Multi-ant Colony System for Evacuation Routing Problem with Mixed Traffic Flow

Xinlu Zong, Shengwu Xiong, Zhixiang Fang, and Qiuping Li

Abstract—**Evacuation routing problem with mixed traffic flow is complex due to the interaction among different types of evacuees. The positive feedback mechanism of single ant colony system may lead to congestion on some optimum routes. Like different ant colony systems in nature, different components of traffic flow compete and interact with each other during evacuation process. In this paper, an approach based on multi-ant colony system was proposed to tackle evacuation routing problem with mixed traffic flow. Total evacuation time is minimized and traffic load of the whole road network is balanced by this approach. The experimental results show that this approach based on multi-ant colony system can obtain better solutions than single ant colony system and solve mixed traffic flow evacuation problem with reasonable routing plans.**

I. Introduction

In some types of large public areas, huge number of pedestrians and vehicles are highly mixed. Once catastrophic events such as hurricanes, fire or terrorist attacks happen, pedestrians and vehicles crowd and congest together, and may lead to serious results to human beings. Recently, the modeling and simulation of emergency evacuation are attracting widespread attentions of researchers [1]-[2].

Route planning is one of the most important aspects in emergency evacuation planning. There have some researches on evacuation planning studied from different perspectives, such as routes planning [3], sheltering site allocation [4]-[5] and individual's microscopic behaviors [6] during evacuation.

Some works studied pedestrian evacuation in buildings. Reference [7] presented a model and studied the evacuation behavior in high-rise building. A model for routes planning of people in a building was proposed in [8]. In addition, a few researches [9] studied evacuation on road network. For example, [3] presented a network flow model for identifying optimal lane-based evacuation routing plans in a complex road network. The model aimed to minimize total travel distance. And a mixed-integer programming solver was used to derive optimal routing plans for the network.

Evacuation route planning is complex due to the complicated traffic conditions. Most of the existing works studied on pedestrian evacuation in building or vehicle evacuation in road network separately. The influence between pedestrians and vehicles, and the route which each pedestrian or vehicle selects will affect the whole evacuation efficiency. Few studies have been reported on evacuation routing and optimization involving mixed traffic flow with both pedestrians and vehicles.

In this paper, an evacuation model and an approach based on multi-ant colony system were presented to tackle mixed traffic evacuation problem. The two objectives of the model are to minimize total evacuation time and balance traffic load of the whole road network. The experimental results show that this approach based on multi-ant colony system can obtain better solutions than single ant colony system and solve mixed traffic evacuation problem with reasonable routing plans.

This paper is organized as follows. Section II describes the necessary background information. Section III introduces a model for evacuation routing problem with mixed traffic flow. Section IV presents an approach based on multi-ant colony system to solve the problem. Section V analyzes the results of computational experiments. Finally, Section VI summarizes the paper and draws conclusions.

II. Background Information

The necessary background information is described in this section to appreciate the work presented in this paper. A brief introduction to multi-objective optimization is provided in Section II A and the basic ant colony optimization algorithm is given in Section II B.

A. Multi-objective Optimization

A multi-objective optimization problem [10]–[12] can be stated as follows:

$\min F(x) = (f_1(x), f_1(x), ..., f_n(x))$, where $n \geq 2$ is the number of objective functions, $x = (x_1, x_1, ..., x_m)$ is decision variable vector and X is the decision variable space, $F(x)$ is objective vector.

A decision vector $u \in X$ dominates another decision vector $v \in X$, denoted by $u \prec v$, if and only if $\forall i \in \{1,2,...,n\}$, $f_i(u) \leq f_i(v)$ and $\exists i \in \{1,2,...,n\}$, $f_i(u) < f_i(v)$.

A solution $x \in X$ is said to be Pareto optimal if and only if there is no other decision vector that dominates x in X . Such solutions are called non-dominated solutions. The set of

Xinlu Zong is with the School of Computer Science and Technology, Wuhan University of Technology, Wuhan 430070, China (email: zongxinlu@sina.com).

Shengwu Xiong is corresponding author, with the School of Computer Science and Technology, Wuhan University of Technology, Wuhan 430070, China(email: xiongsw@whut.edu.cn).

