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Research paper

# Parallel ant colony optimization for the determination of a point heat source position in a 2-D domain

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## HIGHLIGHTS

- The Ant Colony Optimization can be properly used for inverse heat source problem.
- The parallel implementation can increase the speed and accuracy of the algorithm.
- The fine-grained strategy has a higher speedup.
- The coarse-grained strategy shows a robust property of correct rate near to 100%.

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## ABSTRACT

The Ant Colony Optimization (ACO) and its parallel implementations are applied to determine the unknown position of a point heat source in a two-dimensional steady-state heat conduction problem. The heuristic value, the determination of path and the objective function are all studied based on the inverse heat source problem. Some of the standard steps of the ACO are also modified according to the features of the heat conduction problem. In order to accelerate the speed of solving the inverse problem, two kinds of parallel ACO strategies, the fine-grained master-slave strategy and the coarse-grained strategy combined with the above modification are studied in this paper. The results show that the fine-grained strategy has a higher speedup than the coarse-grained strategy whiles the coarse-grained strategy has a higher accuracy rate. This means that the coarse-grained strategy is more proper during the parallel implementation for solving the inverse heat source problem and the parallel implementation of the ACO can improve the computational efficiency.

## 1. Introduction

The determination of the heat source is a type of inverse source problems that belong to the Inverse Heat Transfer Problems (IHTPs). IHTPs rely on temperatures and/or heat flux measurements for the estimation of unknown quantities, such as the heat source or thermal conductivity coefficients appearing in the analysis of physical problems in thermal engineering [1]. The field using the inverse heat transfer problems is broad. Fields of applications include the development of new materials, the casting and welding in steel or polymer processing, the development of a sophisticated temperature measurement related to lifetime analysis of plans, the development of transient calorimeters, etc. [2].

The inverse problem is ill-posed [3], and any small change of the input data can result in a dramatic change of the solution. Nowadays, a wide variety of techniques have been successfully employed to deal with the inverse analyses of heat transfer problems. However, the methods for solving IHTPs are mainly classified into two kinds, gradient-based method and stochastic method [4]. Studies of the gradient-based method include the using of the Gauss–Newton method, conjugate gradient method, etc. Zhou et al. [5] adopted the conjugate gradient method to estimate the surface heating condition in a three-dimensional object. Adili et al. [6] applied the Gauss–Newton method to estimate the thermo-physical properties, Rouquette et al. [7] estimated the parameters of a Gaussian heat source by using the Levenberg–Marquardt method. Some stochastic methodologies, such

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as genetic algorithms, ant colony optimization (ACO), particle swarm optimization (PSO) and artificial bee colony algorithms have been adopted to solve the inverse heat transfer problems successfully. Liu [8] considered a modified genetic algorithm for solving the inverse heat transfer problem to estimate the plane heat source. Tian et al. [9] estimated the temporal dependent heat source by using the PSO algorithm. Rapoport and Pleshivtseva [10] introduced a semi-infinite optimization to solve the inverse heat-conduction problems.

ACO, which was introduced in 1992 by Marco Dorigo, is a probabilistic technique. The main idea of the ACO is to use the self-organizing principles to coordinate populations of artificial agents that collaborate to solve computational problems. Dorigo and Gambardella [11] firstly applied ACO algorithm to solve traveling salesman problem (TSP). Maniezzo and Carbonaro [12] used it in solving frequency assignment problem. Merkle et al. [13] adopted this methodology in the source-constrained project scheduling. Current applications of ACO algorithm include outing, assignment, scheduling, subset, machine learning and network routing [14], etc.

In the field of inverse heat transfer problems, the ACO is rarely used. In a recent study of this problem, Hetmaniok et al. [15] deal with the determination of heat transfer coefficient by using the ant colony optimization. Zhang et al. [16] applied a grid-based continuous ant colony optimization algorithm to solve the inverse problem of a one-dimensional coupled radiation and conduction heat transfer. These studies show that the ACO turns out to be an effective and robust method for solving the IHCPs.

The inverse source problem of determining the point heat source has two features. The first is that the point heat source is applied to 2-D mesh elements, so it is a typical discrete problem. The second is that the inverse problem needs large number of calculations of the direct problems, so it is computationally expensive, especially for the 2-D and 3-D problems. The ACO is an algorithm for discrete optimization [17]. Its parallel nature enables the parallel implementation of the algorithm which allows reaching an acceptable result within a reasonable execution time when solving the 2-D or 3-D problems.

