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Evacuation path optimization based on quantum ant colony algorithm

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ABSTRACT

Evacuation planning contains more than a few decisions which have to be made in a very short period of time and in the most appropriate way. Evacuation path optimization has vital importance in reducing the human and social harm and saving the aid time. Significant research efforts have been made in the literature to deal with evacuation optimization on the basis of deterministic optimization model, nevertheless the stochastic aspects or uncertainty of real-world evacuation have not been taken into account comprehensively. Inspired by the promising performance of heuristic algorithms to solve combinatorial problems, this paper proposes an improved quantum ant colony algorithm (QACA) for exhaustive optimization of the evacuation path that people can evacuate from hazardous areas to safe areas. In comparison with ACO (ant colony optimization) based method, QACA has the capability of finding a good solution faster using fewer individuals and possesses strong robustness, as a result of the quantum representation and updating of pheromone. Experiment results show that the proposed approach executes more effectively during evacuation.

1. Introduction

Swarm intelligence (SI) is based on natural biome communities, which has been used in various engineering applications due to its desirable properties of being adaptive, scalable, and robust [1]. The SI framework encompasses other popular frameworks such as Ant Colony Optimization (ACO) [2], and Particle Swarm Optimization (PSO) [3]. ACO is inspired from the foraging behavior of real world ant colonies, where ants release chemicals, i.e., pheromone on the route so as to mark the routes from the nest to food which would be followed by other members of the colony [4]. As a simulation evolution algorithm with typical swarm intelligence features, ACO is used to solve some complicated NP hard combinatorial optimization problems [5]. The ACO has experienced a tremendous growth, and its diverse applications include traffic congestion control [6], data mining [7], job-shop scheduling [8], and manufacturing [9].

Since evacuation methods have critical applications, scholars have carried out extensive and in-depth researches, and various approaches have been proposed and developed to deal with the evacuation problem [10]. A crowd is expected to move from areas impacted by accidents, terror attacks and other emergency events to safe zones, in short time and in the most appropriate way. However, urban evacuation is a complex adaptive system, as a mass of personnel interactions are involved [11]. Group belongingness, self-organization, and other motion characteristics of how evacuees behave during evacuation have many things in common with ant colony system. If affected by other ants in the colony, the ant would gradually tend to move along the route passed by most of the ants. Such herd behavior is in accordance with small group phenomenon of evacuees. In ACO, individuals' perception and interaction with the environment is represented by positive feedback mechanism, which, together with communication mechanism, are important foundations of the ACO algorithm. Therefore, the ACO algorithm provides a suitable solution to evacuation path optimization regardless of some limitations such as slow astringency, earlier stagnation.

The objective of this work is to design an evacuation path optimization method with high efficiency and strong robustness. This paper introduces the basic concepts and principles of quantum-inspired evolutionary algorithm (QEA) [12] into ACO, and proposes a quantum-inspired ACO algorithm for evacuation path optimization, called quantum ant colony algorithm (QACA). A quantum bit (Q-bit) is used to represent current pheromone information of the ant, and the quantum rotation gate is adopted to update pheromone. Similar to the general evolutionary algorithms, the QACA is characterized by the individuals, the evaluation function, and the

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population. However, instead of using binary or numeric representation, the QACA uses quantum bit to represent the population. When measuring the population fitness, a binary solution (represented by binary bits) is made by observing the quantum states. Although the basis of QACA is the concept and rules of quantum computing, this approach is an evolutionary algorithm rather than a quantum algorithm.

The rest of this paper is organized as follows. Section 2 provides a literature review. Section 3 sheds light on the evacuation problem. Section 4 elucidates an approach for evacuation path optimization based on QACA. Section 5 illustrates some experimental results. Section 6 presents conclusions and discusses some potential further work.

2. Literature review

Path optimization plays a significant role in evacuation, and affects the standard to measure whether an evacuation plan is feasible. On the other hand, evacuation path planning is one kind of path optimization and network flow problems. Therefore, this section covers the literature review on path optimization in general with some focus on applications to evacuation.

While there are various approaches proposed and developed in the literature to deal with evacuations, most of them are based on mathematical modeling, simulation, and soft computing.

Network flow models have been widely used in path optimization. Typically, there are two kinds of networks, i.e., dynamic and static. Dunn et al. [13] presented the maximum flow method for evacuation route within the permitted scope of network capacity. However, a network varies with time in real evacuation scenarios. Cova et al. [14] took into consideration the conflicts within intersections on a lane-based static network. In comparison with static models, dynamic models have some superiority in reflecting the time-varying characteristics. In [15], evacuation schemes, including vehicle allocation plans and routing strategies, are determined by an interval parameter fuzzy evacuation management model. Due to the uncertainty and complexity of the environment in emergency, such models have serious limitations in dealing with the evacuation process based on individual behaviors.

