The Control Group at Leicester

The Control Group at Leicester has an international reputation in the development and application of advanced control system design methods. Much of its research is fundamental and generic with wide applicability across various sectors of industry but particular attention is given to aerospace. The Group is very well resourced with excellent computing facilities.

There are currently five academic staff members in the Group, including two professors (C. Edwards, D.-W. Gu), one senior lecturer (M.C. Turner) and two lecturers (A. Lecchini-Visintini, E. Prempain). In addition, the group currently includes a teaching fellow (R.M. Morales) and a fixed-term lecturer (J. Andrade da Silva).

Major grants and partnerships
The group has been awarded two EPSRC Platform Grants. The first platform grant facilitated collaboration with the University of California at Santa Barbara on constrained control problems as well as work on helicopter control with the Canadian NRC Flight Research Laboratories, Westland Helicopters and QinetiQ. The second platform grant, on the Control of Complex Systems, is being used to support new collaborations; for example, with the CNRS LAAS (Laboratory for Analysis and Architecture of Systems) at Toulouse.
The group has received a UKIERI major award (£549K) "Towards reliable smart adaptable air-vehicles" with the IISc Bangalore, the National Aerospace Laboratories in Bangalore, IIT Mumbai and NIT Tiruchirappalli. The group is also the most active UK university partner in the control-related action groups of GARTEUR (Group for Aeronautical Research and Technology in EURope), which brings together the leading European aerospace companies. The Group is also a Preferred Academic Capability Partner of BAE Systems in the area of Control Systems.

The Group has recently been very active in research on autonomous systems and fault tolerant flight control systems design, with particular interest in uninhabited air vehicles (UAV) and helicopters, the development of innovative routing algorithms, robust and stochastic control and modelling.

This document gives an overview of some of the current research activities in the group.

UAVs (Gu)
Uninhabited vehicles, in air, on ground or under water, have been recognized as a major development area in the 21st century, simply due to their flexibility and no risk of human loss. The latter brings however lack of human intelligence to deal with uncertainties. In the last few years, one of our major research directions has been on raising the autonomy level of such vehicles, including mission scheduling, path planning, health monitoring and management, reconfiguration, network optimisation, etc. Research activities have been carried out in several defence industry-led projects, such as FLAVIIR, NECTISE, SEAS DTC and ASTRAEA. Significant results have been obtained and are welcomed by collaborative companies. Three patents have been generated. The techniques developed are not just for defence applications but also applicable in other complex systems-of-systems/networked systems. Hence there will be potential benefits to users in the manufacturing industry, communication network and medical health systems (NHS), for example.

Key publications:

D.-W. Gu, Y. Kim and I. Postlethwaite. How tight is sphere packed formation flying? *Journal of Aerospace Engineering*, 224(G4):427-435, 2010.

Y. Kim, D.-W. Gu and I. Post lethwaite. Robust Target Tracking Using Distributed UAV Networks. *Journal of Aerospace Engineering*, 244(G4):417-426, 2010.

Y. Kim, D.-W. Gu and I. Postlethwaite. Spectral Radius Minimization for Optimal Average Consensus and Output Feedback Stabilization. *Automatica*, 45(6):1379-1386, 2009.

Y. Kim, D.-W. Gu and I. Postlethwaite. Real-time path planning with limited information for Autonomous uninhabited air vehicles. *Automatica*, 44(3):696-712, 2008.

Y. Kim, D.-W. Gu and I. Postlethwaite. Real-time optimal mission scheduling and flight path selection *IEEE Transactions on Automatic. Control,* 52(6):1119-1123, 2007.

K. Natesan, D.-W. Gu and I. Postlethwaite. Design of Static H-infinity Linear Parameter Varying Controllers for Unmanned Aircraft. *Journal of Guidance, Control, and Dynamics*, 30(6):1822-1827, 2007.

