Institution: University of Leicester		
Unit of Assessment: UoA12		
Title of case study: Advanced control systems for improved and efficient helicopter operation		
Period when the underpinning research was undertaken: 1999–2014		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): 1) Dr Rafael Morales 2) Prof Matthew Turner 3) Dr Emmanuel Prempain	**Role(s) (e.g. job title):** 1) Associate Professor, Aerospace and Computational Engineering 2) Professor of Engineering 3) Senior Lecturer in Control Engineering	**Period(s) employed by submitting HEI:** 1) 2008–Present 2) 1999–2020 3) 2008–Present
Period when the claimed impact occurred: 2014–2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

For over 20 years, the University of Leicester has played an active role in the field of advanced helicopter control techniques. This research has achieved substantial impact on control system design policies, industrial practices, marketplace performance and professional understanding.

Through collaborations with Leonardo Helicopters, Muretex, the Aircraft Research Association, Aerospace Technology Institute, UK Vertical Lift Network and many rotorcraft SMEs, University of Leicester School of Engineering researchers have provided innovative solutions to global industrial issues and created key enabling technologies to facilitate long-term success in rotorcraft benefitting the international aerospace industry.

2. Underpinning research

The University of Leicester (UoL) has, since the 1990s, conducted research into advanced control systems, particularly primary flight systems and the application of robust multivariable control techniques **[R1, R2, R3]**. Most of this work was research-led and supported by the government (EPSRC, QinetiQ–formerly Defence Evaluation and Research Agency) and laid the foundations enabling application of control principles to other areas of rotorcraft. Since 2007 **[R3–R5]**, the industrial focus has been on the application of advanced control algorithms for vibration reduction resulting in several GBP multi-million pound research projects including REACT and RTVP **[G1–G4]** with extensive UoL involvement. As such, UoL has become one of the UK's leading centres of excellence for control systems for rotorcraft.

Advanced Vibration Reduction Control Systems

Leonardo helicopters is one of the UK's leading aerospace companies, currently holding around 10.5% of the world rotorcraft market. The collaborative research with UoL focussed on complex vibration reduction problems resulting in the creation of novel advanced multivariable control algorithms **[R3, R5].** By applying multiple actuators (active lag-dampers, active trailing edge flaps etc.) to rotor blades, the team were able to reduce vibrations in helicopter fuselages, thereby providing improvements in airworthiness, passenger comfort, environmental impact and maintenance requirements. The experimental tests for DLR's (Deutsches Zentrum für Luft und Raum-fahrt e.V.—German Aerospace

Center) novel multiple-swashplate rotor concepts designed during this research collaboration are now internationally adopted control practices.

Control System Design for the National Rotor Test Facility (NTRF)

The NRTF rig is unique in featuring a tilting rotating mechanical system that enables wind tunnel experiments for a wide set of new rotor blades and configurations. This is reliant on the new control laws pioneered at UoL.
Valued at over GBP5M, the facility supports fundamental research relevant to helicopters, tiltrotors and turbo-prop aircraft, as well as emerging personal flying machines, Urban and/or Regional Air Mobility Systems, electric Vertical Take-Off and Landing vehicles, Unmanned Air Vehicles (UAVs), other rotary-wing vehicles (autogyros, rotodynes, turbo-props) and even wind turbines of various types. The rig is powered by an electric motor, which can provide up to 77kW and allows a maximum rotational speed of 3500rpm while its shaft angle can vary between -20 and 90 degrees (measured with respect to a vertical axis).
The NRTF rig and accompanying hardware is designed for portability, enabling its use in wind tunnels nationwide. Its purpose is to allow *dynamic* testing of rotor blades, which can be exploited by practitioners in industry and UK-based researchers. The NRTF will be one of only a handful of such facilities globally, providing a unique asset for UK and worldwide rotorcraft stakeholders.