A considerable number of evacuation solutions rely on simulation models. Earlier simulation software tools include OREMS, DYNEV, VISSIM, and CORSIM. Subsequently, agent-based approaches have been proposed and developed [16,17]. Agents are generated to simulate the behavior of individuals, and accordingly a society system is built through interactive mechanisms among multi-agents. Such approaches could combine organically the microscopic behavior of individuals in a complex evacuation system with the macroscopic features of the system. In [18], an agent-based technique was used to model traffic flows at the level of individual vehicles, further to explore the effectiveness of simultaneous and staged evacuation strategies under different road network structures. Using an agent-based model, Lei et al. [19] simulated the evacuation process in different cases to investigate the effects of occupant density, exit width and automatic fare gates on evacuation time. They concluded that there is a linear relationship between occupant density and evacuation time. The human congestion problem in evacuation is considered in [20], and a distributed guiding navigation protocol was presented to balance the load of moving objects among multiple navigation paths to different exits. Chen et al. [21] proposed a distributed path planning algorithm for sensor network navigation in dynamic hazardous environments, and they constructed a distributed in-network directed navigation graph by using geographic or virtual coordinates of sensors based on a partial reversal method for directed acyclic graphs. Oxendine et al. [22] presented a network-based methodology to provide additional analytic support to emergency services personnel. In addition, a multi-objective, multi-criteria approach was used to determine optimum evacuation routes by using mobile phones. Ren et al. [23] combined the processes of evacuation route planning and traffic signal designing into an integrated model for evacuation, considering uncertain background demands.

Soft computing based intelligent algorithms provide new insights to deal with the evacuation problem. Common intelligent algorithms for evacuation path optimization include neural network algorithms [24], genetic algorithms [25], and swarm intelligence algorithms [26]. Introduced by Marco Dorigo in his Ph.D. thesis (1992), ACO is one of the most representative swarm intelligence algorithms, acting as an important nature-inspired stochastic metaheuristic for hard optimization problems [27]. Forcael et al. [28] developed an ACO algorithm to optimize the evacuation times during tsunamis, further to ensure safe routes. Rahman et al. [29] modified the ACO algorithm by creating exit sign, an agent, to determine the feasible route and guide occupants during the evacuation. They also considered physical obstacles during building evacuation in transitional probability rule of ACO. Zong et al. [30,31] presented a multi-objective ant colony optimization model to solve massive evacuation problems under complex traffic conditions, and a multi-ant colony system was developed to tackle mixed traffic evacuation problems. An improved ACO-based evacuation system was proposed in [32], which uses deodorant pheromone as a new guidance mechanism to erase ACO pheromone traces when dangerous locations are found.

Based on the existing literature, this paper proposes an improved ACO approach called quantum ant colony algorithm (QACA) to cover the exhaustive optimization of the evacuation path that people can evacuate from hazardous areas to safe areas. In order to construct an evacuation optimization method with better performance, QACA integrates the properties of ACO and quantum-inspired evolutionary algorithm (QEA) [33,34].

3. Description of the evacuation problem

This section introduces an intelligible way to build an evacuation network in order to simulate real-world situations. The evacuation problem will be represented as a network flow problem with certain constraints. Based on nodes and arc segments of graph theory, a graph, i.e., $G(N,A)$ needs to be defined with sources and sinks to emulate the flow of evacuees. Inside the buildings, nodes are used to describe rooms, corridors, stairs and halls, arc segments represent the links between the nodes. And likewise, every accessible area, in the outdoors, such as roads, squares, lawns, pavements are represented as nodes, and every link between two neighbor nodes denotes an arc segment.

Thus, a directed digraph $G(N,A)$ is used to represent a network of the evacuation area, where N denotes the set of nodes, and A is the set of links between two nodes. Several nodes are chosen to construct the set of origination nodes, O, while another part of them forms the set of destination nodes, D, and the others are intermediate nodes. Fig. 1 illustrates an evacuation network topology with 18 nodes and 32 links.

The objective of evacuation planning is to find a solution which minimizes the total time that all evacuees finish moving from dangerous zones to safe places. Consequently, time is the most significant factor that should be considered in the evacuation process. In this paper, the objectives are to minimize the total evacuation time of all evacuees and to balance the load of the whole evacuation network.

Following are definitions of some variables and parameters: