Efficient Evolutionary Computation Methods for Large-Scale Optimization and Machine Learning

Thesis submitted in partial fulfillment for the Award of Degree

Doctor of Philosophy

by

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This thesis is dedicated to my beloved family.

For their endless love, support and encouragement

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Preface

Machine Learning (ML) and Deep Learning have undoubtedly contributed to tremendous achievements in Artificial Intelligence (AI) in recent years, and more contributions are likely to follow. On the other side, as technology advances, a vast amount of data is generated, which raises the problem of complexity and computational challenges. Many of these real-world applications now emerge as complex or large-scale optimization problems. Almost every AI-based application has optimization tasks in its core that need to be solved effectively and efficiently.

Recently, large-scale optimization problems emerged as challenging in various application domains like logistic scheduling and data security, as well as core optimization problems in AI, such as structure learning of deep networks, feature learning, model parameter optimization, and many more. Numerous effective optimization techniques are already present to deal with convex optimization problems, whereas non-convex and large-scale optimization problems are still a challenge. Evolutionary Computation (EC), broadly referred to as "Nature-Inspired Computations" (NIC) or "Nature-Inspired Algorithms" (NIA), is widely recognized as a global optimization technique. They are extensively used to improve the performance of ML tasks, giving rise to a new domain known as "Evolutionary Machine Learning".

EC are efficient in solving complex optimization tasks, but a few major challenges, such as slow convergence, local optima stagnation, and scalability, limit their broader applicability. Moreover, they are computationally expensive and have become a hurdle in analyzing real-world problems related to big data, like high-dimensional medical data or stream data. Now large computations are not a problem due to the availability of computational resources. However, only utilizing high computation resources will not solve the whole purpose. We must design efficient optimization techniques that are robust and adaptive for modern applications. Both ML and ECs have their own strengths and limitations, which has sparked a surge in ongoing research in academia as well as industry to integrate these ideas to enhance their performance while overcoming limitations. A few possibilities to deal with the challenges of ECs are: (1) designing hybrids of existing ones by utilizing their strengths; (2) modern hybrids, which are the integration of interdisciplinary concepts like quantum computing from physics, chaos theory from mathematics, reinforcement learning, etc.; and (3) designing a new optimizer by taking inspiration from nature with good local search ability. Thus, in the same spirit, this study focused on designing efficient optimization techniques while addressing a few real-world applications to validate their effectiveness. The range of the applications under consideration varies from complex to large-scale optimization problems and from single-objective to multi-objective optimization for advanced industrial applications.

Based on the above discussion, the primary objective of this thesis is to design efficient optimization techniques that overcome the aforementioned limitations of ECs. We propose a hybrid approach that inherits the properties of self-adaptive Particle Swarm Optimization based on a Directed weighted complex network of particles (DWCN-PSO) and Genetic Algorithm (GA), named as, (GDWCN-PSO). Moreover, the proposed GDWCN-PSO has been validated on both single-objective and multi-objective optimization problems. Besides, we validate on an important real-world optimization problem, namely optimal key generation for image encryption technique. The selection of this application was motivated by the recent demand in the industry related to data privacy and applications for the Internet of Things (IoT). Subsequently, data privacy has become a major concern and is still an open issue. So, the proposal has been applied for optimal key generation by utilizing a specific objective function, and thereafter this key is used to encrypt the images.

Modern hybrids are another possibility that integrates interdisciplinary concepts to address the issues associated with ECs. Nowadays, researchers are fascinated by and make continuous efforts to develop new optimization techniques for challenging problems in robotics, computer vision, and ML by utilizing reinforcement learning, surrogate models, quantum computing, and so on. However, PSO is simple, easy to understand, popular, and suitable for several applications, but recently the Squirrel Search Algorithm (SSA) has been proven to be effective and has characteristics that can be investigated and modified to make modern hybrids while utilizing its strength with other concepts. The interdisciplinary concepts Q-Learning (QL), a component of reinforcement learning, and chaos theory, on the other hand, significantly contribute to improving the convergence and self-adaptive properties of NIC. Another idea from physics that revolutionizes technology is quantum computing. We first combine QL and SSA to create a stable optimizer and test its applicability on a critical feature subset selection problem in ML. Here, QL is used to modify local search in SSA. Further, we incorporated chaos theory with SSA to overcome premature convergence. Three chaotic maps have been investigated in the original SSA, which produced three chaotic versions of the SSA. Additionally, we have used quantum computing's qubit representation and quantum gates to maintain effective search capabilities with population diversity, which has led to quantum-assisted chaotic SSA. For optimal feature subset selection, their applicability and effectiveness have been verified on large-scale genomic datasets.

