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• REVIEW •

Special Focus on Pigeon-Inspired Optimization

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Advancements in pigeon-inspired optimization and its variants

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Abstract The returning of homing pigeons to their lofts from remote and unfamiliar locations with great accuracy remains a mystery. Pigeon-inspired optimization (PIO), which is a novel mono-objective continuous optimization algorithm, is inspired by the hidden mechanism behind the remarkable navigation capacity of homing pigeons. Since their development, PIO and its variants have been widely applied to various fields ranging from combinatorial optimization to multi-objective optimization in many areas, such as aerospace, medicine, and energy. This study aims to review the modifications of PIO from four aspects of improvement measures, namely, component replacement, operation addition, structure adjustment, and application expansion. It also summarizes the problems of existing research and plots the course of future effort.

Keywords pigeon-inspired optimization, homing pigeon, bio-inspired computing, map and compass operator, landmark operator

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1 Introduction

Bio-inspired intelligence computing, a new and vital branch in the field of artificial intelligence, is based on the simulation of complex living systems in nature. Nature has been a consistent source of technological ideas, engineering principles, and significant inventions. Exploration and simulation of the mechanism of nature can not only be applied to solve various practical engineering problems but also strengthen the ultimate understanding of the essence of bionic intelligence.

The homing pigeon, a variety of common pigeons, possesses an inherent ability to search for its way home over exceedingly long distances. Owing to this skill, the homing pigeon has played several critical roles ranging from mail carriers to scouts throughout human history. As early as in the eighth century B.C., the homing pigeon was used to announce the champion in the ancient Greek Olympics [1]. Even when telecommunication had become popular, flexible and adaptable homing pigeons remained indispensable messengers during World Wars I and II [2].

How homing pigeons navigate to their lofts with great accuracy remains unknown, and this mystery is often a topic of research. Many scholars believe that this remarkable homing capacity relies on a "map and compass" concept with two steps [3]: the map step allows homing pigeons to identify their locations relative to the loft via the Earth's magnetic field, and the compass step prompts homing pigeons to transform their relative orientation into actual flying directions by the sun. As homing pigeons gradually

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approach their loft, the impact of the "map and compass" model on their navigation diminishes and is replaced by familiar visual landmarks [4].

Inspired by the above tool-switch behavior in homing pigeon navigation, pigeon-inspired optimization (PIO) was proposed by Duan et al. [5]. This novel bio-inspired computing algorithm comprises two operators: the map and compass operator and landmark operator. The former emphasizes incarnating the navigational impact of the sun and magnetic field, whereas the latter features the landmark. Within a few short years since its introduction, many variants of PIO have been derived and broadly applied to various areas. This paper provides a brief retrospect on relevant research in PIO covering all open access research papers on PIO variants in Google scholar and Baidu scholar before 1 December 2018, summarizes the existing research problems, and provides a reasonable outlook to guide future investigations.

The rest of the paper is organized as follows. Section 2 describes the related research on the pigeon navigation mechanism. Section 3 gives a concise description of the principle of primary PIO. Section 4 reviews relevant research on PIO from the perspective of improvement measures, and Section 5 draws conclusion and presents future research prospects.

2 Pigeon navigation mechanism

The mechanism behind the astounding navigation competence of homing pigeons has never been completely understood. Sun was eventually discovered to be involved in homing pigeon navigation [6], and this concept has been widely accepted by most researchers. However, the observation that homing pigeons are able to find their way back to their loft under completely overcast conditions indicates that other tools in the homing pigeons' navigation system must exist to provide navigation information when the sun is hidden [7].

The phenomenon that homing pigeons are disorientated under sunny conditions with an anomalous magnetic field supports the theory that the magnetic field cooperates with the sun to sustain navigation rather than being a redundancy when the sun is obscured [8]. The navigational effect of the magnetic field has been highly debated because whether homing pigeons could perceive magnetic cues has been doubted. Some physiological research on birds appears to confirm the position of the magnetic field in homing pigeons' navigation systems, and the location of the magnetic signal receptor is hypothesized to be in the upper beak area [9] or eye [10, 11] of these pigeons.