Zhixiang Fang is with the State Key Laboratory for Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China.

Qiuping Li is with the State Key Laboratory for Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China.

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all Pareto optimal solutions in the decision variable space is called non-dominated set or Pareto optimal set and the corresponding set of objective vector is called Pareto optimal front.

B. Ant Colony Optimization

The ant colony optimization (ACO) algorithm was first proposed by Dorigo [13]-[14]. It is used to solve NP-hard problems, such as the traveling salesman problem TSP [15], scheduling problem [16], quadratic assignment problem [17], vehicle routing problem [18].

The ant colony optimization imitates the behavior of real ants when finding food. Ants release some substance called pheromone when they pass a route. The released pheromone will evaporate with time. At the beginning, ants are randomly generated on the nodes, and stochastically moved from a start node to feasible neighbor nodes. During the process of finding food, ants will collect and store information in pheromone. Pheromone will be released by ants while finding shorter path. In addition, the released pheromone will be evaporated over time. As a result, all the ants will be attracted to the shortest path because of the positive feedback mechanism.

The four different phases of ACO can be summarized as follows:

1. Initialization: Place ants randomly on the nodes and lay initial pheromone on the arcs.
2. Node selection: This phase is characterized by the movement of ants on different nodes using a probabilistic approach that is based on a trade off between visibility and pheromone. This is the most crucial phase.
3. Pheromone updating: The density of pheromone decides the motion of ants in the following iterations.
4. Stopping criteria: The algorithm stops when the specific number of iterations has been completed.

III. Problem Formulation

The aim of evacuation problem with mixed traffic flow is to plan routes for each pedestrian and each vehicle so that all the evacuees can evacuate to safe areas with minimum time and balanced traffic load. In this paper, the objectives are to minimize the total evacuation time of all evacuees and to balance the traffic load of the whole road network.

An emergency evacuation road network can be represented as a directed graph $G(N, A)$, where $N = \{1,2,...,n\}$ denotes the set of nodes and A is the set of arcs between two nodes. Here each road segment represents a node. The mathematical modeling of the mixed traffic flow evacuation problem is described as follows:

Indices:

i index of network nodes

g index of groups of evacuees

(g,k) index of evacuee belongs to group g

Parameters:

M number of evacuees

N_g set of nodes that evacuees in group g can visit, here $N_g \subset N$

T time needed to evacuate all evacuees

$t_{ij}^{(g,k)}$ time spending on arc (i,j) of evacuee (g,k) under emergency situation

$P^{(g,k)}$ set of nodes constructed by evacuee (g,k)

l_{ij}^{g} traffic load of group g on arc (i,j) during T

d_{ij} distance from node i to node j

v_0^g traveling speed of members in group g under normal conditions

$v_{ij}^{(g,k)}$ traveling speed of evacuee (g,k) on arc (i,j) under emergency situation

N_{ij}^{g} number of evacuees passed (i,j) in group g during the whole evacuation process

$N_{ij}^{g}(t)$ number of evacuees in group g on arc (i,j) at time t

C_{ij}^{g} passing capacity of arc (i,j) for group g

$$\min f_1 = \sum_g \sum_{k=1}^{M} \sum_{i,j}^{P^{(g,k)}} t_{ij}^{(g,k)} \tag{1}$$

$$\min f_2 = \sum_g \sum_{i=1}^{n} \sum_{j=1}^{n} l_{ij}^{g} \tag{2}$$

Subject to:

$$l_{ij}^{g} = \left| \frac{N_{ij}^{g}}{T \cdot C_{ij}^{g}} - 1 \right| \tag{3}$$

$$t_{ij}^{(g,k)} = \frac{d_{ij}}{v_{ij}^{(g,k)}} \tag{4}$$

$$v_{ij}^{(g,k)} = v_0^g \cdot e^{-w \frac{N_{ij}^{g}(t)}{C_{ij}^{g}}} \tag{5}$$

$$\forall i \in P^{(g,k)}, i \in N_g \tag{6}$$

The objective (1) is to minimize total evacuation time, objective (2) is to balance traffic load of the whole network. Constraint (3) is the formula of traffic load along a road segment. Constraint (4) is the equation of traveling time through arc (i,j). Constraint (5) is the decrease function of the evacuation speed on arc (i,j), it is affected by current saturability of the arc. And w is the parameter that determines the decrease extent of the speed. Constraint (6) ensures that nodes visited by evacuee of a certain group are only allowed for this group to access.

