Institution: University of Sheffield

Unit of Assessment: 15 General Engineering

Title of case study: A new design methodology for civil aero-engine control

1. Summary of the impact

A unified design methodology for tuning gas turbine engine controllers, developed by researchers in the Department of Automatic Control and Systems Engineering (ACSE), is being used by Rolls-Royce across its latest fleet of Civil Aero Trent engines. Trent engines are used to power, for example, Boeing 787 Dreamliner and Airbus A350 aircraft that have been adopted by the world's leading airlines.

This new methodology has made economic impact through the introduction of a new process for tuning gas turbine engine controllers leading to the adoption of a significantly changed technology.

Indicators of impact are:

i) **a new control law and design practice**, resulting in a unified approach for different projects;

ii) **reduced development effort** by shortening and simplifying the design exercise and rendering it suitable for modular insertion; and

iii) **streamlined verification requirements**.

2. Underpinning research

This research was carried out in the Rolls-Royce University Technology Centre in Control and Systems (RR-UTC), hosted and led by ACSE. RR-UTC was established in 1993.

Research undertaken by RR-UTC into gas turbine control law and architecture design, aimed at improving the efficiency and performance of civil gas turbine engines and at reducing development effort, led to the improved design methodology.

In 1994-5, as part of an EPSRC grant (GR/K36591, £156K), Chipperfield (RA) and Fleming (PI) demonstrated [R1] that genetic algorithms afforded the flexibility to search over both controller structure space as well as parameter space to identify the best controller for a specific gas turbine engine (GTE).

In 1998-9, in research funded by Rolls-Royce [text removed for publication], Thompson (RR-UTC RA), Chipperfield (RA), Fleming (PI) [text removed for publication] successfully applied evolutionary multi-objective optimisation in an investigation of alternative distributed control configurations for GTEs [R2], taking account of a range of competing criteria (covering cost and weight, risk, fault diagnosis capability and ease of maintenance).

With Fleming (Supervisor), in the period 1999-2002, PhD students, Silva and Khatib, used evolutionary multi-objective optimisation to explore trade-offs between maximising thrust and minimising fuel consumption and the role of inlet and outlet geometry modifications in conjunction with control law tuning [R3].

In a DTI-funded project with Rolls-Royce and TRW (£148K, 1999-2002), Fleming, with UTC RAs (Breikin, Thompson and Hargrave) and PhD students, (Regunath, Kim and Herbert) investigated low emissions combustion control for GTEs [R4] and, having identified an optimal fuel split between the pilot and main zones of the engine combustor, control strategies were successfully tested at industrial rig test facilities.

Rolls-Royce Civil Aerospace has historically used linear, gain-scheduled proportional-integral (PI) compensation for control of gas turbine fuel flow. Engine dynamics vary with flight and power conditions, and a lengthy design and verification process is required to meet the specification for all conditions. The RR-UTC research studies carried out on control systems architectures for GTE's, which took into account functional as well as operational requirements, informed the choice of the new control law and design methodology for Rolls-Royce civil aero-engines, which address the shortcomings of the traditional control approach.

Following a feasibility study within the UTC, the control system architecture and the design methodology was developed within a PhD programme (Dr Shahid Mahmood), 2002-2007, championed by UTC Research Fellow, Dr Ian Griffin. Griffin and Mahmood worked closely with engineers within the company taking the concept through Technology Readiness Levels to maturity.

The new control architecture and design methodology are based on a nonlinear inverse model. Specifically, the nonlinear model [R5, R6], which describes the response of a dominant engine state variable (high pressure shaft speed) to known changes of fuel, is inverted such that the required fuel flow can be computed for a given flight condition. The behaviour of the resulting controller is analogous to that of a nonlinear PI controller in which the proportional and integral terms are a function of the state of the controller and the proportional and integral gains are non-interacting.

Compared with the established approach, the new control law minimises dependence against engine power level and removes dependence against altitude. The new control law also delivers improved transient performance whilst maintaining robustness.

