Fireworks Algorithm

- A Novel Swarm Intelligence Optimization Method

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About the Author

Fig. 0.1: Dr. Ying TAN

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His research interests include computational intelligence, swarm intelligence, data mining, pattern recognition, intelligent information processing for information security, fireworks algorithm. He has published more than 280 papers in refereed journals and conferences in these areas, and authored/co-authored 6 books and 10 chapters in book, and received 3 invention patents.

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Part I
Fundamentals and Basic Theory

This part describes the principle, fundamentals and basic theory of fireworks algorithm (FWA). The first chapter introduces the study of the origins and motivations, research areas, problems to be solved, features, as well as future research directions, of fireworks algorithms. The second chapter gives the details of fireworks algorithms, including FWA's components and framework, characteristics and comparisons with other SI algorithms. The third chapter gives a stochastic model of fireworks algorithm, proves its global convergence, discusses and analyzes its time complexity, and finally studies the effects of different types of random number generators on the performance of FWA.

Chapter 1
Introduction

This chapter presents the motivation of when, why, and how the fireworks algorithm (FWA), as a novel swarm intelligence optimization algorithm, come out. After a concise review on swarm intelligence domain, a brief introduction to FWA has been presented with primary focuses on four aspects of theoretical analysis, algorithm study, problem solving as well as applications. The characteristics and advantages of FWA is also described. Afterward, overviews of FWA Research are detailed with completed reference citations. Finally, the perspectives and upcoming twenty-five problems to be solved are pointed out.

1.1 Motivations

During my childhood in Sichuan, in Southwest of China, it was a great pleasure for me to set off fireworks and firecrackers with my friends during the Spring Festival, a most important traditional festival in China. Now and then, we competed for the title of master who could ignite firework that could fly highest into the sky and make the loudest noise. Though the time has long passed, the splendid sparks showering the night sky imprinted in my memory.

By the Spring Festival of 2006, I had worked at Peking University for one year. During that time, I devoted to the in-depth study of evolutionary computation (EC) in the computational intelligence. Therefore, I tried to relate any novel phenomena I met to EC during that times. Just at this year, Beijing authorities relaxed firework ban to restriction during the Spring Festival. After many years' ban on firework celebrations, citizens of the Capital were eager for the arrival of the Chinese Lunar New Years Eve and looked forward a livelier and jolly Spring Festival.

On this year's Eve Day, people set off a large amount of fireworks as if it could relieve the whole year's stress. The sparks of diverse colors lighted up the dark sky and made various beautiful patterns. The glorious scene was reminiscent of the childhood memory, brought much joy and comfort to me.

An idea suddenly came out of my mind that the way fireworks explode may be an efficient strategy for searching the solution space. Such a search strategy would be different from the established ones. So I began to study this explosion-like search methodand named it Fireworks Algorithm, i.e., FWA, for short.

Despite the name of "Fireworks Algorithm" sounds intuitive and compact, since this name doesn't directly related to optimization problems it is good at, so some other names are also used by other researchers, such as "Fireworks Optimization", "Fireworks Explosion Algorithm", "Fireworks Explosion Optimization Algorithm", "Fireworks Explosion Search Algorithm", "Explosion Search Method", and so on. In order to avoid the possible confusion, only the original name ”Fireworks Algorithm”, abbreviated by FWA, is used hereafter in this book.

The motivation of studying FWA is to seek a simple and efficient method dealing with complex optimization problems, especially multi-modal optimization problems.

In the summer semester of 2006, Yuanchun Zhu from Jilin University was admitted by Peking University as a PhD student under my supervision and I arranged him to do his graduate project in my laboratory in the early months of the following year. We discussed the idea about FWA and set the project content as the study and implementation of Fireworks Algorithm. Together, we started the thorough study of FWA.

After half year's exploration and study, FWA's main components and overall framework were completely established, finally, the conventional FWA was designed based on the explosive operator. The pioneering work was finished by May, 2007.

But unfortunately, in the following two years, my hosting a project supported by the National High-tech Research and Development Program (863 Program), the FWA related researches were suspended. Till 2010, the original work on FWA was reported at the First International Conference of Swarm Intelligence (ICSI' 2010), entitled ”Fireworks Algorithm for Optimization”. After then, FWA gets increasingly more attention in the field of swarm intelligence.

1.2 FWA: A Novel Swarm Intelligence Optimization Algorithm

Swarm intelligence is an active branch of Evolutionary Computation which is one of the most important research topics in Computational Intelligence (CI) Community. In the past several decades, a fruitful of achievements have been made on the research of Computational Intelligence, such as Artificial Neural Networks[1], Fuzzy Logic and Systems[2], Evolutionary Computation[3], Chaos Computation[4], Simulated Annealing[5], Tabu Search[6] and hybrid strategies, just to name a few. All these methods simulate and give an insight of natural phenomena or biological process.