With the parallel technique becoming mature day by day, scholars began to focus on the parallel implementations of the optimization algorithms. The ACO also finds favor with the scholars because of its characteristics of high parallelism. Dorigo first suggested the parallel implementation of the ACO to improve the computational efficiency. Ellabib et al. divided the parallel ACO into fine-grained and coarse-grained strategies. Bullnheimer et al. [18] applied both of the two strategies to the TSPs and suggested that the coarse-grained strategy which benefits from the reduced communication frequency performs better than the fine-grained ones. In Hetmaniok's study, the ACO algorithm was executed parallel to solve the inverse binary alloy solidification problem which consisting in reconstruction of the heat transfer coefficient [19]. However, most of the studies of parallel ACO focus on specific problems, so there is no generalized point of view on whether one parallel strategy is better than others [20].

In this paper, the ACO algorithm is proposed for the solving of the two-dimensional inverse heat conduction problem for the determination of the point heat source position. Some modifications have been made so that the ACO can be applied to the inverse problem. The definition of path, the building of the objective function and the path selection rules are modified according to the features of the inverse problems. The paper also considers the parallelism of the ACO both in fine-grained and coarse-grained strategies. When solving the case described in this paper, the performances of both strategies are compared with respect to the perspective of speedup, efficiency and efficacy.

## 2. The physical and mathematical models of the direct problem

### 2.1. The physical model

In this paper, a 2-D plate of side length $d = 0.1$ m in the $x-y$ plane with a constant thermal conductivity of $\lambda = 1.3$ W/(m K) and uniform heat generation of 50 W/m$^2$ is selected. The west face of the plate maintains at a temperature of $T_0 = 310.15$ K. The other three faces of the plate are Robin boundary condition. The heat transfer coefficient of these three faces is $h = 13$ W/(m$^2$ K), and the ambient fluid temperatures is $T_f = 297.15$ K. The intensity of the heat source, which is located at the position of (0.0405 m, 0.0305 m), is 72 W. The domain is shown in Fig. 1. The locations of the measurement points are shown in Table 1.

### 2.2. Mathematical model

The governing equation used in two-dimensional steady-state heat conduction problem is:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+S_T=0 \tag{1}$$

where $\lambda$ is the thermal conductivity, and $S_T$ is the source term. The direct problem solution in this paper is the numerical solution of the Eq. (1).

Boundary conditions:

$$\begin{cases} -\lambda\left.\frac{\partial T}{\partial x}\right|_{x=0.1} = h\left(T|_{x=0.1}-T_f\right) \\ -\lambda\left.\frac{\partial T}{\partial y}\right|_{y=0.1} = h\left(T|_{y=0.1}-T_f\right) \\ \lambda\left.\frac{\partial T}{\partial y}\right|_{y=0} = h\left(T|_{y=0}-T_f\right) \\ T|_{x=0} = T_0 \end{cases} \tag{2}$$

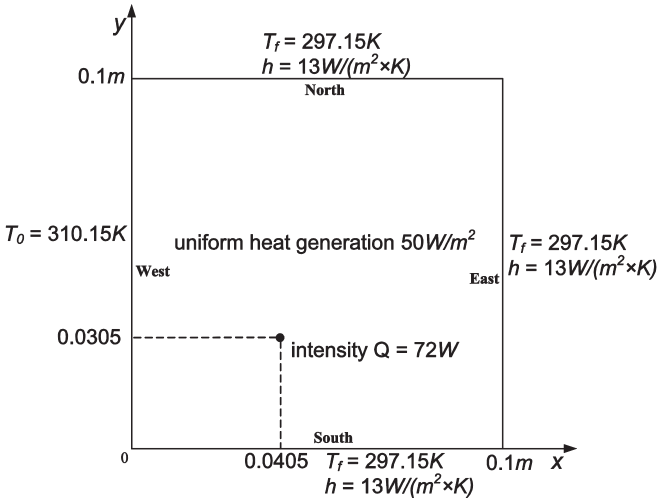

**Fig. 1.** Illustration of the numerical example.