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Advances in Metaheuristic Algorithms for Optimal Design of Structures

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Preface

Recent advances in structural technology require greater accuracy, efficiency, and speed in design of structural systems. It is therefore not surprising that new methods have been developed for optimal design of real-life structures and models with complex configurations and a large number of elements.

This book can be considered as an application of metaheuristic algorithms to optimal design of skeletal structures. The present book is addressed to those scientists and engineers, and their students, who wish to explore the potential of newly developed metaheuristics. The concepts presented in this book are not only applicable to skeletal structures and finite element models but can equally be used for design of other systems such as hydraulic and electrical networks.

The author and his graduate students have been involved in various developments and applications of different metaheuristic algorithms to structural optimization in the last two decades. This book contains part of this research suitable for various aspects of optimization for skeletal structures.

This book is likely to be of interest to civil, mechanical, and electrical engineers who use optimization methods for design, as well as to those students and researchers in structural optimization who will find it to be necessary professional reading.

In Chap. 1, a short introduction is provided for the development of optimization and different metaheuristic algorithms. Chapter 2 contains one of the most popular metaheuristic known as the Particle Swarm Optimization (PSO). Chapter 3 provides an efficient metaheuristic algorithm known as Charged System Search (CSS). This algorithm has found many applications in different fields of civil engineering. In Chap. 4, Magnetic Charged System Search (MCSS) is presented. This algorithm can be considered as an improvement to CSS, where the physical scenario of electrical and magnetic forces is completed. Chapter 5 contains a generalized metaheuristic so-called Field of Forces Optimization (FFO) approach and its applications. Chapter 6 presents the recently developed algorithm known as Dolphin Echolocation Optimization (DEO) mimicking the behavior of dolphins. Chapter 7 contains a powerful parameter independent algorithm, called Colliding Bodies Optimization (CBO). This algorithm is based on one-dimensional collisions between bodies, with each agent solution being considered as the massed object or body. After a collision of two moving bodies having specified masses and velocities, these bodies are separated with new velocities. This collision causes the agents to move toward better positions in the search space. In Chap. 8, Ray Optimization Algorithm (ROA) is presented in which agents of the optimization are considered as rays of light. Based on the Snell's light refraction law when light travels from a lighter medium to a darker medium, it refracts and its direction changes. This behavior helps the agents to explore the search space in early stages of the optimization process and to make them converge in the final stages. In Chap. 9, the well-known Big Bang-Big Crunch (BB-BC) algorithm is improved (MBB-BC) and applied to structural optimization. Chapter 10 contains application of Cuckoo Search Optimization (CSO) in optimal design of skeletal structures. In Chap. 11, Imperialist Competitive Algorithm (ICA) and its application are discussed. Chaos theory has found many applications in engineering and optimal design. Chapter 12 presents Chaos Embedded Metaheuristic (CEM) Algorithms. Finally, Chap. 13 can be considered as a brief introduction to multi-objective optimization. In this chapter a multi-objective optimization algorithm is presented and applied to optimal design of large-scale skeletal structures.

I would like to take this opportunity to acknowledge a deep sense of gratitude to a number of colleagues and friends who in different ways have helped in the preparation of this book. Professor F. Ziegler encouraged and supported me to write this book. My special thanks are due to Mrs. Silvia Schilgerius, the senior editor of the Applied Sciences of Springer, for her constructive comments, editing, and unfailing kindness in the course of the preparation of this book. My sincere appreciation is extended to our Springer colleagues Ms. Beate Siek and Ms. Sashivadhana Shivakumar.

I would like to thank my former and present Ph.D. and M.Sc. students, Dr. S. Talatahari, Dr. K. Laknejadi, Mr. V.R. Mahdavi, Mr. A. Zolghadr, Mrs. N. Farhoudi, Mr. S. Massoudi, Mr. M. Khayatazad, Mr. M. Ilchi, Mr. R. Sheikholeslami, Mr. T. Bakhshpouri, and Mr. M. Kalate Ahani, for using our joint papers and for their help in various stages of writing this book. I would like to thank the publishers who permitted some of our papers to be utilized in the preparation of this book, consisting of Springer Verlag, Elsevier and Wiley.

