Institution: University of Exeter

Unit of Assessment: 10 Mathematical Sciences

Title of case study: Changing the way the European space industry verifies the safety of complex systems

1. Summary of the impact (indicative maximum 100 words)

The difficulty of certifying the safety (often termed Verification and Validation – V&V) of increasingly complex and more autonomous Guidance, Navigation and Control (GNC) systems is now widely accepted to be a serious threat to the success of future space missions. In response to this threat, the European Space Agency has funded Dr Prathyush P Menon and his team to develop a suite of mathematical tools for the V&V of advanced GNC systems. These tools have now been widely adopted throughout the European Space industry, and have been successfully applied by major companies such as Astrium, Thales-Alenia and GMV to systems ranging from flexible and autonomous satellites, to launch vehicles and hypersonic re-entry vehicles.

2. Underpinning research (indicative maximum 500 words)

In the current V&V process for mission-critical space control systems, worst-case deviations from expected system performance due to uncertainties and variations in the system and its environment must be calculated in order to provide confidence that the mission objectives will be met. The European space industry has to date relied almost completely on Monte Carlo (MC) simulations for the V&V of advanced control systems. In this approach, high-fidelity spacecraft computer simulation models are run repeatedly with their parameters randomly scattered to reflect likely sources of uncertainty. However, MC techniques require a large number of simulations to accurately represent the statistical distributions characterizing variations in performance. As a result, MC simulations are one of the largest consumers of time and computing resources for industrial companies involved in ESA missions, with thousands of simulation runs taking weeks of computing time for critical mission phases such as spacecraft rendezvous, planetary entry, descent and landing (EDL). This translates directly into increased development costs, via increased computational and person-hour requirements. There is increasing concern throughout the European space industry that the cost of V&V for future more autonomous and complex systems will become prohibitive using current approaches.

Since his appointment in 2010, Dr Menon and his team at Exeter, which includes Dr Wenfei Wang (Research Fellow), and three industry-funded PhD students, have been working with their industrial collaborators to develop techniques for the V&V of the next generation of space systems. This research [1-6] has investigated how advanced optimisation algorithms could be used to more efficiently search for worst-case scenarios that violate mission-critical performance specifications. This research has resulted in the creation of the worst-case analysis tool (WCAT), a suite of software incorporating advanced probabilistic and deterministic optimisation methods that allow worst-case deviations from multiple performance objectives over any particular phase of the mission to be computed. In collaboration with our industrial partners, the WCAT tool has now been applied on a wide range of different space systems, from flexible telecommunication satellites [2], Earth Observation Satellites [3] and autonomous rendezvous systems [1], to rocket launchers and hypersonic re-entry vehicles [4,5]. These studies have demonstrated the ability of WCAT to deliver more accurate and reliable analysis results (in terms of uncovering true worst-case behaviour of the control system), at significantly lower computational cost, than those produced by current industrial practice [1]. This translates directly into reduced costs for industry via reductions in development timeframes. Results of these studies have been published in leading international journals and conferences [1- 6], including specialist ESA-organised workshops, and several of the leading European space companies, including Astrium, GMV, Thales Alenia, SCISYS and NGC (see list of key supporting grants), have initiated collaborations with Dr Menon's group in order to incorporate the WCAT into their in-house V&V process (see evidence **item a** and evidence **item b** in Section 5).

3. References to the research (indicative maximum of six references)

Evidence of the quality of the research that underpins this case study is provided through the following peer-reviewed publications and grants secured through competitive funding sources.

[1] Verification and Validation of Autonomous Rendezvous Systems in the Terminal Phase, W. Wang, P.P. Menon, D.G. Bates, N. M. Gomes Paulino, E. Di Sotto, A. Bidaux, A. Kron S. Salehi and S. Bennani, Provisionally accepted to the AIAA Journal of Spacecraft and Rockets, 2013 (preliminary results in Proceedings of the AIAA Conference on Guidance, Navigation and Control, Minneapolis, Minnesota, USA, 2012.)

