



A REVIEW OF ENGINEERING APPLICATIONS OF MOTH-FLAME OPTIMIZATION

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Abstract: The Moth-Flame Optimization (MFO) algorithm is a population-based, nature-inspired metaheuristic introduced by Seyedali Mirjalili in 2015 in Knowledge-Based Systems [1]. It models the transverse-orientation navigation of moths, in which an insect maintains a fixed angle relative to a distant light source (the moon) to fly in a straight line but spirals around nearby artificial lights. This spiral convergence toward a set of “flames” (the best solutions found so far) is the mechanism MFO exploits to balance exploration and exploitation. Owing to its conceptual simplicity, small number of control parameters, gradient-free operation, and competitive performance, MFO and its many variants have been applied widely across engineering. This paper reviews representative engineering applications of MFO across power systems, structural design, image processing, biomedical computing, and communication and control systems. The review draws on the original algorithm paper, primary application studies, and peer-reviewed survey articles. It concludes with a synthesis of recurring strengths, documented weaknesses such as premature convergence, and directions reported in the literature.

Index Terms - Moth-Flame Optimization (MFO), Metaheuristics, Swarm Intelligence, Engineering Applications, Power System Optimization, Structural Design, Image Segmentation, Wireless Sensor Networks

A NOTE ON SCOPE AND VERIFICATION

This review is deliberately representative rather than exhaustive. Hundreds of MFO-related papers appeared during the study period, and no single review can responsibly claim complete coverage. Accordingly, the cited studies were checked against indexing records to ensure correct attribution and publication details. Where a claim reflects a finding aggregated by a survey rather than a paper read in full, the survey is cited as the source of that aggregation. Statements that summarize broad trends across the field are attributed to the peer-reviewed review literature on MFO, principally the surveys by Shehab et al. [2] and Nadimi-Shahraki et al. [3]. The intent is that readers can trace each application claim to a verifiable source in the published literature.

1. INTRODUCTION

Metaheuristic optimization algorithms have become standard tools for solving the nonlinear, non-convex, high-dimensional, and often discontinuous problems that arise across engineering. They are attractive because they treat the objective as a black box: they require no gradient information, make few assumptions about the search landscape, and can escape local optima through stochastic search. Within this broad family, swarm-intelligence methods, which coordinate a population of simple agents, have proliferated since the introduction of particle swarm optimization and ant colony optimization.

The Moth-Flame Optimization algorithm was proposed by Seyedali Mirjalili in 2015 and published in Knowledge-Based Systems [1]. Its inspiration is the transverse-orientation navigation strategy of moths. A moth keeps a constant angle to the moon, which, because the moon is effectively at infinity, produces straight-line travel. When the light source is local, such as a candle flame, the same fixed-angle rule traps the moth in a tightening spiral around the light. Mirjalili formalized this spiral as a logarithmic-spiral position update in which each moth moves relative to a flame, with the number of flames decreasing across iterations to shift the search gradually from exploration to exploitation.

In the original paper the algorithm was benchmarked on a suite of test functions and then applied to a set of classical constrained engineering design problems and a computational-fluid-dynamics case, establishing engineering design as MFO's first application domain. In the years that followed, researchers adapted MFO to binary, multi-objective, constrained, and hybridized forms and deployed it in fields ranging from power systems to medical image analysis.

1.1 The Canonical Algorithm in Brief

MFO maintains two equally sized matrices. The first holds the positions of the moths, which are the search agents that explore the space; the second holds the flames, which are the best positions discovered so far and which act as beacons for the moths. Each moth updates its position with respect to a flame using a logarithmic-spiral function parameterized so that the moth can move both toward and around the flame. A key adaptive mechanism reduces the number of flames over the course of a run according to a decreasing schedule, so that early iterations preserve many attractors and promote exploration while later iterations concentrate the population on the best solutions and promote exploitation. Flame selection commonly uses a roulette-wheel mechanism, which several power-system studies cite as a contributor to fast convergence. The method needs only a population size and an iteration budget as principal parameters, which is frequently cited as a practical advantage.

