Bio-inspired Computing: Bio-inspired Algorithms and Application

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***Abstract*—Nature and its diverse flora and fauna have impacted lives since times immemorial. Evolution in mammals, breeding and foraging characteristics in insects and birds, and ecological growth have motivated us to derive efficient and optimized techniques for data handling and optimizing computational tasks. Various meta-heuristics, hyper-heuristics, and multi-objective problems find their solutions using bio-inspired algorithms. This report describes the underlying principles, applications, and use-cases of Evolutionary, Swarm Intelligence, and Ecology-based algorithms.**

***Index Terms*—meta-heuristics, hyper-heuristics, bio-inspired algorithms, multi-objective optimization problems**

I. Introduction

Human beings and ecological diversity stand unmatchable in their capabilities and capacities. An urge to create software and machines that could think like humans and provide results equivalent to the brilliancy of humans prevailed among computer scientists and developers around the globe. Increased knowledge of the biological patterns and the complexity of the computational tasks provoked more researchers to develop algorithms inspired by them.Technological advancements have exhibited a world that was unimaginable a few decades ago. An explosion of data and extensive need for analysis and modeling using machine learning and deep learning techniques have upsurged the need for the development and usage of eloquent methodologies inspired by nature and bio-diversity. refer to [1] to describe the development of the most popular twelve bio-inspired algorithms.

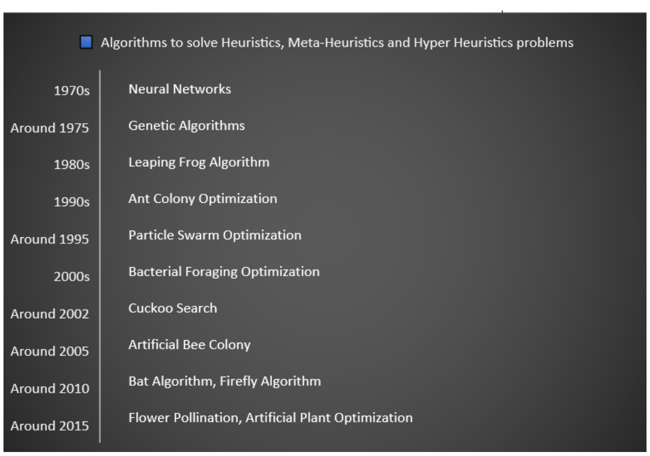

Fig. 1. Development of Bio-Inspired Algorithms and their application in solving complex problems

The human brain and its sophisticated decision-making capability using input from various sources form the basis of neural networks. Insects like ants, wasps, and bees have enabled the formulation of algorithms based on their foraging and preying mechanisms. Flight and food-searching behavior of cuckoo, frogs, and eagles led to the development of algorithms for solving problems involving complex computations. Plants and flowers motivated researchers and scientists to design techniques to find and search for optimal solutions for hyper-heuristics problems. Rapid development in biological behavior study and subsequent algorithm generation has produced a lot of literature in the field. A lot of algorithms remain un-explored and un-implemented. Due to the accuracy and popularity established by a particular algorithm, others remain unidentified, which leads to the force-fitting of an algorithm to all computational problems. The refinement of an algorithm to produce results with high accuracy happen gradually and sometimes takes decades of effort. Neural networks were developed around the 1970s but gained momentum only five to six years ago. Similarly, several other algorithms got attention recently, such as Ant Colony Optimization, Particle Swarm Optimization, and Artificial Bee Colony Optimization algorithms. Their usage remains limited compared to Neural Networks since machine learning and deep learning packages formulated for them remain most used and trusted. An exponential increase in data has mandated the investigation and enhancement of other algorithms to enable multi-objective optimizations with efficient results. We observe in [1] that only a few algorithms have extensive usage, whereas the rest have below 0.5 percent.

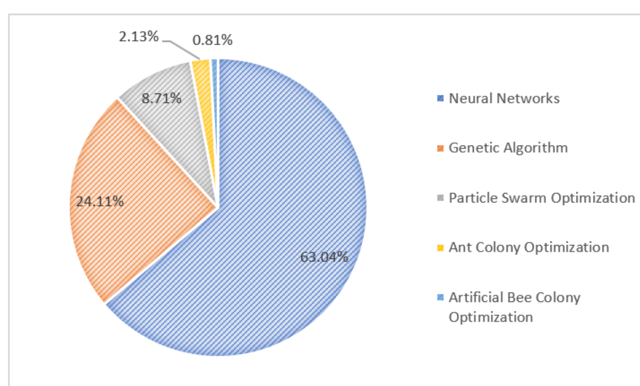

Fig. 2. Research articles, literature availability and frequency of usage of Bio-Inspired Algorithms