My warmest gratitude is due to my family and in particular my wife, Mrs. L. Kaveh, for her continued support in the course of preparing this book.

Every effort has been made to render the book error free. However, the author would appreciate any remaining errors being brought to his attention through his email address: alikaveh@iust.ac.ir.

Tehran, Iran
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A. Kaveh

Contents

Chapter 1
Introduction

1.1 Metaheuristic Algorithms for Optimization

In today's extremely competitive world, human beings attempt to exploit the maximum output or profit from a limited amount of available resources. In engineering design, for example, choosing design variables that fulfill all design requirements and have the lowest possible cost is concerned, i.e. the main objective is to comply with basic standards but also to achieve good economic results. Optimization offers a technique for solving this type of problems.

The term "optimization" refers to the study of problems in which one seeks to minimize or maximize a function by systematically choosing the values of variables from/within a permissible set. In one hand, a vast amount of research has been conducted in this area of knowledge, hoping to develop effective and efficient optimization algorithms. On the other hand, the application of the existing algorithms to real projects has been the focus of many studies.

In the past, the most commonly used optimization techniques were gradient-based algorithms which utilized gradient information to search the solution space near an initial starting point [1, 2]. In general, gradient-based methods converge faster and can obtain solutions with higher accuracy compared to stochastic approaches. However, the acquisition of gradient information can be either costly or even impossible to obtain the minima. Moreover, this kind of algorithms is only guaranteed to converge to local optima. Furthermore, a good starting point is quite vital for a successful execution of these methods. In many optimization problems, prohibited zones, side limits and non-smooth or non-convex functions should be taken into consideration. As a result, these non-convex optimization problems cannot easily be solved by these methods.

On the other hand other types of optimization methods, known as metaheuristic algorithms, are not restricted in the aforementioned manner. These methods are suitable for global search due to their capability of exploring and finding promising regions in the search space at an affordable computational time. Metaheuristic algorithms tend to perform well for most of the optimization problems [3, 4].

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This is because these methods refrain from simplifying or making assumptions about the original problem. Evidence of this is their successful applications to a vast variety of fields, such as engineering, physics, chemistry, art, economics, marketing, genetics, operations research, robotics, social sciences, and politics.

The word *heuristic* has its origin in the old Greek work *heuriskein*, which means the art of discovering new strategies (rules) to solve problems. The suffix *meta*, also is a Greek word, means "upper level methodology". The term *metaheuristic* was introduced by F. Glover in the paper [5].

A heuristic method can be considered as a procedure that is likely to discover a very good feasible solution, but not necessarily an optimal solution, for a considered specific problem. No guarantee can be provided about the quality of the solution obtained, but a well-designed heuristic method usually can provide a solution that is at least nearly optimal. The procedure also should be sufficiently efficient to deal with very large problems. The heuristic methods are often considered as *iterative algorithm*, where each iteration involves conducting a search for a new solution that might be better than the best solution found previously. After a reasonable time when the algorithm is terminated, the solution it provides is the best one that was found during any iteration. A metaheuristic is formally defined as an iterative generation process which guides a subordinate heuristic by combining intelligently different concepts for exploring (global search) and exploiting (local search) the search space, learning strategies are used to structure information in order to find efficiently near-optimal solutions [5–7].

Metaheuristic algorithm has found many applications in different areas of applied mathematics, engineering, medicine, economics and other sciences. These methods are extensively utilized in the design of different systems in civil, mechanical, electrical, and industrial engineering. At the same time, one of the most important trends in optimization is the constantly increasing emphasis on the interdisciplinary nature of the field.

1.2 Optimal Design of Structures and Goals of the Present Book

In the area of structural engineering that is the main concern of this book, one tries to achieve certain objectives in order to optimize weight, construction cost, geometry, layout, topology and time satisfying certain constraints. Since resources, fund and time are always limited, one has to find solutions to optimal usage of these resources.

The main goal of this book is to introduce some well established and the most recently developed metaheuristics for optimal design of structures. Schematic of the chapters of the present book in one glance is shown in Fig. 1.1.

