CHAPTER 1 Introduction

Today's world can be best described by the term global village. Exploration, trade, commerce and scientific advancements have resulted in the breakdown of physical boundaries like mountains and oceans. While the credit for this virtual shrinking of the world is often attributed to the aforementioned factors, the biggest leap in this direction is a direct consequence of the discovery and subsequent improvements in communication systems—particularly wireless communication systems. The performance of these systems is an outcome of their constituent elements—elements whose designs are governed by electromagnetic (EM) formulations. Therefore, the contribution of electromagnetics in shaping the world as we currently know it, cannot be ignored. The demand for better communication systems has resulted in a demand for high performance electromagnetic structures, and as well as accurate, reliable and fast techniques to solve electromagnetic problems.

Almost in parallel with this demand for high performance in electromagnetics, a novel computing technique, called soft computing, is gaining popularity in a multitude of applications. This technique differs from conventional computing techniques by not relying on strict mathematical formulations. In fact, soft computing technique often seeks to emulate biological systems like neural networks, swarm behaviour, etc. Today, soft computing is increasingly being used to tackle non-linear, computationally intensive problems in engineering. Therefore, it is not surprising that these techniques find a comfortable niche in the field of electromagnetics, where there is a ubiquitous need for optimization.

1.1 Design and Optimization Scenarios

While the initial intention of soft computing was to address the problems in engineering design and optimization, the versatility of these techniques resulted in its application to almost all areas of day-to-day life including finance, humanities and medicine. A brief outlook on soft computing for these applications is discussed here.

1.1.1 Engineering applications

Soft computing plays an important role in providing cost effective and efficient means towards attaining the final objective of any engineering application, i.e., actual hardware realization. Hence, industrial applications of soft computing techniques in various fields such as microwave engineering, aerospace engineering, power systems, robotics, etc., are discussed here.

Design and optimization in microwave engineering applications is an important aspect that has been explored by various researchers. Soft computing techniques like *artificial neural network* (ANN) and *genetic algorithm* (GA) are proven to be effective design optimization tools in the field of microwave engineering [Patnaik and Mishra, 2000], and other soft computing techniques like *particle swarm optimization* [Robinson and Rahmat-Samii, 2004] and *bacterial foraging* [Datta and Misra, 2005] are emerging as fast optimization techniques [Choudhury *et al*., 2012]. Computational time and accuracy are the two factors that need to be kept in mind before implementing any optimization technique. This book primarily deals with the implementation of all these techniques in electromagnetic applications with a focus on the key factors. Cost effective solutions are presented to common electromagnetic problems such as improvement of performance of antennas, mutual coupling reduction, fault detection in antenna arrays, radar absorbing material (RAM) design and optimization, metamaterial design and optimization, design and characteristics of transmission lines, and prediction of path loss in rural and urban environments.

Soft computing application holds its position in flight control as well as air traffic control systems [Napolitano *et al.*,1999]. Spacecraft also implements soft computing for various applications such as docking operations, real time estimation of rover positions, etc., [Alvarez *et al*., 1996]. Apart from flight control, other control systems in the circuit branches of engineering have explored the application of soft computing techniques in electric power systems, such as motion control of servo motors [Fahn *et al*., 1999], plasma arc welding [Cook *et al*., 1995], sensorless induction motor drives, etc., [Ben-Brahim *et al*.,1999].

Advances in technology and a need for real-time human interaction with robots have necessitated development of computing systems that behave like human intelligence. Artificial neural network and fuzzy systems are the basic blocks for the development of these intelligent robotic systems. Mobile robots [Baranyi *et al*., 2000], welfare robots [Takagi *et al*., 1999], and emotional pet robots [Kubota *et al*., 2000], are examples of systems that include neuro–fuzzy platform/ technology as the building blocks.

1.1.2 Medical applications

Applications of soft computing techniques are also well established in the field of medical science. These applications include medicine, diagnosis and surgical/ clinical applications. Yardimci [Yardimci, 2009] has discussed the research trend of soft computing in the field of medicine in the last decade. It has been observed that neural network has been used more effectively for search of medicine database compared to other techniques such as fuzzy systems, genetic algorithm, etc. Further a hybrid algorithm of fuzzy systems and neural network has been used in the science of clinical medicine. Shen *et al*., [Shen *et al*., 2005] used a hybrid neuro–fuzzy system for analysis of brain tissue from an MRI report.