IV. Multi-ant Colony System for Mixed Traffic Evacuation Problem

During emergency evacuation, the queuing behavior and self-organization of evacuees are similar to ant colony system in nature. Therefore, ant colony algorithm is suitable for solving evacuation routing problem. However, sometimes the single ant colony system (ACS) may trap in specific local optima because of the positive feedback mechanism of pheromone, which leads to congestion on some optimum routes for evacuation routing. Multi-ant colony system (MACS) [19]-[20] can be employed to avoid this problem because of its ability to consider both positive and negative feedbacks in searching optimum solutions. Similar to the interaction among different ant colony systems in nature, different components of traffic flow compete and affect with each other. Every colony can share information from the other colonies. In order to solve evacuation routing problem with mixed traffic flow, two types of ants are used. The first type of ant is used to imitate pedestrian group, the second type of ant is used to construct routes for vehicles. Fig.1 shows the optimization process by using two ant colonies. Ants belong to one colony find their routes with the same properties. During the process of searching routes, the two ant colonies will interact and share information with each other.

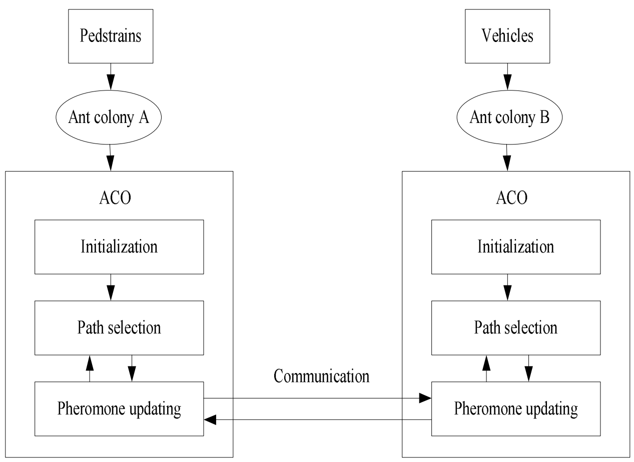

Fig. 1. Multi-ant colony system

A. Route Construction

In this approach, an artificial ant simulates a pedestrian or a vehicle. At the beginning, randomly put all ants on the nodes that allow each type of ant to visit. Artificial ants have some heuristic information while finding routes, unlike the real ants that search food blindly. The heuristic information of ant colony g on arc (i, j) is denoted by η_{ij}^g. This information is defined as the inverse of the passing time and capacity of arc (i, j):

$$\eta_{ij}^g = \frac{1}{t_{ij}^g \cdot C_{ij}^g} \tag{7}$$

Where t_{ij}^g is the traveling time through arc (i, j) under normal conditions.

Denote (g, k) as the ant k of colony g. In each decision step of an ant, the transition probability form node i to j for ant (g, k) is defined as below:

$$P_{ij}^{(g,k)}(t) = \begin{cases} \dfrac{\tau_{ij}^{\alpha}(t)\eta_{ij}^{\beta}(t)}{\sum\limits_{s\in S_{(g,k)}} \tau_{is}^{\alpha}(t)\eta_{is}^{\beta}(t)} & \text{if } j \in S_{(g,k)} \\ 0 & \text{Otherwise} \end{cases} \tag{8}$$

Here, τ_{ij} is the amount of pheromone on arc (i, j), $S_{(g,k)}$ is the set of nodes that ant k can visit at the moment, and α, β are parameters that weight the relative importance of pheromone and heuristic information.