1.2 Why MFO Spread Across Engineering

The review literature attributes MFO's rapid uptake to a consistent set of properties: it requires no derivative information; it has few parameters to tune; it is simple to implement and to hybridize with other operators; and it is flexible and scalable to problems of differing dimensionality. These same surveys are candid about the algorithm's limitations, chiefly a tendency toward premature convergence and stagnation in local optima on certain multimodal and high-dimensional problems, which has motivated a large secondary literature of improved and hybrid variants. The remainder of this paper is organized by application field; within each field the canonical formulations are described and verified representative studies are cited.

Table 1 summarizes the four fields and gives a verified example study in each.

TABLE 1. ENGINEERING FIELDS COVERED IN THIS REVIEW.

Engineering field	Representative problem classes	Example verified study
Power and energy systems	Economic/emission dispatch, optimal power flow, reactive-power dispatch, PV parameter extraction, DG allocation	Allam, Yousri and Eteiba [4]; Lal and Barisal [5]
Mechanical and structural design	Welded beam, pressure vessel, gear train, three-bar/15-bar/52-bar trusses, cantilever and I-beams, springs	Mirjalili [1]
Image processing and biomedical	Multilevel image thresholding, medical image segmentation, feature selection, disease classification	Khan et al. [6]; Abd Elaziz et al. [7]
Communications, networks and control	WSN clustering and cluster-head selection, antenna array synthesis, PID/AGC controller tuning, fractional-order control	Das et al. [8]; Mohanty [9]; Bourouba et al. [10]

2. POWER AND ENERGY SYSTEMS

Power and energy systems are, by volume, the most heavily represented application area for MFO in the verified literature, and the MFO review papers identify power and energy as a dominant domain. The problems share a common structure: a nonlinear, heavily constrained objective, such as cost or loss, must be minimized over generator outputs, control settings, or device parameters, subject to physical and operational limits. These features suit a gradient-free population method well.

2.1 Economic and Emission Dispatch

Economic dispatch seeks the generation schedule that meets demand at minimum fuel cost while honoring generator limits and, in practical formulations, valve-point effects and prohibited operating zones that make the cost curve non-smooth. MFO has been applied to single-objective economic dispatch and to combined economic-emission dispatch, where fuel cost and pollutant emissions are minimized together. An enhanced MFO formulation for non-smooth economic dispatch with emissions was published in *Energy* in 2018, reporting competitive performance against established methods on standard test systems. These dispatch studies are representative of a larger cluster of MFO economic-dispatch papers catalogued in the MFO surveys.

2.2 Optimal Power Flow and Reactive-Power Dispatch

Optimal power flow (OPF) determines control variables, such as generator voltages, transformer taps, and reactive compensation, that optimize an objective like generation cost or active-power loss while satisfying the full set of network equations and security limits. MFO has been applied to OPF on standard IEEE test systems with objectives spanning fuel-cost reduction, voltage-profile and voltage-stability improvement, and active- and reactive-power loss minimization, and a 2017 study reported MFO results validated with non-parametric statistical tests including the Wilcoxon, Friedman, and Quade tests. A closely related problem, optimal reactive-power dispatch, minimizes transmission real-power loss while keeping bus voltages within limits by adjusting reactive sources; MFO formulations for reactive-power dispatch have likewise been reported. Improved MFO variants for OPF subsequently appeared in the power-systems literature, reflecting sustained interest in the problem.

2.3 Load-Frequency and Automatic Generation Control

Automatic generation control (AGC), or load-frequency control, regulates system frequency and tie-line power exchange after load disturbances by tuning secondary controllers. Here MFO is used not on the plant directly but to tune controller gains. A 2019 study [5] used MFO to optimize PID/IDD/PIDD controller gains for a multi-area thermal AGC system, reporting improved settling time, overshoot, and undershoot relative to other tuning methods and extending the analysis to nonlinear systems with generation-rate constraints. Subsequent work combined load-frequency control with terminal-voltage (automatic voltage regulator) control under a single MFO-tuned controller. Controller tuning is discussed again in Section 5 because it spans the energy and control domains.

2.4 Photovoltaic Parameter Extraction and Distributed Generation

Determining the equivalent-circuit parameters of solar cells and modules from measured current-voltage data is a nonlinear regression problem with several local optima, and it became one of the earliest MFO applications. Allam, Yousri, and Eteiba applied MFO to extract the parameters of the three-diode model of a multi-crystalline solar cell and module, publishing in *Energy Conversion and Management* [4] in 2016, the year after the algorithm's introduction. The robustness of parameter extraction prompted a series of improved MFO variants for photovoltaic models, including a double-flame-generation variant published in 2019. MFO has also been applied to the optimal allocation and sizing of distributed generation in distribution networks, a problem of growing importance as renewable penetration increases.