The compass orientation based on the sun is mainly employed when homing pigeons fly in a flock; individuals prefer to rely on familiar visual landmarks [12]. If homing pigeons are provided with visual stimulation of familiar visible landmarks before release, their homing efficiency is substantially improved due to fewer casual strolls [13]. The navigational effect of visual landmarks has been confirmed by electroencephalograph data obtained during the flight of homing pigeons [14]. Besides the aforementioned navigation tools, atmospheric infrasound [15] and gravity [16] are gradually being accepted as indispensable components of the navigation system of homing pigeons.

3 Principle of pigeon-inspired optimization

Inspired by the above pigeon navigation behavior, PIO was proposed by considering the homing flight as an optimization process, where the release site and loft represent the initial potential solution and optimal solution, respectively [5]. As shown in Figure 1, the PIO process comprises two independent operators, namely, the map and compass operator and landmark operator; these operators describe the navigational impact of the sun and Earth's magnetic field and that of familiar landmarks, respectively.

Consider N homing pigeons finding their way back to their loft within a D-dimensional search space. When iteration $\mathrm{Nc} \leqslant \mathrm{Nc}^1_{\max}$, the map and compass operator provide navigation cues for each homing pigeon i, where $\mathrm{Nc}^1_{\max}$ is the maximum iteration of the current operator. The position $X_i^{\mathrm{Nc}+1}$ of homing

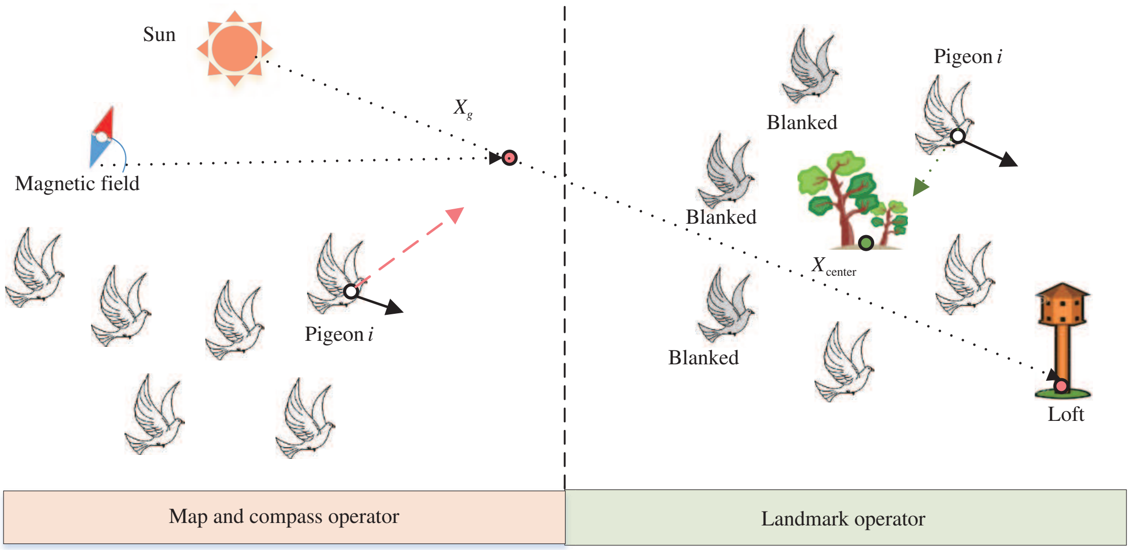

Figure 1 (Color online) Pigeon-inspired optimization process.

pigeon i at iteration $\mathrm{Nc}+1$ is updated by

$$\begin{cases} V_i^{\mathrm{Nc}+1} = \mathrm{e}^{-R\cdot(\mathrm{Nc}+1)} \cdot V_i^{\mathrm{Nc}} + \mathrm{rand} \cdot (X_g - X_i^{\mathrm{Nc}}), \\ X_i^{\mathrm{Nc}+1} = X_i^{\mathrm{Nc}} + V_i^{\mathrm{Nc}+1}, \end{cases} \tag{1}$$

where V_i^{Nc} and $V_i^{\mathrm{Nc}+1}$ are the velocities of homing pigeon i at iteration Nc and $\mathrm{Nc}+1$, respectively, R is the map and compass factor, rand is a random number within $[0,1]$, X_g is the global best position, and X_i^{Nc} is the position of homing pigeon i at iteration Nc.

