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Chaotic fractal walk trainer for sonar data set classification using multi-layer perceptron neural network and its hardware implementation

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ABSTRACT

First, this study proposes the use of the newly developed Stochastic Fractal Search (SFS) algorithm for training MLP NNs to design the evolutionary classifier. Evolutionary classifiers, often experience problems of slow convergence speed, trapping in local minima, and non-real-time classification. This paper also use four chaotic maps to improve the performance of the SFS. This modified version of SFS has been called Chaotic Fractal Walk Trainer (CFWT). To assess the performance of the proposed classifiers, these networks will be evaluated using the two benchmark datasets and a high-dimensional practical sonar dataset. For endorsement, the results are compared to four popular meta-heuristics trainers. The results show that new classifiers suggest better performance than the other benchmark algorithms, in terms of entrapment in local minima, classification accuracy, and convergence speed. This paper also implements the designed classifier on the Filed Programmable Field Array (FPGA) substrate for testing the real-time processing ability of the proposed method. The results of the real application prove that the designed classifiers are applicable to high-dimension challenging problems with unknown search spaces.

1. Introduction

Underwater targets' classification includes discrimination between a target and a non-target object as well as the background clutter which is one of the most complex and challenging research areas because of its different characteristics with other research areas [1–8].

Recently, using Neural Networks (NNs) is taken into consideration for their outstanding achievements [9–11]. High accuracy [12], versatility [13], inherently parallel structure which is very useful in hardware implementation [14,15] specifically Field Programbale Gate Array (FPGA) and then real-time processing are some of the outstanding features of NNs in the sonar dataset classification which motivated us to use the aforementioned classifier.

Multi-Layer Perceptron (MLP) NNs are one of the most applicable tools for data classification [16–18]. This feature (learning) is an essential part of all NNs [19]. Technically speaking, the algorithms that provide learning for NNs are called trainers [11].

Meta-heuristic algorithms (stochastic approach) are one of the most applicable trainers for training the NNs in the high-dimensional problems [19–21]. High local optimums avoidance is the main advantage of stochastic methods [22], specially for the high-dimensional data sets like sonar data set [23].

In the literature, there are some well-known meta-heuristic algorithms in NN training such as Particle Swarm Optimization (PSO) [24], Genetic Algorithm (GA) [25], Artificial Bee Colony (ABC) [26], Ant Colony Optimization (ACO) [27,28], and Differential Evolution (DE) [29]. The recently proposed meta-heuristic trainer algorithms are: Social Spider Optimization algorithm (SSO) [30], hybrid Central Force Optimization and Particle Swarm Optimization (CFO-PSO) [31], Charged System Search (CSS) [32], Chemical Reaction Optimization (CRO) [33], Invasive Weed Optimization (IWO) [34], Teaching-Learning Based Optimization (TLBO) trainer [35], Biogeography-Based Optimizer (BBO) [36], Gray Wolf Optimization (GWO) [37,38] and Lightning Search Algorithm (LSA) [39].

It is worthwhile to mention that No Free Lunch (NFL) theorem [40] is the main reason that causes this field of study become highly active. This theorem has mathematically showed that there is no meta-heuristic algorithm well suited to solve all optimization problems. Many researchers have motivated by NFL theorem to propose novel meta-heuristic algorithms, use existing algorithms for solving various problems, and improve the performance of the present algorithm. This also motivates us to investigate the efficiencies of the newly proposed algorithm called SFS trainer [41] in training MLP NN and then improve its performance for the sake of sonar dataset classification.

Organization of the paper is as follows: Section 2 discuses about the closely related works, Section 3 describes MLP NN training algorithms

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(i.e., SFS and CFWT). In Section 4, MLP NN is trained by trainers. The simulation results and discussion are described in Section 5. Finally, conclusions are presented in Section 6.

2. Closely related works

Regardless of differences between different meta-heuristic algorithms, dividing the search space into two discrete phases as "exploration" and "exploitation" are the joint feature of them. Exploration point to the ability of an algorithm to have extremely random behavior changing the solutions, significantly. Bigger changes in the solutions causes greater consequent exploration ability and then finding the promising regions. However, as the algorithm's tendency toward the exploitation phase become more than before, solutions' tendency toward the locally search become higher than generally search. It should be noted that both exploitation and exploration phases have to exist during the entire optimization process. A good optimization algorithm have to properly balance these two phases, simultaneously.

It is worth mentioning that there is no distinct border between exploration and exploitation phases. In other words, these two correlative phases conflict each other so that reinforcing one results in castrating another, considering the stochastic nature of meta-heuristic algorithms [37]. Finding the proper balance between two phases is the challenging point in types of research.

The SFS trainer is one of the most powerful meta-heuristic algorithms in the industrial global optimization problems. This potency is related to the efficient space exploration without sensitivity to the size of the search space [41]. Basically, SFS trainer is designed based on three main purposes: solving problems faster than other methods, solving large problems, and obtaining a robust method for solving problems [41].

