NATURE- AND BIO-INSPIRED OPTIMIZATION: THE GOOD, THE BAD, THE UGLY AND THE HOPEFUL

OPTIMIZACIÓN INSPIRADA EN LA NATURALEZA Y EN LA BIOLOGÍA: LO BUENO, LO MALO, LO FEO Y LO ESPERANZADOR

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1. INTRODUCTION

Nowadays, optimization has become an important issue for industrial systems and product development. From an engineering perspective, optimization implies adjusting or fine-tuning system designs considering one or more performance factors. Unfortunately, for many complex problems there is no optimization technique that can achieve the optimum solution in a reasonable computation time. As a result, the optimization process is often done manually.

In recent years a myriad of optimization techniques have appeared, all inspired by phenomena observed in nature, such as behavioral patterns in animals (such as the exploration and search for food, moving, hunting, …), physical and chemical processes [1]. These techniques, often referred to as nature- or bio-inspired optimization algorithms, allow users to optimize a problem without requiring special knowledge about it: they only need to be informed about the fitness function to be optimized, and the mechanisms by which new candidate solutions can be produced. Each algorithm defines how existing solutions can be combined and modified to create new ones in an intelligent way to search for the best solution. Although they cannot guarantee that the optimum solution will be eventually achieved, they can automatically yield good solutions in reasonable computation times. These features make bio-inspired optimization proposals a promising research area and a great alternative to optimize complex processes, as has been already showcased in many real-world problems.

In this work we present nature- and bio-inspired optimization from a global perspective. We describe techniques falling in this area, their evolution, how they operate, and why they bridge an important gap not covered by previous optimization techniques. On a critical note, we also give a clear view of the current situation in the area, indicating the positive aspects and issues that should be urgently improved. Considering this critical view, we suggest promising trends that we believe will lead us to a brighter future in nature- and bio-inspired optimization, plenty of successful examples of their application to real-world engineering problems.

The manuscript is structured as follows: Section 2 describes bio-inspired optimization and exposes the reasons and advantages that make this area interesting from the scientific and practical points of view (focusing on introducing what they are and why they are useful). In Section 3 we examine the exciting panorama of recent applications in which nature- and bio-inspired optimization has become a central technology (the *good*), the upsurge of novel metaphors for the design of new proposals that do not lead to innovative solutions (the *bad*), and poor methodological practices that draw misleading conclusions that must be avoided in this field (the *ugly*). Finally, Section 4 summarizes the paper and highlights what is next to be done in the area of bio-inspired optimization (the *hopeful*), especially for engineering applications.

2. NATURE AND BIO-INSPIRED OPTIMIZATION: WHAT AND WHY?

The beginning of nature and bio-inspired algorithms dates back to the previous century. In the 1960s, the first bio-inspired solvers were proposed, mainly inspired by evolutionary principles and concepts: Genetic Algorithms [2], Evolution Strategies [3], Evolutionary Programming [4] and Genetic Programming [5]. In the 1980s, Simulated Annealing was originally presented, whose source of inspiration was found in the annealing process in metallurgy. In the 1990s, additional bio-inspired algorithms were proposed: Ant Colony Optimization, mimicking how ants find the best route to sources of food and communicate to each other via stigmergy; Particle Swarm Optimization, relying on the collective behavior of bird flocks, or Differential Evolution, DE, very influenced by Genetic Algorithms [1]. DE is a significant proposal because, although it initially evidenced a high sensibility of its performance with respect to its parameter values, recent versions of DE have overcome this weakness and have proven to be among the most competitive algorithms as per their results in international competitions [6].

These techniques have several characteristics in common:

- They can be applied to a diversity of optimization problems because they only require 1) a numerical measure of the quality of a solution that helps discriminating better solutions (fitness functions) and 2) a definition of the algorithmic steps by which newly improvised solutions to the problem are created/modified and/or combined.
- Most of them operate in a similar fashion: they use a repository of solutions (population or swarm) that are modified by intelligent search operators, evolving the contents of the population to yield increasingly better solutions to the problem. Usually the search is guided by the solution(s) with best fitness value in the population. The specific operators applied over the population to evolve it depend on the particular algorithm in use.
- The evolution process is repeatedly applied over the solutions stored in the population until a stopping criterion is met, measured in terms of a fixed number of evaluated solutions or a maximum running time.
- Since not all possible solutions to the problem are explored, bio-inspired optimization methods cannot guarantee that the optimum solution to the problem will be encountered over the search. However, in many complex problems the solutions found over the search are good enough for adopting them in practice.