B. Pheromone Updating

After all ants of each colony have completed their tours, the pheromone is updated separately on the basis of the local optimal solutions belong to the two ant colonies. The pheromone on each arc is updated as follows:

$$\tau_{ij}^g(t+1) = (1-\rho)\tau_{ij}^g(t) + \rho\Delta\tau_{ij}^g \tag{9}$$

Where, ρ $(0 \le \rho \le 1)$ is the evaporation rate of pheromone.

$$\Delta\tau_{ij}^g = \begin{cases} \dfrac{1}{\sum\limits_{k=1}^{M}\sum\limits_{i,j}^{P^{(g,k)}} t_{ij}^{(g,k)} \cdot \sum\limits_{i=1}^{n}\sum\limits_{j=1}^{n} l_{ij}^g} & \text{if } (g,k) \text{ passed } (i,j) \\ 0 & \text{Otherwise} \end{cases} \tag{10}$$

C. Communication

The search process can be improved by using communication among colonies. After the two colonies are stagnant or a certain number of iterations has completed, pheromone communication is carried out between the parallel colonies. For each colony, the pheromone is modified by means of using pheromone of the other colony by the following equation:

$$\tau_{ij}^g = \lambda\tau_{ij}^g + (1-\lambda)\tau_{ij}^{g'} \tag{11}$$

Where λ $(0 \le \lambda \le 1)$ is a parameter to weight the relative influence between the current ant colony and another one, $\tau_{ij}^{g'}$ is the pheromone of the other ant colony.

D. Algorithm

S1 Initialize the parameters and pheromone values of ant colonies.
S2 For each ant colony.
S2.1 Randomly put ants into their initial nodes.
S2.2 For each ant, execute following steps to generate route.
S2.2.1 Select a feasible neighbor node to visit based on transition rule by (8).
S2.2.2 Move the ant to the new node.
S2.2.3 Return to S2.2.1 until every ant has constructed a route from its initial node to one of any exit nodes.
S2.3 Determine the non-dominated set.
S2.4 Update pheromone by (9) and (10).
S2.5 Repeat S2.1-S2.4 until stagnation occurs.
S3 Communication among ant colonies. Modify pheromone information of each ant colony by using (11).
S4 Repeat S2-S3 for a specified number of iterations.

V. Experimental Implementation and Results

The area around the stadium of Wuhan Sports Center (China) was selected as the study area. This stadium has 157 nodes in total including bleachers, stairs, exits and passages distributed in all three floors, and the area outside the stadium has 319 roads. The task is to evacuate all pedestrians (inside the stadium) and all vehicles (outside) to the 8 exits leading to safe areas. Fig. 2 shows the network of the study area, the upper figure is the simplified graph of the inner stadium and the lower one is the network for vehicles. Suppose the emergency event has occurred in the node as marked in Fig. 2.

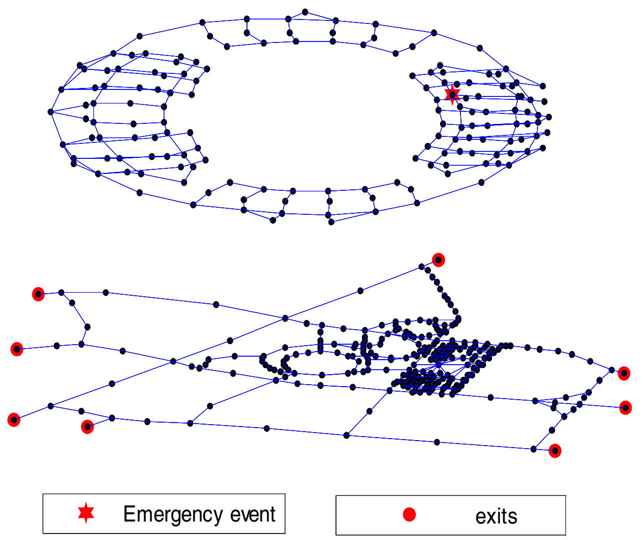

Fig. 2. Network of the study area

Experiments are carried out to justify the performance of ACS and MACS developed in this study. The ACS and MACS optimization algorithms for evacuation routing problem with mixed traffic flow were implemented using MATLAB coding and run on a PC with 3.06GHz, 1 GB RAM. In the two algorithms, the parameters used were set as follows: $\alpha = 2$, $\beta = 3$, $\rho = 0.7$, $w = 1$, and $\lambda = 0.5$ in MACS algorithm. At beginning of simulation, all pedestrian are placed in the central area, and all vehicles are put in the nodes which allow vehicles to access. The aim of routing is to search routes from each initial node to one of the 8 nodes represent exits.