The NRTF construction has two phases. Phase 1 is now complete and provides the hardware and rig control systems incorporating UoL's novel set of control laws to regulate tilting and trimming of the rig. The control system has been validated and shown to work at all specified wind-speeds and configurations **[R4]**. Building on the successful completion of phase I, phase II is underway funded by the GBP3,500,000 EPSRC MENtOR project **[G5]**.

3. References to the research

Publications

R1. Postlethwaite, I., **Prempain, E.**, Turkoglu, E., Turner, M.C., Ellis, K. and Gubbels, A.W., 2005. Design and flight testing of various H∞ controllers for the Bell 205 helicopter. *Control Engineering Practice*, *13*(3), pp.383-398.
R2. Prempain, E. and Postlethwaite, I., 2005. Static H∞ loop shaping control of a fly-by-wire helicopter. *Automatica*, *41*(9), pp.1517-1528. (Received Automatica "Best Application Paper" prize.
R3. Morales, R.M., Turner, M.C., Court P., Hilditch R., and I. Postlethwaite. Force control of semi-active lag dampers for vibration reduction in helicopters. IET Journal of Control Theory and Applications, Vol. 8, no. 6, pp. 409-419, 2014.
R4. Morales, R.M., Turner, M.C., Platts, J., Pugh D. and McCallum, A.T. Control Design of a tilting mechanism for the UK National Rotor Rig Facility. Proceedings of the 43rd European Rotocraft Forum, 2017.
R5. Hao, H. Y., **Morales R. M.** and **Turner M. C.**, Robust Analysis of Principal Components Active Control Systems. IEEE Transactions on Control Systems Technology. 10.1109/TCST.2020.3004996.

Grants

G1. Rotorcraft Embedded Actuator Control Technology (REACT), 2008–2013, TSB (Innovate UK), GBP196,000.

G2. Rotorcraft Technology Validation Programme (RVTP), 2011–2013, Innovate UK, GBP275,000.
G3. Active Rotor Study, 2014, ATI, GBP27,000.
G4. Industrial Fellowship, 2015-2016, RAEng, GBP26,000.
G5. Methods and Experimentation for NOvel Rotorcraft (MENtOR), EPSRC, GBP3,500,00, GBP150,931 to UoL, 2019–2020.

4. Details of the impact

The UK is a world leader in aerospace technology, but global competition is intensifying. The combined rotorcraft world market for the next decade is significant and hence key to the national economy, with a projected production of more than 17,600 rotorcraft worth an estimated USD202,000,000,000 in 2018 (Forecast International). The national helicopter industry is deeply embedded in the UK's industrial base, directly employing more than 7,300 people, generating national revenues of more than GBP2,300,000,000 and exports worth GBP1.3B yearly, and supporting the work of more than 2,300 companies in the supply chain. Although increasing demand for new civil rotorcraft is expected to more than offset the anticipated decline or plateau in military demand, in order to maintain or improve, the UK needs to generate unique innovations. Research conducted at UoL is making important contributions to this objective.

Enabling Long Term World-Leading Rotorcraft Innovation in the UK

The NRTF rotor rig is a physical mechanical/software mechanism, unique in the UK, that enables performance optimisation studies of rotor blades and their impact on rotor-vehicle aerodynamics, facilitating more efficient blade and body designs, reduced noise, improved airworthiness and better handling qualities.

The rotor blade control is governed by the unique algorithms developed by UoL, which have changed rotor blade design processes and increased capabilities for manufacturers to test the safety of the design. These algorithms were based on "*advanced novel H-infinity methods which were able to accurately control the rig pitch when implemented on the rig satisfying the required accuracy demands*" **[E4].** They are "*one of the key enabling technologies*" for the NRTF according to the Aerospace Technology Institute **[E2]**.

The test rig can also be used for other rotor-related studies, including new actuator technologies and flight algorithms, and enabling fundamental research of rotorcraft phenomena not yet well understood, such as whirl flutter, which can have catastrophic consequences for the operation of new vehicles operating at higher speeds. The rig is unique in the UK and is key to boosting the UK's vertical lift capabilities in an increasingly competitive market. "*The participation of the University of Leicester has been vital in the construction of the National Rotor Rig Test Facility*" (Aircraft Research Association) **[E1]**.