Most of these methods are either nature-based or physics-based algorithms, Fig. 1.2. Though many design examples are included, however, the results may

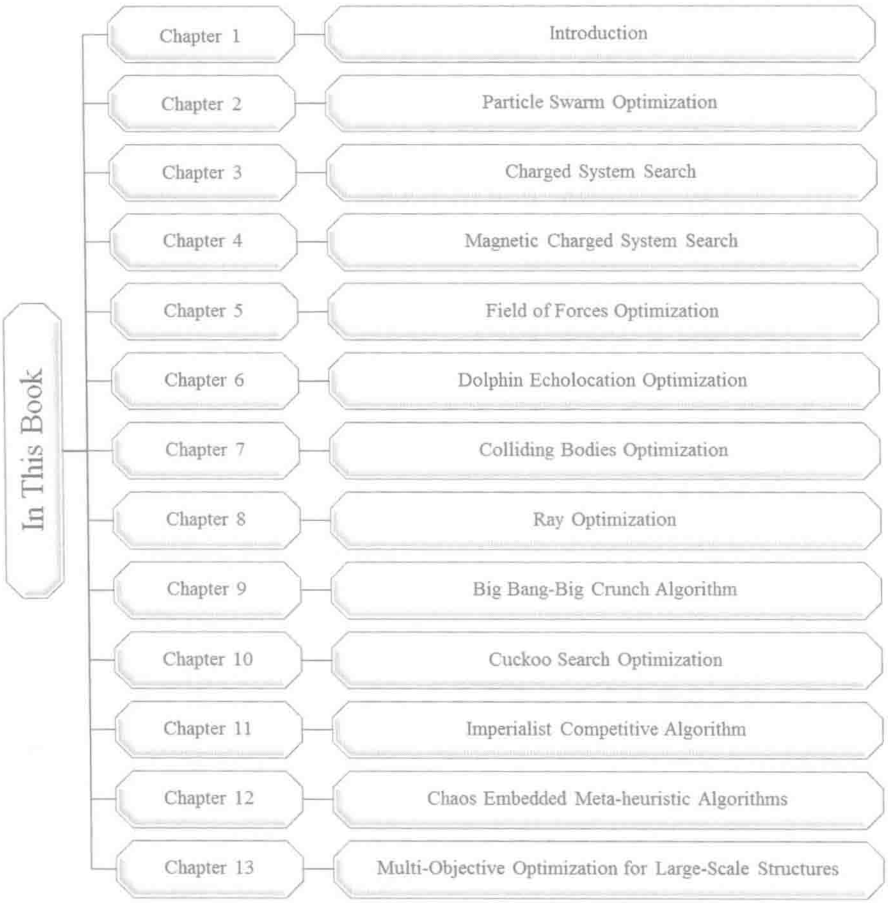

Fig. 1.1 Schematic of the chapters of the present book in one glance

or may not have small constraint violations, and do not constitute the main objective of the book.

1.3 Organization of the Present Book

After this introductory chapter, the remaining chapters of this book are organized in the following manner:

Chapter 2 introduces the well-known Particle Swarm Optimization (PSO) algorithms. These algorithms are nature-inspired population-based metaheuristic algorithms originally accredited to Eberhart, Kennedy and She. The algorithms mimic the social behavior of birds flocking and fishes schooling. Starting with a