Further, and perhaps most importantly, the new design methodology requires fewer tuning parameters (a ten-fold reduction, from 55 down to 5), thus accelerating development time and significantly reducing the cost of downstream software verification.

During the course of the five-year programme within the UTC, besides demonstrating the enormous practical advantages of this new design, difficult tuning and architectural problems were overcome by the introduction of a number of practical innovations, e.g. [R6].

3. References to the research

Key papers providing evidence of the quality of the underpinning research:

R1. Chipperfield A and Fleming P: Multiobjective gas turbine engine controller design using genetic algorithms, *IEEE Transactions on Industrial Electronics,* vol. 43, no. 5, pp. 583-587 1996. doi: 10.1109/41.538616

R2. Thompson HA, Chipperfield AJ, Fleming PJ and Legge C: Distributed aero-engine control systems architecture selection using multi-objective optimisation, *Control Engineering Practice*, vol. 7, no. 5, pp. 655-664, 1999. doi: 10.1016/S0967-0661(99)00011-8

R3. Silva VVR, Khatib W and Fleming PJ: Performance optimisation of gas turbine engine, *Engineering Applications of Artificial Intelligence*, vol. 18, pp. 575-583, 2005. doi: 10.1016/j.engappai.2005.01.001

Additional references:

R4. Breikin TV, Herbert ID, Kim SK, Regunath S, Hargrave SM, Thompson HA and Fleming PJ: Staged combustion control design for aero engines, *Control Engineering Practice,* vol. 14, pp. 387-396, 2006. doi: 10.1016/j.conengprac.2005.02.005

R5. Davies C, Holt JE, Griffin IA (2006). Benefits of Inverse Model Control of Rolls-Royce Civil Gas Turbines, *Proc UKACC International Control Conference*, Control 2006, Glasgow, 2006.

R6. Mahmood S, Griffin IA, and Fleming PJ: Robust control of a gas turbine engine with variable power offtake, *Proc ASME Turbo Expo 2006*, GT2006-91266, Barcelona, Spain, 2006.

4. Details of the impact

Approach to impact

Initially, the research (see Section 2) was undertaken by the team in the Rolls-Royce UTC in Control and Systems Engineering within ACSE who rigorously worked the programme through Technology Readiness Levels (TRLs) 2 and 3 from 2002-2004.

In 2005, the academic team were invited to work closely with an industrial research team [text removed for publication] to demonstrate the feasibility of the concept for large civil engines, working through TRLs 4 to 6.

The role of the RR-UTC team was to provide technical advice, design procedure detail and supporting evidence through detailed simulations. A team of experts representing systems, engine operability, performance and control monitored the scheme.

The scheme was submitted to an Approval Meeting [text removed for publication] for acceptance, and it proceeded through the remaining TRLs.

Economic impacts

1. Rolls-Royce's business performance has been improved through the introduction of the new design process

The new design process achieves a ten-fold reduction in the number of tuning parameters (from 55 to 5) without detriment to control system performance [S5, S6]. This simplification of the design has led to cost savings as a result of *improved design practice, reduced development effort, and streamlined verification requirements.*

Improved design practice:

The simplified design process provides a unified approach across different projects. The simplified process is intuitive and makes the controller easy to tune, thereby making it easier to train engineers to use it. By adopting the same design methodology across the emerging Rolls-Royce fleet, the company has made continued cost savings across projects.

The process has proven robust. A key characteristic of the design methodology is the invariance of the designed controller to changes in the engine design throughout the Engine Development Programme.

There is no need to obtain a linearised model at various set points and no need for an associated frequency-domain analysis. Dispensing with the need for frequency-domain analysis enables the Rolls-Royce control engineers to align with the non-linear time-domain models used by the company's Performance Department.

Reduced development effort:

The design exercise is:

shortened - requiring fewer tuning parameters;

simplified - it is no longer necessary to develop linearised GTE models, nor is it necessary to use these models to define gains at all power conditions and all altitudes; and

suitable - for modular insertion within the existing architecture and, subsequently, to become part of the Rolls-Royce Product Line.