The landmark operator takes over the navigation system of homing pigeons when $\mathrm{Nc}_{\max}^1 < \mathrm{Nc} \leqslant \mathrm{Nc}_{\max}$, where $\mathrm{Nc}_{\max}$ is the maximum iteration of PIO and satisfies the condition $\mathrm{Nc}_{\max} < \log_2(N) + \mathrm{Nc}_{\max}^1$. The generation of position $X_i^{\mathrm{Nc}+1}$ is expressed as in the following equation:

$$\begin{cases} N = \lceil N/2 \rceil, \\ X_{\mathrm{center}}^{\mathrm{Nc}} = \dfrac{\sum_{i=1}^{N} X_i^{\mathrm{Nc}} \cdot w(X_i^{\mathrm{Nc}})}{\sum_{i=1}^{N} w(X_i^{\mathrm{Nc}})}, \\ X_i^{\mathrm{Nc}+1} = X_i^{\mathrm{Nc}} + \mathrm{rand} \cdot (X_{\mathrm{center}}^{\mathrm{Nc}} - X_i^{\mathrm{Nc}}), \end{cases} \tag{2}$$

where $\lceil \cdot \rceil$ is the ceiling function. $X_{\mathrm{center}}^{\mathrm{Nc}}$, the weighted average of all positions at iteration Nc, denotes the landmark. The weight $w(X_i^{\mathrm{Nc}})$ is calculated by the following equation:

$$w(X_i^{\mathrm{Nc}}) = \begin{cases} f(X_i^{\mathrm{Nc}}), & \text{for maximization}, \\ \dfrac{1}{f(X_i^{\mathrm{Nc}}) + \varepsilon}, & \text{for minimization}, \end{cases} \tag{3}$$

where $f(X_i^{\mathrm{Nc}})$ is the cost function value of homing pigeon i at iteration Nc and ε is an arbitrary nonzero constant.

4 Variants of pigeon-inspired optimization

Non-deterministic polynomial (NP) problems are the touchstone of intelligent algorithms [17]. Basic PIO has proven its worth in many aspects of practical NP issues ranging from energy system design [18] and home energy management [19] to protein complex detecting [20] and automatic disease detection [21].