The vast generation of textual data, images, videos, sensor data, maps, and location-based data requires the inculcation of meta-heuristic and hyper-heuristic strategies to develop an efficient and optimized search algorithm. Meta-heuristics are independent of the problem and find application in many domains that need computational efficiency. Multi-objective problems involving search, optimization, and maintaining time efficiency need efficient computational resources and sophisticated infrastructure. These multi-objective problems can be solved using bio-inspired algorithms. Hyper-heuristics adopt efficient machine learning and deep learning techniques to solve search optimization problems. It ensures computational resource utilization and incorporates probabilistic, regression, and classification approaches to solve various multi-objective problems. Using a Bio-inspired algorithm ensures that a computational solution, with time and space efficiency, resource utilization is obtained hence, fulfilling multiple objectives.

II. Review of Bio-Inspired Algorithms and Applications

We review the principles and discuss the applications of bio-inspired algorithms. The twelve algorithms discussed in [1] fall under these major categories, namely Evolutionary algorithms, Swarm Intelligence, and Ecology-Plant Based Algorithms.
The derivation and implementation of these bio-inspired algorithms are out of the scope of this report.

A. Evolutionary Algorithms

The evolution of living species, especially human beings, inspired the development of evolutionary algorithms. Neural Networks and Genetic Algorithms fall under this domain.

1) Neural Networks: It is the most widely used bio-inspired algorithm. The neural network represents neurons in an intelligent organism. The neurons are self-adapting and self-organizing, connected in multiple layers in a network [1]. They learn based on feedback and inputs from their surroundings. Machine-learning and Deep-Learning techniques enable the implementation of neural networks.

Applications: Neural Networks find usage in pattern recognition, problem detection, rule-based associations, and classification problems [1]. Applications in time-series and non-linear regressions are possible. Recurrent neural networks allow language modeling and speech modeling tasks. It can solve predictive modeling tasks with efficiency [2]. Combination with other algorithms is possible for an optimized result [2].

2) Genetic Algorithm: It conceptualizes computational techniques used by nature to create future generations using four operators. The inheritance, cross-over, reproduction, and mutation operators obtain working solutions that possess the positive characteristics of the parent while the inefficient properties are left out. The genetic algorithm does not solve very complex high-dimensional, multi-modal problems [1].

Applications: Genetic Algorithms are capable of job-scheduling, project selection, and network analysis in the industrial domain. It solves multi-variate decision-making, parallel computation problems, navigation problems, and load balancing [1].

B. Swarm Intelligence Algorithms

Inspired by the foraging, mating, and preying behavior of birds, insects, mammals, and bacterial organisms, swarm intelligence-based algorithms are the second most widely used domain of algorithms. Several search-optimization computational techniques originated with inspiration from swarm behavior.

1) Leaping frog Algorithm: The preying and food hunting mechanism of frogs inspires this algorithm. It focuses on searching for the optimal solutions for minimization and maximization problems. The principle behind the algorithm is simple. The virtual frogs represent the vectors and partitions into sub-populations called memeplexes and sub-memeplexes are formulated [1]. The worst frog leaps the food source using its own experience and the knowledge of the best frog. If the position is better, the leap stops, or the entire process repeats to find an optimized solution [1].

Applications: Leaping frog Algorithms finds usage in network scaling, cost minimization problems, permutation-based searching, and optimization problems. It is computationally complex to implement.

2) Ant Colony Optimization: The process of communication between ants while foraging inspires this algorithm. The ants lay pheromones while exploring the environment to direct each other. The pheromones represent numerical information used to form candidate solutions. These solutions are based on probabilistic search[1]. The most optimal candidate solution forms the basis of solutions to a problem.

Applications: Ant colony optimization techniques solve searching and optimization-based problems. Their usage in signal-processing systems, satellite control, target tracking, and social graph mining [1] is most common.

3) Particle Swarm Optimization: The Collective Behavior of a school of fishes, a swarm of insects, or a flock of birds inspires the particle swarm optimization algorithms. It suits the problems wherein discontinuous function is to be optimized and has non-linearly related parameters [1]. The entire group gives their feedback for the generation of fitness functions, and the most optimal candidate solution, with high fitness value, is the solution to the problem.

Applications:Particle swarm optimization gained popularity around the 1990s and found usage in deterministic and constraint-based optimization problems. It is also used in scheduling, segmenting digital images, and multi-criteria decision problems.