As a result, development effort is both reduced and simplified, leading to the need for fewer and less specialist design engineers.

Streamlined verification requirements:

The costs associated with safety-critical aerospace software certification are substantial and inroads into these costs are hugely beneficial commercially to the company. The significant reduction in the number of tuning parameters automatically leads to a simplification of low-level software verification effort. The power dependency is now encapsulated in a single internal table and the altitude dependency is expressed within a simple thermodynamic scaling term.

In the context of the certification-driven environment for introducing changes to civil engines, the adoption and implementation of this new control methodology to be used by Rolls-Royce engineers across the range of configurations across the Trent engine fleet is a remarkable achievement [S1]. "*This is the first new radical control law for over 20 years*" (Control Systems Design Architect, Rolls-Royce).

2. A sector has adopted a significantly changed technology

Control laws designed using this methodology are now implemented across the latest Trent fleet of engines. The Rolls-Royce Trent 1000 engine, achieved on-time certification on August 7, 2007, over seven months ahead of the rival General Electric engine for the Dreamliner [S3]. In 2013

Rolls-Royce was awarded certification for its higher efficiency and thrust "package C" variant of the Trent 1000 engine that will power the Boeing 787-9 Dreamliner aircraft [S4]. The new control system was granted a US Patent in 2012 [S2].

The Dreamliner's first flight was in December 2009 and it entered service with All Nippon Airways (ANA) on October 26, 2011. The engine, has delivered a dispatch reliability of better than 99.9%, which is a record for a wide body aircraft engine [S4].

The control law is currently in use on Trent 1000 (Boeing 787 Dreamliner), Trent XWB (Airbus A350 airframe) and BR725 (Gulfstream G650) engines, and is planned for use on all future variants.

Over 20 customers have selected the Trent 1000 to power their 787 Dreamliners and these include All Nippon Airways, Air China, Air Europa, Air New Zealand, British Airways, Delta, Icelandair, International Lease Finance Corporation, LOT, Thai Airways and Virgin Atlantic. Overall commitments for the Airbus A350, powered by Trent XWB, total more than 592 with 34 customers. With spares, this will mean a requirement for more than 1100 engines. Firm aircraft orders include customers such as Emirates, Qatar, Cathay Pacific and Singapore Airlines.

The control law has also been implemented and validated on industrial engines – evidence of its suitability as part of the wider Rolls-Royce Product Line. Important reported benefits concerning its implementation on industrial engines include simpler code implementation, reduced CPU processing time and less code to maintain as a result of the control code being reduced by approximately 40%.

3. Performance has been improved through highly skilled people taking up specialist roles drawing on their research

[text removed for publication]

The UTC is also proud to record that well over twenty of its engineers have been recruited into Rolls-Royce and Aero Engine Controls; a significant proportion already hold senior technical positions within the company.

5. Sources to corroborate the impact

Factual Statement:

S1. Letter from the Chief of Research and Technology, Electrical Power and Control Systems, Rolls-Royce, plc. This corroborates the claims made in this case study regarding the impact of the research undertaken in RR-UTC, which led to the adoption of a new design methodology for use within the company for civil aero-engine control and industrial gas turbine engine control.

Patent granted in USA:

S2. S. Mahmood: Control System. US Patent, US8321104 B2 http://www.google.co.uk/patents/US8321104.

Reports, reviews, web links and other documented sources of information in the public domain:

S3. R-R press release 2007: Trent 1000 certification and reliability http://tinyurl.com/qfc5k4z

S4. R-R press release 2013: Trent 1000 'package C' variant certification http://tinyurl.com/okc6s46

Confidential reports and documents:

S5. DNS104232 - 'Boeing 787 Airframe / R-R Trent 1000 Control System Sub-System Definition Document (SSDD): Control Laws'. Cerith Davies. Original Issue 1 dated June 2005.

S6. DNS122060 - 'User Guide for the Fuel Control Laws Rolls-Royce Inverse Model (RRIM)'. C Davies/I Griffin. Original Issue 1 dated March 2007.