Institution: The University of Birmingham

Unit of Assessment: B13 - Electrical and Electronic Engineering, Metallurgy and Materials Electronic, Electrical and Computer Engineering submission

Title of case study: Automotive Radar Systems

1. Summary of the impact

Two decades of radar research at The University of Birmingham have had profound impacts on automotive radar systems. This is demonstrated by specific Jaguar LandRover products: adaptive cruise control (ACC); blind spot monitoring; and lane change merge aid. The first two of these are now available across the Jaguar and Land Rover ranges while the third is ready for launch in 2014. Wider economic and road safety impacts are occurring as the technology cascades down from the luxury vehicle market and achieves wider adoption. Automotive radar makes a significant financial contribution to Jaguar LandRover (JLR). Birmingham research has been vital to the development of this industry, in establishing fundamental scientific feasibility and technological viability and in solving deep technical challenges.

2. Underpinning research

Research into the underpinning science and technology required for mm-wave automotive radar systems led to fundamental cost reductions, enabling the development in the UK of one of the world's first mass market applications of radar in the automotive industry.

Automotive radar research has run continuously since 1993, funded by grants totalling over £2M and involving ten academic staff and research fellows and at least six PhD students. The more recent grant details are tabulated below.

Project Title	Awarding Body	PI	Amount, £K	Dates
ROADAR	Foresight Vehicle	Prof P. S. Hall	103	1998-2000
RADARNET	EU FP5	Prof P. S. Hall	273	2000-2003
RALF	Foresight Vehicle	Prof P. S. Hall	21	2002-2003
SHORSENS	Foresight Vehicle	Prof P. S. Hall	103	2000-2003
SLIMSENS	Foresight Vehicle	Prof P. S. Hall	202	2004-2007
JLR Direct	Jaguar LandRover	Prof. M. Cherniakov	220	2008-2011
JLR Direct	Jaguar LandRover	Prof. M. Cherniakov	1500	2012 -

Birmingham was uniquely placed to undertake this research, with an academic team combining world class expertise in: radar (Dr E Hoare, Senior Research Fellow 1990-, M Cherniakov Professor of Aerospace and Electronic Systems, 2000-); antennas and arrays (Professor P S Hall, Professor of Electronic and Electrical Engineering, 1994-); mm-wave sensors and circuits (Hoare); and image processing (Dr. D. Pycock, Senior Lecturer, 1989-). The radar expertise was founded on extensive prior experience in military radar.

In the PROMETHEUS project (1992-1995), Birmingham researchers worked with a European consortium to research systems for reducing road accidents. Using prototype radar units in the laboratory and on Jaguar research vehicles, Cooper and Hoare obtained data in controlled and real environments. After collaborative evaluation of mm-wave and laser radars and optical systems, 77 GHz radar was chosen for its all-weather capability, forming the focus of subsequent groundbreaking research at Birmingham [3.1].

Laboratory radar measurements of vehicles, humans, animals and road infrastructure, on mm-wave antennas and on radar transceivers [3.1] established feasibility at a fundamental level. Research into mm-wave sensors for cruise control and collision avoidance established for the first time the possibility of mass manufacturing, at viable cost, complex sensors which were previously only available in expensive military systems. Advances included algorithms for automated radar self-alignment in production [5.4] and research into false target identification.

European projects, Foresight Vehicle projects and collaborations with Jaguar supported the expansion of the research to cover multiple aspects of automotive radar [3.5].

In ROADAR, Birmingham research showed how image processing could display the road trajectory up to 100m ahead, using radar returns from road edges, curbs, crash barriers and roadside furniture. [3.2–3.4]

The SHORSENS project investigated data fusion from mm-wave ultra-wideband radar and optical systems for pedestrian detection and collision avoidance. Birmingham produced ultra-wideband radar hardware and signal processing. Combining high resolution vision images from Cranfield (with limited range information) with high resolution radar range information from Birmingham (with limited pixel resolution) enabled pedestrian detection for collision mitigation.

In SLIMSENS [3.6] a 16-beam 77 GHz FMCW radar demonstrator, operating through the same aperture as a 63 GHz radio, was successfully developed and demonstrated. E2V and BAE systems built the hardware. Birmingham's expertise was critical in the antenna and system design, and in developing advanced prototype micromachined antennas.