[2] An Integrated Analytical/Numerical Framework for Verification and Validation of Attitude Control Systems for Flexible Satellites, W. Wang, P.P. Menon, D.G. Bates, A. Bidaux, A. Garus, A. Kron, C. Charbonnel, F. Ankersen, S. Bennani, in Proceedings of the AIAA Conference on Guidance, Navigation and Control, Minneapolis, Minnesota, USA, 2012.

[3]** Integrated Structure/Control Optimization Applied to the BIOMASS Earth Observation Mission, M. Watt, M. Yu, A. Falcoz, A. Kron, P.P. Menon, F. Ankersen, L. Massotti, in Proceedings of the AIAA Conference on Guidance, Navigation and Control, Boston, USA, 2013.

[4]** Robust Safety Margin Assessment and Constrained Worst-Case Analysis of a Launcher Vehicle, A. Kamath, P.P. Menon, D.G. Bates, M. Ganet-Schoeller, S. Bennani, in Proceedings of the IFAC Symposium on Robust Control Design, Aalborg, Denmark, 2012.

[5] Worst Case Analysis of a Launcher Vehicle Using Surrogate Models, A. Kamath, P.P. Menon, M. Ganet-Schoeller, M. Guillaume, S. Bennani, D.G. Bates, in Proceedings of the IFAC Symposium on Robust Control Design, Aalborg, Denmark, 2012.

[6]** Robustness Analysis of Attitude and Orbit Control Systems for Flexible Satellites, W. Wang, P.P. Menon, D.G. Bates, S. Bennani, *IET Control Theory and Applications*, 2010, **4** (12), pp. 2958–2970

** Papers that best indicate quality of underpinning research.

Key Supporting Grants:

- Maturation of the Worst-Case Analysis Tool, 2012–2013, European Space Agency, €60K.
- Integrated Guidance Navigation and Control for Mars Sample Return, 2011–2013, European Space Agency, (with GMV-Spain, Thales-France), €55K.
- Scalable Autonomous GNC for Entry Descent and Landing, 2011–2013, European Space Agency, (with SciSys-UK, Thales Alenia-France, NGC-Canada), €35K.
- Modern Satellite Attitude Control, 2011–2012, European Space Agency, (with Astrium-UK), €20K.
- Robust Flight Control System Design Verification and Validation Framework, 2011–2012, European Space Agency, (with Astrium Space Transportation-France), €75K
- Generic Rover Dynamics Model Framework for Autonomous Capability Development, Verification and Validation, Oct 2013 – 2014, CREST2 – UK Space Agency, (with Astrium-UK), £50K

4. Details of the impact (indicative maximum 750 words)

The European space industry has an annual turnover of approximately €8B and employs over

35,000 people [evidence **item c**]. The UK space industry has an upstream turnover of £930M and a downstream turnover of £6.6B per annum, and directly employs over 8,000 people, mostly in highly skilled occupations [evidence **item d**]. Over the past number of years Dr Menon and his group have, uniquely for a UK-based mathematics research group, worked with almost every major European company in this sector, including Astrium (UK/France/Germany, turnover €5B), Thales/Alenia Space (Italy, turnover €2B), GMV Space (Spain, turnover €50M), SCISYS PLC (UK, £43M), Deimos Space (Spain, turnover €20M). Total research income to Dr Menon's group from these contracts has exceeded €400K and has supported 4 full-time PhD students, a level of ESA funding that is unmatched by any other maths-based research group in Europe. As a result of these collaborations, the WCAT software tool developed by Dr Menon's group has transformed the way that the European space industry performs V&V. Use of the tool by European Space companies is now actively encouraged, and increasingly mandated, by the European Space Agency, through specific requirements written into Statements of Work (SoW) [see evidence **item e** and evidence **item f**] for recent and future ESA projects.

By leveraging the power of advanced global optimisation techniques, and packaging these methods in a user-friendly software environment, WCAT allows industrial companies to make significant reductions in the cost of the V&V process for advanced space control systems. This potential has now been demonstrated in a number of different ESA-funded projects, across several different application platforms. The results of the application of the WCAT to an autonomous satellite rendezvous system developed by the Spanish company GMV, where a "chaser" satellite is required to rendezvous with and capture a small canister containing samples from the surface of Mars. While 1000 Monte Carlo simulations (taking more than a week of computations) uncovered no failure cases, the WCAT found a case for which the chaser failed to capture the canister in only 339 simulations [1] representing a saving of 60% in the cost of this stage of the V&V process.