Why are these algorithms interesting, considering that they do not guarantee the optimum? Because the majority of real-world problems do not meet the mathematical requirements imposed by other mathematical optimization tools that could guarantee this optimality (e.g. convexity). Consequently, optimality-guaranteeing solvers cannot be applied. In such situations, the only way to achieve the optimum without a doubt is by performing an exhaustive search, which is impossible for many problems due to the huge cardinality of their domain search. On the contrary, the lack of requirements imposed by nature- and bio-inspired algorithms make them a suitable option for any type of problems, obtaining competitive results independently of the size of the domain search. Even more, they can tackle not only problems with constraints (as often occurs in engineering problems) but they can also consider more than one optimization objective over the search (very frequent in real-world problems where the quality of the sought solution is driven by more than one factor).

The plethora of biologically inspired optimization algorithms is increasing every year, as almost any process observed in nature can be transformed into an optimization algorithm. In particular, the last decade has witnessed a true explosion of newly proposed bio-inspired solvers. Fig. 1. shows the exponential growth of works related to this field in the last 15 years. This has stimulated efforts towards gathering and classifying these proposals under clear taxonomic principles. Among such efforts, we highlight [7], in which two taxonomies categorizing these algorithms are presented. The first taxonomy classifies them based on their natural or biological inspiration, meanwhile in the second one the algorithms are organized based exclusively on their behavior. An insightful conclusion from this latter taxonomy is the fact that behaviorally, all bio-inspired algorithms can be summarized in a subset of influential methods (DE, GA, ACO, PSO and ABC). This finding connects with *the bad and the ugly parts* of bio-inspired optimization research, which we critically discuss in what follows.

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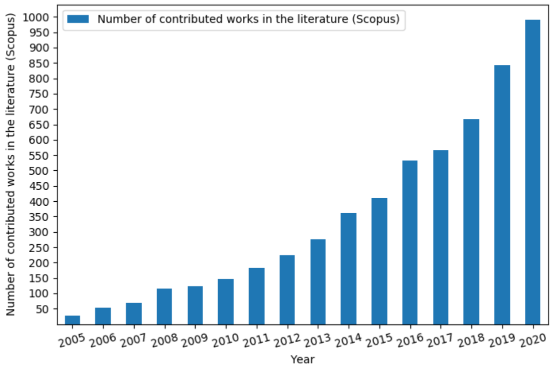

Fig. 1. *Number of papers with bio-inspired optimization and nature-inspired optimization in the title, abstract and/or keywords, over the period 2005- 2020 (Scopus database).*

3. NATURE- AND BIO-INSPIRED OPTIMIZATION: THE GOOD, THE BAD AND THE UGLY

In this section we analyze the current situation of nature- and bio-inspired optimization, stressing on the numerous applications leveraging results from this research area (the good), the lack of algorithmic innovation in algorithms inspired by novel metaphors (the bad) and the poor practices (the ugly) experienced by the area in recent times.

3.1. THE GOOD: A PRESENT AND FUTURE PLENTY OF EXCITING APPLICATIONS

An undeniable fact is that nature- and bio-inspired optimization algorithms have been applied to a great variety of optimization problems emerging in different disciplines. In [8] many examples are presented regarding the usage of bio-inspired techniques to solve real-world engineering processes. Furthermore, structural design and civil engineering have also largely embraced the benefits of nature- and bio-inspired solvers to assorted problems, including the multi-criteria design of structures [9], logistics and supply chain management [10], to cite a few.

From the research perspective, several worldwide competitions have developed over the years to test new proposals in an unbiased and replicable way. In such competitions DE has created a great impact as the core meta-heuristic algorithm of winning competitors in the global optimization competitions held in renowned conferences (GECCO and CEC) over the last decade [11]. Recently, these algorithms have gained momentum by virtue of the evidence reported around their usage to evolve and improve other Artificial Intelligence techniques: most notably, the optimization of the structure and training parameters of deep neural networks [12], or the creation of new data-based models from scratch (i.e. by evolving very essential data processing primitives) that has been recently presented in the groundbreaking work by Google [13].

3.2. THE BAD: NOVEL METAPHORS NOT LEADING TO INNOVATIVE SOLVERS

As previously mentioned, an ever growing amount of new bio-inspired optimization techniques has been proposed in recent decades (see Fig. 1). This overwhelming number of alternatives could make it difficult to choose an appropriate option for a given optimization problem. The vast number of proposals not only casts doubt on the convenience of choosing one or another algorithm, but it has also produced solvers that, even if relying on different metaphors, are mathematically too similar to already existing optimization algorithms. In other words, despite the diversity of methods considering their natural inspiration, such a diversity does not hold as far as mathematical differences are concerned, as exposed by recent studies [14].