As part of the European RadarNet consortium, Hoare and Pycock designed signal processing software and control systems for 76 GHz, 4-sensor arrays on five vehicles, each dedicated to one European manufacturer and optimised for a different application (collision avoidance, pedestrian detection, etc.).

Fundamental 24 GHz ultra-wideband radar system research, funded by Jaguar (2007-2008), established key operational parameters and investigated effects of rain and spray, radar signatures of vehicles, pedestrians, animals and bicycles. The resulting data were used in subsequent JLR funded research (2008-2011) into rear-facing short range 24 GHz radars. Birmingham provided radar expertise to define system operating parameters, to log and evaluate data from extensive road trials and to assess antenna manufacturing issues.

JLR continues to support long-term research into radar sensing of the vehicle environment, including road surface sensing, multisensor high-resolution imaging, and speed over ground.

3. References to the research

The outputs that best indicate the quality of the underpinning research are references 3.3, 3. 4 and 3.6

[3.1] Shearman, E.D.R., Hoare, E.G., and Hutton, A.: 'Trials of automotive radar and lidar performance in road spray', *IEE Colloquium on Automotive Radar and Navigation Techniques*, February, 1998, pp.10/1-10/7. DOI: 10.1049/ic:19980196.

[3.2] Tsang, S.H., Hoare, E.G., and Hall, P.S., 'Advance Path Measurement for Automotive Radar', *IEEE AP-S International Symposium and USNC/URSI National Radio Science Meeting*, Orlando, USA, 1999, pp.1776-1779. DOI 10.1109/APS.1999.788299. (This is the principal international conference in the field of antennas and propagation.)

[3.3] Tsang, S.H., Hoare, E.G., Hall, P.S., & Clarke, N.J., 'Automotive radar image processing to predict vehicle trajectory', *IEEE International Conference on Image Processing*, Vol.3, 1999, pp.867-870. DOI 10.1109/ICIP.1999.817267

[3.4] S. H. Tsang, P. S. Hall, E. G. Hoare and Nigel J. Clarke. "Advance Path Measurement for Automotive Radar Applications." IEEE Trans. Intelligent Transportation Systems, Vol. 7, No. 3, 2006. pp 273-81. DOI: 10.1109/TITS.2006.880614.

[3.5] E.G. Hoare and R. Hill. "System requirements for automotive radar antennas." IEE Colloquium on Antennas for Automotives (Ref. No. 2000/002). 2000 , Page(s): 1/1 – 1/11. DOI: 10.1049/ic:20000001

[3.6] E.G.Hoare, N.E.Priestley, R.Henderson, N.J.Clarke, P.S.Hall, R.N.Foster, "SLIMSENS – A Single Aperture Automotive Radar and Communications Sensor", *JSAE Annual Congress 2008,* Yokohama, Japan, 23 May 2008. JSAE paper no 20085103. (This is arguably the most important international conference in the world of automotive systems.)

4. Details of the impact

The research has had profound impacts during the 2008-2013 qualifying period:

- Economic impact through contributions to innovative product development. Access to the expertise of the Birmingham group enabled JLR to cut the time to market significantly and has provided a competitive edge in a market of great significance to the company. (Confidential quantitative details are in source [5.1].)
- Wider economic impact resulting from the cascading of automotive radar technology and products from the luxury end of the vehicle market downwards.
- Impacts on practitioners and professional services, through contributions to new technical standards ([5.4] and [5.5]) and through professional, research informed training courses.
- Impacts on the safety of road users through the development of automotive radar systems and their standardisation ([5.4] and [5.5]).

4.1 Economic Impact

4.1.1. Adaptive Cruise Control (ACC) radar

JLR has been equipping vehicles with ACC as an option since 1999. The currently advertised list price for this popular option is £1275.

ACC capability in both Ford and JLR is built on the underpinning research described above. The automotive radar research experience was shared with parent company Ford and assisted the design of the production systems for both brands by Delphi. These systems are now in full scale production.

