Aero Engine Health Management System Architecture Design Using Multi-Criteria Optimization

Rajesh Kudikala[1], Andrew R. Mills[1], Peter J. Fleming[1], Graham F. Tanner[2], Jonathan E. Holt[2]

[1]Automatic Control and Systems Engineering, The University of Sheffield, Sheffield, UK.
{r.kudikala, a.r.mills, p.fleming}@sheffield.ac.uk

[2]Rolls-Royce plc, PO Box 31, Derby, UK.
{graham.tanner, jonathan.holt}@rolls-royce.com

ABSTRACT

A design process for system architecture design using multi-criteria optimization is described using a case study of an aero engine health management (EHM) system. The EHM system functional operations need to be deployed in order to satisfy their operational attribute requirements within the constraints of resource limitations. Considering the large discrete search space of decision variables and many-objective functions and constraints, an evolutionary multi-objective genetic algorithm along with a progressive preference articulation (PPA) technique, is used for solving the optimization problem. Using the PPA technique, the industrial decision maker is able to identify the most significant design constraints ("hot spots") and experiment with changing goals for objectives, in order to arrive at a satisfactory non-dominated solutions that takes account of domain knowledge.

Categories and Subject Descriptors

C.0 [**General**]: System architectures; G.1.6 [**Numerical Analysis**]: Optimization—*constrained optimization.*

Keywords

System architecture design, multi-criteria optimization, many-objective optimization, genetic algorithms.

1. INTRODUCTION

Designing a complex system architecture can be a difficult task involving multi-faceted trade-off decisions. The design process often needs to consider experience, models and data from many design disciplines. Many of the architecture design frameworks concentrate on problems having 2 to 3 objective functions. However, in general, real-world design problems will have many-objective functions to be optimized [1], i.e. greater than 3. Preference based MOEAs are one of the proven techniques in such scenarios. Visualization of the Pareto surface also becomes difficult for many-objective functions [3]. The task of a multi-objective evolutionary algorithm (MOEA) is to provide an accurate and useful representation of the trade-off surface to the decision-maker (DM).

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2. EHM SYSTEM MULTI-CRITERIA OPTIMIZATION PROBLEM

Engine health management (EHM) system has become an essential part of aero engines. The main aim of an EHM system is to perform real-time parameter analysis and anomaly detection of the aero engine. Output from on-board analysis can be passed to an on-ground computer resource for further analysis to predict, classify and locate developing engine faults and anomalies [4]. The optimum combination of the on-engine and on-ground computational resources for the EHM system will deliver the benefits of reducing the engine through life operating and maintenance costs. The baseline EHM system for the aero engine is developed as a SysML model by system engineers. The EHM system primary functionalities are decomposed into 74 EHM functional operations (OPs). For each functional operation (OP) several operational attributes: **'Data flowrate'**, **'Processing power'**, **'Criticality'**, **'Immediacy'**, **'Coupling'**, **'Security'**, **'IP sensitivity'** and **'Flexibility'**, are defined in qualitative levels ('high', 'medium' and 'low'), which indicate the specific requirements of that operation. The current EHM system architecture design process seeks to find an optimal deployment of these 74 EHM OPs over four physical architecture component locations: (i) engine monitoring unit (EMU), (ii) engine electronic controller (EEC) (both on-engine), (iii) on-aircraft, and (iv) on-ground, such that the OP attribute requirements are satisfied within the constraints of physical architecture component limitations.

The EHM system architecture design problem has been formulated as a multi-criteria optimization problem.

$$\text{Minimize} \quad Z_k = \sum_{i=1}^{74} E_{ik}^2, \quad k = \{1, 2, ..., 6\} \tag{1}$$

$$\text{subject to} \quad \sum_{i=1}^{74} d_{ir} \leq D_r, \quad r = \{1, 2, 3, 4\} \tag{2}$$

$$\sum_{i=1}^{74} p_{ir} \leq P_r, \quad r = \{1, 2, 3, 4\} \tag{3}$$

$$x_i = \{1, 2, 3, 4\}, \quad i = \{1, 2, ..., 74\} \tag{4}$$

where, x_i are 74 decision variables, which can have values {1, 2, 3, 4} to represent the deployment locations of the corresponding operation. D_r and P_r are the constraint limitations of **'Data flowrate'** and **'Processing capacity'** on

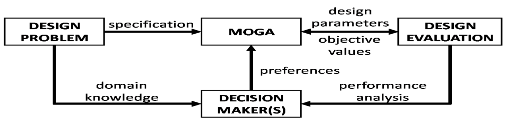

Figure 1: Interactive multi-criteria optimization design framework.

the four physical architecture locations, and, d_{ir} and p_{ir} are individual attribute requirement measures of each operation deployed at the corresponding location. Z_k are six qualitative objective functions in OP attributes **'Criticality'**, **'Immediacy'**, **'Coupling'**, **'Security'**, **'IP sensitivity'** and **'Flexibility'** in terms of total excess requirements E_{ik} of 74 OPs.

