector is known as a 'just-in-time' industry, as milk needs to be delivered from farm to shop in 36 hours. Stork's filling machines mould plastic into bottles, fill them with milk and cap them, ready for distribution to sellers. In this industry, production targets are top priority and reliability comes second. This is despite breakdowns costing a dairy upwards of GBP300,000 per day in fines for breach of contract, lost production, repair labour and spare parts (S2).

Stork was introduced to the IIR in 2009 and quickly grasped the potential of the anomaly detection techniques that had been developed for flight safety. Following a double KTP (G3) with University of Portsmouth (between 2010 and 2013), these anomaly detection techniques were adapted to create an automated system called The Virtual Engineer (TVE) to detect and predict faults on these milk fillers (G5). The former General Manager at Stork said (S2) that *"From 1 August 2013, across 11 fillers in 3 separate dairy sites, TVE detected a total of 31 faults earlier and before they reached critical states, including main bearing faults, gearbox faults and shaft alignment problems. My engineers assessed the faults that were alerted to us by TVE and concluded that if they were left undetected, the total cost to the dairies was estimated to be over GBP15,000,000*". TVE identified parts of the Stork filler that failed more often than others. *"Greater customer engagement, due to TVE, led to a design change as certain components suffered failure more than others (e.g. universal joint). Customers noted that this level of engagement was not found from our competitors*." (S2)

TVE initiated a change in culture at the dairies. Before TVE, faults were only repaired after breakdown, which meant a loss of production and often higher repair costs. After TVE, dairy staff were actively discussing the TVE outputs to determine when best to schedule repairs without interrupting production. In addition, our technology reduces food waste; Stork estimated that we prevented the waste of 7000 litres of milk during the trial (S2).

Stork engineers improved their skills by combining what they could see on the machine with the results of TVE, which led to more effective filler care, and the promotion of staff who had acquired improved skills and achievements through the project. The General Manager said (S2) *"Engineers have also learned how the vibration profiles of the machines change when the machine speed changes. This led to them being able to identify faults quickly at both high and low machine speeds. In the past, only at high machine speeds could they detect faults."*

Innovate UK regarded the results of this double KTP (G3) as 'outstanding' and awarded the partnership the top grade in 2014 (S3).

Flight Data Services Ltd

Safety is a major focus of the aviation industry as equipment failures can result in multiple deaths and the loss of aircraft. Annex 6 of the International Civil Aviation Organization's (ICAO) Convention on International Civil Aviation for aircraft over 27 tonnes stipulates that all such aircraft should undertake flight data monitoring (FDM).

FDS is the world's largest dedicated provider of Flight Data Analysis services encompassing FDM Flight Operations Quality Assurance (FOQA) and FDR Readout technology. Before collaborating with the IIR, data had to be analysed manually, which could take several days. This meant that an aircraft could be flying with a faulty recorder, which would put lives at risk as mechanical faults or dangerous flying would go undetected. Our research into anomaly detection (R1, 2, 4) formed the core technology of Express Readout, the world's first service that automatically detects errors in the flight data recorder, which was launched by FDS in October 2015. Express Readout allowed the FDR to be analysed automatically within minutes at less than half the cost of conventional manual analysis (S1). The Chief Technology Officer at FDS, L3Harris says (S8); "*This automated service is revolutionary for the industry as it provides operators with the ability to test their equipment and generate the necessary documentation faster than ever before*". Additionally, he comments (S8): "*With Express Readout, operators are provided with a much faster and higher level of accuracy when compared with human validation alone; saving time and resources*."

FDS protected this intellectual property (IP), which stems from the above research through a series of patents within the UK, USA and Australia:

- Flight data monitoring and validation, UK Patent: GB2494487B (2013), US Patent: US9346557B2 (2016) (S5)
- Flight data validation apparatus and method, UK Patent: GB2494569B (2014) (S6)
- Flight data monitoring method and system, UK Patent: GB2494553B (2017), Australia Patent: AU2015201517B2 (2016), Australia Patent: AU2015201516B2 (2016), Australia Patent: AU2013205845B2 (2014) (S7)

Based on this IP, L3Harris Technologies Incorporated purchased FDS in June 2019. L3Harris are a global aerospace and defence technology innovator with revenues of 18 billion USD (03-2020) (S9), who are known for their 'black boxes' like their SRVIVR25™ line of crash-protected voice and flight data recorders. The sale of FDS (including the intellectual capital behind Express Readout), totalled GBP8,000,000. The importance of IP (including the IP that resulted directly from our research) to this sale is evidenced by the fact that the proportion of this sale that was due to intellectual capital was valued at USD7,000,000 (06-2019) (S4).

In conclusion, the research mentioned from the University of Portsmouth team has generated a combined savings and revenue of GBP20,000,000 in these two industries.

5. Sources to corroborate the impact

(S1) Flight Data Services Website: https://www.flightdataservices.com/2015/10/16/services-express-readout

(S2) Testimonial from General Manager of Stork UK to support financial figures 05/11/2019
(S3) Innovate UK gave outstanding grade to the KTP with Stork - 2014
(S4) Form 8-K L3Harris Technologies 31st July 2019
(S5) Flight data monitoring and validation - patent 2016
(S6) Flight data validation apparatus and method - patent 2013
(S7) Flight data monitoring method and system - patent 2015
(S8) Aerospace Tech Review Article 09/04/2020
(S9) Value of L3Harris Technologies