Particular reasons aside, some algorithms are not created to solve problems and provide a practical advantage, but mainly to be published and gain notoriety without any consideration to their lack of algorithmic novelty and innovation. Examples of this controversy can be found in [15], which claims that several algorithms can be considered as particular cases of previous ones. In these cases, the new proposals may be simpler than their preceding ones, but fail to attain better results. Summarizing, the inspirational novelty of the

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proposal design occludes a comparatively worse performance than other established solvers, or even the mathematical equivalence of its algorithmic steps when compared to other algorithms.

3.3. THE UGLY: POOR METHODOLOGICAL PRACTICES

An alarming issue that prevails in the area besides the number of metaphor-based proposals is the lack of a fair experimental study to prove their competitiveness when compared to existing solvers. In many research contributions, the newly introduced bio-inspired optimization algorithms are not compared to relevant techniques, but only to classical solvers already surpassed by more recent approaches. Therefore, improving their performance in a benchmark is not actually a reliable proof of performance competitiveness, but rather a convenient choice of comparison counterparts. Moreover, the experimental design is often not right: for example, the optima of the tested functions is often at the center of the domain search, which favors solvers that focus their search over this region of the solution space. In addition, the statistical significance of the performance gaps reported among algorithms is also frequently overlooked despite the variability of the results imprinted by the stochastic nature of these algorithms.

Another important concern in the area is the questionable reproducibility of published studies: the only proof that a proposal is competitive is done experimentally, so it is of utmost importance that results can be reproduced, checked and verified by third parties, ideally by a different team to that proposing the new algorithm. Unfortunately, in the majority of cases this is not possible because the implementation of the algorithms is not available, or because important information for the replicability of the experiments is missing or not reported whatsoever [16].

More and more researchers are advocating that a novel metaphor is not enough for a new bio-inspired algorithm to be considered a step beyond the state of the art. Instead, several factors should be proven with empirical evidence, such as a superior performance to the state of the art, innovation in the design of its mathematical components and operators, or non-functional benefits that make them more appropriate for real-world optimization problems when compared to other alternatives, e.g. less computational complexity, smaller memory footprint or faster convergence properties [17].

We strongly urge interested readers to embrace the methodological practices recommended in [18], considering proposals that have been tested against modern techniques, using standard benchmarks and with adequate statistical testing to shed light on the relevance of performance gaps. Unfortunately, many recent proposals do not follow these guidelines, remaining as evidence of the *ugly* side that still prevails in this research area.

4. THE HOPEFUL: WHAT IS NEXT IN NATURE- AND BIO-INSPIRED OPTIMIZATION?

The first *grand challenge* within bio-inspired optimization is to improve methods discovered so far by the community, and leave behind the search for new biological sources of inspiration to conceive new models. An unified notation and description of new bio-inspired proposals could be useful to ascertain whether there is any value in them, and letting everybody acquire a clear, unambiguous knowledge of where the state of the art of the area currently stands.

Another direction of interest for the future of bio-inspired optimization research is the development of frameworks and libraries that could ease the application of these algorithms to complex engineering problems, without any expert knowledge about them. For those engineering problems in which evaluating a single solution can take a long time (such as those cases where simulations are needed for the purpose, e.g. computational fluid dynamics), it is becoming increasingly necessary to design algorithms specially designed to cope with this circumstance. Scenarios with conflicting objectives are also in demand by engineering processes, stimulating further research on bio-inspired solvers for real-world multi- and many-objective optimization problems.

Finally, we foresee that bio-inspired optimization will take a capital role when used for improving the generalization of Artificial Intelligence techniques, capitalizing on the inherent parallelism of this class of algorithms. We warmly emphasize the potential of bio-inspired solvers to evolve data processing primitives, which can unveil radically new generations of data-based models and learning algorithms that differ structurally and operationally from those known today.

To summarize, as a main conclusion, we highlight that nature- and bio-inspired optimization is more than just a passionate field of research with similar difficulties to other fields with an increasing number of proposals. Algorithms belonging to this field are great tools for optimizing complex engineering problems. Advances in the field benefit us all by offering wider possibilities and an uncharted territory for further research, which will crystallize in practical impact whenever good methodological practices and a global commitment of the community for valuable research is ensured. It is only by following this principled path when innovative solvers with nature- and bio-inspired algorithms at their core will proliferate vigorously in real-world engineering applications.

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