Table 1 Existing variants of pigeon-inspired optimization

Classification	Author (year)	Variant	Modification
Component replacement	Hao et al. (2014) [22]	–	Modify map and compass factor using fractional calculus
	Jia and Sahmoudi (2016) [23]	ECPIO	Modify map and compass factor using population dispersion degree
	Chen and Duan (2017) [24]	MGMPIO	Modify map and compass factor using variable parameter mechanism
	Lin et al. (2018) [25]	AWPIO	Add a nonlinear dynamic inertia weight coefficient to map and compass operator
	Tao and Li (2018) [26]	CPIO	Add a cognitive factor and a compressive factor to map and compass and landmark operators, respectively
	Zhou et al. (2017) [27]	MAIPIO	Replace center and global best with personal bests' weighted average and anterior neighbor's personal best
	Li and Duan (2014) [28], Zhang and Duan (2015) [29], Xian and Chen (2018) [30]	BQPIO	Replace map and compass operator with quantum mutation operator
	Pei et al. (2017) [31]	QCPIO	Replace landmark operator with quantum mutation operator
	Liu et al. (2016) [32], Dou and Duan (2017) [33], Zhang et al. (2017, 2018) [34, 35], Yang et al. (2018) [36]	LFPIO	Replace map and compass operator with Lévy-flight-based search operator
	Duan and Yang (2018) [37], Yang et al. (2018) [38]	CMPIO	Replace center and global best with Cauchy variants
Operation addition	Hao et al. (2014) [22]	–	Add crossover operation
	Li and Duan (2014) [39]	SAPIO	Add simulated annealing operation
	Sun and Duan (2014) [40], Zhang and Duan (2017) [41]	PPPIO	Add prey-predator operation
	Zhang and Duan (2015) [42], Hu and Duan (2016) [43]	GPIO	Add Gaussian mutation operation
	Chen and Duan (2017) [24]	MGMPIO	Add multi-scale Gaussian mutation operation
	Deng et al. (2016) [44]	HMCPIO	Add communication operation
	Duan and Wang (2016) [45]	OPIO	Add orthogonal initialization
	Cheng et al. (2016) [46]	SOPIO	Add sub-space division orthogonal initialization
	Pei et al. (2017) [31]	QCPIO	Add chaotic local search operation
	Zhou et al. (2017) [27]	MAIPIO	Add competition operation
	Jiang et al. (2017) [47]	–	Add threat heuristic operation
	Sushnigdha and Joshi (2017, 2018) [48, 49]	–	Add constraints handling operation
	Hua et al. (2019) [50]	–	Add personal best learning operation
	Xu and Deng (2018) [51]	ADID-PIO	Add adjacent-disturbance operation
	Sun et al. (2018) [52]	HCLPIO	Add heterogeneous comprehensive learning operation
	Khan et al. (2018) [53]	HPIO	Add new harmony improvisation operation
	Li and Deng (2019) [54]	QEPIO	Add Quantum entanglement combing operation
Structure adjustment	Li and Duan (2014) [39]	SAPIO	Conduct one of the two operators probabilistically
	Deng and Duan (2016) [55]	–	
	Duan et al. (2015) [56]	PEPIO	Combine the two operators
	Tao and Li (2018) [26]	CPIO	Conduct one of the two operators crosswise
	Duan et al. (2015) [56], Mohamed et al. (2017) [57]	PEPIO	Divide pigeons into predators and escapees
	Xu and Deng (2018) [51]	ADID-PIO	Divide pigeons into the top, medium and inferior
	Zhang and Duan (2018) [58]	SCPIO	Divide pigeons into different ranks
Application expansion	Qiu and Duan (2015, 2018) [59, 60], Deng et al. (2017) [61]	MPIO	Extend to multi-objective optimization
	Shan et al. (2017) [62]	DKPIO	Extend to discrete optimization
	Bolaji et al. (2018) [63]	BPIO	Extend to combinatorial optimization

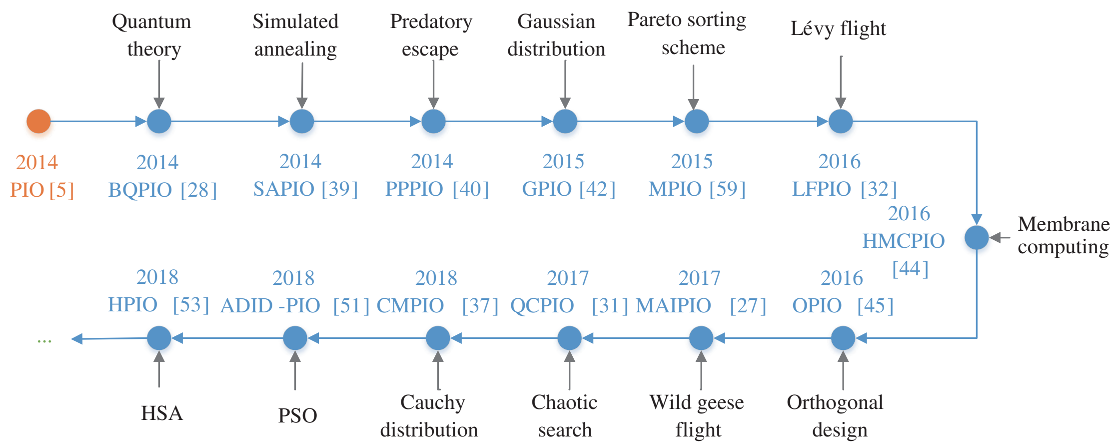

Figure 2 (Color online) Development of pigeon-inspired optimization by adopting mature concepts.