Swarm intelligence (SI) is regarded as the collective behavior of decentralized, self-organized, and populated systems. A typical swarm intelligence system consists of a population of simple agents which can communicate (either directly or indirectly) locally with each other by acting on their local environment. Though the agents in a swarm follow very simple rules, the interactions between such agents can lead to the emergence of very complicated global behavior, far beyond the capability of individual agents. Examples in natural systems of swarm intelligence include bird flocking, ant foraging, and fish schooling.

Inspired by such behavior of swarms, a class of algorithms are proposed for tackling optimization problems, usually under the title of Swarm Intelligence Algorithm. In SI Algorithm, a swarm is made up of multiple artificial agents. The agents can exchange heuristic information in the form of local interaction directly or indirectly (via environment). Such interaction, in addition with certain stochastic elements, generates the behavior of adaptive search, and finally leads to global optimization.

The most respected and popular SI algorithms are Particle Swarm Optimization (PSO) which is inspired by the social behavior of bird flocking or fish schooling , and Ant Colony Optimization (ACO) which simulates the foraging behavior of ant colony. PSO is widely used for real-parameter optimization while ACO has been successfully applied to solve combinatorial optimization problems, the most well-known of such problems are the Traveling Salesman Problem (TSP) and Quadratic Assignment Problem (QAP).

Swarm intelligence algorithms can fall into two major categories Bio-inspired and Non-bio-inspired [7] The former includes Ant Colony Optimization (ACO) [8], Particle Swarm Optimization (PSO) [9], Fish Schooling Search (FSS) [10], Firefly Algorithm-I [11], Firefly Algorithm-II [12] Buccock Algorithm [13]

Bat Algorithm citeyang2010new, Artificial Bee Algorithm (ABC)[14][15][16],Bacterai Foraging Optimization (BFO)[17] and so forth. Non-bio-inspired algorithms consist of Fireworks Algorithm (FWA)[18] Water Drops Algorithm[19] Brain Storm Optimization (BSO) [20] Magnetic Optimization Algorithms [21], just to name a few.

Nowadays, research efforts on swarm intelligence mainly devoted to algorithm design, problem solving and applications. Swarm intelligence algorithms are more and more applied to large-scale problems to tackle the issues of the curse of dimension and big data. Hybrid algorithms and variants are actively proposed.

1.3 Brief Introduction to FWA

FWA is an iterative algorithm just like conventional swarm intelligence algorithms, which is made up of four key components or building blocks, i.e., Explosive Operator, Mutation operation, Mapping rule and Selection Strategy. Where, Explosive Operator can be divided further into Explosion Strength, Explosion Amplitude, Shift Mutation and other operators. Gaussian Mutation is the most widely used mutation operator. Mirror mapping rule and stochastic mapping rule are two popular mapping rules for FWA. As for selection strategy, there are distance-based selection and stochastic selection, etc.

Specifically, workflow of FWA can be stated as follows. First, N fireworks are generated randomly as the initial swarm. Then, every firework conducts explosion operation and mutation operation, and mapping rule is triggered if necessary. Finally, N fireworks are selected from all the fireworks and generated sparks according to the selection strategy. The iteration continues until particular termination criterion is satisfied. As the iteration proceeds, better optimization result can be achieved eventually.

The study of FWA mainly focuses on four aspect: theoretical analysis, algorithm study, problem solving as well as applications.

1. Theoretical Analysis
   Theoretical analysis involves FWA's mechanism, convergence quality, trajectory and parameters. It will help the design of new algorithm as well provide helpful insight for improving established algorithm.
2. Algorithm Study
   By analyzing and adjusting FWA's components, we try to improve FWA's performance (convergence, solution quality and time efficiency), and come up with improved FWA variants. In the meantime, it will be helpful to integrate FWA with other methods, ending up with efficient hybrid algorithms.
3. Problems to be Solved

   - Single-Objective Optimization Problems
   - Constrained Single-Objective Optimization Problems
   - Multiple-Objective Optimization Problems - MOO
   - Constrained Multiple-Objective Optimization Problems
   - Many-Objective Optimization Problems - ManyOO
   - Combinatorial Optimization Problems - CO
   - Dynamic Optimization Problems - DOP
   - Other optimization problems

4. Applications
   FWA can be directly applied to many different real-world problems from which an optimization task can be drawn.

