Institution: University of Southampton

Unit of Assessment: 10 Mathematical Sciences

Title of case study: 10-10 Optimising Spacecraft Design for A World-leading Space Agency

1. Summary of the impact

Through close collaboration with scientists at the European Space Agency (ESA), research at the University of Southampton has developed new algorithms and an associated software tool that have contributed to more efficient spacecraft design. Now a standard component of the ESA's design technology, the tools have doubled the speed in which crucial design processes can be completed, resulting in increased efficiency over the REF period of 20 person-years – equivalent to €1 million in monetary terms - and maintaining the ESA's manufacturing competitiveness. The success of this work led to a €480,000 EU grant to adapt the tools for the avionics industry as part of efforts to meet ambitious environmental targets under the EU Clean Sky Initiative.

2. Underpinning research

Spacecraft are used for a variety of purposes: communications, meteorology, navigation, exploration and transportation. Designing spacecraft is an incredibly complex process; a vast number of parameters, including component geometry and material properties, must be taken into account. Rather than looking to optimise a single objective, engineers simultaneously weigh up several competing criteria such as cost, weight and durability in a process known as multi-objective optimisation. The design of heat pumps in spacecraft is a case in point; the cost and weight of the pumps need to be minimised, while their mechanical efficiency must be maximised. Engineers rely on mathematical algorithms to solve these multi-objective problems as efficiently as possible.

Standard techniques for multi-objective optimisation – for example weighting objectives and adding them up – involve the transformation of the given problem into an infinite family of parameterised standard optimisation problems. Solving *all* such problems for *all* possible parameters amounts to solving the original problem, but requires the solution of an infinite number of sub-problems. Thus in the real world one usually resorts to solving a finite number of these problems to obtain an approximate answer to the original question. This approach leaves various important numerical questions unanswered that need to be considered before practical algorithms can be designed, in particular:

1. What are the numerical properties of transformations from a multi-objective problem to a family of parameterised single-objective problems?
2. Is there an efficient way to discretise the parameter space of such a family of parameterised single-objective problems?
3. Is it possible to use information from one parameterised problem to draw conclusions about the solutions of another parameterised problem?

The University of Southampton's Joerg Fliege (Professor, 2007-present) is an expert in mathematical and multi-objective optimisation and has contributed to a greater understanding of all aspects of these problems, from the underpinning mathematics to the design of efficient algorithms. He showed that a certain class of transformations have favourable numerical properties that can be exploited to reduce computation times **[3.1]**. Together with colleagues in Brazil, he developed, for the first time, a highly efficient algorithmic scheme for discretizing parameter spaces in an efficient manner **[3.2]** and designed a sensitivity analysis that found it was indeed possible to provide a solution to the third question outlined above.

This highly efficient numerical scheme makes use of recent algorithm developments, notably an adaptive scheme for the parameter space of a multi-objective programming problem. From 2008-2010, a team comprising Fliege, Gerdts (University of the Federal Armed Forces Munich), Vicente (University of Coimbra) and scientists at the European Space Agency (ESA) employed these ideas to develop new algorithms and produce a computational toolbox to solve multi-objective problems in spacecraft design **[3.3]**.

The multi-objective optimisation algorithm was implemented and incorporated into the toolbox in a follow-up project **[3.4]**. The Nonlinear Programme Solver code that was developed included a Graphical User Interface that allows an efficient exploration of the design space for a given multi-objective problem and consideration of trade-offs between the different objectives. ESA engineers were then able to explore the full parameter space in an efficient way to significantly improve the design process and enhance the quality of the final product.

3. References to the research

Publications:

3.1 (*) Fliege, J. (2007): The effects of adding objectives to an optimisation problem on the solution set. *Operations Research Letters*, 35, (6), 782-790.

3.2 (*) Fliege, Drummond, M.G. and Svaiter, B.F. (2009): Newton's method for multicriteria optimisation. *SIAM Journal on Optimisation*, 20, (2), 602-626.

3.3 Gerdts, Fliege, Vicente, L.N. (2009): FGS Toolbox Software Manual. European Space Agency Study Contract Report 22170/08/NL/ST WP3000. September 2009.

3.4 Fliege, J. and Xu H. (2011): Stochastic Multiobjective Optimisation: Sample Average Approximation and Applications. *Journal of Optimisation Theory and Applications*, 151 (2). 135-162.

(*) These references best indicate the quality of the underpinning research.

Grants:

3.G1 European Space Agency Study Contract Report 22170/08/NL/ST 'Versatility of Filtering Techniques in Non-Linear Programming Optimisation'. Awarded to the Universities of Birmingham, Southampton, and Coimbra. November 2008 – January 2010, EURO 180,000.

3.G2 European Space Agency Contract t 5001003472, FGS-ECM-RfQ-1001 'MCO Add-On for FGS Toolbox'. Awarded to the University of Southampton. December 2010 – April 2011, EURO 20,000.