3. MECHANICAL AND STRUCTURAL DESIGN

Mechanical and structural design was the first engineering domain in which MFO was demonstrated, because the original 2015 paper validated the algorithm on a battery of classical constrained design problems. These benchmarks remain the most reliably attributable mechanical applications of MFO, since they appear in the source paper itself.

3.1 Classical Constrained Design Benchmarks

In the introducing paper, MFO was evaluated on nine classical engineering design problems: welded-beam design, gear-train design, three-bar truss design, pressure-vessel design, cantilever-beam design, I-beam design, tension/compression spring design, 15-bar truss design, and 52-bar truss design [1]. Each of these is a constrained minimization, typically of weight, cost, or deflection, subject to stress, geometry, and deflection

limits, with a mixture of continuous and, for gear trains, effectively discrete variables. The paper reported that MFO produced competitive results on these problems, which is why they recur throughout the later MFO literature as standard testbeds.

3.2 Trusses and Continued Use as a Design Optimizer

The truss problems from the original paper, in particular the three-bar, 15-bar, and 52-bar trusses, illustrate MFO applied to structural sizing, where member cross-sections are chosen to minimize weight under stress and displacement constraints. In subsequent years these same constrained design problems, including welded beam, pressure vessel, multiple-disc clutch brake, three-bar truss, and tension/compression spring, were repeatedly used to validate improved and hybrid MFO variants, confirming that mechanical design remained an active proving ground for the algorithm. Because the most cleanly verifiable structural results are those in the source paper and in variant-validation studies, this section is intentionally conservative: it reflects what can be confirmed rather than the full breadth of design papers indexed in the surveys.

4. IMAGE PROCESSING AND BIOMEDICAL COMPUTING

Image processing and biomedical computing form a large and well-documented MFO application cluster, and the MFO surveys list image processing and medical applications among the principal domains. Two problem types dominate: multilevel image thresholding, and feature selection for classification, the latter often in a medical-diagnosis context.

4.1 Multilevel Image Thresholding and Segmentation

Multilevel thresholding partitions an image into regions by selecting several intensity thresholds that optimize a criterion such as Otsu between-class variance or Kapur/Tsallis entropy. As the number of thresholds grows, exhaustive search becomes intractable, which makes the problem a natural target for metaheuristics. MFO and its variants have been used to select optimal thresholds for grayscale, color, and medical images. The medical case is significant because segmentation is a preprocessing step for downstream diagnosis; verified examples include MFO-based and hybrid-MFO approaches for medical image segmentation, such as a hybrid of the marine-predators algorithm with MFO for multilevel thresholding applied to COVID-19 computed-tomography images.

4.2 Feature Selection and Disease Classification

In machine-learning pipelines, feature selection removes redundant or irrelevant features to improve accuracy and reduce dimensionality; cast as a binary optimization over which features to keep, it suits binary MFO variants. An opposition-based MFO improved by differential evolution for feature selection was published in *Mathematics and Computers in Simulation* [7] in 2020. In biomedical imaging, MFO has been embedded in classification pipelines: a 2021 study in *Diagnostics* [6] used an improved MFO to select the most discriminative deep-learning features for multiclass skin-lesion segmentation and classification. These studies exemplify MFO's role not as the classifier itself but as the optimizer that prunes the feature space feeding a classifier.

5. COMMUNICATIONS, NETWORKS, AND CONTROL

This section groups three related engineering areas in which MFO has a verified presence: wireless communication networks, antenna design, and control-system tuning. They are treated together because they share the pattern of optimizing a small set of design or control parameters against a performance objective.

5.1 Wireless Sensor Networks and Routing

Energy efficiency and network lifetime are the central concerns of wireless sensor networks (WSNs), and clustering with cluster-head selection is a standard way to address them. MFO has been applied to cluster-head selection, for example within the LEACH-C framework, and to energy-efficient clustered routing for WSNs, with a stable-clustering routing approach published in *Wireless Personal Communications* in 2018 [11]. Related work applied MFO to fuzzy clustering in WSNs and to clustering for vehicular ad hoc networks. These results are catalogued among the networking applications in the MFO review literature.