Sliding mode & fault tolerant control - Aerospace (Edwards)

A strand of work pioneered at Leicester has been the use of sliding mode observers for Fault Detection and Isolation. The novelty of this approach lies in the ability of sliding mode observers to reconstruct un-measurable signals in the process being monitored, by appropriate scaling and filtering of the so-called 'equivalent output error injection'. This approach is quite different from typical residual generation methods for fault detection. The fact that the faults are reconstructed allows the possibility of using the reconstructions to compensate for the fault effects – for instance by directly 'correcting' the output of a faulty sensor to achieve fault tolerant control. These ideas have been applied to aerospace control problems within the context of the GARTEUR (Group for Aeronautical Research and Technology in Europe) Action Group on Fault Tolerant Control FM-AG16 which aimed to demonstrate the capabilities of modern Fault Detection and Isolation methods applied to realistic, nonlinear problems and to assess their contribution to flight safety. As part of this activity sliding mode schemes for fault tolerant control were tested on the SIMONA motion simulator at the Technical University of Delft. It has been shown that sliding mode schemes in conjunction with so-called control allocation, have the capability to maintain a good level of performance even in the face of total failures of certain actuators, which currently would render the aircraft difficult to fly, and in certain cases, has resulted in the loss of the aircraft. An ESPRC grant in conjunction with Airbus considered these ideas within the context of 'Active Aircraft' and an ongoing EU FP7 project 'ADDSAFE' (also in conjunction with Airbus) aims to use these ideas to develop model-based FDD methods for aircraft flight control systems (predominantly sensor and actuator malfunctions).

Key publications:

C. Edwards and T.J.J Lombaerts, and H. Smaili (Eds.). *Fault Tolerant Flight Control: A Benchmark Challenge*, Springer-Verlag: Lecture Notes in Control and Information Sciences, 399, 2010.

C. Edwards and S.K. Spurgeon *Sliding Mode Control: Theory and Applications* Taylor & Francis, 1998.

H. Alwi, C. Edwards, O. Stroosma and J.A. Mulder. Evaluation of a sliding mode fault tolerant controller for the EL AL incident, *AIAA Journal of Guidance Control and Dynamics*, 33:677-695, 2010.

S. Baev, Y. Shtessel, C. Edwards, S. Spurgeon. HOSM observer for a class of non-minimum phase causal nonlinear MIMO systems. *IEEE Transactions on Automatic Control*, 55:543-548, 2010.

C.P. Tan and C. Edwards. Robust fault reconstruction in linear uncertain systems using multiple sliding mode observers in cascade. *IEEE Transactions on Automatic Control*, 55(855-867), 2010.

H. Alwi, C. Edwards and C.P. Tan. Sliding Mode Estimation Schemes for Incipient Sensor Faults, *Automatica*, 45:1679-1685, 2009.

H. Alwi, C. Edwards, O. Stroosma and J.A. Mulder. Fault Tolerant Sliding Mode Design with Piloted Simulator Evaluation. *AIAA Journal of Guidance and Control*, 31:1186-1201, 2008.

H. Alwi and C. Edwards. Fault tolerant control using sliding modes with online control allocation. *Automatica*, 44:1859-1866, 2008.

H. Alwi and C. Edwards. Fault Detection and Fault Tolerant Control of a Large Civil Aircraft Using a Sliding Mode Based Scheme. *IEEE Transactions on Control System Technology*, 16:499-510, 2008.

C.P. Tan and C. Edwards. Sliding Mode Observers for Robust Detection and Reconstruction of Actuator and Sensor Faults. *International Journal of Robust and Nonlinear Control*, 13:443-463, 2003.

C.P. Tan and C. Edwards. Sliding Mode Observers for Detection and Reconstruction of Sensor Faults, *Automatica,* 38:1815-1821, 2002.