1.1.3 Finance

Although soft computing was developed for engineering applications, it has also caught the attention of those in the financial trading sector. Specifically, these techniques have been used for the prediction of trend in future stock value [Tan, 2001; Quah and Srinivasan, 2000]. Soft computing techniques have been applied to a variety of markets such as Forex market [Chan and Foo, 1995], S&P 500 [Chenoweth *et al.*,1995], etc. The implementation of these techniques has been carried out at an academic level using neural network and fuzzy logic. The extension of these techniques into actual markets is still under process as developers need to accommodate practical trading constraints into the soft computing model [Vanstone and Tan, 2003].

1.1.4 Humanities and social sciences

The realm of soft computing has advanced to also include problems pertaining to humanities and social sciences. These techniques are mainly used in language processing and face recognition. Specifically, soft computing techniques are used to detect conditional and causal statements in language texts [Khoo *et al.*, 1998], hypothesis and refutations, [Castiñeira *et al.*, 2000], etc. The relationship between soft computing and the humanities is a two way relationship. On one hand, soft computing is used for the above mentioned applications; on the other hand, an effort is being made to model social behaviour into the development of soft computing based artificial intelligence models.

1.2 Electromagnetic Design Challenges

Electromagnetic design is a complicated procedure being dependent on the electrical length of the structure rather than its physical length. Further, material properties also contribute to the efficiency of the EM design. EM design involves three important steps, viz. processing, modelling and formulation. As design of electromagnetic structures is dependent on the frequency of operation and the material properties, care must be taken to choose the right material with the right electrical dimensions. As a result, performance improvements are often obtained through iterative manipulations of design geometry as well as material. Therefore, a compressive understanding of the issues faced during EM design will help the designer incorporate techniques to mitigate these issues during the design process. Ultimately, this technique will lead to quick, practical EM designs. In this section, sensitivity analysis, an important aspect of EM design towards actual hardware realization, has been taken up and discussed briefly.

Soft computing routes for EM designs often result in optimized design parameters for high performance. These optimized parameters may be accurate up to very high precision levels. However, the practicality of this accuracy, i.e., whether such designs may be achieved using the current fabrication technology, is a factor that must be discussed. For example, in adaptive antenna pattern synthesis problems, an optimized design may require a phase shifter of 2.5°, but only 6° phase shifters are commercially available. Similarly, an optimized metamaterial based absorber design may provide 99.9% absorption [Choudhury *et al.*, 2013], whereas fabrication and material impurities may affect the performance of the EM design. Hence, it is always desirable to provide sensitivity analysis along with optimized design for practical applications.

1.2.1 Fabrication sensitivity

Fabrication issues depend on the type of fabrication technology as well as the EM design. Photo–lithography is a widely used fabrication technique for microwave designs. The photo–lithography equipment currently available can fabricate devices with minimum feature size of 2–2.5 μm. Hence sensitivity analysis in microwave range should be done with respect to the above mentioned size. Secondly, for design in the higher frequency ranges such as sub-millimetre wave and terahertz ranges, photo–lithography cannot be used for the fabrication of the optimized EM designs, as the design parameters may be smaller than 2 μm. However, these dimensions can be easily realized using electron–beam lithography, and this technique is recommended for fabrication of ultra-thin EM designs. However, a margin of 5–10% must be allowed for practical deviations from the design.

1.2.2 Material sensitivity

EM design and development of industrial hardware applications depend extensively on the intrinsic properties of materials. EM material parameters, such as permittivity and permeability of dielectrics, depend on the material synthesis and roughness. Similarly, reliability of the design depends on the accuracy to which the EM material parameters have been measured. Hence, considering the material issues, it is recommended to allow for a 5% shift in the material properties in order to compensate for any impurities in the material.