3.G3 Fliege, J. EU FP7 CLEANSKY Programme, call ID SP1-JTI-CS-2012-03, 'AWACS – Adaption of WORHP to Avionics Constraints'. Awarded to the University of Southampton, April 2013 – April 2015, EURO 474,000. http://www.cleansky.eu/

4. Details of the impact

Europe is one of the world's leading players in space engineering, competing in the commercial markets for telecommunications and launchers and forming a key partner for the United States, Russia and other countries. The ESA employs more than 2,000 people and has an annual budget of €4 billion. The European Space Research and Technology Centre (ESTEC) which makes use of the Southampton research is ESA's technical heart with a workforce of around 2,700 and an annual budget of €2.4 billion **[5.C1]**. ESTEC guarantees investors a return rate of 96%; thus, the annual value it adds to the European economy exceeds €2 billion, excluding spin-off companies.

Each year, well over 100 payloads worth $100 billion are launched into space **[5.C2]**. Arianespace, the ESA's major launch provider and Europe's foremost commercial space transportation company with an annual revenue of €1 billion, accounts for about half the commercial market. Each of their satellites contains at least one antenna system, several heat pumps and various other items whose efficiency and cost require careful optimisation. Currently, the ESA has 20 spacecraft and missions in the planning and design phases with launch dates between 2013 and 2022 and costs for each mission ranging from several hundred million to one billion euros. Each contains various subsystems with conflicting design objectives. With costs of up to $40,000 to bring just one kilogramme of payload into orbit, the design of efficient but lightweight system components plays a key role in spacecraft engineering.

Southampton's research has led to the development of a software tool capable of efficiently solving multi-objective optimisation problems that occur in space engineering and spacecraft design. The toolbox has, since April 2011, been a standard part of the ESA's design technology. It has been applied to the thermal design of spacecraft subsystems and in optimising the shape of antenna systems. The use of these tools has halved the computational time for optimising the thermal design of spacecraft sub-systems and the shape of antennae systems, leading to an increased efficiency equivalent to savings of 20 person-years (approximately €1 million). As the Head of the ESA Guidance Navigation and Control Section will confirm, Southampton's research has significantly lowered the hurdles to new spacecraft designs and allowed the ESA to maintain a competitive edge in the manufacture of these products **[5.1]**.

As a specific example, in the design of a heat pipe an engineer needs to vary the design parameters that specify the basic geometry and the properties of the materials used in construction to maximise the heat throughput, while minimising the weight and the cost. These criteria are combined to produce a trade-off curve, which reveals the optimum performance. Previously this involved a large number of one-off calculations and there was no certainty that the optimum scenario was indeed achieved, often resulting in a large waste of computational effort and preventing a comprehensive exploration of the design space. The new process developed by Southampton automatically generates the design curve along with the associated parameters and cost. This enables designers to explore the parameter space in an efficient and user-friendly way, while the GUI interface allows them to develop an intuitive insight into the problem. In particular, the toolbox has enabled designers to find previously undiscovered regions of the design space and rapidly find the limits to a particular design, which aids the development of new and innovative solutions to the problem **[5.C3]**.

According to the official report of Dr G Ortega Head of the ESA Guidance, Navigation, and Control Section and responsible for evaluating the project '*ESA has concluded with high success the development of a Nonlinear Programming Solver (NLP) for numerical optimization. The Development Team has been deeming to be classified as fully outstanding. The newly developed NLP solver increases capacity and capability of European industry in the area of numerical optimization for applications such as launcher design optimization and material optimization*.' In a measure of the value the ESA places on our research, it gave €200,000 in funding in 2010 to enable the German software company Astos Solutions to develop the Southampton co-designed software tool further **[5.2]**, as part of the ESA's own General Support Technology Programme (GSTP). These GSTP activities, now in their fifth five-year cycle, are designed 'to ensure the right technologies at the right maturity are available at the right time' **[5.C4]** and to convert the best concepts into mature products.

The success of the software tool inspired €480,000 in EU funding to Southampton to adapt the tool to meet design challenges in the avionics industry under the EUP FP7 project *AWACS - Adaption of WORHP to Avionics Constraints*, coordinated by Thales, the world's third-largest avionics service provider **[3.G3]**. AWACS is funded under the EU Clean Sky Initiative, which aims to develop technologies that will achieve a 75% reduction in CO_2 emissions per passenger kilometre, a 90% reduction in nitrogen oxide emissions and a 65% reduction in perceived aircraft noise. These targets pose significant challenges for aircraft trajectory optimisation and AWACs is one of the first projects to attempt to develop a corresponding software solution to optimise aircraft trajectory.

5. Sources to corroborate the impact

Contextual References:

5.C1 http://www.esa.int/About_Us/ESTEC/ESTEC European Space Research and Technology Centre

5.C2 Governmental budgets for space activities in *The Space Economy at a Glance* 2011, OECD Publishing (2011)

5.C3 The design features of the toolbox and GUI interface are described in detail in ESA Study Contract Report, 5001003472, 'MCO-FGS Software Toolbox Manual'; ESA Study Contract Report, 5001003472, 'MCO-FGS Architectural Design Document' and 'ESA Study Contract Report, 5001003472, 'Multicriteria Optimisation'.

5.C4 http://www.esa.int/Our Activities/Technology/About the General Support Technology Programme GST

Sources to corroborate the impact:

5.1 Head of the Guidance, Navigation and Control Section, European Space Agency (ESA) **[He can confirm the increased efficiency saving resulting from the use of the computational toolbox]**

5.2 http://www.worhp.de/content/history. [**This specifically mentions University of Southampton's involvement in the WORHP development].**