4) Bacterial Foraging Optimization: It draws inspiration from the elimination of organisms because they are less capable of preying and searching for food for their survival. Usage of operators like swarming, reproduction, chemotaxis, and elimination-dispersal provides an optimal solution [1]. The algorithm finds an optimal solution based on dispersion and elimination principles. It exhibits poor convergence for complex optimization problems [1].

Applications: It finds usage in job scheduling operations, multi-objective problems, pattern recognition and dynamic resource allocation.

5) Cuckoo Search: The breeding behavior of cuckoos inspires the algorithm. The cuckoo exhibits co-operative breeding, nest takeover, and intra-specific brood parasitism [1]. These mechanisms formulate the algorithm. The nests in which eggs lay and new candidate solution generation identification is possible through a Levy flight. An egg or multiple eggs laid by cuckoo form candidate solutions. Re-distribution and mixing of eggs enable the formulation of an optimal solution.

Applications:It finds application in multi-objective scheduling and allocation problems. Cuckoo search algorithm finds extensive usage in path identification for network analysis and knapsack problems [1].

6) Artificial Bee Colony Optimization: The algorithm draws inspiration from the communication, task allocation, foraging, site selection, and mating behaviors of honey bees [1]. It finds the most optimal numerical solution based on the cumulative and collective decision of the worker honey bees. The fitness functions based on various parameters derive several candidate solutions. The most optimal function based on parametric evaluations forms the solution.

Applications: Artificial bee colony algorithm solves routing and task allocation problems. It is computationally efficient for multi-modal, multi-objective, and multi-variate problems [1]. It finds usage in maximization minimization and multi-level thresholding problems.

7) Firefly Algorithm: The luminescent signaling mechanism of fireflies to avoid prey forms the basis of this algorithm. The best-suited solution formulates by creating a population of several fireflies and modifying different fitness parameters in the process [1]. The process runs iteratively until an optimal solution emerges. The firefly algorithms perform better than other swarm algorithms with multi-modal functions.

Applications: Firefly algorithm finds usage in multi-modal functions, NP-hard problems, continuous and discrete search problems [1]. Combination with other swarm intelligence algorithms is possible to achieve high optimization. It provides an efficient computational complexity.

8) Bat Algorithm: It uses the echolocation behavior of bats to find food and prey. Fitness values determine the optimal candidate solution. The flight velocity, flight frequency, and loudness of the cry are adjusted iteratively to obtain an optimal solution [1].

Applications: It applies to multi-objective optimization, constrained optimization search, combinatorial optimization and scheduling, inverse parameter estimation, classification, clustering, vector matching, and multi-valued systems-based optimization [1]. The convergence challenge remains suspended when using the bat algorithm. It provides better performance than Genetic Algorithms and Particle Search Optimization in constrained optimization tasks.

C. Ecology-based Algorithms

Nature encapsulates various species and categories of seasonal and non-seasonal plants. Each of them exhibits a specific survival trait. These behavioral competencies provoked the researchers and scientists to determine algorithms that could solve complex problems in computations by applying these techniques. Several algorithms inspired by plant and their survival mechanisms have gained attention.

1) Flower Pollination Algorithm: It draws inspiration from the pollination mechanism in flowers. A solution is analogous to pollen, and the pollination process stimulates the best pollens that are the candidate solution vector iteratively to obtain an optimal solution [1]. The pollination pool constantly updates if the fitness function is not optimal. It is computationally complex to implement.

Applications: Flower Pollination Algorithm finds application in civil engineering, energy management, emission control, electromagnetism, and linear programming problems[1]. It solves global optimization problems and high complexity convergence problems.

2) Artificial Plant Optimization Algorithm: It draws inspiration from the growth mechanism in plants. Oxygen, water, and sunlight affect photosynthesis in plants [1]. Similarly, essential parameters for determining the candidate solution are selected. Considering Oxygen and water would be distributed equally, the plant growth would be affected if the light distribution is not uniform. Phototropism [1] is used to find an optimal solution, which states that plant growth takes place in the direction of light. The ideal solution receives all the parametric values in equity and is the best solution.

Applications: It finds application in global optimization problems like protein folding and wireless sensor networks [1]. It applies to network configuration simulation and molecular structure analysis [1].

III. Recent History and Evolution of Bio-Inspired Algorithms

Bio-inspired algorithms have evolved and refined since their development. Complex biological processes inspire researchers to develop efficient and optimized problem-solving algorithms. Patterns and behavior studies of animals such as whales, packs of wolves, lions, eagles, and others impact the creation and usage of new techniques in computation. The evolution of bio-inspired algorithms enables us to categorize them into their domains of application, theoretical or practical advancements. Several algorithms failed to capture the attention of researchers and hence lost prominence. As discussed in [1] various bio-inspired algorithms can be categorized into four quadrants.