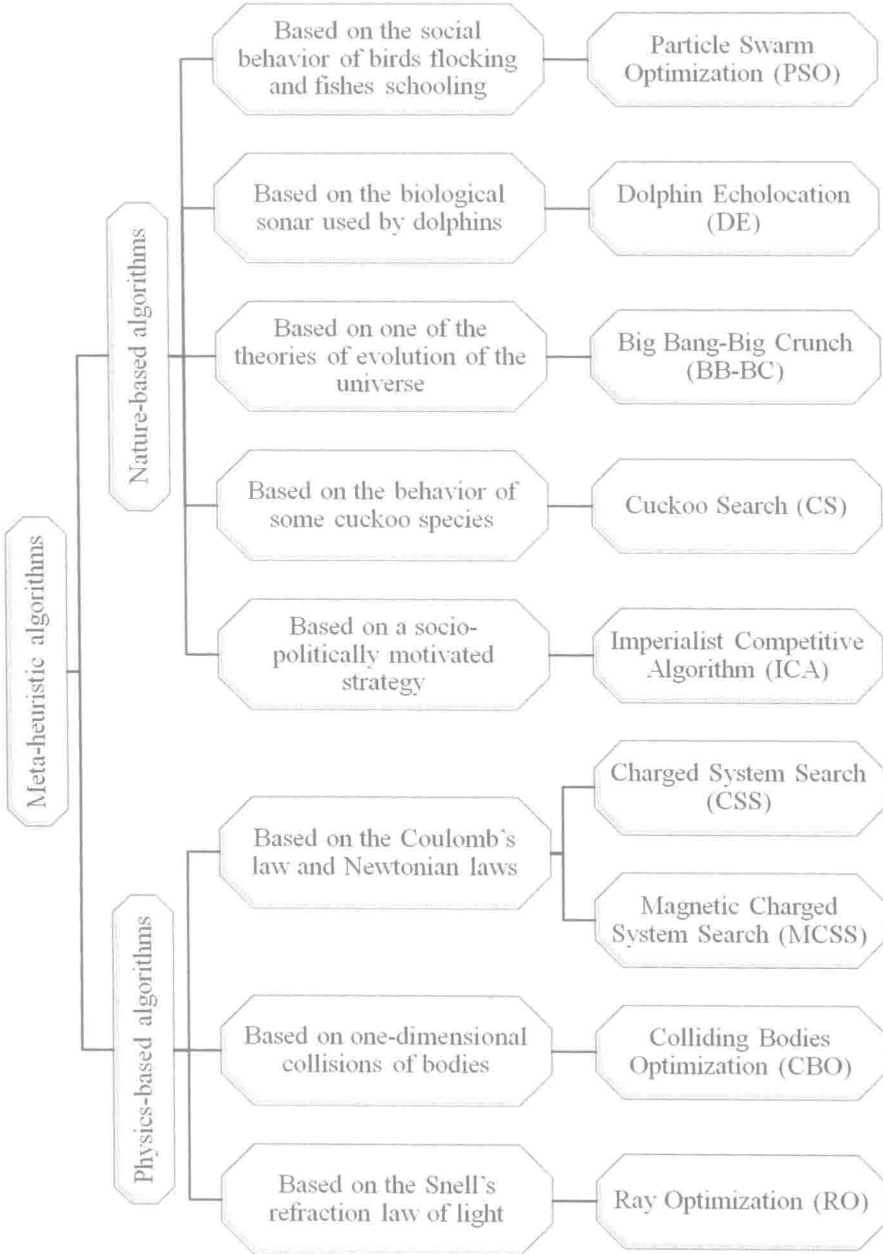

Fig. 1.2 Classification of the metaheuristics presented in this book

randomly distributed set of particles (potential solutions), the algorithms try to improve the solutions according to a quality measure (fitness function). The improvisation is preformed through moving the particles around the search space by means of a set of simple mathematical expressions which model some inter-particle communications. These mathematical expressions, in their simplest and most basic form, suggest the movement of each particle towards its own best experienced position and the swarm's best position so far, along with some random perturbations.

Chapter 3 presents the well established Charged System Search Algorithm (CSS), developed by Kaveh and Talatahari. This chapter consists of two parts. In the first part an optimization algorithm based on some principles from physics and mechanics is introduced. In this algorithm the governing Coulomb law from electrostatics and the Newtonian laws of mechanics are utilized. CSS is a multi-agent approach in which each agent is a Charged Particle (CP). CPs can affect each other based on their fitness values and their separation distances. The quantity of the resultant force is determined by using the electrostatics laws and the quality of the movement is determined using Newtonian mechanics laws. CSS can be utilized in all optimization fields; especially it is suitable for non-smooth or non-convex domains. CSS needs neither the gradient information nor the continuity of the search space. In the second part, CSS is applied to optimal design of skeletal structures and high performance of CSS is illustrated.