1.4 Characteristics and Advantages of FWA

Some of FWA's characteristics and advantages are summarized as fellows

1. Explosiveness: Each iteration, every firework explodes and generates a number of sparks within the radiation range. Then, selection procedure is triggered to choose a fixed number of fireworks for the next iteration.
2. Instantaneity: The sparks are Instantaneous, which means that sparks that don't be selected will vanish.
3. Simplicity: every agent has only limited capability, thus the whole algorithm is very simple to implement.
4. Locality: For a particular firework, its explosion amplitude is smaller than the feasible bound, so it can only exploit locally in the search space.
5. Emergent properties: Though following simple rules, by cooperation and competition, the swarm, as a whole, shows complicated behaviors, far more complex than every single firework can, i.e., intelligence emerges.
6. Parallelism: There is no central control mechanism among fireworks, thus the fireworks are highly independent, much suitable for parallelization.
7. Diversity: The diversity is threefold. First, fireworks are of diversity. Proper selection guarantee that the selected fireworks distribute in diverse places in the search space. Second, there are diverse explosion strengths and amplitudes. According to their particular fitness, different fireworks will have various explosion strengths and amplitude. Besides, there are multiple mutation operators in the FWA. Two of the well-studied mutations are displacement mutation and Gaussian mutation. Displacement mutation is subjected to the firework's fitness while Gaussian mutation firework is of independent. The two mutations of very different flavor guarantee the diversity of the mutation procedure.
8. Robustness: As the fireworks are highly independent, the swarm behaves won't degrade too much with the presence of few individuals' failure.
9. Flexibility: The problem don't need to have an explicit expression to be optimized by FWA. Thus FWA can address a very broad range of problems for which conventional optimization procedures unfortunately fail.

1.5 Overviews of FWA Research

Since the inception of FWA introduced by the seminal paper entitled "Fireworks algorithm for optimization [18]" by the author et. al., FWA has drawn much attention from both academic and industrial fields. Much effort has been devoted to analyzing the conventional FWA and many improvements have been proposed to compensate its shortcomings. Several hybrid algorithms have been introduced too. These research efforts lead to a huge leap in terms of FWA's performance. Many applications are reported, where FWA is successfully utilized to tackle diverse problems.

A brief summary of these achievements on the studies of FWAs is listed as follows.

1. Theories

   Liu et al. [22] analyzed FWA's convergence property theoretically. The authors pointed out that FWA is an absorbed Markov Process. Besides, in this book, we also studied the impact of random number generators on the performance of FWA, for the first time.

2. Algorithms

   Ding et al. [23] proposed a GPU based parallel FWA, dubbed GPU-FWA. GPU-FWA achieved 200+ speedup compared to the CPU implementation. GPU-FWA made some major modifications on FWA, to minimize the inter-firework communication thus maximize the utilization of GPU.
   Pei et al. [24] proposed a method to accelerate FWA's convergence by appropriating the objective function. The experiments show that the optimal performance is achieved when a quadratic model is utilized with random selection strategy. The proposed method outperforms the conventional FWA significantly.
   [25] observed FWA extensively and proposed several improvements accordingly. The authors proposed Enhanced FWA (EFWA), which modifies all the key components of the conventional FWA.
   In [26] and [27], Zheng S et. al. and Li et. al. devoted to studying the adaptation in FWA's explosion amplitude, as a result, Dynamic Search FWA and Adaptive FWA were proposed, respectively.
   Besides, some researchers studies the combination of FWA with other SI algorithms and then proposed several hybrid FWAs. In [28] and [29], Zheng Y. and Yu et. al. devoted to the hybrid of FWA and DE. In [28], the proposed FWA-DE shows advantage over both FWA and DE on several benchmark test functions. In [30], Gao et. al. combined FWA with Cultural Algorithm and then applied it to the optimization of digital filter design. Gao et. al. compared the proposed algorithm with two PSO variants [31][32]. The experimental results show that the new algorithm achieved the best performance of the three. Zhang et. al. proposed BBO-FWA, which outperformed BBO and FWA with clear advantages [33].
3. Varieties of Optimization Problems
   FWA has been used to solve single-objective and multi-objective real-valued optimization problems. Zheng Y. et. al. proposed a multi-objective FWA (MOFWA) and applied it to the oil crops' fertilization problem [34]. The comparative experiments show that MOFWA could obtain better performance than other popular swarm intelligence multi-objective algorithms. In this book, we will describe, for the first time, the applications of FWA on tackling the well-known combinatorial optimization problem of Travelling Salesman Problem (TSP).
4. Applications
   FWA has been applied to diverse real-world problems, for example, equation solving [35], nonnegative matrix factorization (NMF) [36], spam detection [37], distance metric [38], filter design [30], crops fertilization [34], swarm robot [39]. [40] proposed an improved FWA to solve nonlinear equation and system problems. His experiments shew that the FWA have advantage over the other algorithm in solving variable-coupling equations and also gave an analysis to disclose why the improved FWA is more effective. Recently, Nantiwat, Pholdee and Sujin Bureerat, in [41], systematically compared and studied the optimizing performance of 24 meta-heuristic algorithms for mass minimization of trusses with dynamic constraints, gave an objective ranking among which FWA is above the average with a promising performance. Mohamed Imran, Kowsalya and Kothari, in [42] and [43], presented a novel integration technique for optimal network reconfiguration and distributed generation (DG) placement in distribution system with an objective of power loss minimization and voltage stability enhancement. They used Fireworks Algorithm (FWA) to simultaneously reconfigure and allocate optimal DG units in a distribution network. Six different scenarios are considered during DG placement and reconfiguration of network to assess the performance of the proposed technique. Simulations were carried out on well-known IEEE 33- and 69-bus test systems at three different load levels to demonstrate well the performance and effectiveness of the proposed FWA method. Very recently, in [44], R. Rajaram et.al., presented their latest work of selective harmonic elimination in PWM inverter using fireworks algorithm in which a slightly modified FWA and Firefly were used to solve the selective harmonic elimination problem in inverter output waveforms. It turns out from experiments that the FWA works faster than modified Firefly algorithm as

