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Application of improved krill herd algorithms to inverse radiation problems

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A B S T R A C T

A nature-inspired metaheuristic krill herd (KH) algorithm was introduced to inverse transient radiative problems for the first time. Three improved KH (IKH) algorithms were developed to accelerate convergence in the later stage of the searching process. Radiative source terms were then estimated in a parallel slab of participating medium to investigate the performance of the proposed algorithms. Results showed the superiority of the three IKH algorithms to the original one. Additionally, the extinction coefficient and scattering albedo in a parallel slab with short pulse laser incident were retrieved using the IKH algorithms. Radiative properties cannot be estimated accurately with measurement errors when the media were optically thick and scattering dominated in the inverse transient radiative problems. Hence, adopting a shorter incident pulse was suggested to solve this problem. Consequent numerical simulations indicated that radiative properties can be retrieved accurately even with measurement errors. Finally, the proposed IKH algorithms were applied to a 2D media to obtain the optical properties of the inclusion.

1. Introduction

Researchers have made it known that reconstructing radiative properties in turbid media from various types of radiation measurements is very practical and useful in many different areas, such as the laser light-scattering flame diagnosis, optical tomography in medical imaging, atmospheric remote sensing, temperature distribution reconstruction in combustion chambers, and manufacturing and materials processing system optimization [1–3]. Therefore, various analytical models, numerical simulations and experimental aspects have been reported in relation to the retrieval of the extinction coefficient, absorption coefficient, single-scattering albedo, phase function, or optical thickness from radiation measurements at boundaries in different geometries [4,5]. McCormick has extensively reviewed the early development in a series of studies [6–8].

One of the biggest issues in the inverse problems is the methodology, which can be grouped into two categories based on the nature, deterministic and random intelligent approaches [9]. Various solution techniques have been successfully employed for the inverse radiative problem, such as the Gauss–Newton, Levenberg–Marquard, and Conjugate Gradient method [10,11]. However, the retrieval results of all these traditional gradient-based deterministic methods heavily depend on initial values, which are difficult to determine for problems without prior experience. Furthermore, the first or second derivative of the objective function should be determined for these gradient-based methods that usually require the objective functions to be relatively simple or have analytic expressions [11].

Based on this situation, quite a few random search intelligent algorithms, such as the generic algorithm (GA) [12–14], simulated annealing [15], ant colony optimization [16], differential evolution (DE) [17], and particle swarm optimization [18–20], have garnered great attention in recent years. These algorithms have been widely applied to inverse problems of radiative transfer, such as estimation of radiative source terms and radiative properties in 1D and 2D turbid media [11,18,20,21], recovery of the particle size distribution in particle systems [22,23], geometric optimization [24], and optical tomography [25]. Intelligent algorithms possess outstanding characteristics compared with traditional gradient-based methods (e.g., independence of initial values), and do not require the calculation of the objective function derivative. Moreover, even ill-posed and

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Nomenclature

d	sensing distance
D	diffusion speed
D_i	movements induced by random diffusion
F_i	movements induced by foraging action
F	objective function
g	scattering asymmetry parameter
N_θ	number of polar angle
K	fitness
N	total number of the krill individuals
NN	total number of the neighbors
NV	number of the variables
N_i	movements induced by other krill
N_x	number of grid
R	reflectance
r	random value
t	time or iteration
t_p	pulse laser duration (the width of pulse)
UB	upper boundaries of the variable
LB	lower boundaries of the variable
V_f	foraging speed
X_i	position of the ith krill
x	axial coordinate

Greeks symbols

α_i	local and target effect
β_i	impact of food or the best krill
β	extinction coefficient, m^{-1}
Δs	search step
δ	random directional vector
Φ	scattering phase function
μ	direction cosine
μ_0	incident direction cosine
σ_s	scattering coefficient, m^{-1}
τ	optical thickness
ω	single scattering albedo
ω_n	inertia weight of the motion
ω_f	inertia weight of the foraging motion

Subscripts

c	collimated radiation component of incident laser pulse
d	diffused radiation component of incident laser pulse
exa	exact value
i	ith krill individual
$i$best	best previously visited position of the ith krill
in	incident laser pulse
max	maximum value
mea	measured value
old	speed of the krill at the last generation
p	pulse
rel	relative value
sim	simulated value

non-linear problems can be solved using intelligent algorithms. A characteristic feature of these random search optimization methods is that they can solve global optimal problems reliably and obtain high-quality global solutions. Hajimirza et al. [26] reported that the global random search optimization techniques tend to perform better than local gradient-based methods, especially for higher problem dimensions. The major drawbacks of these random search algorithms are that the convergence velocity is relatively low during the final iterative procedure and the calculation is time consuming. However, computational time can be reduced substantially with the advent of high-speed computers and parallel processing techniques.

The krill herd (KH) algorithm is a nature-inspired metaheuristic algorithm first introduced in 2012 by Gandomi and Alavi [27]. The KH algorithm analogy is drawn from the natural herding behaviors of krill individuals [28], which includes foraging action, movement influenced by other krills, and physical diffusion of krill individuals. Since its introduction, the KH algorithm has drawn the attention of scholars in various fields worldwide, including economic load dispatch [29] and structural optimization [30]. The KH algorithm is generally highly exploited. Simplicity is the crucial advantage of the KH algorithm, thus facilitating easy implementation and employment for parallel computation [9]. To the best of the authors' knowledge, the application of the KH algorithm to inverse radiation analysis has not yet to be reported. The current study aims to introduce the KH algorithm to solve inverse radiative problems in semitransparent participating media. Furthermore, considering that the original KH algorithm may become trapped into the local optima, three improved KH (IKH) algorithms are proposed to enhance the global searching ability and accelerate convergence efficiency.

The remainder of this work is organized as follows. Section 2 discusses the detailed theoretical overview of the original KH and IKH algorithms. Section 3 presents the description of the steady state radiative transfer problem and the retrieval results. First, the distribution of the source term is reconstructed. Afterward, the 1D transient radiative transfer problem is introduced, followed by the retrieval results of the extinction coefficient β and scattering albedo ω. The influence of random errors in each case is also examined. The influence of the duration of laser pulse is analyzed. Finally, the proposed IKH algorithms were applied to a 2D media to obtain the optical properties of the inclusion. Main conclusions are provided in Section 4.

2. Inverse model

2.1. KH algorithm

KH algorithm is a newly proposed bio-based swarm intelligence algorithm [27], which is proposed based on the following movements of an individual krill: (i) movement induced by other krill individuals; (ii) foraging action; and (iii) random diffusion. In the KH algorithm, these three movements are represented by N_i, F_i, and D_i, respectively, where i stands for the ith krill individual. Hence, the Lagrangian model of the KH algorithm for an n-dimensional problem is expressed as [27]:

$$\frac{dX_i}{dt} = N_i + F_i + D_i \tag{1}$$

where dX_i/dt can be considered as the moving speed of the ith krill.

Generally, a krill individual is affected by local, target, and repulsive effects [27,31]. Therefore, the motion induced by other krill individuals N_i is defined as [27]:

$$N_i = \left(\alpha_i^{\text{local}} + \alpha_i^{\text{target}}\right) N^{\max} + \omega_n N_i^{\text{old}} \tag{2}$$