Quadrant 1: Zone of Theory Development
Amoeba
Artificial plant optimization
Bean optimization
Dove
Eagle
Fruit fly
Glow-worm
Grey wolf algorithm
Krill-herd
Lion
Monkey
Wolf

Fig. 3. Summary of bio-inspired algorithms which reflect the zone of development

Various biological entities inspired the development of these algorithms. As described in [1], we see a lot of scope in both incremental development of the algorithms and comparative analysis among the algorithms. There is a tremendous scope of refinement of these algorithms.

Quadrant 2: Zone of Applications
Bacterial foraging
Bat algorithm
Bee colony
Cuckoo search
Firefly algorithm
Flower pollination

Fig. 4. Summary of bio-inspired algorithms which capture the zone of Application

These algorithms are mature in their theoretical concepts and apply to various disciplines. There is tremendous scope for application in business management, intelligent systems, expert systems, and artificially intelligent robots. Areas like industrial engineering, information systems, financial management, and supply chain management [1] find applications of these algorithms.

Quadrant 3: Zone of Rediscovery
Leaping Frog
Shark
Wasp

Fig. 5. Summary of bio-inspired algorithms which need rediscovery

These algorithms failed to interest the research community and lost relevance due to challenges faced in implementation [1]. Academic communities and researchers might want to explore and combine it with other algorithms.

Quadrant 4: Zone of Commercialization
Ant colony optimization
Genetic algorithm
Neural Networks
Particle swarm

Fig. 6. Summary of bio-inspired algorithms which reflect the zone of commercialization

These algorithms are adopted and extensively researched by the scientific community [1]. Development of modules and machine-learning packages for implementation enables the usage in meta-heuristics and multi-objective problems. Neural networks form the principle of intelligent machines. Robotic enhancements enable more life-like devices capable of self-healing and self-restoration properties [3].

IV. Recent Applications of Bio-inspired Optimizations

A wide variety of domains finds applications of Bio-inspired algorithms. Usage of these algorithms in medicine, social media data analysis, cyber security, and gaming [4] have advanced. We will discuss the areas of applications in brief.

A. *Social Network Analysis:*

The research community is developing strategies for efficient data mining, data analysis, social data mining, natural language processing, and graph theory [4].Evolutionary Algorithm approaches [4] have been utilized to solve single- and multi-objective problems modeled over the social network structures [4]. Bio-inspired techniques are used to guide the searching for inner structures, such as clusters or communities and finding the most appropriate nodes, optimizing and analyzing the diffusion of information throughout the network [4]. It is used for isolating the network of selected central nodes or studying the network dynamics when modeling a non-stationary information source[4]. Many practical applications inspired by optimization techniques, such as e-health, smart cities, or energy transmission networks [4] have been possible.

B. Medicine and health systems:

The medical domain has benefited from Artificial Intelligence methods[4] since the development of the first expert systems for disease diagnosis [4]. The increasingly complex challenges faced by medical and health systems in the last years have grown the need for new decision support systems aimed to help health experts improve the diagnosis accuracy [4]. Artificial Bee Colony (ABC) algorithm is proposed to determine the IIR filter coefficients efficiently [4]. It is capable of eliminating Doppler noise present in the aortic valve [4]. Artificial Bee Colony is used to automatically detect region with lumps around breasts or nipple using bilateral subtraction [4]. An improved (Ant Colony Optimization) ACO algorithm which is indeed a particularly prevailing medical application addressed by the bio-inspired optimization community is used to segment MRI brain images [4].Modern bio-inspired approaches are lately entering the health arena which resorts to the Firefly Algorithm for breast cancer classification [4], or where the Bat Algorithm is used to isolate skin lesions in medical images [4].

C. Cybersecurity and Privacy:

Bio-inspired methods have been lately applied to improve the overall response and resiliency of computer-based systems, thereby facing with success common computer attacks such as denial-of-Service, spoofing, phishing and eavesdropping[4].The automatic detection of malware has enabled the application of bio-inspired algorithms in recent contributions using a hybrid method encompassing an adaptive neuro-fuzzy inference system [4] and Particle Swarm Optimization [4]. A novel method that employs Deep Learning models to improve the detection of malware is proposed [4]. In this approach, Bat Algorithm [4] solves the problem of class imbalance among different malware families, which is a frequent problem in data-based studies related to cybersecurity.