C. Edwards, S.K. Spurgeon and R.J. Patton. Sliding Mode Observers for Fault Detection *Automatica*, 36:541-553, 2000.

Robust control of constrained systems - helicopter flight control (Turner)

All real-life systems are constrained by the capability of their actuators. It is well known that if a controller demands more control activity than an actuator can cope with, the actuator will saturate, causing the system to exhibit degraded performance and even to become unstable. Recent research has been focused on the development of anti-windup compensators – retro-fits to existing controllers – which are able to assist the original controller during periods of saturation, limiting performance degradation and improving its stability properties. Several algorithms have been developed for the design of anti-windup compensators which can provide nonlinear stability and performance guarantees – properties which are not present in traditional anti-windup design methods. The compensators are suitable for implementation in complex, multivariable systems and compensators have already been implemented on a fly-by-wire experimental aircraft and have also been used in a proto-type drive-by-wire application.

Other research has been conducted in the area of helicopter flight control systems, with industrial support from with QinetiQ, AgustaWestland and the NRC Flight Research Laboratory, Canada. In particular, the Group is well-known for designing and flight testing the first H-infinity control system on the NRC's FBW experimental helicopter. Several subsequent flight tests honed the algorithms, including results on anti-winding up techniques, and have led to efficient design procedures for helicopter control systems. Level 1 handling quality has been achieved in-flight, using Leicester designed controllers. The control methodology used has the potential to improve helicopter performance while offering a shorter design cycle, with less reliance on flight tests. In fact, results from the flight tests have already fed into the TSB supported Rotorcraft Aeromechanics DARP in which Leicester designed control systems for the EH101 helicopter. A further TSB supported project, REACT, (Rotor Embedded Actuator Control Technology) is currently investigating control systems to reduce vibrational effects of the main rotor to reduce pilot fatigue, to reduce maintenance costs and to improve the performance of the rotor system, using embedded actuators on the helicopter's rotor blades.

Key publications:

M.C. Turner, G. Herrmann and I. Postlethwaite. Incorporating robustness requirements into anti-windup design. *IEEE Transactions on Automatic Control*, 52(10):1842-1855, 2007.

M.C. Turner, G. Herrmann and I. Postlethwaite. Improving sector-based results for systems with dead-zone nonlinearities and constrained control applications. *Automatica* 45(1):155-160, 2009.

O. Brieger, M. Kerr, D. Leißling, I. Postlethwaite, J. Sofrony and M.C. Turner. Flight testing of a rate saturation compensation scheme on the ATTAS aircraft. *Aerospace Science and Technology , in press*, 2008

M.C Turner, M.L Kerr and I. Postlethwaite. On the existence of stable causal multipliers for systems with slope restricted nonlinearities. *IEEE Transactions on Automatic Control* 54(11):2697-2702, 2009.

J. Sofrony, M.C. Turner and I. Postlethwaite. Anti-windup synthesis for systems with rate limits using Riccati equations. *International Journal of Control* 83(2):233-245, 2010.

Monte Carlo methods for the control of complex systems - Air Traffic Management (Lecchini-Visintini)

In the context of stochastic dynamical systems, Monte Carlo methods can be used to perform recursive estimation and to carry out the optimization of deterministic and stochastic performance criteria. In principle, by being simulation-based, Monte Carlo methods can be employed to solve very complex problems as long as models are available for simulations. The objective of this research theme has been to develop new methods for the control of complex systems based on the use of Monte Carlo methods. The research has focused both on rigorous theoretical analysis and on the development of challenging real-world applications. The theoretical work led to the formulation of rigorous finite-time guarantees on the performance of stochastic optimization algorithm based on Markov chain Monte Carlo (MCMC) sampling in approaching the global solution of stochastic optimization problems defined over continuous domains. The applied work has dealt with the design of innovative tools for Air Traffic Management (ATM) in the framework of two consecutive EU projects on ATM. Current. In this context, Dr Lecchini-Visintini has been guest editor, together with Prof. John Lygeros at ETH Zurich, of a special issue titled “Air Traffic Management: Challenges and opportunities for advanced Control” in the International Journal of Adaptive Control and Signal Processing

Key publications:

A. Lecchini-Visintini, J. Lygeros and J. Maciejowski. Stochastic optimization on continuous domains with finite-time guarantees by Markov chain Monte Carlo methods*. IEEE Transactions on Automatic Control,* 55(12):2858-2863, 2010.

