Institution:	University of Oxford
Unit of Assessment:	9 - Physics
Title of case study:	[13] Non-contact sensors for automotive and aerospace applications

1. Summary of the impact

A device developed for spintronics research at the University of Oxford has been adapted as the basis for robust, high-performance position or composition sensors to detect many different materials including metals, plastics, ceramics and fluids. These sensors are capable of making contactless measurements in very hostile environments. A spin-out company was formed in 2004 to exploit and apply this technology to a wide range of technical and engineering problems and has achieved over £2.5m revenue. These sensors form the key elements of products that have been successfully deployed in automotive and other transport applications. Benefits to end users include ease of use, speed and the cost savings.

2. Underpinning research

The underpinning research was funded by a collection of four European Commission network grants (HotSEAMS, Tunnelsense, Dynaspin, Nanomem) between 1995 and 2001 in which Professor John Gregg (appointed to Oxford as Lecturer in 1984) was either Coordinator or Co-Investigator. Professor Gregg's group also included postdoctoral research assistants W. Allen (student 1995-1999 then PDRA 1999-01) and M. Thornton (PDRA 1999-2001) and drew on the skills of R. Bendall, head of the Clarendon workshops in Oxford Physics.

This research was in the field of Spintronics – specifically the Giant Magnetoresistive (GMR) behaviour of thin magnetic sandwiches, thin granular magnetic films and magnetic tunnel junctions – and the magnetic dynamics of nanoscale magnetic elements. A question arose as to the mechanism that underlies the electrical resistance of a ferromagnetic domain wall. This was a subject of controversy in the 1960's and two competing models were advanced to explain the effect. In 1996, the Oxford Spintronics group and their York and Strasbourg collaborators developed a new model based on the same spin-dependent scattering that causes GMR. To test these models rigorously through experiments, the global magnetic switching properties of thin film samples first had to be characterised. However, existing magnetometer devices were neither fast nor sensitive enough for these systems and a SQUID would have been impractical (e.g. requiring cryogenic conditions) and overcomplicated. In order to address this problem, Prof Gregg's group in Oxford developed a novel, highly sensitive radiofrequency circuit that responded to changes in each of the two components of magnetic susceptibility of the films as they switched. This circuit consisted of a resonant, positive feedback system that was designed, refined and constructed in Oxford Physics and drew directly on Prof Gregg's expertise in the properties and behaviour of entire analogue electronic circuits.

With this new magnetometer, custom samples were validated quickly, effectively and without risk of damaging them, so they could be further investigated with confidence. As a result, quantitative agreement of the model with experiment was successfully demonstrated [1] and this is now the accepted model of domain-wall resistance. The high sensitivity of this circuit enabled a number of other applications within spintronics research, including for characterisation of granular GMR films during annealing in the growth chamber and for fast characterisation of the phase diagram of colossal magnetoresistive (CMR) material [2].

However, the very precautions necessary to shield these measurements from external influences suggested to Professor Gregg the potential to adapt the circuit to make a mechanical sensor that could detect the presence and motion of a moving object. The object could be magnetic, metallic or insulating, depending on the precise configuration of the circuit and whether spintronic material was incorporated, and crucially would not need to be tagged with additional components.

This approach was developed within an EC network project, HotSEAMS, coordinated by Professor Gregg. The new mechanical sensor device was reported at the Network's mid-term meeting in 1998, at which the challenge was set to demonstrate it by carrying out a practical function. A demonstrator was therefore produced by the Oxford group that successfully applied the device to control the ignition-timing function on a second-hand 5 litre Mercedes V8 M117 engine. This showed that the new sensor gave rise to less ignition skipping than the standard Bosch variable-reluctance sensor, which was known to be prone to this problem at low speed.

In 2001, Isis Innovation (the University of Oxford's technology transfer office), conscious of the wide range of applications of the device [3], filed a set of patents describing the sensor with Professor Gregg as sole inventor. These patents were granted in 2006 in the EU, US and Japan [4].

3. References to the research (Oxford authors underlined; * denotes best indicators of quality)

1. *J.F. Gregg, W. Allen, K. Ounadjela, M. Vieret, M. Hehn, S.M. Thomson and J.M.D. Coey (1996). Giant magnetoresistive effects in a single element magnetic thin film. *Phys. Rev. Lett.* **77** 1580. DOI:10.1103/PhysRevLett.77.1580.
   This paper, with collaborators in Strasbourg, Dublin and York, reported the first direct observation of ferromagnetic domain wall scattering, and proposes the new model, based on measurements using the new device.

2. *K. Ounadjela, S.M. Thompson, J.F. Gregg, A. Azizi, M. Gester and J.P. Deville (1996). Correlation between the structural and transport properties of as-grown epitaxial phase-separated Co-Ag thin films. *Phys. Rev. B* **54** 12252. DOI:10.1103/PhysRevB.54.12252.
   This paper, published with collaborators from Strasbourg and York shortly after [1], uses measurements from the device to reveal the effects of spin diffusion length on giant magnetoresistance.

3. R.P. Borges, M. Bari, J.M.D. Coey, J.F. Gregg, M. Thornton and W. Allen (2001). Versatile radiofrequency sensor. *Sensors and Actuators A-Physical* **91** 39. DOI:10.1016/S0924-4247(01)00497-6.
   This paper, from the proceedings of the Third European Conference on Magnetic Sensors & Actuators, presents the sensor circuit, demonstrates its signal-to-noise behaviour and outlines its distinct advantages over alternative technologies. Its capabilities were demonstrated through detection of metal and plastic gearwheels and of a falling liquid drop.

4. J.F. Gregg (2006). Position and Electromagnetic Field Sensor.
   EU Patent EP1269110 B1 (filed 13/3/2001, granted 28/6/2006).
   Also as US Patent US6984994 B2 (filed 13/3/2001, granted 10/1/2006).