Modified PIO, a variant of PIO with improvements to specific problems, is full of unlimited potential. As shown in Table 1, the modification could be divided into the following four aspects.

(1) Component replacement. Following the original structure, primary PIO has been modified in two directions: coefficient modification and operator replacement. In the coefficient-modification direction, Hao et al. [22] revised the map and compass factor R by fractional calculus to balance the convergence rate with the search breadth. Jia and Sahmoudi [23] presented expand and contract PIO (ECPIO) by the population dispersion degree, and Chen and Duan [24] amended R by considering a variable parameter mechanism in particle swarm optimization (PSO). Lin et al. [25] proposed adaptive weighted PIO (AW-PIO) by adding a nonlinear dynamic inertial weight coefficient to the map and compass operator to handle the contradiction between local search ability and global search ability. Tao and Li [26] appended cognitive and compressive factors to the map and compass operator and the landmark operator, respectively, to avoid premature convergence. In PIO, the map and compass factor R represents individual inertia, while $\mathrm{rand}\cdot(X_g - X_i^{\mathrm{Nc}})$ and $\mathrm{rand}\cdot(X_{\mathrm{center}}^{\mathrm{Nc}} - X_i^{\mathrm{Nc}})$ represent social learning. R and $\mathrm{rand}\cdot(X_{\mathrm{center}}^{\mathrm{Nc}} - X_i^{\mathrm{Nc}})$ could avoid plunging into local optimum at a certain level. Thus, the appropriate value of R and proper learning strength from the global best position X_g and the center $X_{\mathrm{center}}^{\mathrm{Nc}}$ are crucial to improve algorithm performance.

In the operator-replacement direction, Zhou et al. [27] replaced the center $X_{\mathrm{center}}^{\mathrm{Nc}}$ and global best position X_g with the weighted average position of all personal bests and personal best position of the anterior neighbor in descending order of weight $w(X_i^{\mathrm{Nc}})$; this modification was inspired by the mechanism in wild geese. Li and Duan [28] and Pei et al. [31] presented Bloch quantum-behaved PIO (BQPIO) and quantum chaotic PIO (QCPIO), respectively, by substituting a Bloch quantum encoding mutation operator for the map and compass operator and the landmark operator to improve search ability and optimization efficiency. Liu et al. [32] proposed Lévy-Flight PIO (LFPIO) by displacing the map and compass operator with a Lévy-flight-based search operator and modifying the landmark operator by an adaptive Logsig function. Duan and Yang [37] proposed Cauchy mutation PIO (CMPIO) by adding a Cauchy mutation offset to the global best position X_g and the center $X_{\mathrm{center}}^{\mathrm{Nc}}$. In PIO, the global best position X_g and the center $X_{\mathrm{center}}^{\mathrm{Nc}}$ are responsible for the direction guidance of evolutionary learning, and the roles of these two parameters are similar to those of beacons in marine navigation. The properties of PIO are significantly enhanced by replacing the global best position X_g and the center $X_{\mathrm{center}}^{\mathrm{Nc}}$ with more beacons.