N. Kantas, A. Lecchini-Visintini, J. Maciejowski. Simulation Based Optimal Design of Aircraft Trajectories for Air Traffic Management. *Int. Journal on Adaptive Control and Signal Processing*, 24(10):882-899, 2010. Special Issue: Air Traffic Management: Challenges and opportunities for advanced Control.

E. Crisostomi, A. Lecchini-Visintini and J. Maciejowski,
Combining Monte Carlo and worst-case methods for trajectory prediction in air traffic control: A case study. *Automatic Control in Aerospace*, 2(1), 2009

A. Lecchini-Visintini, J. Lygeros and J. Maciejowski. Simulated Annealing: Rigorous finite-time guarantees for optimization on continuous domain. In: Advances in Neural Information Processing Systems 20, (Proceedings of NIPS 2007), MIT Press.

A. Lecchini, W. Glover, J. Lygeros and J. Maciejowski. Monte Carlo Optimisation for Conflict Resolution in Air Traffic Control. *IEEE Transactions on Intelligent Transportation Systems*, 7(4):470-482, 2006.

Gain scheduling & LPV Systems - Aerospace (Prempain)

Gain scheduling methods extend the validity of the linearization approach to a range of operating points. Typically, an aerospace system is linearized at some point of the flight envelope (e.g. altitude, Mach number, angle of attack) and linear controllers are then designed at each equilibrium point. The resulting family of controllers is implemented as a single controller with parameters changing according to the scheduling variables. However, one drawback of robust gain scheduling controller synthesis techniques is that they produce controllers of order equal to that of the system to be controlled. That is, the complexity of the feedback controller is equal to the complexity of the system to be controlled. Such complexity in the feedback system is most of the time unwanted and unnecessary. Ideally, it would be desirable to obtain feedback controllers with simple architecture. This problem is theoretically challenging. In many situations, low order feedback controllers can deliver similar performance to full order feedback controllers. Recently, within a recent ESA project the techniques developed at Leicester were applied to the problem of controlling the lateral-directional dynamics of a re-entry vehicle. It was demonstrated that a low order gain-scheduling controller designed much performed better that the baseline feedback controller provided by our industrial partner. High performance robust gain-scheduling missile autopilots have also been designed with the tools developed at Leicester. This research is currently supported by DGA/DSTL within the Domain I of the ITP initiative.

Key publications:

E. Prempain, M. C. Turner, G. Sandou, G. Duc, Dave H. Vorley, J.P. Harcaut. Dynamic Controllers: Flight Control Design Over a Large Flight Envelope. MCM-ITP 2010 - 19 & 20, Manchester, UK.

Prempain, E., Postlethwaite, I. L2 and H2 Performance Analysis and Gain-Scheduling Synthesis for Parameter-Dependent Systems. *Automatica,* 44(8):2081-2089, 2008.

E. Prempain, M. C. Turner and I. Postlethwaite. Coprime factor based anti-windup synthesis for parameter-dependent systems. *Systems & Control Letters*, 58(12): 810-817, 2009.

E. Prempain and I. Postlethwaite. Static H-infinity loop shaping control of a fly-by-wire helicopter, *Automatica*, 41(9):1517-1528, 2005. **IFAC Automatica Best Paper Award.**

E. Prempain and I. Postlethwaite. Static Output Feedback Stabilization with H-infinity Performance for a Class of Plants, *Systems & Control Letters*, Vol. 43(3):159-165, 2001.