well as other popular algorithms of Ant colony, PSO and GA. Moreover, specific comparisons with other methods in the literature like GA[45], Ant colony[46], Bees intelligence [47] suggested that Fireworks algorithm worked excellent and Firefly was also good for this application. Noora Hanni Abdulmajeed and Masri Ayob, in [48], applied the FWA to the capacitated vehicle routing problem (CVPR) which is an improtant problem in the industry sector with many applications in the field of transportation, distribution and logistics. Based on the tests on 14 instances of Christofides bechmarks, the FWA is very much competitive in terms of the quality of the solutions when compared to other SI methods like OCGA, AGES, and AHMH[48].
The application of FWA on document clustering is also presented in this book for the first time.

For a detailed review of FWAs, readers can refer to [49]-[50].

1.6 Perspectives

FWA is still in its infancy era. Many areas are yet to be explored and novel ideas are increasingly emerging. The future research of FWA may happen in the following areas

1. Theoretical analysis. Global convergence, computational efficiency, parameters' setting, etc.
2. Performance improvement. One of the most important topics is to establish efficient cooperation mechanisms in FWA.
3. Hybrid algorithms. Combination of FWA with other SI algorithms.
4. Problem solving in the scenario of big data.
5. Dynamic optimization problems, such as dynamic object or target tracking and multi-targets tracking in search of swarm robots.
6. Applications in a variety of real-world problems

1.7 Twenty-Five Problems to Be Solved

Based on our years of study on FWA, we come up with 25 problems that are critical and to be researched in the coming 5 years below.

1. Trajectories of fireworks in the FWA during optimization procedure.
2. Convergent theories and properties.
3. Performance analysis based on probabilistic models.
4. Efficiency improvements on FWA.
5. Parameters' setting.
6. The intrinsic mechanism of the explosion operator.
7. Simplified FWA with less parameters.
8. Exploring the FWA with different probability distributions.
9. Specifically the FWA with the Lèvy distribution.
10. Cooperative and competitive mechanisms in the FWA.
11. Improving the performance of FWA and its variants.
12. Studying hybridized algorithms with other SI algorithms.
13. Researches on FWA for multi- and many-objective optimization problems.

14. FWA for dynamic optimization problems.
15. FWA for constrained optimization problems.
16. Discrete FWA for combinatorial optimization problems.
17. FWA for Big Data.
18. FWA in the scenario of high-dimensional applications.
19. Efficient parallel implementation of FWA.
20. Paralleled Fireworks algorithms based on GPUs.
21. Application in intelligence power grid.
22. Application in data mining and knowledge discovery.
23. Application in search and control of swarm robots.
24. Application in processing and analysis of speech and image.
25. Application in Internet search.

1.8 Conclusions

A brief overview of studies on FWAs is presented in this chapter. The motivation and origin of FWA is first described. Then the relevant terminologies on FWA and swarm intelligence are defined and explained concisely, followed by a summary of FWA's basic components and key properties. After a short literature review of FWA researches, we gave out our perspectives on the future research trends in FWA research.

The detailed description of each topic on FWA will be presented in the successive chapters.