Tailoring Computational Electromagnetics to Industry's Needs

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Abstract

Computational electromagnetics is a fascinating subject with plenty of opportunity still for scientific study and applied research. The commercial world can benefit from such work provided that it is useful, credible, and easy to adopt. My colleagues and I have sought a balanced approach in our work in communications engineering, pursuing contracts with industry while developing new computational methods. Areas of increasing importance are likely to be mathematical verification of numerical methods and analysis and optimal design of complex systems requiring a combination of existing methods.

Introduction

An astounding variety of engineering applications can be derived from a small number of principles of electromagnetism, established by Maxwell and put into practice during subsequent years. About 30 or 40 years ago, computational aspects of electromagnetism took over from theoretical aspects as the main partner to experimentation in engineering development [1]. This shift was due to the availability of automatic computers, and has been reinforced since by desire to depart from geometries suitable for theoretical analysis, development of numerical methods for approximate solution of Maxwell's equations, and possibilities of design automation through computer optimisation.

Electromagnetics and antennas research at CSIRO began with radar development during the Second World War and has continued to the present day. Computation is now a major part of our research effort and supports most of our commercial work.

From the point of view of business this should be a good time to be doing research and development in Australia. Some economic indicators are discussed in an interesting study of the role of innovation [2] in the economy. The ratio of R&D expenditure to turnover, or R&D intensity, of Australian manufacturing was below 1.5% during the late 1970s and early 1980s but has increased since then to 4.2% in 1995. This was still below that of the main OECD countries but the rate of increase is higher. In the 1997-98 financial year the proportion of Australian goods exports that were "elaborately transformed" was 22%, or 69% of manufactured goods, following an annual growth of nearly 15% per annum during the preceeding decade. We hope that these indicators will fulfil their promise of a greater involvement of Australian industry with our work. Below I will show how involvement with industry has been to our benefit, how our work environment is being affected, and what areas are of growing interest in the field of computational electromagnetics.

Benefits of working with industry

Working with industry brings our research closer to the action, giving the incentive of seeing our work in use and giving us access to privileged information about how our industrial customers work and what their priorities are. I will give two concrete examples. Both are concerned with replacing traditional cut-and-try design methods that cause long development times. Direct electromagnetic design, when sufficiently accurate, can satisfy performance requirements without a time-consuming experimental phase.

Antennas for satellite communications, both on the ground and in space, are a long-term interest for our group [3]. This field is very competitive and satellite manufacturers are great innovators. We have relied on regular contact with the industry to learn what problems are important to address. In the contract I worked on we supplied software for analysing on-board satellite antennas. Our early preference was to supply a complete package, but I'm sure our software would not have been used if we had. We were persuaded to write modules for new capabilities that used existing industry-standard software as an engine [4], thereby building incrementally onto the company's existing design system and minimising the training time for their engineers. As a result our software became part of their major tool for antenna design.

We presently have a contract to supply analysis and design software for a type of UHF/VHF broadcast antenna. These antennas are manufactured with adjustable features. We believe these features can be replaced using a design that is simpler to manufacture and easier to analyse. The success of the new design would depend entirely on accurate predictions of antenna performance enabling production without adjustment, and there is a great deal of scepticism about the possibility of analysing these structures accurately enough. Therefore, we are first solving the more difficult problem, analysing the antennas with adjustable features, to address the industry's more immediate need and to achieve credibility.

What have we learnt from these and similar experiences? The commercial world can benefit from our work provided that it addresses their current problems, is easy to adopt, and is well proven in a practical sense. Direct contact with industry is the best way to learn what problems might be of interest in the future. Far from being a distraction from our research activities our commercially-oriented work is a stimulant. Problems of practical interest often stretch the state of the art and encourage a new approach, whereas a researcher's natural tendency is to explore each approach to its outermost limits. In this normal sense science acts as the preserver and refiner of a body of knowledge as Kuhn pointed out [5], although he had a wider scope in mind, and industry stimulates minor revolutions in the way we solve problems.

A foot in each camp

But there is danger in focusing only on commercial work. Deciding what to work on in a purely reactive manner will lead to fragmentation of effort and in time there will be no base of solid research to draw on. Some aspects of a research environment are not compatible with industry. Participating in the world-wide community allows a research group to normalise its work against international standards, and research groups contained within an industry can wither through lack of communication. An important responsibility of independent groups is to seek a balance between dissemination and discretion. The normal ethics of commerce have always applied to commercially-oriented research and have not necessarily inhibited it. Publication of new work may be restricted and delayed, and some aspects may never appear. On the other hand, it is possible to be too cautious about publication. In the commercial world even more than the research world it is the first past the post who gets the prize. Once success is achieved it may not matter who finds out the crucial techniques, and the type of knowledge divulged in a technical publication may be less important than the accumulated expertise and experience of the group that enable its application. These attributes are not easily acquired; they can only be nurtured over time.

Strategic decisions must be made on areas for research that build on present capabilities and anticipate future engineering needs. Dedicated effort, difficult to apply in an environment where commercial pressures affect the time available, is necessary to make real progress on a fundamental problem. We find that post-graduate students and post-doctoral fellows play a dominant role in maintaining long-term research programs, and in recent times major successes have been achieved by colleagues of this kind [6,7].