D. Gaming Industry (Development of Video Games):

Video games have [4] intensely embraced Artificial Intelligence numerous problems and challenges [4], such as Procedural Content Generation (PCG), development of virtual players and bots generation.[4]. Co-evolutionary bio-inspired algorithms have been proposed to generate game AI [4]. The development of game bots [4] which dynamically adapt to various difficulty levels as well as new variables in the gaming environment [4] is possible with the bio-inspired algorithm. Ant Colony Optimization heuristics are used to implement real-time gaming bots for dynamic game environments [4].

V. Further Research and Development Bio-inspired Algorithms

It is fascinating to note that most of these bio-inspired algorithms have had their roots in the engineering [4] and pure science-based domains [1]. There is a huge potential [4] to use these methods across different domains of problems as methods and their associated concepts become more mature with time. [1]. A diverse application is witnessed [5] business and management domains. Genetic algorithms, neural networks, and ant colony optimization are applied for developing optimal solutions.[4]. In particular, a lot of these algorithms have been used in production management, information systems management, and supply chain management [1].

The increasing amount of data and the need to produce optimized and efficient results enable the development of new algorithms. Although several bio-inspired algorithms have been formulated, not all gained the same popularity. It is not wise to keep creating new biologically inspired algorithms and not refine or augment them.

Neural networks are a highly demanded focus of research. It has attracted the attention of researchers due to continual optimizations and refinements of the algorithm to produce excellent results [5]. Machine learning and deep learning techniques are employed to carry out research-intensive simulations. Some of the most promising research within the field of genetic algorithms involves their application to multi-objective problems, and the use of heuristic meta-models within the genetic algorithm as a means to increase speed of convergence without affecting the accuracy and the usefulness of the final solution [5].

Ant Colony Optimization is very promising when applied to single objective optimization although it has been somewhat overtaken in application by more common genetic algorithms or simpler search strategies where compute power or time is limited. There have been some efforts to modify ACO to multi-objective paradigm and this is an interesting avenue that is perhaps deserving of further study [5].

Artificial Bee Colony algorithms [5] is a proficient area of research that has surfaced relatively recently in terms of swarm intelligence-based algorithms. Because of this there is considerable scope further research in various applications of these algorithms. One amazing field of application of the Artificial Bee Colony algorithms, where they show promising abilities, is in the domains of data clustering and data mining. [5]. Further research in the area is currently largely around the improvement of the application of the algorithm to multi-objective optimization. [5].

In conclusion, the applications of these matured algorithms have given promising results in the domain of information systems, focusing on decisions at the operational level [1], tactical level [1],functional level strategic decisions [1], business level strategic decisions [1] and corporate level strategic decisions across domains like healthcare, military, education,urban planning, governance, agriculture, and other application industries.

VI. Conclusion

We reviewed the twelve most popularly used bio-inspired algorithms in this report. Comparative performance evaluation of the algorithms is possible only if sufficient literature is available for the newly developed algorithms. Over the last few decades, neural networks have become the most popular algorithm for any intelligent algorithm. Optimization for Artificial Plant-based algorithms, Flower-Pollination algorithms, and Cuckoo Search enables their usage into similar multi-objective problems. Hybridisation of nature inspired algorithms together in a similar way to that in which many algorithms combine solutions, appears to be a clear direction for iterative improvement of these algorithms and has been for some time [5]. Additionally, utilising machine-learning models such as artificial neural networks to reduce objective function overhead whilst maintaining accuracy seems promising, although such solutions may well need to be bespoke for each kind of application problem [5].

Nature is truly fascinating and full of intriguing phenomena still to be understood [4].Unrevealed paradigms underneath this science will surely continue fostering new advances in bio-inspired optimization [4], featuring unseen levels of performance and computational efficiency.

REFERENCES

[1] Arpan Kumar Kar, " Bio Inspired Computing - A Review of Algorithms and Scope of Applications," *April 2016, Expert Systems with Applications*

[2] Amrita Chakraborty, Arpan Kumar Kar, " A Review of Bio Inspired Computing Methods and Potential Examples." *February 2016*

[3] Josh Bongard, " Biologically Inspired Computing ." *University of Vermont*

[4] Javier Del Ser, " Bio Inspired Computation:Where we stand and What's next." *August 2019, Swarm and Evolutionary Computation*

[5] Willam Sayers, Hassan Chizari, Shu-jun Zhang, " Review and Classification of Bio-Inspired Algorithms and Their Applications." *May 2020, Journal of Bionic Engineering*