Chapter 11

Meta-Heuristic Paradigms and Swarm-Based Models for Large-Scale Optimization

D. Renuka Devi
https://orcid.org/0000-0002-6525-1172
Stella Maris College, India

T. A. Swetha Margaret
https://orcid.org/0000-0002-4693-8219
Stella Maris College, India

ABSTRACT

Swarm Intelligence and other metaheuristics have recently gained attention as optimization methods in large-scale data analytics, particularly in control engineering. With the increasing use of big data, IoT devices, and real-time processing, traditional techniques are facing challenges in dealing with high-dimensional and nonlinear problems. Swarm intelligence methods are based on the collective behavior of natural systems, providing robust and scalable solutions for optimizing control parameters, system identification, and fault detection in large environments. The combined use of swarm intelligence and metaheuristics will improve optimization for control engineering applications, focusing on large-scale analytics as discussed in this chapter. Case studies presented in this chapter demonstrate the effectiveness of these methods in optimizing complex control systems where traditional methods struggle due to size or complexity.

1. INTRODUCTION

Metaheuristic algorithms have been developed as high-level procedures for optimization problems and they aim at finding global optimum within a reasonable time (Yang, 2013). This is in contrast to exact algorithms that always guarantee to find the best possible solution; however, in scenarios where it would be too expensive or complicated for traditional approaches, metaheuristics can be applied effec-

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tively to achieve good solutions (Turgut et al., 2023). Control systems engineering deals with designing systems that regulate the behavior of other dynamic systems, ensuring they behave in a desired manner.

The field is very important in various engineering applications including robotics, aerospace, automotive systems, and industrial automation. Following are examples of using metaheuristics to tune controller parameters such as PID (proportional-integral-derivative) controllers; for instance, traditional methods would be less effective when dealing with complex nonlinear systems as compared with metaheuristics which can efficiently search for parameter spaces to get optimal or suboptimal sets of parameters. There are many challenges in identifying system models (e.g., transfer functions) from data. The best fitting parameters can be optimized by applying the Metaheuristic algorithm to it.

In situations involving optimal control where finding a control law that minimizes a cost function is the aim, particularly when faced with nonlinear dynamics or limitations, metaheuristics can be used to navigate the difficult solution space. Detecting and diagnosing faults may prove difficult in extensive or complicated systems. The detection of faults can be optimized using these metaheuristics leading to improved reliability and safety. One of the biggest challenges is how to keep a control system effective in the presence of different uncertainties.

The design of resilient controllers through optimization across different scenarios or model variations is achievable through metaheuristics. Metaheuristic algorithms are powerful mechanisms for handling intricate optimization issues faced by engineers specializing in control theory and systems engineering (Sadeeq & Abdulazeez, 2023). Engineers can tune a controller, create fault detection systems, create system models and design resilient control systems among other things with these algorithms whenever they seem difficult using traditional methods. Metaheuristic algorithms also have the capability to fully optimize non-linear, complex and high-dimensional systems.

These algorithms apply to many different types of control problems, including system identification and controller design (Çavdar et al., 2024). Metaheuristics help prevent the problems associated with local optima that are found in traditional optimization methods. In control engineering, where global optimum is usually vital for performance and stability, this quality is particularly important. Control engineering issues usually include a number of different objectives like reducing errors, minimizing energy loss or avoiding excessive wear on components. One such algorithm is NSGA-II (a multi-objective genetic algorithm) which helps engineers to achieve pareto optimal solutions with respect to competing objectives (Ma et al., 2023).

Algorithms may be versatile tools because they use techniques that can be modified for various kinds of control problems including controller design; system identification etc. They work by evading local optimum which occurs in classical optimization methods thus avoiding stagnation as seen in other traditional optimization approaches. This aspect is very crucial within control engineering where arriving at a globally optimal control law or topology is vital since it affects both the overall stability and performance of a given system. Numerous decisions must therefore be made at once when dealing with control engineering problems such as minimizing errors made by machines while operating, reducing energy consumption levels among others. Engineers have come up with multi-objective genetic codes like NSGA-II algorithm which allows them to balance performance criteria among competing alternatives thus arriving at pareto useful options hence making them applicable across many fields.

Even though they are powerful, many metaheuristic algorithms are relatively simple to implement and can be easily customized or hybridized with other methods. Often metaheuristics exhibit robustness against system parameter variations and uncertainties that are key factors in control engineering applications characterized by difficulty in precisely modelling. Metaheuristic algorithms may be com-