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Research paper

Pity beetle algorithm – A new metaheuristic inspired by the behavior of bark beetles

Nikos Ath. Kallioras[a], Nikos D. Lagaros[a,*], Dimitrios N. Avtzis[b]

[a] Institute of Structural Analysis & Antiseismic Research, Department of Structural Engineering, School of Civil Engineering, National Technical University of Athens, 9, Heroon Polytechniou Str., Zografou Campus, GR-15780 Athens, Greece
[b] Forest Research Institute, National Agricultural Research Foundation, Hellenic Agricultural Organization Demeter, GR-57006 Vassilika, Thessaloniki, Greece

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ABSTRACT

In the past years a great variety of nature-inspired algorithms have proven their ability to efficiently handle combinatorial optimization problems ranging from design and form finding problems to mainstream economic theory and medical diagnosis. In this study, a new metaheuristic algorithm called Pity Beetle Algorithm (PBA) is presented and its efficiency against state-of-the-art algorithms is assessed. The proposed algorithm was inspired by the aggregation behavior, searching for nest and food, of the beetle named *Pityogenes chalcographus*, also known as six-toothed spruce bark beetle. This beetle has the ability to locate and harvest on the bark of weakened trees into a forest, while when its population exceeds a specific threshold it can infest healthy and robust trees as well. As it was proved in this study, PBA can be applied to NP-hard optimization problems regardless of the scale, since PBA has the ability to search for possible solutions into large spaces and to find the global optimum solution overcoming local optima. In this work, PBA was applied to well-known benchmark uni-modal and multi-modal, separable and non-separable unconstrained test functions while it was also compared to other well established metaheuristic algorithms implementing also the CEC 2014 benchmark and complexity evaluation tests.

1. Introduction

Engineers are challenged to pursue optimal solutions in complex systems, exploiting the ever increasing available computational power. Such systems must be as economic as possible yet efficient and/or strong enough to withstand the most demanding functional requirements arising during their service life. The traditional trial-and-error design approach is not sufficient to determine economic designs satisfying also durability criteria. On the other hand, design optimization provides a numerical procedure that can replace the traditional design approach with an automated one. During the last decades many numerical methods have been developed to meet the demands of engineering design optimization. These methods can be classified in two categories, gradient-based and derivative-free ones. Oft-used brute force design methodologies are systematically replaced by state-of-the-art nature-inspired algorithms, which are able to solve combinatorial problems. Heuristic and metaheuristic algorithms are nature-inspired or bio-inspired search procedures and belong to the derivative-free class of search algorithms. In nature, evolution is achieved by following rules such as the survival of the fittest or selective reproduction, while several species have also developed some sophisticated techniques concerning their search for food or nests. By studying these behaviors several algorithms referred to as heuristic and metaheuristic algorithms were inspired. Some of the modern and well established metaheuristic algorithms are: particle swarm optimization, inspired by the social behavior of bird flocking (PSO) [1], ant colony optimization, based on the foraging behavior of ants [2], artificial bee colony algorithm [3], firefly algorithm, inspired by the flashing behavior of fireflies [4], cuckoo search algorithm, mimicking the brood parasitism of cuckoo species [4], simulated annealing, based on the process of slowly cooling heated object to avoid defects [5], harmony search, inspired by the improvisation procedure of jazz bands [6], differential evolution [7], ray optimization, inspired by Snell's light refraction law [8], genetic algorithms, inspired by natural selection [9], bat algorithm, inspired by the echolocation behavior of microbats [9], dolphin echolocation, inspired by the biological sonar that dolphin use to navigate and hunt [10], krill herd, based on the simulation of the herding behavior of krill individuals [11]; variants of existing methods [12] chaotic swarming of particles, combining swarm intelligence and chaos theory [13] or the thermal exchange optimization, based on Newton's law of cooling [14].

Swarm optimization characterize a stochastic, population-based group of algorithms inspired by the social behavior of birds flocking,

* Corresponding author.
E-mail addresses: nkallioras@yahoo.com (N.A. Kallioras), nlagaros@central.ntua.gr (N.D. Lagaros), dimitrios.avtzis@fri.gr (D.N. Avtzis).

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fish schooling etc. [15]. Briefly, an initial population of particles (birds, fish, etc.) are positioned randomly into the multidimensional search space examined [15]. Every particle, whose position represents a solution, "travels" into the search space seeking for a better position/solution. During the iterations of the algorithm each particle adjusts its position based on its own experience, built by memorizing the best position encountered, as well as that of neighboring particles. PSO algorithms combine local search (self-experience) with global search (neighboring experience), aiming to balance exploration and exploitation. This procedure continues until the termination criterion is satisfied [16]. PSO algorithms have attracted a significant amount of interest in the past years [17–19], since it was proved efficient in handling real-world optimization problems too [20].