5.2 Antenna Array Synthesis

Antenna-array design seeks element excitations and spacings that shape the radiation pattern, commonly to reduce side-lobe levels while preserving the main beam. MFO was applied to the design of linear and circular antenna arrays for side-lobe reduction, with results published in the *International Journal of Numerical Modelling* in a 2018 study by Das and colleagues [8]. This is a representative electromagnetics application in which MFO optimizes a continuous parameter vector against a pattern-quality objective.

5.3 Control-System and PID Tuning

Beyond the AGC controllers of Section 2.3, MFO has been used more broadly to tune controllers. A 2018 study applied MFO to design a fractional-order PID controller [10] with a model-reference adaptive-control tuning configuration. Across these control applications the pattern is consistent: a controller structure is fixed, an error-based objective such as integral time-weighted absolute error is chosen, and MFO searches the controller-gain space. The recurrence of MFO in controller tuning reflects both the practical importance of the problem and the algorithm's suitability for low-dimensional, expensive-to-evaluate objectives.

6. CROSS-CUTTING DEVELOPMENTS: VARIANTS AND HYBRIDS

A defining feature of the MFO literature is that application advances are tightly coupled to algorithmic improvements. The review papers classify MFO variants into modified versions, hybridized versions, and multi-objective versions, alongside binary forms used for discrete problems such as feature selection. Modifications frequently introduce mechanisms to counter premature convergence, including opposition-based learning, Levy-flight steps, chaotic maps, and Gaussian or Cauchy mutation. Hybrids couple MFO with other methods, for example particle swarm optimization, simulated annealing, or the marine-predators algorithm, to combine complementary search behaviors. Multi-objective MFO formulations introduce an archive and non-dominated sorting to return a Pareto front rather than a single solution. In practice, many of the strongest application results in Sections 2 through 5 were obtained with such enhanced variants rather than the canonical algorithm, a point the surveys emphasize.

7. SYNTHESIS AND DISCUSSION

Read across the four fields, several consistent themes emerge. First, MFO is overwhelmingly used as a parameter or decision-variable optimizer wrapped around a domain model: it tunes controller gains, selects thresholds or features, sizes structural members, or sets generator outputs, while the domain physics or model supplies the objective. Second, the most fruitful domains are those whose problems are nonlinear and constrained but moderate in dimensionality, which matches the algorithm's strengths. Third, reported limitations are remarkably consistent across fields. The surveys and many primary papers note premature convergence and local-optimum stagnation, especially on high-dimensional and strongly multimodal problems, which is precisely why the variant-and-hybrid literature of Section 6 is so large.

It is also worth noting a methodological critique present in the broader metaheuristics literature: some authors have argued that metaphor-inspired algorithms, MFO among them, are sometimes promoted on the strength of their inspiration rather than rigorous, like-for-like comparison, and have called for more careful benchmarking. A balanced reading of the MFO record therefore credits its genuine practical successes while treating performance claims, particularly those resting only on a handful of test cases, with appropriate caution.

8. CONCLUSION

From its introduction in 2015 to the end of 2022, the Moth-Flame Optimization algorithm moved quickly from a benchmark-and-design-problem demonstration to a widely used optimizer across engineering. In power and energy systems it has addressed economic and emission dispatch, optimal power flow, reactive-power dispatch, controller tuning for automatic generation control, and photovoltaic parameter extraction. In mechanical and structural design, it was validated on the classical constrained benchmarks introduced in the source paper and reused as a sizing optimizer thereafter. In image processing and biomedical computing, it has driven multilevel thresholding, medical image segmentation, and feature selection for classification. In communications, networks, and control it has been applied to wireless-sensor-network clustering and routing, antenna-array synthesis, and PID and fractional-order controller tuning. Throughout, progress in applications has gone hand in hand with a steady stream of improved and hybrid variants designed to mitigate the algorithm's known tendency toward premature convergence. The literature reviewed in this study thus shows MFO to be a versatile, easily implemented metaheuristic whose practical value is best realized through problem-specific adaptation and careful evaluation.

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