The measures of performance for the model include minimum total evacuation time and minimum total traffic load. Different proportions between pedestrians and vehicles and the corresponding results are listed in Table I.

Table I shows that with different proportions, solutions by using MACS are improved by means of communication between colonies.

Fig.3 illustrates the non-dominated solutions by using ACS and MACS with both 300 ants in two colonies. It is shown that there is no single optimal solution, but a set of Pareto optimum solutions for multi-objective optimization problem. The trade-off between the two objectives is useful for the evacuation planner to decide and select an appropriate plan according to different demands. In Fig.3, it can be clearly seen that a more optimum Pareto front is obtained by MACS than ACS by virtue of pheromone communication between different ant colonies.

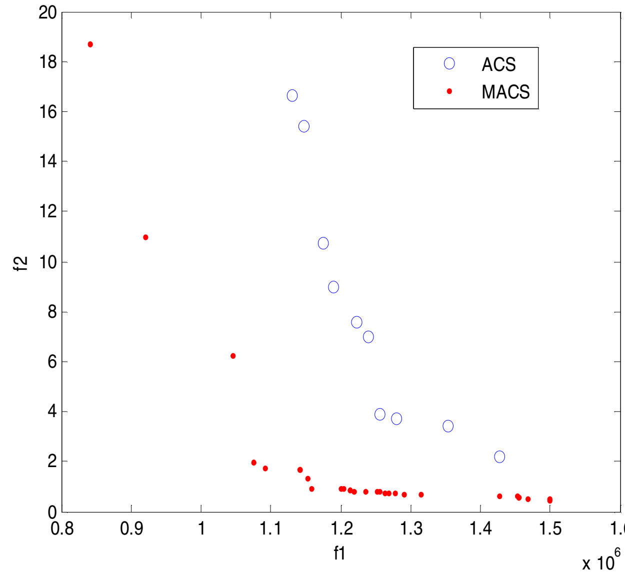

Fig. 3. The non-dominated solutions of the two approaches

Table II lists the number of pedestrians or vehicles evacuated from each exit with the proportion of 5: 1 by using MACS. The percentage of pedestrians evacuated from each exit ranges from 1.4% to 47%, and that of vehicles changes from 2% to 30%, all the 8 exits are used effectively for evacuation. We can see that the proportion of pedestrians to vehicles for each exit ranges from 2:1 to 8:1, and the average proportion is 5:1, which is the same as the ratio of pedestrians to vehicles. It demonstrates that pedestrians and vehicles have evacuated in proportion to each other without congestion.

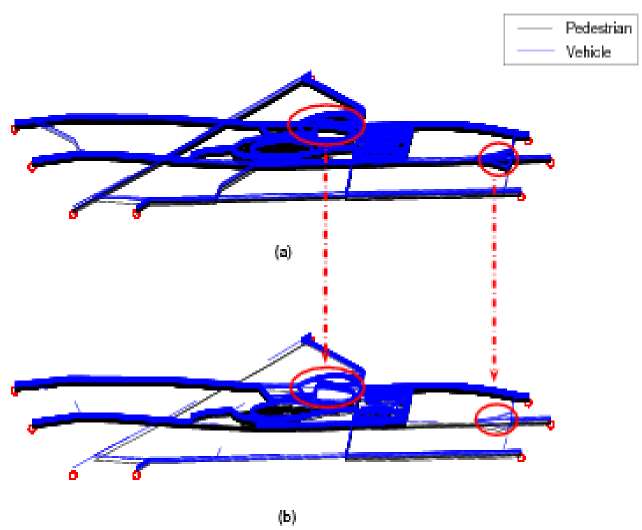

Fig. 4. Evacuation routes: (a) ACS; (b) MACS

One of the optimum evacuation plans is drawn in the form of routes in Fig. 4. Fig. 4 (a) draws the evacuation routes obtained by ACS with 1000 ants in total, and Fig. 4 (b) shows the routes by using MACS approach with 500 ants for each colony. Some differences between the two routing plans are marked in the figure. In Fig. 4 (a), it can be seen that the marked areas are rather crowded because the positive feedback mechanism of single ant colony system and in turn causes congestion. Comparing with Fig. 4 (a), the corresponding areas in Fig. 4(b) are not so crowded and the traffic load of the whole area is balanced efficiently.