In this work, a new metaheuristic algorithm called pity beetle algorithm (PBA) [21] that belongs to the swarm optimization class of algorithms is presented and its efficiency is studied against state-of-the-art metaheuristic algorithms. In addition to the work presented in [21], a detailed description of the algorithm is presented regarding: i) the biology of the beetle, ii) the random sampling technique, iii) the sensitivity analyses over its parameters, and iv) the performance of the algorithm over various tests. The proposed algorithm was inspired by the aggregation behavior of *Pityogenes chalcographus* (Coleoptera, Scolytinae), also known as six-toothed spruce bark beetle. This beetle has the ability to infest large forest areas starting from a single brood (colony), employing a strategy that is more or less common among the species of Ipini tribe [22]. In particular, it usually attacks less healthy trees first, which are more susceptible, however, when its population exceeds a specific threshold, it can also attack robust trees as well. Initially, a number of male bark beetles (commonly called pioneer beetles) fly through the forest – searching in space for suitable (weakened) trees – solution vectors. These pioneer beetles are searching randomly into the forest for suitable hosts (trees), when a host is found, pheromone is spread, inviting other beetles to the host. Each male beetle creates a nest in the tree while feeding from the bark of the tree. Female beetles are attracted to the nests and new generations of beetles are created. Every offspring is then taking the role of pioneer beetle searching for a new host either randomly inside the forest or at close range from its birth position. Once a new host is identified, the procedure described above is repeated. As it was proved in this study, PBA can be applied to NP-hard optimization problems regardless of the scale, since PBA has the ability to search for possible solutions into large spaces and to find the global optimum solution while overcoming local optima. In this work, PBA was applied to well-known benchmark unimodal and multi-modal, separable and non-separable unconstrained test functions while it was also compared to other well established metaheuristic algorithms. In particular, the performance of the algorithm is examined for thirteen benchmarking test function while sensitivity analysis on the performance of the algorithm with reference to its parameters is also presented. Furthermore, the algorithm is compared against various modern and well-established metaheuristic algorithms in order to further evaluate its efficiency implementing also the CEC 2014 benchmark [23] and complexity evaluation tests.

2. Pity beetle algorithm

In this section the biology of the six-toothed bark beetle along with its numerical implementation are described.

2.1. *Pityogenes chalcographus*

Within the subfamily of Scolytinae, belong some of the most important forests pests worldwide. Despite the great differences among the various species, a common feature for all of them is the employment of a rather sophisticated system of communication that is based on chemical signals (pheromones). By using these signals, bark beetles are often able to cultivate mass population outbreaks with devastating effects on forest health. Among the different Eurasian bark beetle species, the six-toothed spruce bark beetle, *Pityogenes chalcographus* (Coleoptera, Scolytinae) is one of the most common and important bark beetles in Europe [24] that infests mainly Norway spruce (*Picea abies*) together with pines (*Pinus* sp.) and larch (*Larix decidua*) [22,25–27]. *P. chalcographus* occurs widely in central and northern Europe, while it has been also found in Elatia (Drama, Greece) [28]. *P. chalcographus* is able to establish two generations per year, depending on the environmental temperature [29]. However, under favorable conditions a third generation may also be established while in higher elevation, the number of generations is restricted to only one [25,30–32]. It exhibits a polygamous mating behavior, with the male mating with 3 to 6 females. The males of *P. chalcographus* bore into the phloem of already weakened trees excavating there a nuptial chamber. While feeding, they transform host terpenes into pheromones, attracting females, with which they mate in the nuptial chamber. From this chamber, in a star-like arrangement, females deposit 40–70 eggs in egg niches [31].

In summary, the process followed by *P. chalcographus* particles can be divided into stages. Initially, pioneer male beetles locate a suitable host (searching stage) by exploiting the chemical traits that weakened trees emit. When these beetles start feeding on the host, they produce an aggregation pheromone that attracts males and females (aggregation stage), increasing locally the population. Once a specific population threshold is surpassed, then the defence mechanisms of the host can no longer contain this mass infestation, while at this population level, both robust and weakened trees can be attacked. However, as an overcrowded host tree can have a negative impact on infestation (less feeding space, higher probability of infectious diseases), when the infestation density becomes too high then feeding beetles emit an anti-aggregation pheromone that discourages more beetles to attack this tree, turning them to other trees (anti-aggregation stage). By doing that, infestation expands gradually into the forest creating groups of dying or dead trees around the initially attacked tree.

2.2. Numerical implementation of PBA

The mathematical formulation of an optimization problem can be expressed in standard mathematical terms as a non-linear programming problem, which in can be stated as follows:

$$\min F(\boldsymbol{x}),\ \boldsymbol{x} = [x_1, x_2, \ldots, x_D]^T$$
$$L_i \le x_i \le U_i,\ i = 1, 2, \ldots, D \tag{1}$$

where $F(\boldsymbol{x})$: $R^D \to R$ is a real-valued objective function to be minimized (without loss of generality) and R is the set of real numbers, $\boldsymbol{x} \in R^D$ is the design variables vector of dimension D, while L_i and U_i are the lower and upper bounds of the ith design variable.

In this section, the numerical simulation of the six-toothed bark beetle's peculiar new generation creation behavior is provided. In particular, PBA is based on the implementation of the suitable host search and reproduction behavior of the bark beetles. Contrary to PSO the swarm in PBA is called *population*. In a D-dimensional search space, the jth member of the population at the gth search step (generation) of the algorithm is defined by its current position vector $\boldsymbol{x}_j^{(g)} \in R^D$. PBA consists of three basic steps: *Initialization, New Hypervolume Selection Pattern* and *Update Population Position*, while a population consists of males and females; some males act as *pioneer* particles that search for the most suitable host. In the first step of the algorithm, the first population (gallery/colony) position is generated randomly into the search space (first generation). In the second step, particles of the initial population move to other positions inside different hypervolumes, in order to create there new populations (second generation). In every generation new populations are generated and in the third step, new populations replace the previous ones. A flowchart of PBA is presented in Fig. 1, the algorithmic parameters are provided in Table 1, while the steps of the algorithm are described in the next sections. The three-step procedure is