1.3 Objectives and Scopes

Soft computing techniques are emerging as important tools in design and optimization of various complex electromagnetic (EM) problems. In view of this, an attempt has been made in this book to cover the application of soft computing based solutions to EM problems.

Books that are currently available often focus on one particular algorithm of soft computing amongst *artificial neural network* (ANN), *particle swarm optimization* (PSO), *genetic algorithm* (GA), etc. No book examines the implementation of all these techniques for varied suitable applications. On the other hand, the proposed book examines the application of different soft computing techniques to various problems in electromagnetics.

Furthermore, another emerging algorithm of soft computing that is based on *bacterial foraging* (BFO) has also been introduced and implemented for the same class of problems along with a comparative study of computational efficiency and accuracy.

Some of the main objectives of this book are mentioned below:

- To provide low cost and real time solutions to various critical design problems. For example, resolving problems, such as fault detection and compensation in active antenna arrays, are important for the aerospace community. Finding out real time, cost effective solutions to these problems are demonstrated in this book using various soft computing techniques.
- To demonstrate solutions to non-linear problems concerning antenna engineers worldwide, such as (i) miniaturized antennas, (ii) reduction of mutual coupling, and (iii) overall improvement in EM performance.

- To introduce the implementation of soft computing techniques in a relatively new area in science and technology— metamaterial and its applications. A user-friendly CAD package for metamaterial *split ring resonator* (SRR) design using soft computing is also included here. Some of the important applications in electromagnetics such as antenna design and performance enhancement through PSO and BFO have also been incorporated.
- To describe the design and optimization of radar absorbing material (RAM) using PSO. The PSO algorithm is used to determine the optimum thickness of each layer of a Jaumann absorber followed by a more complicated problem statement, which necessitates the need for selection of materials from a database and optimization of the thickness of each layer of material for improved RAM performance. Later, the same algorithm is used to design metamaterial based RAM in both microwave and terahertz regimes.
- To help students and engineers learn implementation of soft computing techniques for their application domain effectively. In this regard, one dedicated chapter, which provides algorithms of soft computing techniques such as ANN, GA, PSO, BFO, etc., and implementation of these algorithms for solving simple mathematical function is discussed.
- To provide a comprehensive review of application of soft computing techniques in various state-of-the-art EM problems, for better exposure to the optimization scenario.
- Other topics covered in the book include the characterization of planar transmission line using artificial neural network (ANN) and a CAD package for ray-tracing in rural and urban environments.

To summarize, the main objective of this book is to provide effective solutions to critical EM design problems in a short frame of time through the soft computing optimization tool. The book provides information on the development of a computational engine that can integrate optimization techniques to EM solvers so as to achieve quick, highly efficient EM designs for non-linear applications where no analytic solution exists.

1.4 Organization of the Book

Soft computing methods play an important role in design and optimization in diverse engineering disciplines including those in electromagnetic (EM) applications. Soft computing techniques are characterized by their ability to provide quick, robust and economically viable solution(s) despite imprecision, uncertainties, and approximations in the formulation. The last decade has witnessed wider use of soft computing techniques such as *artificial neural network* (ANN), *fuzzy logic* and *genetic algorithm* (GA), in the RF and microwave domain. These include design and performance enhancement of antennas, *frequency selective surfaces* (FSS), *radar absorbing material* (RAM), metamaterial, etc. The aim of this book is to identify the suitability of other soft computing techniques such as *particle swarm optimization* (PSO), *bacterial foraging optimization* (BFO) along with *genetic algorithm* (GA) and *artificial neural network* (ANN) for various EM design and optimization applications.

The book also covers the use of soft computing techniques for some important electromagnetic applications such as fault detection in antenna arrays, path loss prediction in urban and rural areas and the design and optimization of metamaterials. Chapter 1 of the book provides an overview of the background of soft computing techniques in electromagnetics along with the challenges in implementation of these techniques.