(2) Operation addition. As shown in Figure 2, modified PIO is unable to disengage from the wisdom of its predecessors. Considering mature concepts in intelligent computing, the variants of PIO present endless possibilities. Inspired by the features of the genetic algorithm, Hao et al. [22] added a crossover operation behind the landmark operator to ameliorate population variety. Li and Duan [39] presented simulated annealing PIO (SAPIO) by conducting Gaussian disturbance at the end of the algorithm to avoid plunging into local optima. Sun and Duan [40] proposed prey-predator PIO (PPPIO) by introducing

a predator-prey concept to primary PIO; here, the worst potential solution was treated as the predator, and the other solutions attempt to keep a safe distance from the predator. Zhang and Duan [42] executed a Gaussian mutation operation after the landmark operator, and Gaussian PIO (GPIO) was produced to overcome the weakness of PIO in exploration competence. To improve the performance of basic PIO, Chen and Duan [24] introduced multi-scale Gaussian mutation PIO (MGMPIO) by applying a multi-scale Gaussian operation to all positions and the global best position X_g in the map and compass operator. Inspired by the membrane computing model, Deng et al. [44] put forward hybrid membrane computing-based PIO (HMCPIO) by adding a communication operator after the landmark operator. Duan and Wang [45] applied an orthogonal design strategy to the initialization of PIO, and called the novel algorithm with a rich population diversity orthogonal PIO (OPIO). Cheng et al. [46] also designed sub-space division orthogonal initialization steps to ensure the superior distribution of the initial population and called this solution sub-space orthogonal PIO (SOPIO). Pei et al. [31] conducted a chaotic local search operation at the end of QCPIO to avoid premature convergence. Inspired by the interactive behaviors in the multi-agent model, Zhou et al. [27] proposed multi-agent improved PIO (MAIPIO) by executing a competition operator to reinforce the learning behavior from superior individuals. To punish for inferior solutions, Jiang et al. [47] and Sushnigdha and Joshi [48] respectively appended a threat heuristic operation and constraint handling mechanism to primary PIO. Referring to the cognition-only model in PSO, Hua et al. [50] and Xu and Deng [51] attempted to update pigeons' positions and velocities based on personal past best solutions and global best solutions in the map and compass operator. Sun et al. [52] also proposed heterogeneous comprehensive learning PIO (HCLPIO), a hybrid of heterogeneous comprehensive learning strategy and PIO. Harmony search algorithm (HSA) also provided Khan et al. [53] with inspiration. As a result, harmony PIO (HPIO) was proposed by improvising new harmonies in the landmark operator. Li and Deng [54] put forward quantum entanglement PIO (QEPIO) by adding a quantum entanglement combing operation at the beginning of the map and compass operator. Owing to the efforts of many researchers, the search capability of PIO has been greatly improved.

(3) Structure adjustment. Modification of the structure of basic PIO consists of two aspects: the execution order of the two operators and the classified updating of pigeons. In the first aspect, Li and Duan [39] opted to conduct the map and compass operator or the landmark operator according to a probability distribution by considering the uncertainty of pigeons' navigation strategy. Given the convenience of algorithm parameter adjustment, Duan et al. [56] combined two operators by a transition factor designed by the fundamental concept of PIO. In the modified PIO, pigeons fly based on the coupled updating equation, and the transition factor ensures that the global best position X_g and the center $X_{\rm center}^{\rm Nc}$ dominate the previous and later iterations, respectively. Tao and Li [26] proposed crossed PIO (CPIO) by invoking one of the two operators crosswise. The two operations in CPIO are executed in the following order: the map and compass operator, the landmark operator, the map and compass operator, and the landmark operator. In basic PIO, the learning effect from the global best position X_g and the center $X_{\rm center}^{\rm Nc}$ is a staged process. Simultaneous or crossed learning from the two approaches may yield surprising results on some issues. In the second aspect, Duan et al. [56] presented predatory escaping PIO (PEPIO) by dividing pigeons into predators and escapees to intensify the capacity for global search. In PEPIO, the predator approaches the global best position of escapees, and the escapee keeps away from predators. Xu and Deng [51] developed adjacent-disturbances and integrated-dispatching PIO (ADID-PIO) by separating updating for the top, medium, and inferior pigeons. In ADID-PIO, top pigeons fly to the global best X_g and respective personal best, medium pigeons learn from the individual personal best and the center of the top, and inferior pigeons approach X_g. Inspired by the hierarchy in pigeon flocks, Zhang and Duan [58] put forward social-class PIO (SCPIO) by establishing a hierarchical social network in which pigeons will learn from the past best of pigeons with the same rank. In basic PIO, all individuals update their positions based on identical rules, which would not make full use of the differences among individuals during evolution. Classified updating is done to design specific rules for individuals with different characteristics by considering the whole pigeon flock as a heterogeneous network.

