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NEW CHALLENGES IN DESIGN OPTIMISATION OF ELECTROMAGNETIC DEVICES

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***Abstract* – This keynote will review the state of the art and new challenges in design optimisation of electromagnetic devices. The talk will introduce the concepts of hierarchical design and no-free-lunch theorem. The notion of pareto optimisation will be discussed and the balance between exploration and exploitation emphasised. The recent advances in kriging assisted surrogate modelling will be presented and finally the importance of finding the robust optimum will be stressed.**

Introduction

This talk builds on previous publications [1] and [2], with a suitable update on the latest advances. Several important developments have taken place as reported recently at the Compumag conference held in Montreal at the end of June 2015 [3]. Useful benchmarks are described on the web page of the International Compumag Society [4]. Readers interested in some background information are referred to the relevant book [5], whereas the most comprehensive treatment of some aspects of shape design in electricity and magnetism may be found in [6].

Computational Electromagnetics for Design Optimisation

Contemporary design of electromechanical and electromagnetic devices inevitably involves the use of numerical modelling tools usually based on a finite element or related technique. There are many excellent packages on the market providing accurate simulation of electromagnetic fields in two and three dimensions, with full allowance for non-linear and/or anisotropic material characteristics, inclusion of eddy current, motional effects and coupled fields (stress and thermal), as well as representation of the driving circuitry. The available software is a result of hundreds of man-years of development and offers a mature tool which can be used in design office environment. Optimisation forms integral part of the design process and many techniques have been developed over the years to meet the needs of the designers. Traditionally, optimisation methods have been classified as deterministic or stochastic, with the former fast and efficient but only guaranteeing reaching a local minimum, whereas the latter offering a much better chance of finding a global one, at the expense, however, of much increased computing times due to the requirement of many objective function evaluations. It is the peculiarity of the design of electromagnetic devices that each such evaluation will normally require full finite element solution of the field distribution, or even several such simulations – for example at different positions of the moving part of the device – in order to establish a characteristic or estimate an average value of, say, torque. While in principle such repeated simulations are possible, in the industrial design environment the process may simply become inefficient and thus impractical. The effort is therefore directed at developing various types of surrogate models which – even if being only approximations – allow fast computation. The crucial decision in the iterative process is always where to put the next point for evaluation to achieve a careful balance between exploitation and exploration, in other words efficient usage of information already available while searching further in case the global optimum is elsewhere. One of the most promising recent techniques is based on kriging.

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The following aspects of the design optimisation process will be emphasised:

- the concept of *hierarchical design*, where models of varied complexity are used from simple and fast (e.g. equivalent circuits) to accurate but slow (typically 3D transient finite elements). Interestingly, these different stages may require that diverse optimisation methods are most appropriate, thus the choice of the best method is by itself an optimisation problem.
- the *no free lunch* theorem, which prohibits the existence of an algorithm which would outperform all other optimisation algorithms, when averaged over all possible problems. Therefore – as design engineers are only interested in a subset of problems – it is possible to identify a set of algorithms which outperform others over a particular domain of interest.
- *multi-objective optimisation* and in particular the *Pareto-Optimal Front* (POF). In the absence of other criteria, all POF solutions are equally relevant and as many should be found as possible. Achieving a good balance between convergence to and diversity along the POF is important to all algorithms. Multi-objective methods using surrogate models may be categorised as *scalarizing* and *non-scalarizing*. The multi-objective problem is often converted into a single-objective representation using weights and a vast number of combinations exist.
- *surrogate modelling and kriging***.** The simplest to construct and visualise are polynomial models. However, they have several shortcomings: low-order polynomials are incapable of modelling complex functions, whilst high-order ones often result in ill-conditioned matrices. The *Efficient Global Optimisation* (EGO) algorithm uses the concept of *expected improvement*, which may be viewed as a fixed compromise between exploration and exploitation; weights obviously may be added as well as other criteria. The *kriging* assisted surrogate modelling is particularly advantageous as it assesses the chances (probability) of making a better decision, although no guarantees ever exist, of course.
- the dangers of a *combinatorial explosion*. As the complexity of the surrogate model increases the size of various ‘correlation’ matrices may exceed the available dynamic memory of a computer. Practical remedies include *zoom-in* techniques, improving storage efficiency and removing some of the design points. The challenge here is to remove points containing less important information, while not discarding such information altogether.
- the concept of *robustness* of the design. When practical aspects of manufacturing are considered, the design variables are often subject to tolerances and/or uncertainties; these may be specified directly (e.g. as machining tolerances) or defined stochastically. Performance over the whole range of the parameter changes becomes relevant, not just the best point; the shape of the objective function close to a minimum becomes important. Various techniques for assessing the quality of the optimum have been put forward, including using a *gradient index* and *sensitivity*, the *worst case optimisation* and *six sigma quality*.

The above concepts will be illustrated using test functions, animated iterative sequences and practical electromagnetics devices; in particular TEAM 22 and TEAM 25 problems [4] will be demonstrated, which have been specifically formulated for the purpose of comparisons between methods and for assessing the performance of algorithms.

References

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