Chapter 2 introduces the theoretical and algorithmic details of the techniques that come under the umbrella of soft computing. The focus is basically on evolutionary computing techniques like *genetic algorithm* (GA), *particle swarm optimization* (PSO) and *bacterial foraging optimization* (BFO) and the well-known *artificial neural networks* (ANN). These techniques can be used in all engineering applications including electromagnetics for the benefit of a wide range of readers. Therefore, in order to equip readers with a complete understanding of the concepts presented, an attempt has been made to describe the algorithms using specific examples. Computer codes provided at the end of each section in this chapter will also enhance the reader's understanding of the concepts.

The popularity and scope of soft computing in electromagnetics is brought out in Chapter 3. This chapter is an extensive literature review of the current trends in the field of soft computing in electromagnetics, which includes frequency selective surfaces, antenna miniaturization and performance enhancement, microwave devices, and invisibility cloaks.

Bacterial foraging optimization is an emerging soft computing technique. Literature on this algorithm is scarce. Therefore, in order to understand the behaviour of this algorithm as well as the effectiveness of its implementation in the field of electromagnetics, a chapter has been devoted to the implementation of BFO for practical problems. Chapter 4 discusses the design and performance enhancement of antennas using BFO. Towards this, BFO is implemented in order to optimize a metamaterial superstrate for a fractal antenna. The effect of the presence of this optimized layer on the gain and bandwidth of the antenna is discussed. Further, a similar optimization technique for mutual coupling reduction in elements of an antenna array is studied in detail. The ideas presented in this chapter are intended to facilitate the design of high performance, miniaturized antenna systems.

Absorbers find applications in various fields, the most important one being stealth technology. These absorbers, also called radar absorbers, are extremely complicated EM designs due to their inherent multilayer nature. Chapter 5 focuses on the implementation of PSO, a global optimization technique, for the optimization of radar absorbing material (RAM). A review of the application of various algorithms for optimization of conventional RAM is carried out, followed by a discussion on the PSO implementation of the same for Jaumann absorber and a multi-layered RAM. The technique is then extended to include optimization of metamaterial RAM designs in both the terahertz and microwave domains. While the RAM designed for microwave frequencies can be used in stealth technology, the terahertz RAM finds extensive application in terahertz biomedical spectroscopy.

Chapter 6 includes implementation of ANN for characterization of transmission lines. The analysis involves the determination of the characteristic impedance (Z_o) and the effective permittivity (ε_{eff}). The design includes finding of different dimensions of the transmission lines.

The properties of active antennas such as beam steering, null placing and radiation pattern synthesis has attracted the attention of the aerospace community. These active antennas feature a unique advantage of restoring the original radiation pattern through proper change of feeding distribution from the base-station. Chapter 7 focuses on the implementation of soft computing techniques for antenna array fault detection. In order to restore the original radiation pattern in a faulty antenna array, it is necessary to diagnose the array from the far-field perspective.

This problem has been solved through different routes using soft computing techniques such as ANN, GA, PSO, and BFO.

The chapters mentioned above discuss the application of single objective algorithms. Chapter 8 focuses on design of terahertz devices using multi-objective PSO. The algorithm involves the structural optimization of a terahertz metamaterial along with optimization of another application specific parameter.

EM designers prefer user friendly CAD models for analysis of various computationally intensive applications. Soft computing based CAD packages are gaining momentum in the field of electromagnetic (EM) applications because of their properties namely global optimization, quick response and accuracy. Chapter 9 discusses two in-house CAD packages developed using soft-computing techniques. The first CAD model uses PSO to design an optimized SRR structure for a specific frequency, while the second uses ANN, in order to predict path loss in rural and urban environments.

1.5 Summary

This book covers approaches to solving various complex electromagnetic problems through the novel route of soft computing. The theory behind these techniques is presented along with algorithms and their corresponding software codes. Emerging soft computing algorithms such as PSO and BFO are also tested for multi-objective optimization problems. Further, developments of computational engines that can integrate the optimization tool along with EM solvers are also discussed to provide a visibility into solving complicated non-linear problems, for which analytical formulations do not exist.