Ford, having acquired Jaguar Cars in 1989, formed a World-Wide Radar Evaluation Committee in 1998. It visited all major potential automotive radar developers and suppliers in the US, Europe and Japan to evaluate performance, quality, production time, costs and reliability and to establish a suitable production supplier. Hoare was appointed to this panel as the sole radar expert and the sole member external to the company, by virtue of his expertise built up during research work at Birmingham.

4.1.2. Blind Spot monitor

This product was launched by Jaguar in 2008. The current list price for the option is £460.

Initial work was started in 2006 with road trials undertaken by Jaguar and Birmingham University in 2007. Research at Birmingham resolved deep practical issues, such as the penetration of radar signals through the painted bumper (radars are mounted behind the bumper material), and the interaction of the signals with the body of the vehicle. Birmingham provided expertise in resolving manufacturing issues with the supplier of switched beam antennas, and in the performance evaluation and vehicle integration.

4.1.3. Lane Change Merge Aid

Research has continued and evolved into the development of a long range (80m) mm-wave Lane Changing Merge Aid radar system. This rear looking radar system measures range, velocity and angle, providing information in the blind spot and beyond, to assist a driver when changing lanes and merging into traffic. Full development at JLR has led, within the REF qualifying period, to prototype systems. Full scale production will begin in 2014.

4.2 Contributions to Technical Standards

Hoare sat on the EU automotive radar committee setting International radio standards to enable

mm-wave radars to be operated within radio spectrum management regulations, as well as personally reporting at the International Telecommunications Union in Geneva. The committee ran for 4 years with experts from Birmingham, BMW, Daimler Benz, Fiat, Volvo, and GEC Plessey. The resulting EN 301-091 [5.4] set the standard for Europe and was used as the template for the FCC standard for North America.
Hoare also sat on the EU committee setting standards for 24GHz radar systems. The committee, comprising experts from Birmingham, BMW, Daimler Benz, Fiat, Volvo and Siemens, set the spectrum occupancy standard and addressed objections from existing users of the 24 GHz band. The resulting standard, EN 302 288 [5.5] remains in force until 2016.

4.3 Professional Practitioner Training

A dedicated 3-day course, "Understanding Automotive Radar, Theory, Practice and Current Development," was developed and delivered by Hoare at Birmingham, at Jaguar Cars, and at Ford Detroit between 1999 and 2009, with approximately 30 attendees per course. The course is for automotive engineers with no formal background in radar to enable them to understand the capabilities of radar systems and issues associated with their deployment. The impact arises from the fact that many participants are now in management positions with responsibility for radar sensing within JLR.

4.4 Ongoing Impacts

Research described at the end of section 2 is paving the way for further novel, technologically advanced, cost effective and saleable features which will increase vehicle sales revenues and contribute further to improving the safety of all road users in accordance with EU directives.

5. Sources to corroborate the impact

[5.1] **The primary source** of corroborating evidence is in a confidential letter from JLR held in the School, giving details of the impact of Birmingham's research on JLR products and revenue.

Below are **Patents** in JLR's IPR portfolio on several aspects of the research, naming Birmingham researchers among the inventors, demonstrating the ongoing impact:
[5.2] Motor vehicle trajectory measurement: US67445110, Jun 2004; EP1256015, Nov 2002; WO0157552, Aug 2001; GB2358975, Aug 2001; DE60009167, Apr 2004
[5.3] Optimum monopulse radar for automotive intelligent cruise control: GB2367438, Oct 2004.
[5.4] Automotive radar elevation alignment: GB2375671, Nov 2002; DE60100596, Sept 2003; EP1257843, Aug 2003.

Outputs of the standards committees (sect 4.2):
[5.4] ETSI EN 301 091-1 V1.3.3 (2006-11) European Standard (Telecommunications series) Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices; Road Transport and Traffic Telematics (RTTT); Radar equipment operating in the 76 – 77 GHz range.
[5.5] ETSI EN 302 288-2 V1.6.1 (2012-03) Technical Report Electromagnetic compatibility and Radio spectrum Matters (ERM); Radio equipment to be used in the 24 GHz band; System Reference Document for Short Range Radar.