(4) Application expansion. Basic PIO is proposed to address air robot path planning, a mono-objective

continuous optimization problem [5]. Currently, PIO has been developed to solve various types of issues from continuous and discrete optimization to mono- and multi-objective optimizations by designing specific initialization and evaluation rules. Qiu and Duan [59, 60] proposed multi-objective PIO (MPIO) based on the Pareto sorting scheme. In MPIO, pigeons are evaluated by non-dominated sorting and crowded-comparison instead of calculating cost function value. MPIO has been applied to two multi-objective optimization problems, namely brushless direct current motor design and unmanned aerial vehicle distributed flocking. Shan et al. [62] presented discrete knowledge PIO (DKPIO) for energy efficiency optimization in discrete manufacturing workshop, a discrete optimization problem. In DKPIO, the positions of pigeons are discretized by a two-step process: rounding and completion. Bolaji et al. [63] proposed binary PIO (BPIO) in allusion to the multidimensional knapsack problem, a combinatorial optimization task. In BPIO, a binary representation model is built to match the features of the search space in a multidimensional knapsack problem.

5 Conclusion and prospects

The influence of basic PIO and its variants has penetrated numerous fields. Herein, the improvement measures utilized in PIO's variants from the viewpoint of component replacement, operation addition, structure adjustment, and application expansion are reviewed. Although the research on PIO is very vigorous, some complications may obstruct its future development.

(1) According to Occam's razor theorem: "Entities should not be multiplied unnecessarily". Thus, the necessity of modifying PIO's variants requires attention and study. In other words, the absolute predominance of basic PIO or one of its variants on a certain issue is ambiguous.

(2) Sufficient theoretical analysis is indispensable for many processes from simulation tests to practical applications. However, the convergence and complexity of only a few variants have been analyzed [35, 41, 58–60]. The parameters of most variants are set based on experience and intuition.

In conclusion, building a complete evaluation system to identify the superiority of basic PIO and its variants is an urgent necessity. Intensive testing for primary PIO and its variants on benchmarks must be conducted to determine what types of problems are suitable for which algorithm, as well as the optimal configuration of parameters for each algorithm. Besides, reviewing the theoretical analysis of existing variants to promote practical engineering applications is necessary.

Currently, PIO is at the turning point of technology from theoretical to engineering applications, and many bottlenecks hinder its further widespread applications. Therefore, PIO presents broad prospects, both in terms of innovative theories and industrial applications, as follows:

(1) Model improvement. Nature is a rich source of wisdom. The latest research reveals the mystery of the flight of pigeons from the viewpoint of decision making based on group structures [64], obstacle avoidance based on flight postures [65], and visual perception based on orthographic processing [66]. Model improvement based on newly discovered biological research results will undoubtedly inject a steady stream of vitality into PIO and indirectly promote the understanding of the nature of swarm intelligence behaviors.

(2) Application intensification. Although the application scope of PIO covers many fields, its application depth is inadequate. As can be observed from the published research results, most of the related applications remain in the simulation stage, and the majority of the available research is based on the simplification of the constraints of the actual problems. Further research on this topic is needed, especially in the areas of dynamic optimization, stochastic optimization, and multi-objective optimization. Accelerating the convergence speed and reducing the time complexity of PIO are particularly important endeavors.

(3) Hardware development. Under the premise that artificial intelligence has developed into an irreversible trend, the production of novel PIO-based hardware by integrated pigeon intelligence technology is bound to become the development direction of related applications. The development of a universal, practical, and standardized chip based on PIO is an inevitable technology that is projected to provide a

great service to the public. Concurrent with the development of deep-learning chips, nerve bionic chips, and intelligent computing chips, realizing their coordinated development by learning from their respective virtues is a problem worthy of deep thought.

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