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Cambridge University Press
978-1-107-12248-2 - Soft Computing in Electromagnetics: Methods and Applications
Balamati Choudhury and Rakesh Mohan Jha
Excerpt
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CHAPTER 2 Soft Computing Techniques

Soft computing is defined as a group of computational techniques based on artificial intelligence (human like decision) and natural selection that provides quick and cost effective solution to very complex problems for which analytical (hard computing) formulations do not exist. The term soft computing was coined by Zadeh [Zadeh, 1992]. Soft computing aims at finding precise approximation, which gives a robust, computationally efficient and cost effective solution saving the computational time. Most of these techniques are basically enthused on biological inspired phenomena and societal behavioural patterns. The advent of soft computing into the computing world was marked by research in machine learning, probabilistic reasoning, artificial neural networks (ANN), fuzzy logic [Jang *et al.*, 1997] and genetic algorithm (GA). Today, the purview of soft computing has been extended to include swarm intelligence and foraging behaviours of biological populations in algorithms like the particle swarm optimization (PSO) and bacterial foraging algorithm (BFO) [Holland, 1975; Kennedy and Eberhart, 1995; Passino, 2002].

Soft computing methods are associated with certain distinctive advantages. These include the following:

- Since Soft computing methods do not call for wide-ranging mathematical formulation pertaining to the problem, the need for explicit knowledge in a particular domain can be reduced.
- These tools can handle multiple variables simultaneously.
- For optimization problems, the solutions can be prevented from falling into local minima by using global optimization strategies.
- These techniques are mostly cost effective.
- Dependency on expensive traditional simulations packages can be reduced to some degree by efficient hybridization of soft computing methods.
- These methods are generally adaptive in nature and are scalable.

Of late, soft computing techniques have attracted recognition amongst researchers of various branches of engineering in order to arrive at solutions to problem statements [Patnaik and Mishra, 2000; Patnaik *et al.*, 2005; Samii, 2006; Choudhury *et al.*, 2012]. The sturdiness of the above techniques has been well tested pertaining to various problems encountered in every sphere of engineering. Indeed, the last decade has seen the implementation of soft computing in microwave applications. This chapter gives a glimpse of the various soft computing techniques that are widely used in the field of electromagnetics.

2.1 Artificial Neural Networks

Certain features of human brain such as the capability to recognize and perceive, have been studied for decades. The remarkable characteristics of the human brain drove researchers into attempting to emulate these characteristics in computers. Indeed, the outputs of these attempts have been incorporated into parallel processing systems and are collectively called as artificial neural networks (ANN). ANN, in the most general terms, is a network structure consisting of neurons (interconnected processing elements) with connection strengths (weights). They operate in parallel and the computation is performed at the processing element level [Haykins, 1999].

The artificial neural network was first developed by McCulloch in 1943. Some of the inherent capabilities of ANN are:

- Suitable for solving hard problems, as processing takes place in parallel instead of in serial mode [Christodoulou and Georgiopoulous, 2000].
- Capability to learn in both supervised and unsupervised mode. In supervised mode, the network is trained with the correct response, and in unsupervised mode, the network self-organizes and extracts patterns from the data presented to it [Wasserman, 1993].
- ANN is suitable for solving pattern matching problems [Haykins, 1999], pattern classification, optimization, self-organization, and associative memory.
- Hardware implementations of ANN systems are possible using VLSI technology [Zebulum *et al.*, 2002].

2.1.1 Concept of ANN

An artificial neural network (ANN) is evolved from a biological neural network, which is made up of a large scale of neurons interconnected. From an engineering perspective, it can be regarded as an extension of conventional data–processing techniques. ANNs may be best perceived as a huge parallel processor, which is capable of storing knowledge gained through experience [c.f. Haykins, 1999]. The basic similarities between ANN and human intelligence are (1) ANN acquires the knowledge through learning, and (2) knowledge gained through experience is stored as connection strengths (synaptic weights).

From Fig. 2.1 it can be concluded that the basic unit of an artificial neural network is also a neuron, analogous to its biological counterpart. These neurons are capable of strengthening or weakening the connections between each other and are hence capable of adapting themselves to arrive at solutions, i.e. the neurons have the capability of adjusting interconnections to arrive at the desired output. An individual neuron does the same by adjusting its 'weights' and 'biases'.