Chapter 4 extends the algorithm of the previous chapter and presents the Magnetic Charged System Search, developed by Kaveh, Motie Share and Moslehi. This chapter consists of two parts. In first part, the standard Magnetic Charged System Search (MCSS) is presented and applied to different numerical examples to examine the efficiency of this algorithm. The results are compared to those of the original charged system search method. In the second part, an improved form of the MCSS algorithm, denoted by IMCSS, is presented and also its discrete version is described. The IMCSS algorithm is applied to optimization of truss structures with continuous and discrete variables to demonstrate the performance of this algorithm in the field of structural optimization.

Chapter 5 presents a generalized CSS algorithm known as the Field of Forces Optimization. Although different metaheuristic algorithms have some differences in approaches to determine the optimum solution, however their general performance is approximately the same. They start the optimization with random solutions; and the subsequent solutions are based on randomization and some other rules. With the progress of the optimization process, the power of rules increases, and the power of randomization decreases. It seems that these rules can be modelled by a familiar concept of physics known as the *fields of forces* (FOF). FOF is a concept which is utilized in physics to explain the reason of the operation of the universe. The virtual FOF model is approximately simulated by using the concepts of real world fields such as gravitational, magnetic or electric fields.

Chapter 6 presents the recently developed algorithm known as Dolphin Echolocation Optimization, proposed by Kaveh and Farhoudi. Nature has provided inspiration for most of the man-made technologies. Scientists believe that dolphins are the second to human beings in smartness and intelligence. Echolocation is the biological sonar used by dolphins and several kinds of other animals for navigation and hunting in various environments. This ability of dolphins is mimicked in this chapter to develop a new optimization method. There are different metaheuristic optimization methods, but in most of these algorithms parameter tuning takes a considerable time of the user, persuading the scientists to develop ideas to improve these methods. Studies have shown that metaheuristic algorithms have certain governing rules and knowing these rules helps to get better results. Dolphin Echolocation takes advantages of these rules and outperforms some of the existing optimization methods, while it has few parameters to be set. The new approach leads to excellent results with low computational efforts.

Chapter 7 contains the most recently developed algorithm so-called Colliding Bodies Optimization proposed by Kaveh and Mahdavi. This chapter presents a novel efficient metaheuristic optimization algorithm called Colliding Bodies Optimization (CBO), for optimization. This algorithm is based on one-dimensional collisions between bodies, with each agent solution being considered as the massed object or body. After a collision of two moving bodies having specified masses and velocities, these bodies are separated with new velocities. This collision causes the agents to move toward better positions in the search space. CBO utilizes simple formulation to find minimum or maximum of functions; also it is internally parameter independent.

Chapter 8 presents the Ray Optimization (RO) Algorithm originally developed by Kaveh and Khayat Azad. Similar to other multi-agent methods, Ray Optimization has a number of particles consisting of the variables of the problem. These agents are considered as rays of light. Based on the Snell's light refraction law when light travels from a lighter medium to a darker medium, it refracts and its direction changes. This behaviour helps the agents to explore the search space in early stages of the optimization process and to make them converge in the final stages. This law is the main tool of the Ray Optimization algorithm. This chapter consists of three parts. In first part, the standard Ray optimization is presented and applied to different mathematical functions and engineering problems. In the second part, RO is employed for size and shape optimization of truss structures. Finally in the third part, an improved ray optimization (IRO) algorithm is introduced and applied to some benchmark mathematical optimization problems and truss structure examples.

Chapter 9 presents a modified Big Bang-Big Crunch (BB–BC) Algorithm. The standard BB–BC method is developed by Erol and Eksin, and consists of two phases: a Big Bang phase, and a Big Crunch phase. In the Big Bang phase, candidate solutions are randomly distributed over the search space. Similar to other evolutionary algorithms, initial solutions are spread all over the search space in a uniform manner in the first Big Bang. Erol and Eksin associated the random nature of the Big Bang to energy dissipation or the transformation from an ordered state (a convergent solution) to a disorder or chaos state (new set of solution candidates).

Chapter 10 presents the Cuckoo Search (CS) Optimization developed by Yang and colleagues. In this chapter CS is utilized to determine optimum design of