4. Details of the impact *(citations e.g. [A] are to corroborative sources in section 5)*

The realisation that this was a significant platform technology with applications in multiple domains led to the formation of the spin-out company Oxford RF Sensors in September 2004. Oxford RF Sensors was renamed Salunda in 2013 to reflect a new business strategy in oilfield applications. During the assessment period, January 2008 to July 2013, Salunda employed an average of 14 people.

The company's business model, to exploit this invention in novel sensing devices, has been underpinned by an exclusive licence to the patents. Salunda summarise the contribution from the research in this way:

> *"The research conducted by Prof Gregg and his collaborators at the Department of Physics has become the core technology at Salunda, without which the company would not have been formed and none of these projects would have been possible."* [A]

Approximately 90% of Salunda's revenues during the assessment period came from the development of bespoke sensors for clients in the road transport, aerospace and oil and gas industries. A further £336k revenue came from sales of two fully-manufactured products that Salunda (as Oxford RF Sensors) had developed and commercialised. The impact of these devices spans two main areas, reflecting their ability to detect either position or – if measuring at a pre-determined position – composition, both through changes in susceptibility within a given volume around the device. Salunda explain, "*the ability to provide non-contact sensors that can work in extremely harsh environments has been a major competitive advantage and this core technology arose directly from Prof Gregg's contribution*" [A].

Position and speed sensors

An aftermarket speed sensor for turbine blades in automotive turbo chargers was developed and manufactured for the market-leading supplier [text removed for publication]. This allows the rotational speed of turbine blades to be measured, without having to attach any physical target to a blade, so that performance can be more accurately monitored. In turn, this allows the speed to be controlled to stay within design limits, preventing damage or reduction in performance. This device was launched in 2007 as the Turbocharger Speed Sensor TS-180. The primary market for these devices has been motorsport, particularly rally car racing, and several hundred are now in use by racing teams.

In a major project, worth £2.35m in revenue to Salunda between 2008 and July 2013 [A], sensors were developed for a major aircraft engine manufacturer ([text removed for publication]). These sensors measured tip clearance and speed in the intense environment of commercial jet engines that operate at temperatures in excess of 1000°C. Another R&D project developed position sensing of piston and spool in rock drills, for a leading supplier of construction equipment ([text removed for publication]).

Analysis of fuel content and level

Salunda developed a hand-held sampling device that uses the sensor technology to measure the biofuel content and contamination of biodiesel, in collaboration with [text removed for publication], a top-tier supplier of parts to the automotive industry. It measured composition against the EN590 standard for automotive diesel fuel in Europe, which permits up to 7% biodiesel. The product was marketed from 2010 as the Delphi YTD533 Diesel Analyser Kit and was nominated for the 2011 Equip Auto Innovation Awards [B]. Over 550 of these products have been sold since their launch [A], for uses including the following:

- To address a critical issue in the haulage industry, where fuels may come from a variety of different sources and significantly affect engine performance and maintenance. The ability to sample fuel content immediately using unskilled labour removes the need for laboratory based sample analysis. Control of this issue also leads to considerably improved air quality and the reduction of harmful emissions.
- To give easier diagnostics of problems with diesel engines by enabling checks of diesel composition. Since only a small sample volume (46ml) is required, measurements can be taken from different parts of the fuel system to identify where any contamination occurs. For example, a case study in an industry publication (sponsored in part by the supplier) quoted one garage owner investigating warranty claims:

  "Using the fuel analyser, we were able to quickly and easily identify the fuel

> *in the system did not meet EN590 and consequently was the likely cause of defect. Not only did it save our company lost earnings in un-claimable labour hours, but reaffirmed the quality of our repair and reputation."* [C]

A number of commercial garages and workshops advertise this facility to their customers, including a depot in Bristol who describe that "*unlike most other fuel testing services, this is fast and efficient enough to determine warranty stipulations*" [D] and another in Nottingham who identify an advantage in getting "*immediate and accurate results without the need to send samples to a specialist laboratory for analysis, saving both time and money*" [E].

Revenue to Salunda also arose through development projects for other clients [A], including

- Condition monitoring of the AdBlue diesel additive in trucks for a manufacturer of car and truck components ([text removed for publication])
- Measurement of dissolved or entrained gas content and hydraulic fluid levels in landing gear for an aircraft manufacturer ([text removed for publication])
- Measurement of aviation fuel levels and detection and quantification of water in fuel, for a 'Tier One' supplier to the aviation and automotive industries ([text removed for publication])

Investment attracted

In July 2013, Salunda raised substantial further investment to develop sensors for oilfield applications, having already established collaborations with leading suppliers of oilfield services and technologies (such as [text removed for publication]).

5. Sources to corroborate the impact

All claims of sales by and financial benefit to Salunda, including during time as Oxford RF Sensors, and reliance on research at Oxford:

A. Chief Executive Officer, Salunda Ltd, letter held on file.

Uses and benefits of Fuel Analyser:

B. Delphi Press Release, 11th October 2011. http://delphi.com/news/pressReleases/pressReleases_2011/pr_2011_10_11_007/

C. Delphi's Diesel Fuel Analyser – A Case Study, Top Technician, 2011. http://www.toptechnician.co.uk/webcontent/2011/11/delphis-diesel-fuel-analyser-a-case-study/

D. DTM Diesel and Petrol Injection Specialists Ltd [retrieved 18th September 2013]. http://www.dtmfuel.co.uk/Diesel_Fuel_Analysis_Testing.htm

E. P. Atkins Ltd, Fuel Analysis [retrieved 18th September 2013]. http://www.patkins.co.uk/fuel-analysis.html