We explored a few natural phenomena with inspiration from earlier studies in order to design a novel optimizer that is simple, adaptive, and has good convergence with diversity. Researchers in the applied research area demand a simple and effective optimizer that is less conceptually complex, easily adaptable, cost-effective, and suitable for a variety of applications. But the No Free Lunch (NFL) Theorem states that no optimizer is a universal optimizer, thereby opening up the possibility of designing new optimizers. Therefore, this study has made an effort to achieve the aforementioned desirable qualities by introducing Murmuration-Flight based Dispersive Optimization (MDO) algorithm in both single and multi-objective versions (MDO-M). For this, we looked into the phenomenon of migrating birds, starling murmuration, and Levy flight. In order to design better search capabilities from the initial point of local search, this study also introduced a population initialization approach rather than considering a random population. Additionally, it is verified for two distinct applications, including optimal key generation and optimal feature subset selection (using MDO and MDO-M) for classification problems. We investigated different types of data with different complexity in terms of the number of attributes as well as classes and domains to validate our proposal's applicability in various application domains. According to the analysis, the MDO reduced computation time drastically while sacrificing minor accuracy on datasets. It appears to be a strong contender and advantageous for low-end devices for making initial assessments for critical tasks.

Finally, this work concentrates on the Generative Adversarial Network (GAN), a more promising and advanced architecture for computer vision. Training instability and mode collapse are the major challenges of GAN. Another significant issue is the requirement for a large amount of labeled data to train such architectures for realistic image generation, which is not possible with images of rare diseases or old dead paintings. The requirement of paired data is somehow resolved by another potential architecture, Cyclic-GAN, but the training instability, vanishing gradient, and mode collapse issues become more complex and challenging. The overall problem can be formulated as an optimization problem belonging to large-scale optimization problems. On the other hand, we know that ECs have great potential to solve optimization problems. Therefore, we have introduced a new approach for model training by combining EC, multi-objective optimization, and Cyclic-GAN along with different selection mechanisms, resulting in

Evolutionary Multi-objective Cyclic-GAN (EMOCGAN). This work is further extended by introducing an intelligent gradient-aware selection scheme. Basically, we have incorporated three objective functions for Pareto-based selection for more realistic unpaired image translation. Thereafter, quantization has been incorporated to make it suitable for future IoT devices.

We also proposed a Parallel Corner Sort, which uses CUDA to parallelize the Pareto-optimal solution finding as well as the dominance calculations. We compared the performance of serial and parallel approaches implemented in CUDA C++. Because no public industrial large data (more than 1 lac solution) is available, the performance of the Parallel Corner Sort is still being studied. However, preliminary results show a significant improvement.

Overall, the approaches proposed in this thesis are validated on mathematical benchmarks and real-world datasets from various application domains, demonstrating the efficacy of EC techniques on a broader scale.

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Symbol	**Description**
$\overrightarrow{x_i}$	Position vector
x_i^t	Solution of optimizer at time stamp t
$x_i^{(t+1)}$	Generated new solution at time stamp $t+1$
$U(,)$	Uniform distribution
$N(,)$	Normal distribution
v_i	Swarm velocity
$D(x_i, x_j)$	Euclidean distance between node i and j
R	Threshold radius
p	Probabilistic factor
G	Graph
E	Set of edges
W	Weight of edges
Ω	Search space
$\mathbb{R}^p$	Objective space
ρ	Set of all possible features
F	Feature subset
μ	Minimum step
n	Population
$\hat{Q}$	Set of action

Symbol	**Description**
$R(.)$	Reward function
$L(.)$	Lévy function
β	Discount parameter
α	Learning rate
X_n	Chaotic variable
L_e	Lyapunov exponent
N_p	Number of flying squirrels
d_g	Gliding distance
G_e	Gliding constant
$Q(t)$	Quantum population
$P(t)$	Chromosomes
P_{best}	Particle's best position
A	Adjacency matrix
G_{best}	Global best position of the particle
$U(\phi)$	Rotational quantum gate
ϕ_i	Angle of rotation
Ht	Hickory tree
At	Acorn tree
Nt	Normal tree
s^c	Seasonal constant

Abbreviations

Abbreviation	**Description**
AI	Artificial Intelligence
AES	Advanced Encryption Standard
CSSA	Chaotic Squirrel Search Algorithm
DES	Data Encryption Standard
DWCN	Directed Weighted Complex Network
EC	Evolutionary Computation
EMOCGAN	Evolutionary Multi-objective Cyclic Generative Adversarial Network
FID	Frechet Inception Distance
GA	Genetic Algorithm
GAN	Generative Adversarial Network
GWO	Grey Wolf Optimizer
IoT	Internet of Things
IS	Inception Score
MA	Mantegna's Algorithm
MDO	Murmuration-flight based Dispersive Optimization
ML	Machine Learning
NIA	Nature Inspired Algorithm
NIC	Nature Inspired Computation
PSO	Particle Swarm Optimization

Abbreviation	**Description**
QCSSA	Quantum-assisted Chaotic Squirrel Search Algorithm
QL	Q- Learning
RL	Reinforcement Learning
SSA	Squirrel Search Algorithm
SSIM	Structural Similarity Index Measure
SVM	Support Vector Machine
UQI	Universal Quality Index
WOA	Whale Optimization Algorithm
WTL	Win-Tie-Lose