In another recent study [2], use of the WCAT for the V&V of an attitude control system for a flexible telecoms satellite revealed significant shortcomings in the traditional Monte Carlo simulation approach. For a range of satellite fuel-tank filling ratios (FR), two hybrid optimisation algorithms encoded in the WCAT (HGA and HDE) were able to identify higher values than Monte Carlo simulation (MC) of a sensitivity function (S) reflecting the fragility of the attitude controller to uncertainties in the bandwidth of the satellite's flexible modes. This more accurate evaluation of the controller's robustness was achieved in each case with fewer simulations than the 1000 typically required to ensure adequate statistical confidence intervals in MC simulation campaigns.

Based on the demonstrated successes of the WCAT tool on several recent projects, Dr Menon's group were approached by ESA in 2012 to produce an updated version of the tool [evidence **item e**]. This work, funded directly by ESA via a €60K research contract directly with Exeter University (ESA Contract No. 4000104541) will leverage recent theoretical work by Dr Menon's team on surrogate modelling and robust safety-margin analysis to produce an enhanced and expanded version of WCAT for application to a number of future ESA missions [4,5].

Head of Guidance and Control at ESA [see evidence **item a**]

'Our team at ESA and other key industrial partners significantly benefit from the advanced verification and validation tools developed at Exeter. The benefits are in terms of the reduction of the time to market and associated development cost while achieving sufficiently reliable validation and verification results for multiple projects. Especially the methodology and tools developed at Exeter is capable of determining the worst case performance and safety margins of designs and missions in an efficient and consistent manner.'

Dr Menon was keynote speakers at an international workshop on "Worst Case Analysis Tools For Guidance Navigation & Control Systems" organized by ESA at ESTEC headquarters in Noordwijk on November 13th & 14th 2012 [evidence **item g**]. This workshop, which included participants from all the major European space companies, research organizations (CNES-France, DLR-Germany) and leading US/EU universities (Berkeley, Minnesota, Stuttgart, Exeter) has effectively set the agenda for ESA-supported research and development in this field for the next five years. In

February 2013, Dr Menon’s group initiated a new collaboration with the Advanced Studies Group at Astrium UK in Stevenage, with the aim of further integrating the WCAT tool into Astrium’s design process for a range of current and future missions [evidence **item b**]. In October 2013, Dr Menon’s group was awarded £50K, by esteemed CREST 2 – UK Space Agency initiative of significant national importance [evidence item h], to integrate the Worst Case Analysis Tool for developing a rapid auto tuning tool for the Generic Rover Dynamics Model framework with Astrium Ltd., Stevenage, which also aim towards final integration and testing at ESA Harwell Centre, Harwell, Oxford.

5. Sources to corroborate the impact (indicative maximum of 10 references)

a. Letter of corroboration from Head of Guidance Navigation & Control Systems European Space Agency

b. Letter of corroboration from Head of AOCS/GNC & Flight Dynamics, EADS Astrium

c. Eurospace Annual Report, 2011

d. UK Space Agency Report, 2011

e. SoW for WCAT-II Maturation of the Worst Case Analysis Tool, TEC-ECN-SoW-SB-02, Dt. 28-06-2011.

f. SoW for “Scalable EDL GNC & Avionics System Demonstrator” Appendix 1 to ITT AO AO/1-5966/08/NL/BJ -ESA issue 2 rev 3

g. ESA-CNES-DLR Workshop on Worst Case Analysis Tools for Guidance, Navigation and Control Systems, ESA-ESTEC, Noordwijk, 13-14 Nov. 2012. (http://space-env.esa.int/indico/confLogin.py?confId=18)

h. UK Space Agency CREST Initiative: http://www.bis.gov.uk/assets/ukspaceagency/docs/crest-guidelines.pdf