Fig. 5 draws the varying number of evacuated pedestrians or vehicles with time by two approaches with 500 pedestrians and 500 vehicles. It can be observed that this MACS approach can evacuate all pedestrians before time 100, while more than 350 time periods are required for the ACS approach, which is three times than that of MACS. The results suggest that this MACS approach is suitable and efficient for solving evacuation routing problem with mixed traffic flow.

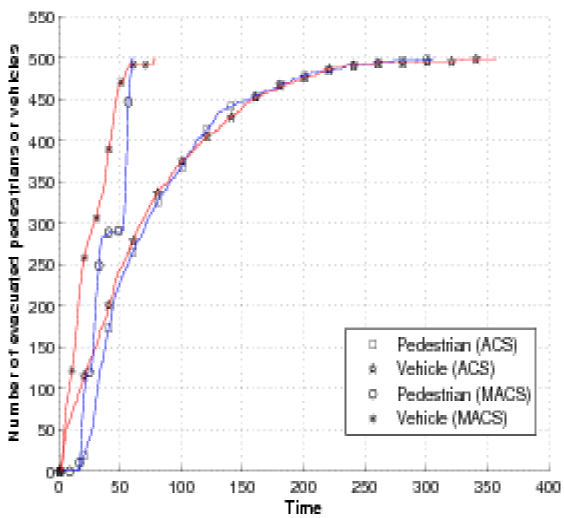

Fig. 5. Number of evacuated pedestrians/vehicles with time

VI. Conclusion

Large public areas with mixed traffic flow are easily attacked by catastrophic events, which cause serious results. Ant colony optimization is suitable for solving evacuation routing problem because of the queuing behavior and self-organization of ants in nature are similar to the movements of evacuees in evacuation process. But the positive feedback mechanism of single ant colony system may lead to congestion on some optimum routes. Different components of traffic flow compete and interact with each other during evacuation process, like different ant colony systems in nature.

In this study, an approach based on multi-ant colony system was proposed to tackle evacuation routing problem with mixed traffic flow. Total evacuation time is minimized and traffic load of the whole road network is balanced by this approach. The performance of MACS is compared with that of ACS approach. The experimental results show that the proposed approach based MACS can obtain better solutions than single ant colony system and solve evacuation problem under mixed traffic conditions with reasonable routing plans.

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TABLE I
RESULTS OF ACS AND MACS APPROACHES

Approach	Proportion	Pedestrians	Vehicles	f1	f2
ACS	1:1	300	300	1.2427e+006	7.9540
	1:1	500	500	2.3614e+006	9.7818
	5:1	500	100	1.9022e+006	19.996
	10:1	1000	100	1.0984e+007	19.453
	15:1	1500	100	8.3528e+008	28.638
MACS	1:1	300	300	1.2397e+006	2.1512
	1:1:	500	500	1.9495e+006	4.1079
	5:1	500	100	1.7432e+006	15.953
	10:1	1000	100	1.0648e+007	18.476
	15:1	1500	100	7.6106e+008	22.044

TABLE II
NUMBER OF EVACUEES EVACUATED FROM EACH EXIT

Exit No.	P	Percentage	V	Percentage	Proportion
1	235	47	30	30	8:1
2	23	4.6	3	3	7:1
3	15	3	9	9	2:1
4	13	2.6	2	2	7 : 1
5	7	1.4	3	3	2 : 1
6	40	8	19	19	2 : 1
7	69	13.8	16	16	4 : 1
8	98	19.6	18	18	5 : 1
Total	500	100	100	100	5 : 1
Average	62.5	12.5	12.5	12.5	5 : 1