Despite the aforementioned advantages, SFS trainer, same as other meta-heuristic algorithms, has the problem in finding the proper balance between exploration and exploitation, particularly in high-dimensional problems like sonar dataset classification. Meta-heuristic algorithms may become trapped in local minima with an improper balance between exploitation and exploration.

Before introducing SFS algorithm by Hamid Salimi as an optimization algorithm [41], researchers try to improve the fractal process modifying a fractal shape, some common methods such as: iterated function systems [42], strange attractors [43], L-systems [44], finite subdivision rules [45] and random fractals [46] are used.

Due to the novelty of SFS optimizer, there is little in the literature for improving its performance. However, Rahman [47] just used SFS optimizer, without any improvement, for monitoring an aerospace structure. This research compared the performance of SFS against several other optimization techniques to optimize the parameters of an SVM classifier. In this work, it has been proved that SFS has a better or comparable result compare to the other benchmark optimizers.

In [48,49] researchers have tried to eliminate the various drawbacks of the SFS by hybridization it with Differential Evolution (DE) and TOPSIS algorithms, respectively. Regardless of their promising results, increased computational cost is the main shortcoming of these methods. Considering the real-time processing necessity in sonar dataset classification, the hybrid methods are not applicable.

Improved Stochastic Fractal Search Algorithm (ISFSA) is a modified approach of SFS used for multi-objective optimal dispatch solution of solar-wind-thermal system [50]. ISFSA uses a newly proposed operator named scale factor instead of random operator in SFS algorithm to enhance exploration and exploitation capability during optimization.

Using a determined scale factor for SFS could yield better performance in some special cases. However, one determined strategy for all situation may not lead to a general optimizer with good performance. The aforementioned algorithms have various distinctive features that make them profitable for different problems. Table 1 indicates the advantages and disadvantages of various approaches of SFS.

So, these inevitable deficiencies should be noted especially in solving high-dimensional problems. The literature indicates that combining the chaos maps with meta-heuristic algorithms is one of the low computational-cost methods for improving both exploration and exploitation phases [50–55]. This is the motivation of this research, as well as NFL theorem, whereby we utilize chaotic maps to improve the performance of SFS optimizer for the first time. Chaotic maps are actually deterministic systems which also indicate stochastic behaviors. To have a real-time classification process, considering the parallel structure of the MLP NN and SFS trainer, the designed classifier was finally implemented on FPGA substrate.

To sum, in this paper, first, MLP NN has been trained by SFS trainer to classify sonar data (including real target and non-target), then improve this trainer by using chaotic maps, and finally, designed classifier was hardwarely implemented.

3. Trainer algorithms

3.1. Fractal

Mandelbrot introduced the fractal concept to describe geometric designs in nature [56]. Fractal means "fractured" or "broken". It has a Latina root named "fractus". Fractals are mathematical models or natural patterns that indicate a repeating event that exhibits at every scale. So, fractals are the features of an object or phenomenon that describe self-homology on all scales. For illustration, we simulate some samples of fractal phenomena in Fig. 1 [57].

3.2. Stochastic fractal search trainer

Stochastic fractals can be produced by adjusting the iteration process by stochastic formulas such as Gaussian and Brownian flight, Levy and self-avoiding walk, percolation clusters, narrow discharge branching (dielectric breakdown) and so on. [41]. Diffusion Limited Aggregation (DLA) method, which is a physically based model, can generate some stochastic fractals such as the bacterial colony clusters [58]. In this method, the first particle is at the origin of the plane, and then the diffusion is formed by generating other particles stochastically around the first particle. The diffusion process is simulated by using a mathematical model like Gaussian walk or Levy flight. Finally, the cluster is constructed by repeating the diffusion process. Potential theory and fractal method (DLA) are used for constructing the SFS trainer. Thus, SFS trainer uses three main laws to get a solution:

- Each searching agent (particle) has individually a potential energy.
- Each diffused particle causes other stochastic particles to be generated, and the energy of the source particle is divided between other generated particles.
- Only worthy particles subsist in each generation, and other worthless particles are discarded.

As shown in Fig. 2, particle diffusion leads the generation of new particles with various stochastic locations around source particle. The outcome of the diffusion process is the generation of new particles. SFS trainer uses both Levy flight and Gaussian walk to generate new particles in the diffusion process. A Levy flight is a fractal walk in which the steps are determined with the step-lengths having a heavy-tailed probability distribution function. A Gaussian walk is a stochastic walk having a step size that varies pursuant to a Gaussian distribution function.

Consider P particles, where $1 \leq P \leq 20$ [41], are taken care of finding the solution for a problem. Initially, each particle P_i has been stochastically located in the search space having the energy E_i acquired from Eq. (1):