UoL research has significantly improved industrial understanding and awareness of advanced control design methodologies; notable examples of this include the Aircraft Research Association (ARA) for the NRTF rig and Muretex for the entire control system. ARA is an independent research and development organisation providing a range of specialist services to the global aerospace industry including aerodynamic design and consultancy, computational fluid dynamics, high precision wind tunnel model design and transonic wind tunnel testing. As a result of collaboration with UoL, ARA were able to "*greatly increase our awareness and*

understanding of their novel control algorithms some of which have been fully implemented into the NRTF and experimentally tested" and they also comment favourably on the algorithm's *"excellent performance, meeting demands of less than 0.1-degree accuracy for the rotor shaft tilting motion*" **[E3].** The result of this collaboration is that operators now understand the use and benefits of the UoL algorithms with ARA stating that "*These algorithms alleviate the operator's workload significantly, hence improving the safety under standard operation*" **[E3]**.

Systems engineering company Muretex specialise in augmenting human performance through automation and control systems development and are a partner in the NRTF development. In addition to algorithm development, UoL provided Muretex with *"advanced know-how to the control systems team, which allowed the implementation of algorithms crucial to the rigs' functionality*" and unique contributions that "*not only enabled rig functionality to be achieved, but also enhanced the appreciation of advanced control techniques by Muretex personnel*". As a result, the Muretex control system development toolbox is now "*more complete thanks to the collaboration with Leicester*" **[E4].**

Changing Aircraft Design Processes, Policies and Opening New Markets

Excessive vibration in rotorcraft causes a multitude of significant issues including making pilot control more difficult causing reduced flight quality, rotorcraft reliability and flight safety, increasing fuel consumption through reduced efficiency and negatively affecting passenger comfort and experience. New algorithms developed at UoL **[E1, E2, R5]** provide 50-75% reduction in vibration compared to standard industrial methods whilst also guaranteeing increased reliability. This is accomplished through a combination of more accurate robust stability tests and having low-order and a **single** set of control algorithms operating over the flight envelope. This facilitates the system's certification for production and provides an economical computational infrastructure.

Leonardo is one of the biggest suppliers of defence and security equipment to the UK Ministry of Defence. It makes a significant contribution to the UK economy with revenues of over GBP2,000,000,000, around 50% of which are in exports. According to Leonardo: *"[Morales'] expertise in advanced control system design for vibration reduction highlighted the importance of actuator limitations and how comprehensive algorithms that take this information into account can be exploited to further improve both airworthiness and performance with respect to existing methods*" **[E1]**.

Leonardo confirmed that the results of the collaboration are now "*applied to vibration mitigation systems currently operating on our products, such as the Active Control of Structural Response (ACSR) system*" **[E2]** which are included as key selling points on the AW101, AW169 and AW139 helicopters **[E5]**. As of October 2020, Leonardo had sold 71 AW101 machines as well as at least 450 AW169 and 1100 AW139 units generating revenues of up to USD23,900,000,000 **[E6]**.

The Aerospace Technology Institute (ATI) promotes transformative technology in air transport through substantial research and development funding and responsibility for defining the technology strategy for the UK aerospace sector. UoL research and involvement has achieved significant impact on ATI through providing "*new understanding and awareness into [their] design methods*' leading to *'impact on policies and design procedures for both the UK Aerospace Strategy and for the rotorcraft industry in the UK*" **[E1, E2].**

5. Sources to corroborate the impact

E1. Letter from Beneficiary Leonardo Helicopters.
E2. Letter from Beneficiary ATI.
E3. Letter from Beneficiary ARA.
E4. Letter from Beneficiary Muretex.
E5. Leonardo Helicopters Product Brochures Website.
E6. Sales figures and Cost Data from media outlets.