The importance of a well-functioning interaction between a country's science, engineering, and industry is clear. New approaches to innovation also stress the significant role of tacit knowledge embodied in the people, and the consequent importance of personal networks, lifelong learning, and mobility [2]. For a researcher these aspects are enhanced by regular contact with industry and undertaking commercial contracts is one way to achieve this. Participation in Cooperative Research Centres is another way. Secondment to industry for a period is another, and possibly the most rewarding for an individual, but this happens quite rarely due perhaps to the difficulty of emloyment arrangements, consideration of intellectual property, and the sense that no-one can be spared due to pressure of work. In practice, a similar result is achieved by frequent career changes that younger researchers are experiencing these days.

Computational electromagnetics involves a great deal of computer programming, and we are developing a programming culture that is between what is typical in research and what is expected in industry. Software used in support of commercial work, especially when it is delivered to industry, requires more rigour than developmental code that supports research. Numerical rigour and efficiency are achieved mainly by attending to special cases that might cause floating-point errors, accounting for finite machine precision, and understanding how data, particularly multi-dimensional arrays, are arranged in memory. Successful installation and maintenance depend on using standard language features that are supported by a variety of compilers. The licencing arrangements for third-party software, such as libraries with mathematical functions and standard algorithms, delivered to industry are quite different from those that apply for research use.

Designing and implementing numerical algorithms and mathematical approximations and developing appropriate program and data structures is very creative work. Individual styles and personalities relate to thought processes and therefore to creativity, so we allow much greater individual freedom than would be possible in a software company. But, we do not follow the structured and "ego-less" software development method favoured by many professionals [8]. For reasons of confidentiality and scale, we also stop well short of the open-source development method that is rapidly maturing [9]. We require adequate documentation, we specify clear interfaces between programs and subprograms, we partition code into separate "work areas" that only one person edits at a time, and at all stages we test our programs using benchmark examples.

These numerical and coding precautions are consistent with the scientific method, which also requires verification of computed results using experimental models. Ultimately this is the final measure of success, because software development will never be a deterministic process. When we are careful of all the points above and document the verification of our numerical methods, we find that developmental code can be adapted for commercial use with a minimum of fuss. Rewriting programs from scratch is a luxury we cannot afford.

Where are we going?

Engineering work in electromagnetism is rarely dull. Perhaps this is because in this field practical applications and basic theory are rather closely linked. It is not unusual for application papers to refer to Maxwell's equations and show how their results develop from first principles. The field is also "compact" in the sense that no other bodies of theory are required to analyse many practical structures. When horns and waveguide systems, scattering of radiation, or microstrip circuits are analysed using Maxwell's equations, very good agreement between experiment and theory can be obtained. Usually it is assumed only that all media are homogeneous and isotropic and all metals are perfect conductors, and these assumptions can be weakened with appropriate care.

Despite the closeness of principle and practice, boundary-value problems in applied electromagnetism are not tackled with the same rigour as in other fields such as structural mechanics or fluid dynamics [10]. The great success of existing methods and the low cost of failure – loss of income rather than loss of life – have reduced the incentive to explore numerical analysis in detail. Complex boundary conditions and the presence of divergence conditions make numerical analysis in electromagnetism quite difficult. Nevertheless, the long-term development of computational electromagnetics will be aided by mathematical assurance of the convergence and accuracy of methods, and some papers addressing these issues are starting to appear in the engineering literature [11]. Further transfer of knowledge from the mathematical sciences may well point the way to new numerical methods [12,13].

More immediately, wide percentage bandwidths and strict gain and isolation requirements are continuing to drive advancement of existing methods. Radio astronomy has in the past been a breeding ground for unusual requirements that have later been mirrored by industry, so we have a strong interest in the proposed Square Kilometer Array [14]. A new synthesis of diverse techniques may be encouraged by the convergence of optical and millimetre-wave engineering, and perhaps, even more diverse, by the significance and harnessing of quantum effects in a variety of materials. Organisations that can combine skills in different fields will be able to take part in these emerging fields.

We are finding that whole systems rather than individual components must be analysed to satisfy demands for improved performance [15]. Higher levels of integration are muddying the boundaries between components. Interactions between components have significant effects and can be modelled by combining different analysis methods. If a full scattering matrix can be calculated for the components then standard network theory can be used to calculate a scattering matrix for the whole system. For this purpose we are having to address the problem of combining intermediate results calculated by software from different authors, learning some lessons in standardisation along the way. Often scattering matrices are not available, and either an existing method must be applied to larger and more complex objects than before, or several methods must be combined so that each is used in the situation where it is most efficient. In the literature there has been a proliferation of such hybrid methods, recognisable by various combinations of three- or four-letter acronyms. One of the most challenging applications for modelling complex systems is electromagnetic compatibility testing [16], where the aim is to estimate unintended interactions. In general, such estimates are beyond the present state of the art, and experimental results are interpolated or extrapolated with uncertain results.

The essential problem to industry is design, and analysis is its concomitant. Optimisation at the component level is a major preoccupation of researchers once their numerical analysis is complete and tested. Various methods are available for multi-dimensional optimisation ranging from traditional simplex and gradient-search methods to simulated annealing and evolutionary methods, although sophisticated optimisation will not compensate a poor intuition about the problem, and we have found the fastest methods to be those that incorporate knowledge of the analysis method [17]. When interaction effects can be modelled, system optimisation has the potential to trade off performance in one component against another, obtaining the best cost compromise.

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