3. INTERACTIVE MULTI-CRITERIA OPTIMIZATION FRAMEWORK

The proposed EHM system many-objective optimization problem is solved using a multi-objective genetic algorithm (MOGA), integrated with a unique progressive preference articulation technique [2], in the MATLAB environment. The MOGA design framework with progressive preference articulation technique is shown in Figure 1. This denotes the process of introducing, incorporating and modifying designer preferences in an interactive and progressive way at any time during the optimization search process; this is a key feature for multi-criteria decision making (MCDM). In this study elitism is incorporated in MOGA by maintaining an archive of non-dominated solutions of fixed size, which will keep the best non-dominated solutions found so far in all the generations. With a view to increasing the confidence in the Pareto solutions, MOGA was run for 50 times using a different seed for the random number generator in each run and various performance metrics were also evaluated. A "parallel coordinates" graph in the MOGA software suite facilitates visualization of the interplay between the different objectives.

The Pareto optimal solutions obtained for the EHM system architecture design are shown in Figure 2, as a "trade-off graph", where criteria 1 to 8 are constraints, and criteria 9 to 14 are objective functions. In order to clearly distinguish between them, the constraints are shown in the shaded region and objectives are shown in the unshaded region. Each connected line in the trade-off graph represents a Pareto optimal solution for the EHM system architecture design. Goal points for each of the objectives are marked with an **"x"** in the trade-off graph. In the trade-off plot, it can be observed that crossing lines between criteria 9 and 10 demonstrate that the objectives 'criticality' and 'immediacy' are in conflict with each other, while concurrent lines between criteria 12 and 13 demonstrate that the objectives 'security' and 'IP sensitivity' are in relative harmony with each other. Using the PPA facility, the DM can progressively specify desired goal values for each objective, in order to arrive at the desired compromise solution.

It can be seen from the trade-off graph that the data flowrate requirements for on-ground (4) and the processing resource requirements on EMU (5) are the most significant design constraints ("hot spots"). The PPA technique in MOGA enables the DM to explore different architecture design scenarios, such as improved processor technology on the EMU and improved wireless transmission rate between onboard and on-ground systems. By increasing the goal values for different constraints, the DM can explore future ("what-if") architecture design scenarios and analyse prospective performance improvements.

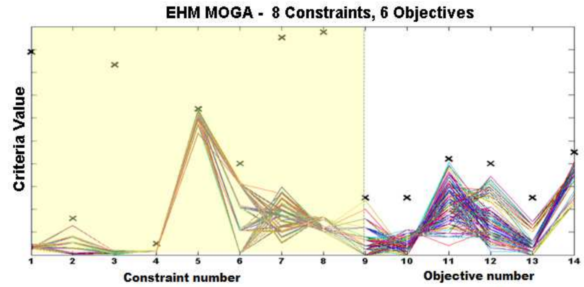

Figure 2: MOGA parallel coordinates trade-off representation with progressive preference articulation.

4. CONCLUSIONS

In this paper a design process for an aero engine EHM system architecture design using a multi-criteria optimization technique has been presented. A strategy for optimal deployment of the functional operations on physical architecture component locations has been successfully developed using an MOEA. The optimizer supports the decision maker by providing a facility for progressive preference articulation, empowering closely coupled user and optimization process interaction. Various architecture design scenarios, such as hardware upgrades to data input rates and processor capacities can be explored by changing the goal values of constraints. It is found that improved system performance can be achieved through modest relaxation of the critical design constraints. This strategy is deemed to be easily applied to other systems architecture design studies.

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6. REFERENCES

[1] P. Fleming, R. Purshouse, and R. Lygoe. Many-objective optimization: An engineering design perspective. In *Evolutionary Multi-Criterion Optimization*, pages 14–32. Springer, 2005.

[2] C. Fonseca and P. Fleming. Multiobjective Optimization and Multiple Constraint Handling with Evolutionary Algorithms. I. A Unified Formulation. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, 28(1):26–37, 1998.

[3] H. Ishibuchi, N. Tsukamoto, and Y. Nojima. Evolutionary Many-Objective Optimization: A Short Review. In *IEEE Congress on Evolutionary Computation*, pages 2419 –2426, june 2008.

[4] G. Tanner and J. Crawford. An integrated engine health monitoring system for gas turbine aero-engines. *IEE Seminar on Aircraft Airborne Condition Monitoring*, 2003(10203):5–5, 2003.